CHAPTER 1

MOLYBDENUM-CATALYZED ASYMMETRIC ALLYLIC ALKYLATIONS

CHRISTINA MOBERG

KTH School of Chemical Science and Engineering, Organic Chemistry, SE 100 44 Stockholm, Sweden

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kimo@kth.se

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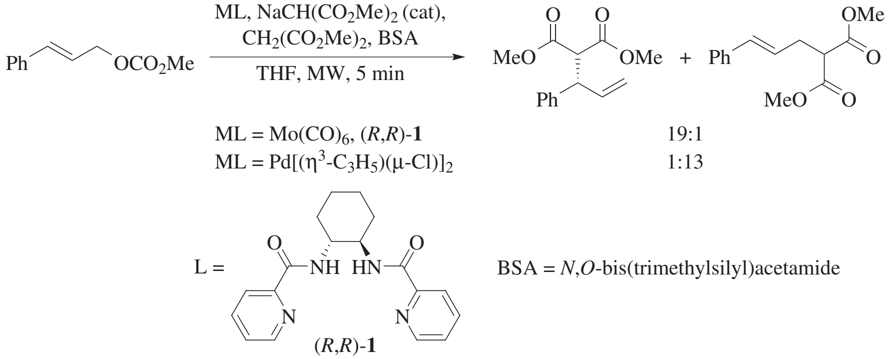
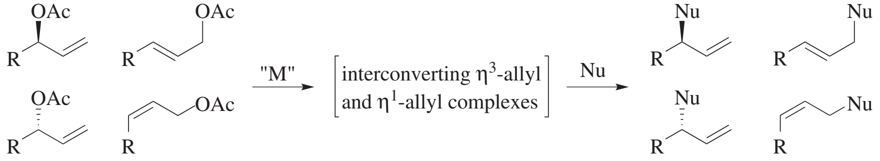
INTRODUCTION

Metal-catalyzed asymmetric allylic alkylations constitute synthetically versatile reactions whereby carbon–carbon and carbon–heteroatom bonds are formed, often with high chemo-, site-, and stereoselectivities. A variety of transition-metal complexes containing Pd, Mo, W, Ir, Ru, Rh, Fe, Cu, Ni, and Pt[1–3] catalyze the process by activating otherwise slow-reacting allylic groups. The substrates most commonly used are derivatives of allylic alcohols such as allylic acetates or other carboxylic esters, allylic carbonates, or phosphates. Stabilized or non-stabilized carbanions as well as nitrogen, oxygen, and sulfur nucleophiles can be used to displace the electrophile. The reactions usually occur under milder conditions than ordinary S_N2 or S_N2' reactions of halides or sulfonates. Catalysts containing palladium have been explored most extensively and applied in asymmetric synthesis.[4,5] The first molybdenum-catalyzed reactions were introduced by Trost and Lautens.[5a] Molybdenum,[6] as well as iridium[7] catalysts exhibiting high site- and stereoselectivity are known and serve as useful complements to the palladium catalysts since they typically form products with different connectivity. For example, whereas the molybdenum-catalyzed microwave-mediated reaction of 3-phenyl-2-propenyl methyl carbonate with sodium dimethyl malonate in the presence of ligand **1** provides the branched and linear products in a 19:1 ratio, the analogous palladium-catalyzed reaction gives the same isomers in a ratio of 1:13 (Scheme 1).[8]



Scheme 1

All asymmetric allylic alkylations (Pd, Mo, W, Ir, Ru, Rh, Fe, Cu, Ni, Pt) proceed via η^3- and/or η^1-allylmetal intermediates. The site- and stereoselectivities of the reactions are governed by several equilibria. Depending on the nature of the initially formed allyl complex and the extent of equilibration of the allyl intermediates, the original constitution and configuration of the substrate may be retained, inverted, or lost (Scheme 2). Loss of substrate constitution and configuration may lead to high selectivity even from mixtures of substrates differing in absolute configuration, configuration of the olefinic bond, and the site of the substituent, since the isomerization may lead to a single allyl intermediate. Under appropriate conditions, such selectivity is observed in reactions using catalysts based on palladium as well as molybdenum and iridium. The actual result of the catalytic reactions is a function of several factors, including the metal, the ligand, the nucleophile, and the substituents on the allyl system. For this reason the different types of catalysts can be highly complementary.

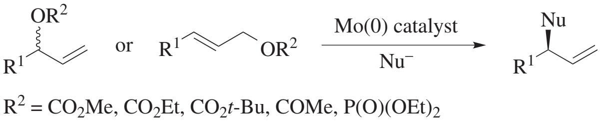


Scheme 2

Previous reviews covering molybdenum-catalyzed asymmetric allylic alkylations (AAA) are available.[9] Surveys of Mo-catalyzed AAA are also included in more general reviews that cover other metal-containing catalysts[1–3,6,10,11] or several types of processes.[12] Allylations catalyzed by Mo(0) complexes containing chiral ligands are described and listed in the Tables. Reactions proceeding via Mo(II)[13,14] and Mo(IV)[15] complexes are also known, but have different characteristics and proceed by a different mechanism. No examples of asymmetric induction in the Mo(II)/Mo(IV) processes are known, and therefore these reactions are not included here.

MECHANISM AND STEREOCHEMISTRY

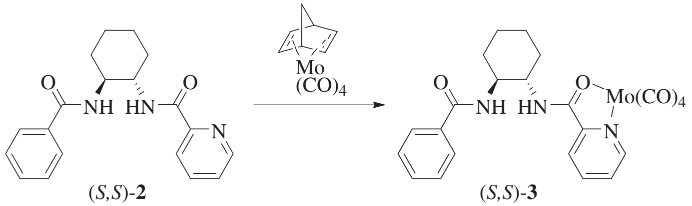
The mechanism of molybdenum-catalyzed nucleophilic substitutions of allylic acetates or carbonates has been studied in detail, in particular by Lloyd-Jones. The reactions proceed via oxidative addition of the substrate to a ligated Mo(0) species to form an asymmetric η^3-allylmolybdenum(II) complex, followed by coordination of the nucleophile to the metal, and final reductive elimination to form the product. The η^3-allyl complexes that are intermediates are rapidly equilibrating, which leads to the formation of a single major complex and thereby to high site- and stereoselectivity in the catalytic reactions (Scheme 3). Equilibration of intermediate η^3-allyl complexes is usually rapid in comparison to nucleophilic attack, and therefore close to equal mixtures of enantiomers and constitutional isomers are obtained from enantioenriched or racemic branched substrates as well as from linear substrates. However, under conditions where equilibration is slow compared to nucleophilic attack, lower enantioselectivity is observed in reactions using branched racemic substrates.



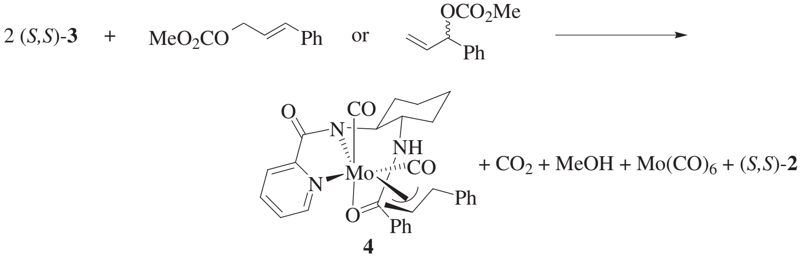
Scheme 3

Catalytic Cycle

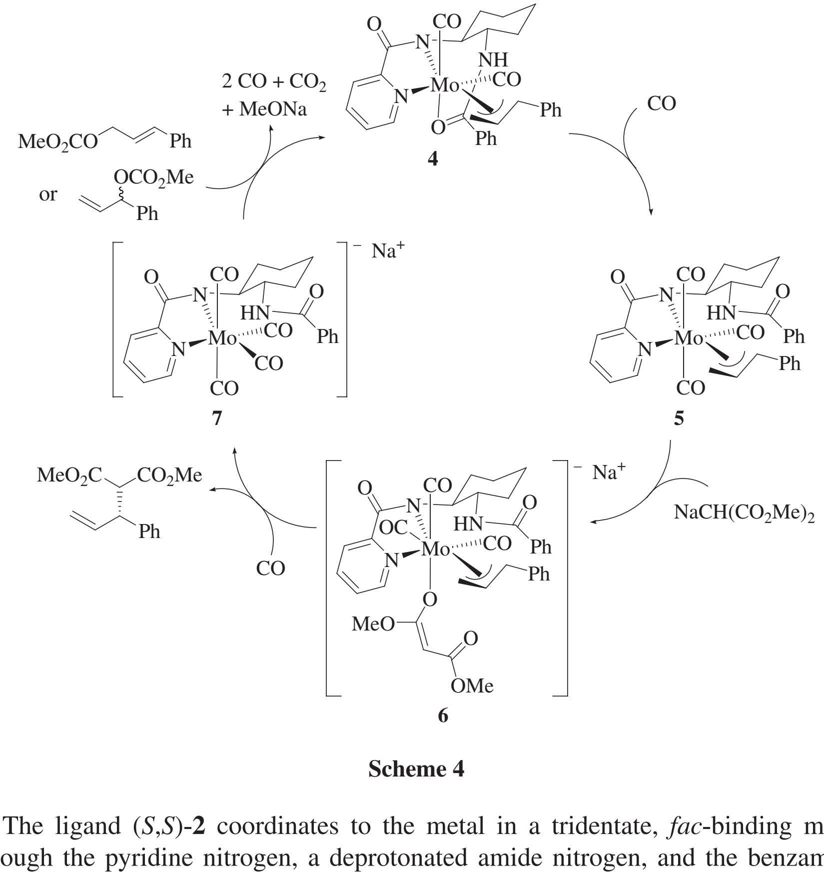
Detailed mechanistic studies have been performed using the monopyridine ligand (*S,S*)-**2**.[16] The generation of the catalytic intermediate is shown in Eqs. 1 and 2, and the catalytic cycle proposed for the reaction, which is in accordance with NMR spectroscopic and single-crystal X-ray structural data as well as with results from deuterium-labeling studies (see Enantiodifferentiation section), is shown in Scheme 4.[16,17] Ligand **2** combines with Mo(CO)$_4$(norbornadiene) to yield the neutral Mo(0) complex **3** (Eq. 1). Complex **3** then reacts with the substrate (linear or branched) to generate complex **4**, an 18-electron η^3-allylmolybdenum(II) complex with close to octahedral geometry, as determined by X-ray crystallography (Eq. 2).[18] The stoichiometry for the generation of complex **4** involves formation of one equivalent each of complex **4**, CO$_2$, MeOH, Mo(CO)$_6$, and free ligand from two equivalents of complex **3** and one equivalent of the allylic carbonate.



(Eq. 1)



(Eq. 2)

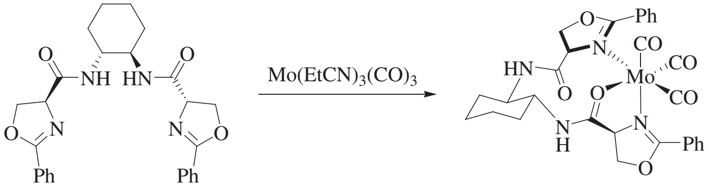


Scheme 4

The ligand (*S*,*S*)-**2** coordinates to the metal in a tridentate, *fac*-binding mode through the pyridine nitrogen, a deprotonated amide nitrogen, and the benzamide oxygen. The allyl group is slightly non-symmetrically bound ((1*R*,2*R*) configuration, close to η^3 coordination), is *syn* orientated with respect to two CO ligands, and is situated *trans* to the picolinamide nitrogen and *cis* to the benzamide oxygen.[17] The solid-state structure is consistent with that found in solution (see Enantiodifferentiation section).[19] The computed structure is also in good agreement with the observed structure.[20]

In the next step, the weakly bound amide carbonyl oxygen in structure **4** is replaced by a CO ligand (with formation of complex **5**), followed by coordination of malonate, likely through oxygen as shown in the suggested structure **6** (Scheme 4). Final reductive elimination yields the product and complex **7**, which together with complex **4** is the major ligand-containing species observed in solution. No reaction occurs when sodium malonate is added to isolated complex **4** in the absence of CO, since CO is needed for the formation of complex **5**, which reacts with malonate.[18] When $Mo(CO)_6$ is added to the mixture, it serves as the source of CO and the allylation reaction occurs.

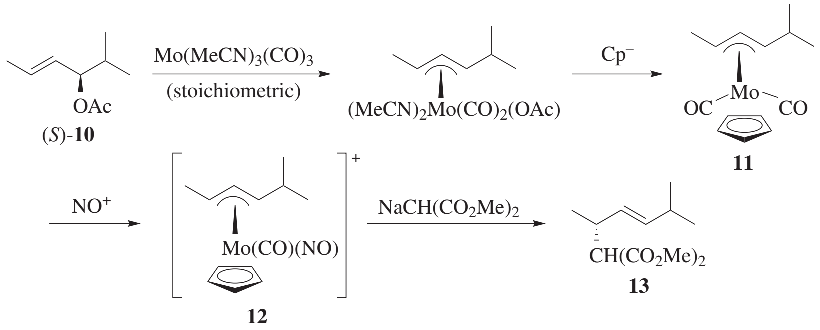
A Mo(0) complex of tetradentate bisoxazoline ligand (*S,R,R,S*)-**8** is obtained from reaction of the ligand with $Mo(EtCN)_3(CO)_3$ and its structure (complex **9**) has been determined by single-crystal X-ray analysis (Eq. 3).[21] The ligand binds to the metal via the two dihydrooxazole nitrogen atoms and one of the amide carbonyl groups. The remaining coordination sites are occupied by CO ligands. It is probable that an analogous complex, with both nitrogen atoms in the pyridine rings taking part in coordination to Mo, is initially formed in the catalytic cycle involving the bispyridinylamide ligand **1**.



(*S,R,R,S*)-**8** **9** (Eq. 3)

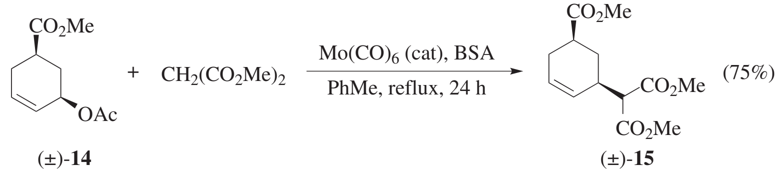
Stereochemistry

Oxidative addition of allylic acetates to Mo(0) species can proceed through either a retentive or an invertive mechanism. Addition of non-racemic acetate (*S*)-**10** to a stoichiometric amount of $Mo(MeCN)_3(CO)_3$ yields, after ligand exchange, η^5-cyclopentadienyl complex **11** with retention of configuration (Scheme 5), as established by X-ray crystallography.[22] (The same stereochemical course is observed upon oxidative addition of a cyclic allylic acetate to $Mo(MeCN)_3(CO)_3$).[23] Reaction of the cationic complex **12**–obtained by displacement of one carbonyl group of complex **11** by NO^+–with the sodium salt of dimethyl malonate at the more sterically accessible site affords the product (**13**) with inversion of configuration.[22] Net inversion of configuration is thus observed for the stoichiometric reactions.



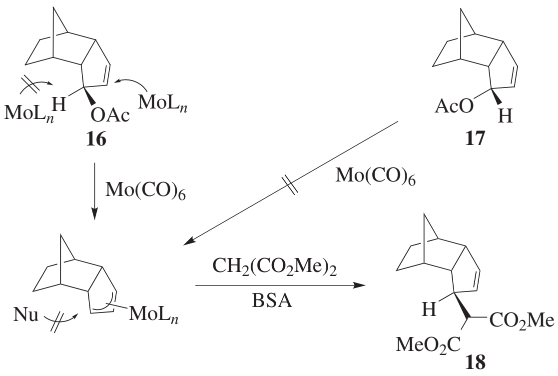
Scheme 5

In contrast, the major products obtained from chiral substrates (racemic or enantiomerically enriched) under catalytic conditions are those formed by overall retention of configuration, as shown by the reaction of racemic acetate **14** to yield malonate **15** (Eq. 4).[24,25]



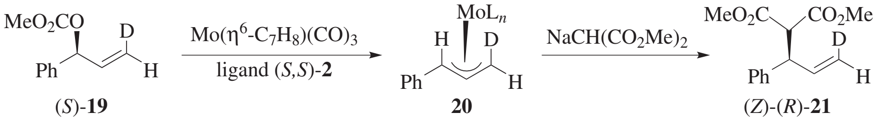
(Eq. 4)

The stereochemical course observed in Eq. 4 may be the result of either double inversion or double retention of configuration. Diastereomeric acetates **16** and **17**, which are inert toward attack from the *endo* face, serve as probes to elucidate the stereochemical course of each step in the catalytic process.[26] Whereas allylic acetate **16** reacts readily with $Mo(CO)_6$ followed by dimethyl malonate to provide product **18**, epimer **17** is inert, suggesting a mechanism in which both steps proceed by retention of configuration (Scheme 6).

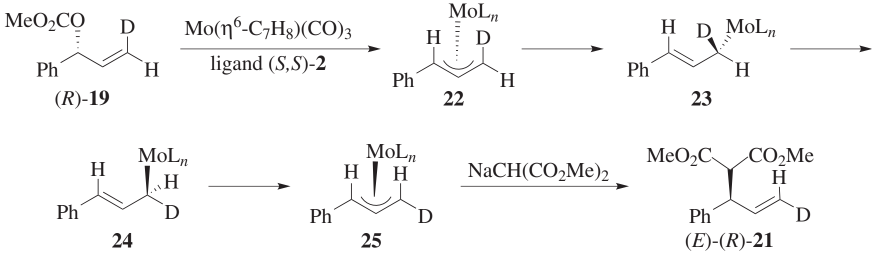


Scheme 6

Conclusive evidence for a retention-retention pathway was obtained using ligand (*S*,*S*)-**2** and Mo(η^6-C_7H_8)$(CO)_3$ in reactions of deuterium-labeled allylic carbonates (*S*)- and (*R*)-**19** with NaCH$(CO_2Me)_2$ as the nucleophile.[27] Substrate (*S*)-**19** affords malonate (*Z*)-(*R*)-**21** as the final product (Scheme 7), whereas (*R*)-**19**, which is the mismatched substrate, gives a product with the same absolute configuration but with inversion of configuration of the olefinic bond, malonate (*E*)-(*R*)-**21** (Scheme 8). The crystal structure of the protio allyl complex containing ligand (*S*,*S*)-**2**, complex **4** (see Catalytic Cycle section), corresponds to η^3-allyl complex **20**. This complex reacts with malonate to give the same product as substrate (*S*)-**19**, i.e., malonate (*Z*)-(*R*)-**21**. This result shows that substrate (*S*)-**19** affords an η^3-allyl complex with retention of configuration (**20**) and that the final product is obtained with retention of both absolute and geometrical configuration (Scheme 7). In contrast, allylic carbonate (*R*)-**19** forms an intermediate allyl complex that undergoes η^3–η^1–η^3 equilibration (intermediate **22** -> **23** -> **24** -> **25**, Scheme 8).[28,29] These results demonstrate that the reactions of the deuterated compounds are stereospecific. Both isomers of the substrate react with retention of configuration at the allylic carbon center, the apparent inversion of one isomer being the result of equilibration of the allyl complex. Overall, the two reactions are stereoconvergent at the allylic center.

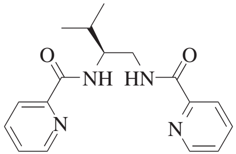


Scheme 7



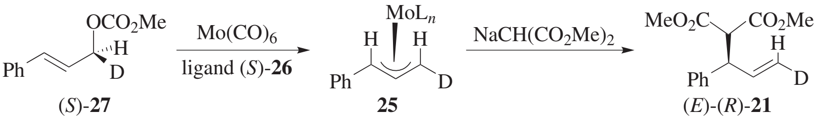
Scheme 8

Reactions of allylic carbonates (*S*)- and (*R*)-**19** in the presence of ligand (*S*)-**26** lead to the same products as those obtained using ligand (*S*,*S*)-**2**.[28] In the presence of the enantiopure ligand, the two enantiomers of carbonate **19** react at different rates: the fast-reacting isomer, (*S*)-**19**, is matched with ligand (*S*)-**26** and its enantiomer is mismatched. A small portion of slow-reacting enantiomer (*R*)-**19** (about 2.5% of the total amount of product) reacts with net inversion, possibly as a result of Mo–Mo transfer with inversion.



(*S*)-**26**

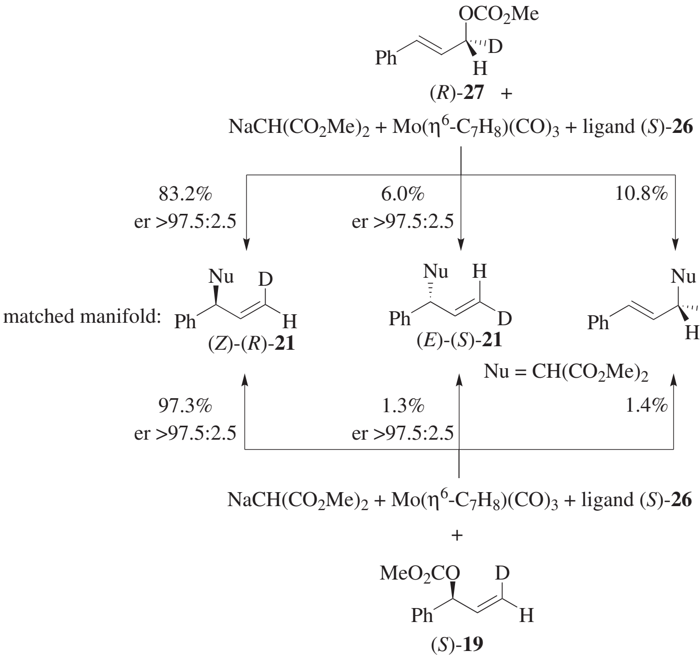
Linear substrates with a deuterium in the 1-position also react by a retention-retention pathway. Thus, linear, enantiomerically enriched deuterium-labeled carbonate (*S*)-**27** combines with $Mo(CO)_6$ and ligand (*S*)-**26** to form the η^3-allyl complex **25**, wherein the metal enters from the same side as the leaving group (Scheme 9).[27] Reaction of complex **25** with sodium dimethyl malonate yields product (*E*)-(*R*)-**21** with retention of configuration at the stereogenic center and at the newly formed double bond.



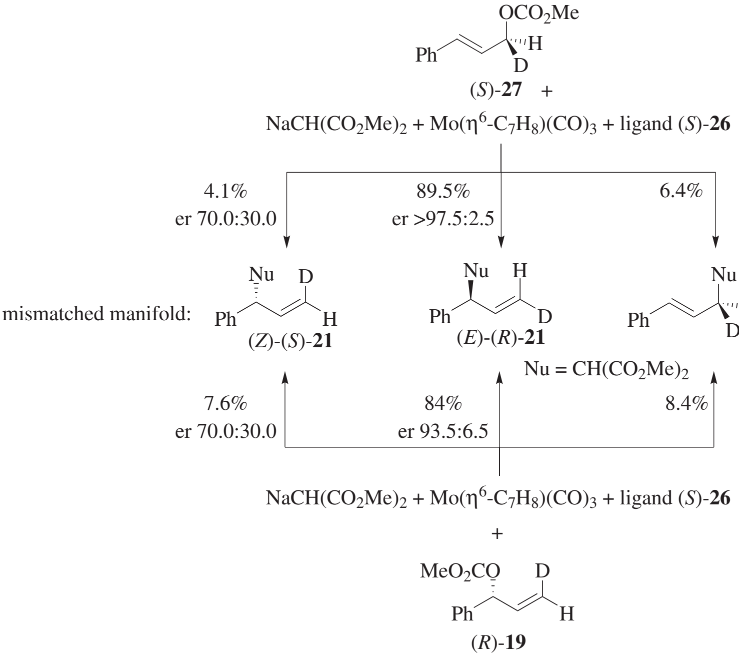
Scheme 9

The enantiomeric substrate, (*R*)-**27**, affords a branched product with the same absolute configuration as that obtained from allylic carbonate (*S*)-**27**, but with a (*Z*) configuration of the double bond. The minor, linear, constitutional isomer obtained from substrate (*R*)-**27** has the (*R*) configuration, whereas that formed from substrate (*S*)-**27** has the opposite absolute configuration; i.e., in both cases net retention of configuration is observed.[28] The reactions are summarized in Schemes 10 and 11, which show the matched and mismatched manifolds, respectively.[28] The matched and mismatched substrates provide branched products with the same absolute configuration, but the enantiomeric purity of that from the former is higher.

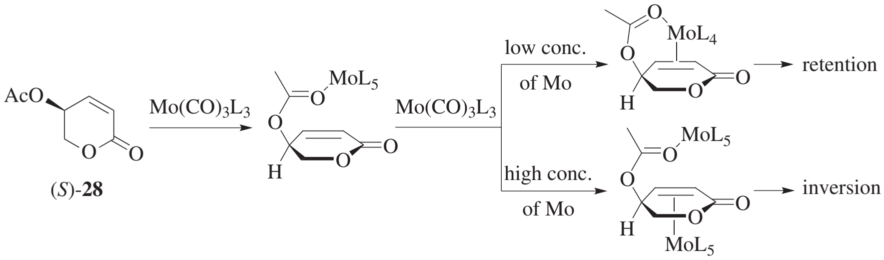
A rationale for the divergent stereochemical course of stoichiometric (net inversion) and catalytic (net retention) processes is provided on the basis of results from the oxidative addition of dihydropyranone (*S*)-**28** to $Mo(DMF)_3(CO)_3$, $Mo(toluene)_3(CO)_3$, and $Mo(CO)_6$.[30] Retention of configuration is favored at low effective concentration of the molybdenum complex (dilute solution, ≤ 1 equivalent of Mo(0)) and with easily displaced ligands, whereas inversion is observed at higher concentrations of Mo(0) (concentrated solution, >1 equivalent of Mo(0)). This suggests that transition structures leading to products from retention and inversion of configuration involve one and two Mo centers, respectively (Scheme 12). In contrast, initial coordination to the olefinic bond is observed with palladium catalysts under catalytic conditions, leading to oxidative addition with inversion of configuration.[31]



Scheme 10



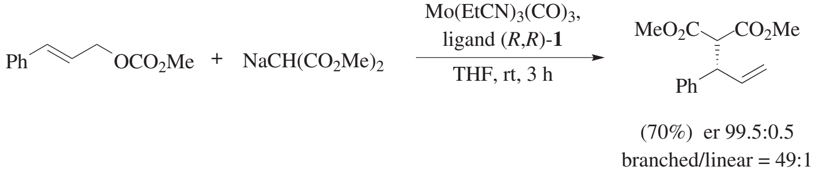
Scheme 11



Scheme 12

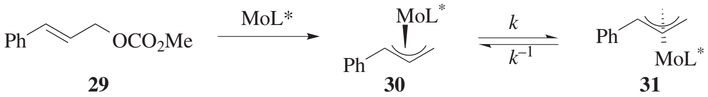
Enantiodifferentiation

The first enantioselective molybdenum-catalyzed reactions were discovered by Trost and coworkers.[32] A range of chiral ligands can be used to control the stereochemical course of the reactions of achiral or racemic substrates in molybdenum-catalyzed reactions. The most commonly used ligand is the readily accessible bis(pyridinylamide) **1** (Eq. 5),[32] although somewhat better results are achieved with derivatives carrying π-donating substituents on one[33] or both[34] pyridine rings (see Chart 1 and the Tabular Survey).



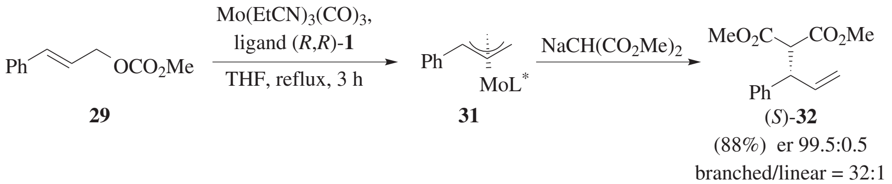
(Eq. 5)

In reactions with linear, achiral substrates such as allylic carbonate **29**, the catalyst may recognize one of the enantiotopic faces leading to selective formation of one of the diastereomeric η^3-allyl complexes **30** or **31** (Scheme 13). Alternatively, the two complexes may be in dynamic equilibrium, with one of them being preferentially attacked by the nucleophile. Both situations may lead to efficient enantiodiscrimination.



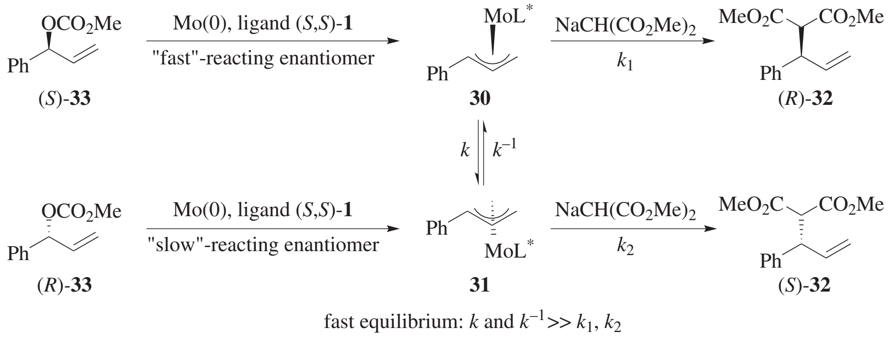
Scheme 13

In the presence of a catalyst prepared from $Mo(EtCN)_3(CO)_3$ and ligand (*R*,*R*)-**1**, (*E*)-3-phenyl-2-propenyl methyl carbonate (**29**) reacts with sodium dimethyl malonate to give malonate (*S*)-**32** as the major product (Scheme 14).[32] Knowing that the reaction proceeds via a retention-retention pathway, the major product must therefore be formed via complex **31**.



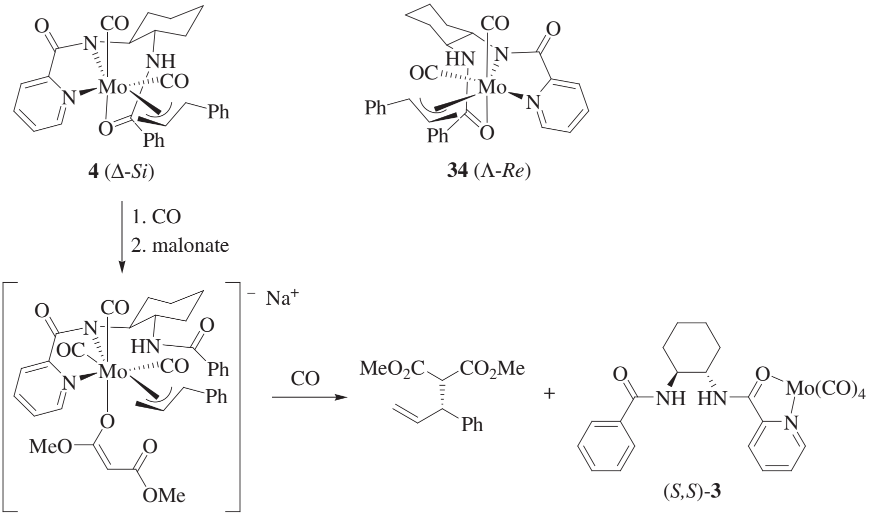
Scheme 14

Oxidative addition of allylic carbonates (*S*)-and (*R*)-**33** to the Mo•(*S*,*S*)-**1** catalyst leads to complexes **30** and **31**, respectively (Scheme 15; in the published[35] scheme an inversion-inversion mechanism was depicted). The absolute configuration of the product is determined by whether complex **30** or **31** reacts with the nucleophile. In contrast to the situation with linear substrates, reaction of the branched substrates in racemic form would, in the absence of isomerization of intermediate allyl complexes, inevitably lead to the formation of racemates. If, in contrast, equilibration of the diastereomeric η^3-allyl complexes is fast compared to nucleophilic attack, a dynamic kinetic asymmetric transformation (DYKAT)[36] results, which may lead to formation of a single enantiomer.[35] Branched substrates frequently react with somewhat lower enantioselectivity than the corresponding linear substrates, demonstrating that equilibration under certain conditions is not sufficiently rapid, resulting in a memory effect (see Memory Effects section). The isomerization process interconverting complexes **30** and **31** proceeds mainly via η^1-allylmolybdenum intermediates, although an analysis of the results from deuterium-labeling studies (Schemes 10 and 11) suggests that Mo–Mo transfer with accompanying inversion of configuration may account for the small portion of the net inversion observed[28] (compare Scheme 12).



Scheme 15

Several stereoisomers of the octahedral Mo(II) complex from oxidative addition of the allylic substrate to the Mo(0) precursor are possible. Pyridinylamide **2**, with only one pyridine ring, coordinates facially via the pyridine nitrogen atom, one deprotonated amide nitrogen atom, and one carbonyl oxygen atom (see Catalytic Cycle section), resulting in either of two diastereomeric complexes (with opposite configurations at Mo). In each structure, three diastereotopic coordination sites remain for the allylic group (opposite to pyridine, to nitrogen, and to oxygen), which can bind via either of its two faces, thus giving rise to twelve possible stereoisomers. In addition, the allylic group can rotate around the Mo–allyl axis. A single major compound is observed in solution. This major allyl complex is in dynamic equilibrium with a diastereomeric complex with molybdenum bound to the same face of the allylic group, present in about 1% abundance. By multinuclear solution NMR studies of the major complex, its structure is identified as having either Δ-*Si* (**4**) or Λ-*Re* (**34**) configuration (Scheme 16);[17] the former structure corresponds to that found in the solid state.[18]



4 (Δ-*Si*)

34 (Λ-*Re*)

6

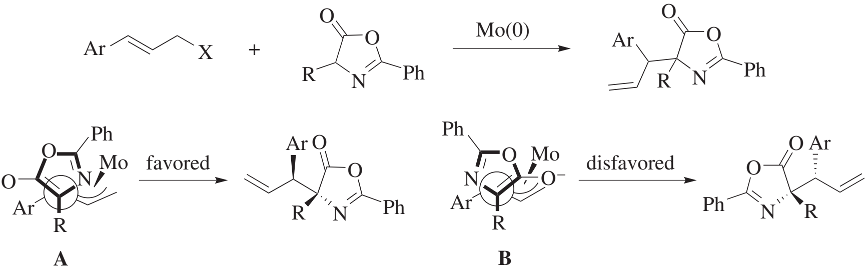
(*S*,*S*)-**3**

Scheme 16

Although one face of the allylic group in **4** clearly is open for approach by the nucleophile, attack by malonate from that direction leads to the product of opposite configuration to that observed.[16] The product obtained in the catalytic reaction may therefore be the result of nucleophilic attack on a minor, not observed, complex or of pre-coordination of the nucleophile to the metal followed by reductive elimination, and thus attack occurs at the allylic group from the side of the metal. ^{1}H NMR spectroscopic studies of the η^3-allyl complexes and products obtained using deuterated substrates (*S*)-**19** and (*R*)-**19** reveal that the latter situation is what actually occurs (Scheme 16, compare Schemes 7 and 8). The retention-retention pathway can thus be rationalized by the mechanism that proceeds via CO coordination to form a tris(CO) intermediate followed by complexation of the nucleophile to form a seven-coordinate intermediate, which undergoes reductive elimination to yield the final product (see Scheme 4).

According to DFT calculations, complex **4** is the most stable of the possible isomers for electronic as well as steric reasons; bonding and back-bonding interactions between molybdenum and the η^3-allyl ligand are maximized and steric interactions are minimized.[20]

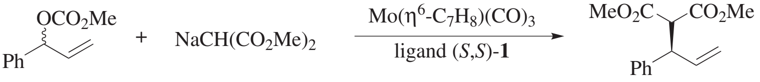
Rationales for the stereochemical course observed in reactions with other nucleophiles have been provided on the basis of stereochemical course of the catalytic process with malonate. In reactions of prochiral α-imino lactone enolates and cinnamyl derivatives (Scheme 17), the facial selectivity with respect to the allylic unit is the same as with malonate. This conclusion is deduced from the absolute and relative configurations of the amino acid obtained by hydrolysis of one of the products (with Ar = 2-bromophenyl, R = methyl), as determined by single-crystal X-ray analysis. Structures **A** and **B**, which represent different face selectivities with respect to the enolate, have been suggested as models for the transition structure. The observed product is that originating from structure **A**, where the enolate reacts from its *Re* face. MM2 calculations suggest this diastereomer to be more stable than that originating from structure **B**.[37] Analogous models are suggested to explain the diastereoselectivity in reactions with prochiral oxalactims[38] and 3-aryloxindoles.[39]



Scheme 17

Memory Effects

With some ligands, slightly different enantio- and site selectivities are observed in products obtained from linear and branched substrates; the slower-reacting, mismatched enantiomer of the branched precursor may result in a product with lower enantiomeric purity. For example, in the presence of ligand (*S,S*)-**1** and Mo(η^6-C_7H_8)$(CO)_3$, carbonate (*R*)-**33** is the mismatched, slower-reacting substrate.[35] Transformation of substrate (*R*)-**33** to the major product enantiomer, (*R*)-**32**, requires isomerization of the intermediate allyl complex (see Scheme 15). Incomplete isomerization leads to the formation of a higher proportion of the minor enantiomer, (*S*)-**32**, from (*R*)-**33** than from (*S*)-**33**, resulting in a memory effect. (A memory effect can be defined as a situation in which isomeric substrates, e.g., enantiomers, lead to different products or product ratios, when the basic mechanism predicts that they should not.[40]) The extent of this memory effect is dependent on the solvent because the relative rates of the two processes vary with different solvents (Scheme 18).[35] In the presence of ligand (*S,S*)-**1**, carbonate (*S*)-**33** thus reacts faster, with higher enantioselectivity, and with higher branched to linear ratio with dimethyl malonate than its enantiomer.[35] For this reason, the product obtained during the first half of the reaction of racemic carbonate **33** has high enantiomeric purity, which deteriorates as the reaction proceeds (from er 99.0:1.0 to er 93.5:6.5 at 48° in THF) at the same time as the branched to linear ratio decreases from 35:1 to 25:1. The k_{rel} for the two enantiomers is 9 (see Kinetic Resolution section, Scheme 21). Under the same conditions, the enantiomeric ratio of the product obtained from linear substrate **29** is constant over time (98.5:1.5 er).[35]



rac-**33**

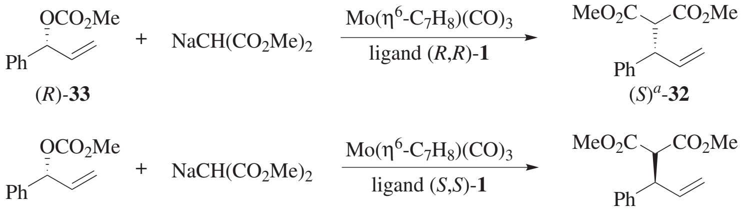
(*R*)^a-**32**

Solvent	Temp (°)	er
THF	48	93.5:6.5
MeCN	48	91.5:8.5
PhMe	60	98.0:2.0

[a] Erroneously reported with the opposite absolute configuration in ref. 35.

Scheme 18

Reaction of allylic carbonate (*R*)-**33** in the presence of the matched ligand (*R*,*R*)-**1** affords malonate (*S*)-**32** with er 99.5:0.5 and er 99.0:1.0 in THF and MeCN, respectively (Scheme 19).[35] In the presence of mismatched ligand (*S*,*S*)-**1**, carbonate (*R*)-**33** provides a product with opposite configuration with er 85.0:15.0 and er 72.0:28.0 in THF and MeCN, respectively (Scheme 19).[35] For the mismatched case in THF, the enantioselectivity is improved to er 95.5:4.5 by slow addition of the nucleophile, consistent with the assumption that slow equilibration of the diastereomeric η^3-allyl complexes is the reason for the memory effect (compare Scheme 15). A more reactive nucleophile, dimethyl methylmalonate,[25] accordingly results in a more pronounced memory effect.



(*R*)-**33**

(*S*)^a-**32**

(*R*)-**33**

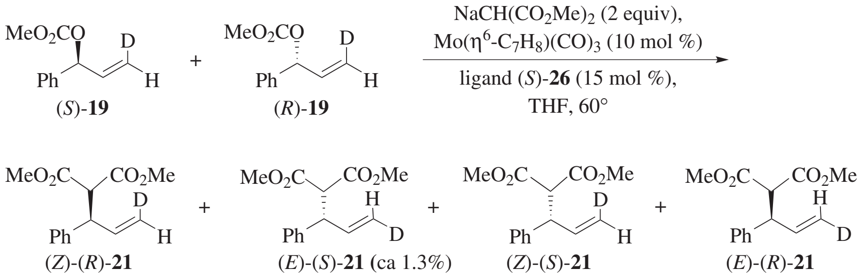
(*R*)^a-**32**

Ligand	Solvent	Temp (°)	er
(*R*,*R*)-**1**	THF	48	99.5:0.5
(*S*,*S*)-**1**	THF	48	85.0:15.0
(*R*,*R*)-**1**	PhMe	60	99.75:0.25
(*S*,*S*)-**1**	PhMe	60	95.0:5.0
(*R*,*R*)-**1**	MeCN	48	99.0:1.0
(*S*,*S*)-**1**	MeCN	48	72.0:28.0

[a] Erroneously reported with the opposite absolute configuration in ref. 35.

Scheme 19

Reaction of allylic carbonate *rac*-**19** with sodium dimethyl malonate in the presence of Mo(η^6-C_7H_8)(CO)$_3$ and ligand (*S*)-**26** permits the fate of the two individual enantiomers to be determined over time.[28] Substrate (*S*)-**19**, which is the matched enantiomer with regard to ligand (*S*)-**26**, affords product (*Z*)-(*R*)-**21** with high selectivity, along with trace amounts of (*E*)-(*S*)-**21**, which has inverted double bond geometry (Scheme 20). In the initial phase of the reaction (at <30% conversion) the mismatched substrate, (*R*)-**19**, affords predominantly the opposite enantiomer, (*Z*)-(*S*)-**21**, but because of the different rates of reaction of the two enantiomers, (*Z*)-(*R*)-**21** is the major product, although with low er. After about 30% conversion, the memory effect disappears and generation of malonate (*Z*)-(*S*)-**21** thus ceases. For this reason the er of malonate (*Z*)-(*R*)-**21** increases, from 78.5:21.5 after 46% conversion to 98.0:2.0 at 46–100% conversion; at full conversion the overall er is 90.0:10.0. The origin of the attenuation of the memory effect as the reaction proceeds is in this case not due to a decrease in concentration of the nucleophile, since an excess of malonate was used. Instead it may be related to depletion of carbon monoxide and/or Mo(CO)$_6$ due to the high reaction temperature (60°); carbon monoxide is essential for catalytic turnover and a lower concentration results in lower rate of nucleophilic attack, which leads to more efficient equilibration of the diastereomeric η^3-allyl complexes (see Scheme 15).



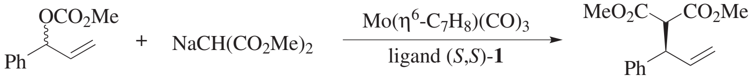
at 60% conversion: (*Z*)-(*R*)-**21** major, er 78.5:21.5
at 100% conversion: (*Z*)-(*R*)-**21** major, er 90.0:10.0

Scheme 20

Kinetic Resolution

In the presence of a chiral, nonracemic ligand and a molybdenum source, reaction of a racemic, branched carbonate leads to two diastereomeric allylmolybdenum complexes (via retentive oxidative addition). Because of rapid equilibration of the diastereomeric η^3-allylmolybdenum complexes, the same major enantiomer of the product is obtained from either enantiomer of the substrate. The rates by which the two enantiomers of the carbonate react with the chiral molybdenum complex may be different, the fast-reacting enantiomer leading to the matched complex and the slow-reacting isomer leading to the mismatched complex. The result is a kinetic resolution, which may afford both enantioenriched starting material and product.

A large difference in relative rates of reaction of the two enantiomers does not necessarily lead to large memory effects, as this effect is a result of the equilibrium being slow compared to nucleophilic attack. For carbonate *rac*-**33**, k_{rel} values in the range 8–13 are observed in reactions with sodium dimethyl malonate in different solvents catalyzed by Mo(η^6-C_7H_8)(CO)$_3$ and ligand (*S*,*S*)-**1** (Scheme 21).[35]



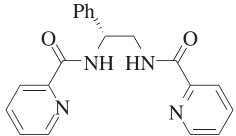
rac-**33**

Solvent	Temp (°)	k_{rel}[a]
THF	48	9
MeCN	48	8
PhMe	60	13
i-PrOAc	48	8
tetrahydropyran	48	8
$ClCH_2CH_2Cl$	75	10

[a] Determined from $k_{rel} = \ln[(1 - c)(1 - ee)]/\ln[(1 - c)(1 + ee)]$ at 50% conversion.

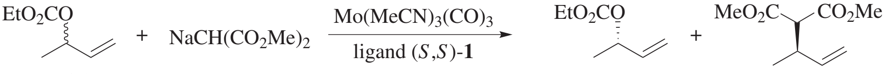
Scheme 21

The relative rates of the reactions of the carbonate enantiomers are dependent on the ligand. Thus, lower selectivity factors are observed in reactions with ligands (*S*)-**26** and its (*R*)-phenyl analogue (*R*)-**35** (k_{rel} = 2 in favor of the (*S*)-substrate and k_{rel} = 3 in favor of the (*R*)-substrate, respectively, in THF)[28] than in reactions with ligand (*S*,*S*)-**1**.



(*R*)-**35**

Kinetic resolution of carbonate *rac*-**36** takes place in the allylation of sodium dimethyl malonate in the presence of Mo(MeCN)$_3$(CO)$_3$ and ligand (*S*,*S*)-**1**. Use of substoichiometric amounts of malonate affords carbonate (*S*)-**36** in up to er 82.0:18.0 at 47% conversion (Eq. 6).[41] The process thus constitutes a method for the preparation of enantioenriched allylic carbonate (*S*)-**36** and, after hydrolysis, the corresponding alcohol.



rac-**36** 0.5 equiv (*S*)-**36**

er 82.0:18.0 at 47% conv.

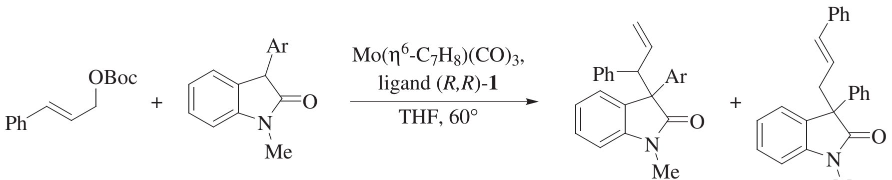
(Eq. 6)

SITE SELECTIVITY

The site selectivity is a function of the ligand, the allylic substrate, and the nucleophile. In early studies complexes with achiral ligands exhibited rather poor site selectivity. The site selectivity has been suggested to be governed by the charge, the more positive carbon atom in the allylmetal fragment being preferentially attacked by the nucleophile.[42] Consideration of frontier-orbital overlap leads to the same conclusion.[42]

The site selectivity is not a consequence of reaction via an η^1-allylmolybdenum species bound through the C(3)-allylic carbon since that mechanism would not explain the observed memory effect, as branched and linear carbonates would lead to the same η^1-allyl intermediate.[16] Therefore, η^3-allyl complexes are more likely intermediates.

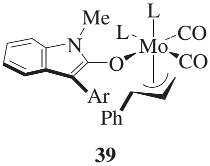
Enolates can bind to Mo(II) via carbon[43] as well as oxygen[44] and the mode of binding as well as the rate of interconversion of the two types of complexes has been suggested to influence the constitution of the product.[39] A relationship between the electronic properties of the *para*-substituent of 3-aryloxindoles and the branched/linear selectivity is observed: increasing the electron-withdrawing character of the substituent leads to both lower branched to linear (products **37**/**38**) selectivity and diastereoselectivity (Scheme 22).[39] In contrast to expectations, oxindoles with sterically demanding aryl groups, such as 3-(2-tolyl) and 3-(1-naphthyl), have a strong preference for the formation of branched products, whereas those containing smaller aryl groups, such as 2-thienyl and *N*-methyl-3-indolyl, afford exclusively linear products.[39] This outcome is rationalized by suggesting that larger aryl groups should favor the sterically less-congested oxygen-bound enolate structure **39** over carbon-bound structure **40**. In addition, lower steric strain in the oxygen-bound enolate allows bond formation to the substituted allylic terminus to occur.



37 **38**

Ar	**37**/**38**	dr **37**
Ph	18:1	8:1
4-MeOC_6H_4	18:1	8:1
4-ClC_6H_4	13:1	5.5:1
4-NCC_6H_4	7:1	4.5:1

Scheme 22



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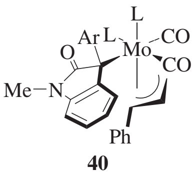
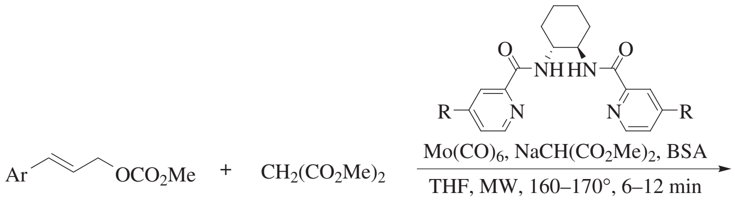
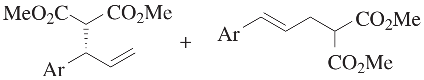


40

A reaction mechanism involving divergent modes of reaction for oxygen-bound (**39**) and carbon-bound (**40**) enolate complexes has been suggested to rationalize the different site selectivities observed with different nucleophiles.[45]

The site selectivity is also influenced by the substituents on the electrophile and on the ligand. In reactions with 4-substituted (*E*)-cinnamyl methyl carbonates with sodium dimethyl malonate in the presence of ligand (*R,R*)-**1** (R = H), or derivatives of ligand (*R,R*)-**1**, and $Mo(CO)_6$ under microwave conditions, lower branched/linear site selectivity (products **41/42**) is observed for substrates with electron-withdrawing substituents (Scheme 23).[34] π-Donating substituents in the ligand lead to increased site selectivity (Scheme 23).[34]





(*S*)-**41** **42**

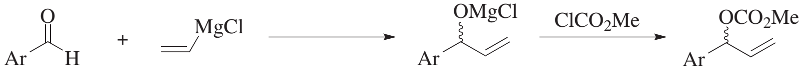
Ar	R	**41/42**
Ph	H	19:1
Ph	Cl	74:1
Ph	1-pyrrolidinyl	88:1
4-$MeOC_6H_4$	H	51:1
4-$MeOC_6H_4$	Cl	57:1
4-ClC_6H_4	H	32:1
4-ClC_6H_4	Cl	47:1
4-$CF_3C_6H_4$	H	11:1
4-$CF_3C_6H_4$	Cl	22:1

Scheme 23

SCOPE AND LIMITATIONS

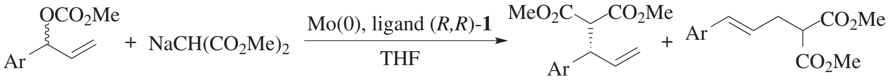
The Allylic Substrate

Because allylic carbonates are more reactive substrates than allylic acetates, the comparison of allylic moieties will be done for their carbonates. *rac*-1-Aryl-2-propenyl methyl carbonates are conveniently prepared by the addition of vinylmagnesium chloride to the appropriate aryl aldehyde and subsequent treatment with methyl chloroformate (Scheme 24).[46] Cinnamyl derivatives are less readily available, and although enantioselectivities due to memory effects may be somewhat lower starting from the branched substrates, the latter are usually the substrates of choice because of their availibility. Isomerization of branched to linear substrates is, however, possible using both palladium(0)[47] and palladium(II)[48] catalysts.



Scheme 24

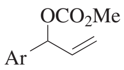
Allylic substrates with aryl (carbonates **43** and **44**) and alkenyl substituents (e.g., carbonate **45**[49]) undergo reaction, although the latter type of substrate requires higher reaction temperatures. Both electron-rich (e.g., methyl 1-(2-thienyl)-2-propenyl carbonate[32] and methyl 3-(4-methoxyphenyl)-2-propenyl carbonate[34]) and electron-deficient (e.g., methyl 1-(2-pyridinyl)-2-propenyl carbonate[32] and methyl 3-(4-(trifluoromethyl)phenyl)-2-propenyl carbonate[34]) aromatic compounds, as well as moderately hindered (methyl 1-(1-naphthyl)-2-propenyl carbonate) aromatic substrates provide high yields of products, with the branched to linear ratio as well as the enantiomeric purity of the branched product depending on the nature of the substrate and the catalyst (Scheme 25). Substrates with alkyl substituents, such as carbonates **46** and **47**, react sluggishly and therefore require prolonged reaction times, and substrates **48–51** fail to react.[50] Allyl sulfones have been used but only in combination with achiral catalysts; the sulfone group proves to be a better leaving group than an aliphatic chloride substituent.[51]



(*S*)-**41** **42**

Ar	Conditions	Yield (%) **41 + 42**	**41/42**	er	Refs.
2-thienyl	$Mo(EtCN)_3(CO)_3$, reflux, 2–3 h	78	19:1	94.0:6.0	32
2-pyridinyl	$Mo(EtCN)_3(CO)_3$, reflux, 2–3 h	69	8:1	98.0:2.0	32
Ph	$Mo(EtCN)_3(CO)_3$, reflux, 2–3 h	70	13:1	96.0:4.0	32
Ph	$Mo(CO)_6$, MW, 165°, 6 min	76	13:1	98.0:2.0	34
4-ClC_6H_4	$Mo(CO)_6$, MW, 165°, 6 min	78	26:1	98.0:2.0	34
4-$CF_3C_6H_4$	$Mo(CO)_6$, MW, 165°, 6 min	48	10:1	99.0:1.0	34
1-naphthyl	$Mo(EtCN)_3(CO)_3$, reflux, 2–3 h	82	99:1	93.5:6.5	32

Scheme 25



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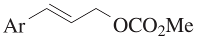

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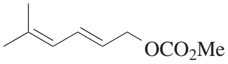

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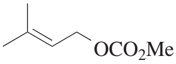

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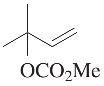

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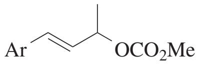

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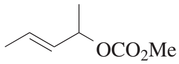

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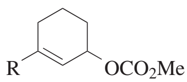

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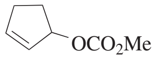
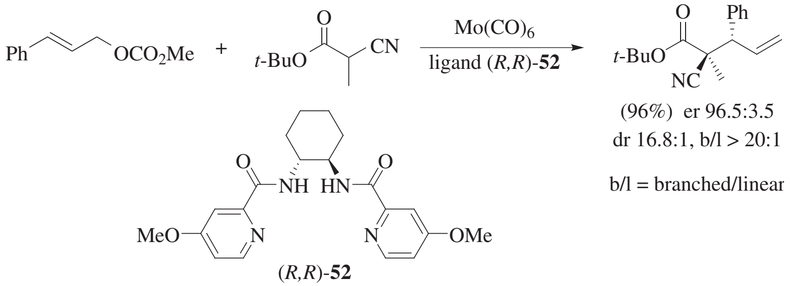


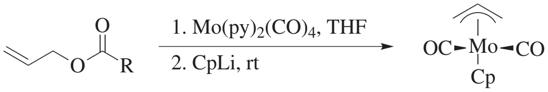
51

Quaternary centers on the nucleophile can be created with good stereocontrol.[37−39,52] Cyano-esters, for example, react with allylic carbonates in the presence of $Mo(CO)_6$ and ligand **52** (Eq. 7).[52]



(Eq. 7)

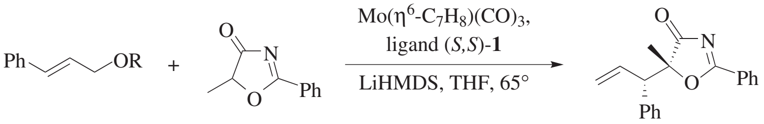
The Leaving Group. The rate of oxidative addition of the allylic substrate to Mo(0) is dependent on the donor ability of the leaving group. This observation is in line with the proposed mechanism, which involves initial coordination of Mo to the carbonyl oxygen. An optimum among acyl groups in terms of reaction time and yield is reached with the unsubstituted benzoate (Scheme 26).[53] A further increase in donor capacity of the leaving group leads to further increase in reaction rate, but yields decrease.



R	Time (h)	Yield (%)
CF_3	25	70
Me	10	75
$4\text{-}FC_6H_4$	8	82
$4\text{-}ClC_6H_4$	7	88
Ph	6.5	94
$4\text{-}MeOC_6H_4$	5.5	80
$4\text{-}Me_2NC_6H_4$	4	47

Scheme 26

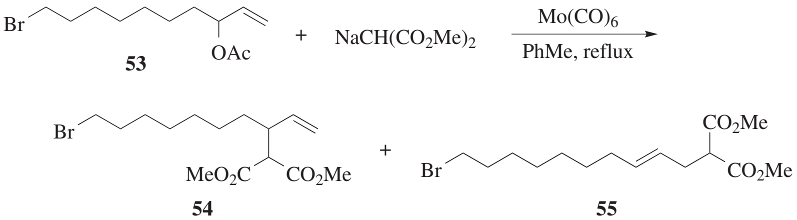
In reactions with oxalactims (oxazolidine-4-ones), the carbonate serves as a better leaving group than the phosphate, as demonstrated by the higher branched to linear ratio, diastereomeric ratio, and enantiomeric purity of the product (Scheme 27).[38]



R	er	dr	b/l
MeO_2C	>99.5:0.5	11.5:1	99:1
$(EtO)_2PO$	98.0:2.0	8.1:1	7:1

Scheme 27

Functional-Group Compatibility. Molybdenum-catalyzed allylic alkylations are compatible with the presence of ketone, enone, ester, sulfone, acetal, olefin, alkyl halide, silyl,[54] allyl ether, silyl ether, and enol ether functional groups.[25,51] In the presence of $Mo(CO)_6$ displacement of only acetate by malonate takes place in bromo-substituted allylic acetate **53** in refluxing toluene to yield compounds **54** and **55** in a ratio of 5.5:1 (Eq. 8), whereas in the absence of the molybdenum complex displacement of bromide occurs instead.[25] In contrast to the situation with palladium catalysts, silicon substituents in allylic or vinylic position are not protodesilylated.[25] (*E*) Double bonds are preferentially formed over (*Z*) double bonds from substrates with both (*E*) and (*Z*) configurations.[25]

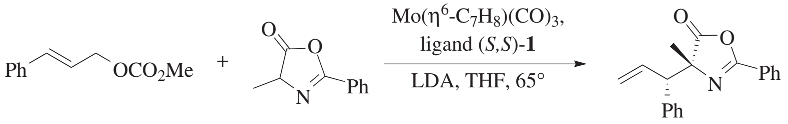


54 + **55** (82%), **54**/**55** = 5.5:1

(Eq. 8)

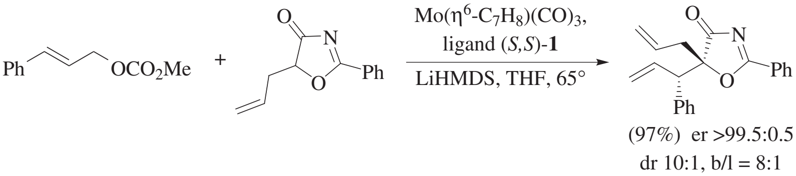
The Nucleophile

Molybdenum-catalyzed allylic substitutions are currently limited to the use of stabilized carbon nucleophiles. Most reactions to date have been performed using dialkyl malonates as the nucleophiles. The more hindered diethyl methylmalonate reacts readily, but a further increase in steric bulk to diethyl allylmalonate slows the reaction.[32] β-Diketones and β-keto esters are usually not sufficiently reactive to serve as the nucleophiles, but the sodium salt of 2-carbomethoxycyclopentanone is allylated by 2-[(trimethylsilyl)methyl]allyl acetate under ligand-free conditions ($Mo(CO)_6$, toluene, reflux).[55] In contrast, the anions of 4-alkyl-2-phenyloxazol-5(4*H*)-ones (α-imino lactones, Eq. 9),[37] 5-alkyl-2-phenyloxazol-4(5*H*)-ones (oxalactimes, Eq. 10)[38] and oxindoles (Eq. 11)[39,45,56,57] are competent as nucleophiles and represent the first examples of control of configuration at the nucleophile. 3-Aryloxindoles with sterically demanding aryl groups, such as 2-naphthyl and 2,4-diphenyl-5-oxazolyl, are readily allylated with high preference for bond formation at the internal allylic position. From these reactions, highly functionalized chiral oxindoles bearing a quaternary stereocenter and an adjacent tertiary stereocenter are obtained.

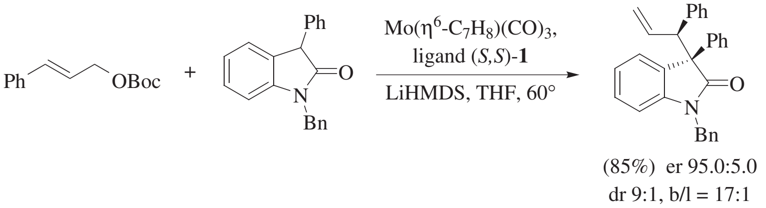


(92%) er 99.5:0.5
dr 32:1

(Eq. 9)



(Eq. 10)

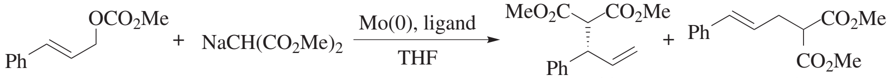


(Eq. 11)

Chiral Ligands

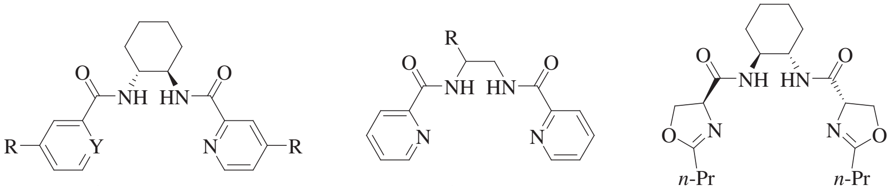
Molybdenum(0) complexes such as $Mo(EtCN)_3(CO)_3$, $Mo(\eta^6\text{-}C_7H_8)(CO)_3$ (C_7H_8 = cycloheptatriene), or $Mo(CO)_6$ can be used as catalyst precursors together with chiral ligands. Enantiomerically enriched *trans*-1,2-bis[(2-pyridinylcarbonyl)amino]cyclohexane (**1**) and derivatives of this ligand[58] impart high enantio- and site selectivity (branched product **32** versus linear product **56**) in molybdenum-catalyzed asymmetric allylic alkylations (Scheme 28).[32] The parent ligand **1**, is conveniently prepared in one step,[59] even on large scale,[60] and is also commercially available in both enantiomeric forms. Ligands wherein one 2-pyridinyl ring is replaced by either a 3-pyridinyl or a phenyl group (ligand **2**) afford comparable or even higher asymmetric induction compared to ligand **1**, although the catalytic activity is reduced, whereas replacement of both pyridinyl groups by phenyl groups results in a poor ligand.[19] Increased steric bulk leads to reduced reactivity, as demonstrated by ligands containing one or two 2-quinolyl groups instead of 2-pyridinyl groups; use of the former results in only traces of product.[19] The presence of π-donating substituents in the 4-position of one or both of the pyridinyl rings (ligand **52**) increases the enantio- and site selectivities (Scheme 28).[33,34,45]

Methylation of one of the ligand amide groups results in reduced activity, and methylation of both groups affords an unreactive ligand.[28] Replacement of an amido group with an ester group produces ligands with very low (**58**)[28] or no (**59**)[61] activity, and ligands with two ester groups are inactive.[19] C_1-Symmetric pyridinylamides, prepared from readily available amino alcohols (obtained by reduction of naturally occurring amino acids) are viable alternatives to C_2-symmetric ligand **1**.[19,28] The enantioselectivities obtained with the C_1-symmetric ligands vary with the nature of the substituent on the diamine and decrease in the order *i*-Pr (ligand **26**) > Ph (ligand **35**) > CH_2Ph > *t*-Bu.[28] Thus, two rigid amide groups, one stereocenter, and one pyridine ring are essential in the ligand for the asymmetric allylic alkylation reaction to proceed selectively.



(*S*)-**32** **56**

			Yield (%)				
Ligand	Mo catalyst	Conditions	**32 + 56**	**32/56**	er	Config.	Refs.
(*R,R*)-**1**	$Mo(EtCN)_3(CO)_3$	65°, 3 h	88	32:1	99.5:0.5	(*S*)	32
(*R,R*)-**52**	$Mo(CO)_6$	MW, 4 min	88	41:1	>99.5:0.5	(*S*)	33
(*S,S*)-**2**	$Mo(EtCN)_3(CO)_3$	—	90	60:1	99.5:0.5	(*R*)	19
(*S*)-**26**	$Mo(EtCN)_3(CO)_3$	60°, 12 h	68	32:1	99.0:1.0	(*R*)	33a
(*R*)-**35**	$Mo(EtCN)_3(CO)_3$	60°, 4 h	63	8:1	96.0:4.0	(*S*)	33a
(*S,S,S,S*)-**57**	$Mo(EtCN)_3(CO)_3$	70°, 1 d	83	6:1	99.0:1.0	(*R*)	21

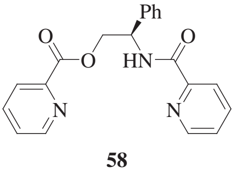


(*R,R*)-**1**, Y = N, R = H
(*R,R*)-**52**, Y = N, R = OMe
(*S,S*)-**2**, Y = CH, R = H

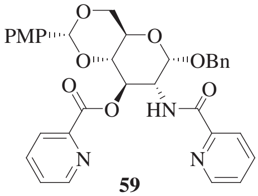
(*S*)-**26**, R = *i*-Pr
(*R*)-**35**, R = Ph

(*S,S,S,S*)-**57**

Scheme 28

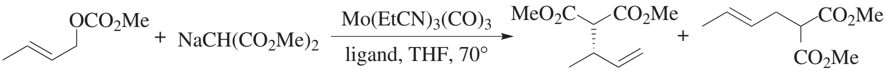


58



59

Ligands such as **8** (see Eq. 3) and **57**, containing dihydrooxazole rings in place of pyridinyl rings, provide products with high site- (branched product **60** versus linear product **61**) and enantioselectivities (Scheme 29).[21,62] The presence of four stereocenters presents the opportunity for the preparation of diastereomeric ligands.



(*S*)-**60** **61**

		Yield (%)			
Ligand	Time (d)	**60 + 61**	**60/61**	er	Config.
(*S,R,R,S*)-**8**	3	76	7:1	92.5:7.5	(*S*)
(*S,S,S,S*)-**57**	1	81	9:1	98.5:1.5	(*R*)

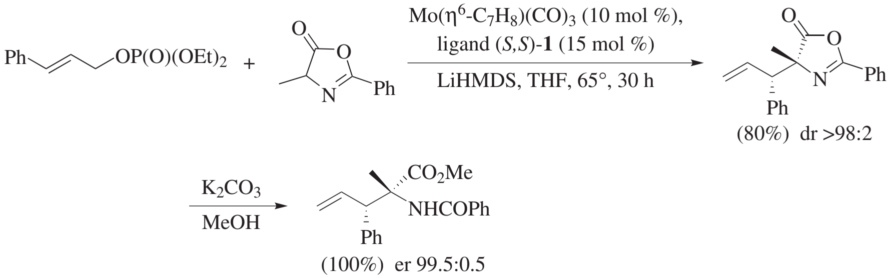
Scheme 29

APPLICATIONS TO SYNTHESIS

Appropriately substituted allylic derivatives serve as starting materials for the preparation of various biologically active compounds using molybdenum-catalyzed asymmetric allylic alkylation as a key step.

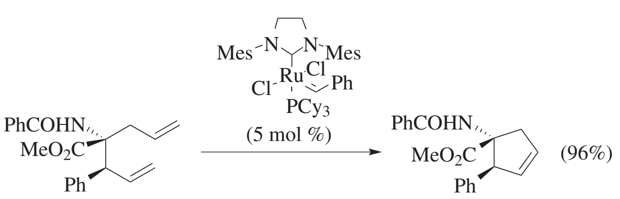
α-Amino Acids

Unnatural α-substituted α-amino acids are obtained with high enantiomeric excess by reactions of allylic carbonates or phosphates with 4-alkyl-2-phenyloxazol-5(4*H*)-ones (α-imino lactones).[37] The use of lithium hexamethyldisilazane as the base affords, in most cases, only the branched isomer, whereas some linear product is obtained when sodium or potassium hexamethyldisilazane is used. Hydrolysis without isolation of the initially formed product provides high isolated yields (76–92%) of the branched isomers (Scheme 30).[37] Lower catalyst loading (examined with cinnamyl methyl carbonate and 4-benzyl-2-phenyloxazol-5(4*H*)-one) gives the product with equally high diastereoselectivity although with somewhat lower enantioselectivity and increasing amounts of the linear isomer. The reaction is an example of control of stereochemistry at the nucleophile as well as the electrophile.



Scheme 30

Further synthetic manipulations of these products can lead to other amino acids. A product with two terminal olefinic bonds, amino acid **62**, undergoes ring-closing metathesis to give a cyclic amino acid derivative (Eq. 12).[37]

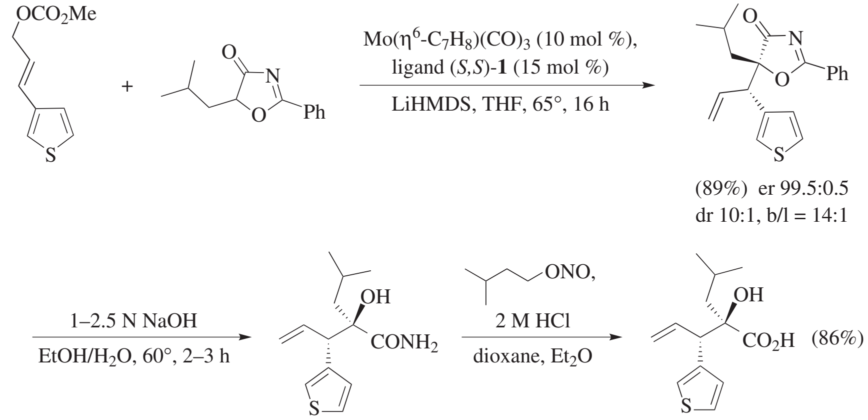


62

(Eq. 12)

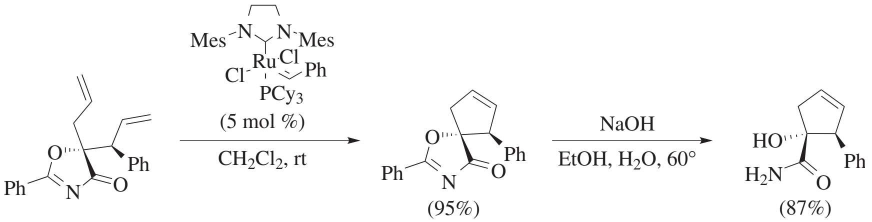
α-Hydroxy Acids

α-Hydroxy acids are obtained with high stereocontrol with respect to both the nucleophile and the electrophile by the analogous reaction with 5-alkyl-2-phenyloxazol-4(5*H*)-ones (oxalactims) (Scheme 31).[38] The site selectivity (5.5:1 to 49:1 in favor of the branched isomer) is dependent on the nature of both the 2- and 5- substituents and decreases somewhat with increasing size of the C-5 alkyl group.



Scheme 31

An oxalactim with a 2-propenyl group at C-5 results in an allylated compound containing two terminal olefinic bonds. Subjection of these compounds to ring-closing metathesis affords products that can be converted into cyclic hydroxy carboxamides by hydrolysis (Scheme 32).[38]

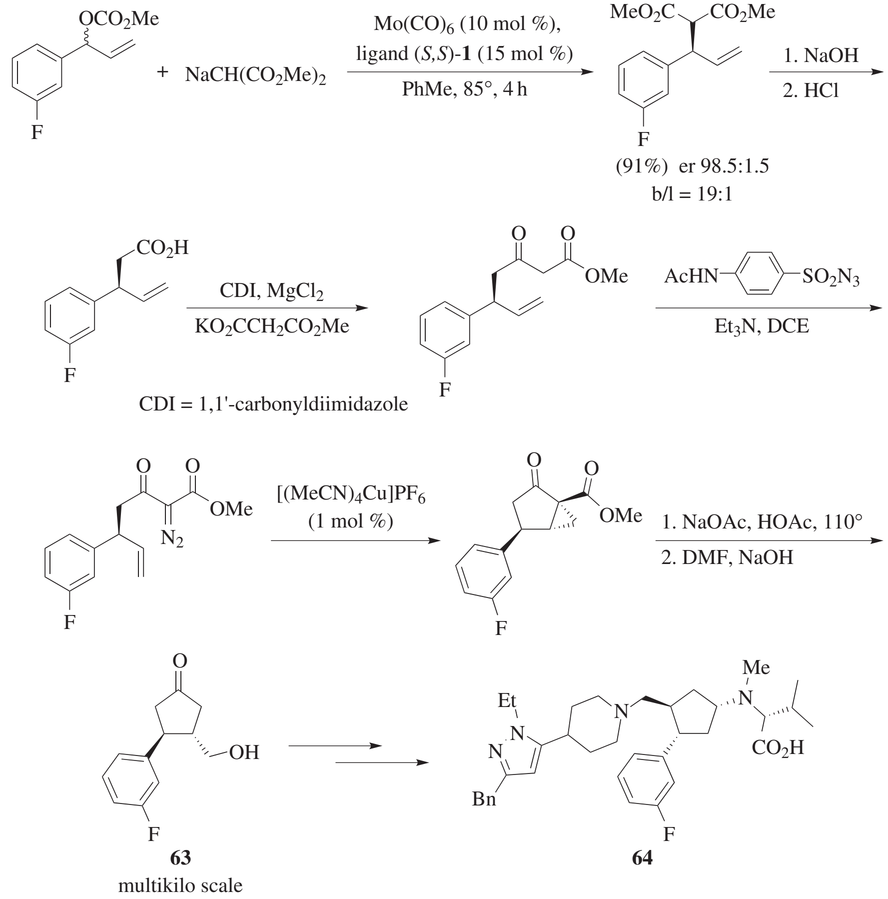


Scheme 32

(3*S*,4*S*)-3-(3-Fluorophenyl)-4-(hydroxymethyl)cyclopentanone

(3*S*,4*S*)-3-(3-Fluorophenyl)-4-(hydroxymethyl)cyclopentanone (**63**), a key intermediate in the synthesis of the anti-HIV drug candidate **64**,[63] is prepared employing molybdenum-catalyzed allylation for the installation of the first stereocenter (Scheme 33).[64] Alkylation of *rac*-1-(3-fluorophenyl)-2-propenyl methyl carbonate with sodium dimethyl malonate, using a catalyst obtained by heating Mo(CO)$_6$

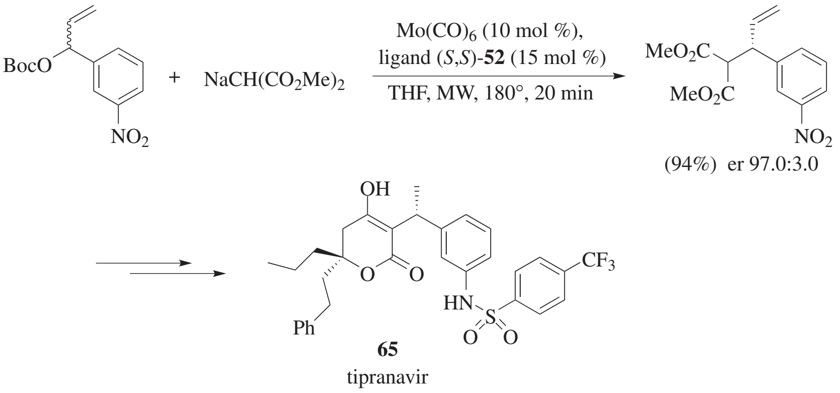
(10 mol %) and ligand (*S,S*)-**1** (15 mol %) at 85–88° for 4 hours, affords the desired dimethyl 2-[(1*R*)-1-(3-fluorophenyl)-2-propenyl]propanedioate in 91% yield and er 98.5:1.5, and with a branched/linear ratio of 19:1 after 15 hours at 85° in toluene.



Scheme 33

Tipranavir

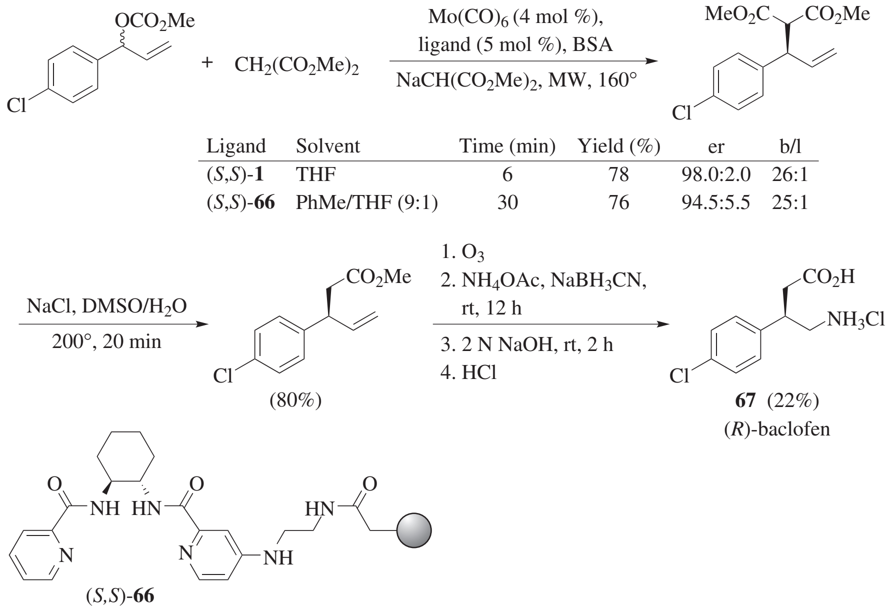
A convergent synthesis of tipranavir (**65**), a nonpeptidic HIV-protease inhibitor, uses molybdenum-catalyzed substitution of *rac*-1-(3-nitrophenyl)-2-propenyl *tert*-butyl carbonate with sodium dimethyl malonate to prepare a key intermediate (Scheme 34).[65] The desired branched isomer is obtained in excellent yield (94%) and enantioselectivity (er 98.0:2.0) using a catalyst prepared from Mo(η^6-C_7H_8)(CO)$_3$ and ligand (*S,S*)-**1** at 67°. Under microwave irradiation, the reaction (catalyzed by Mo(CO)$_6$ and ligand (*S,S*)-**52**) is complete within 20 minutes, as compared to 24 hours at 67°, and the product is obtained with only a slight loss in enantioselectivity (er 97.0:3.0) (Scheme 34).[65]



Scheme 34

(*R*)-Baclofen

(*R*)-Baclofen (**67**) is an analogue of γ-aminobutyric acid (GABA), an important neurotransmitter in the central nervous system. Baclofen activates $GABA_B$ receptors and is used for the treatment of spastic movement.[66] The therapeutically active (*R*)-enantiomer is prepared using allylation of dimethyl malonate in the presence of $Mo(CO)_6$ and either ligand (*S,S*)-**1** or its immobilized analogue (*S,S*)-**66** under microwave conditions for the introduction of the stereogenic center (Scheme 35).[67]

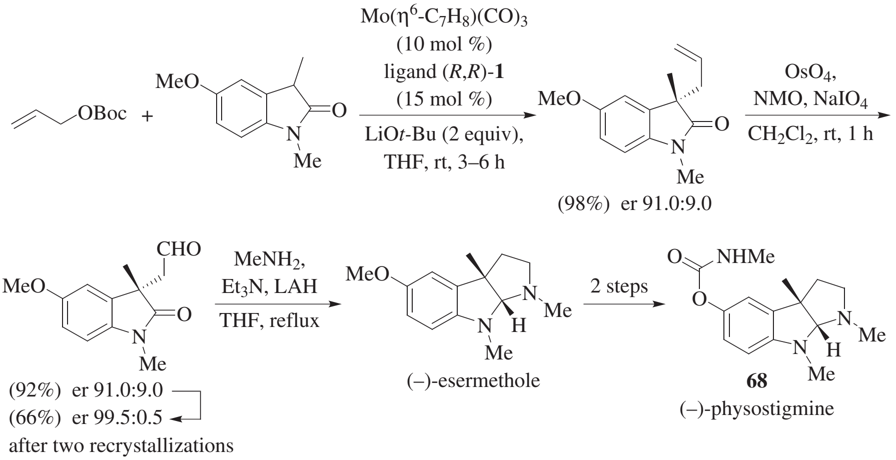


Ligand	Solvent	Time (min)	Yield (%)	er	b/l
(*S,S*)-**1**	THF	6	78	98.0:2.0	26:1
(*S,S*)-**66**	PhMe/THF (9:1)	30	76	94.5:5.5	25:1

Scheme 35

(−)-Physostigmine

In contrast to the palladium-catalyzed process, molybdenum-catalyzed asymmetric allylic alkylations of 3-aryl-[39] and 3-alkyloxindoles[56] proceed with high enantioselectivity to yield 3,3-disubstituted oxindoles, which are versatile building blocks for alkaloid synthesis.[68] The utility of the reaction is demonstrated by a formal total synthesis of (−)-physostigmine (**68**), a powerful inhibitor of acetyl cholinesterase (Scheme 36).[56]



Scheme 36

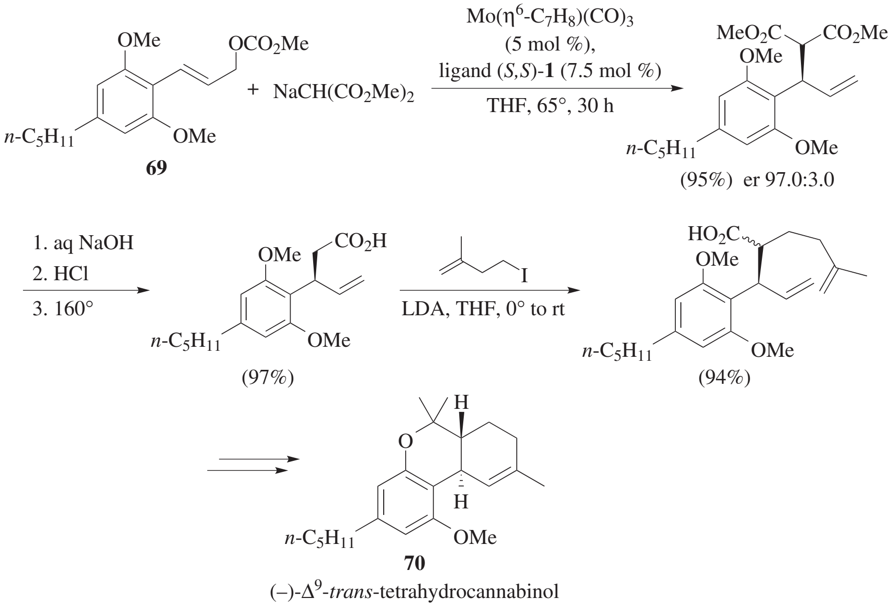
(−)-Δ⁹-*trans*-Tetrahydrocannabinol

Molybdenum-catalyzed asymmetric allylic alkylation is employed as a key step in the synthesis of (−)-Δ^9-*trans*-tetrahydrocannabinol (**70**) (Scheme 37), the primary psychoactive component in marijuana.[48] Carbonate **69**, which is sensitive to both acid and base, is prepared at −78° and used after washing with cold water. Due to severe steric hindrance in the substrate, the reaction is slow, but affords the branched product exclusively in high yield and with high enantioselectivity (er 97.0:3.0). After an additional six steps, the final product is obtained in 30% overall yield.

COMPARISON WITH OTHER METHODS

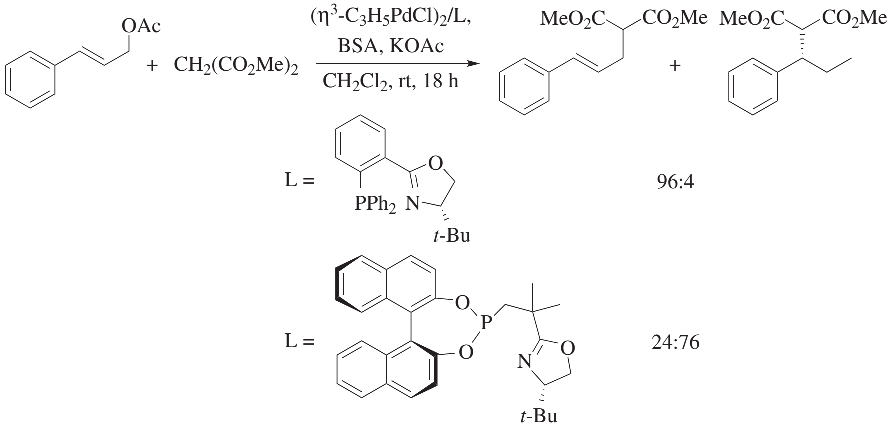
Metal-Catalyzed Allylations

Palladium complexes have been most extensively studied and employed in synthetic applications of asymmetric allylic alkylations.[4,69,70] High enantioselectivity can be achieved with different types of allylic substrates. A large variety of chiral ligands that induce high enantioselectivity are known, most of them bidentate with P–P, P–N, or N–N donor atoms, although recently also several monodentate ligands have been successfully employed.[71] As a general rule, palladium-catalyzed substitutions



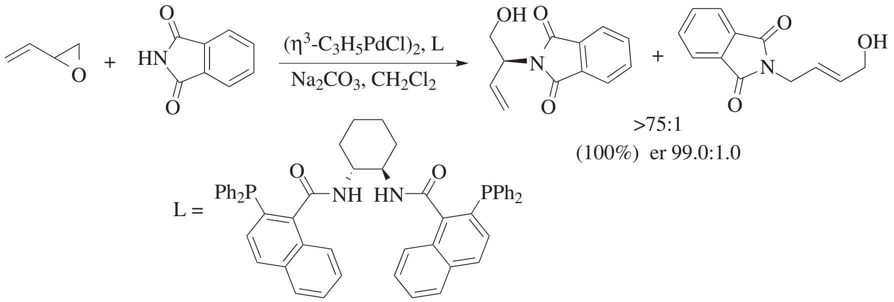
Scheme 37

result in formation of linear, achiral products from monosubstituted allylic substrates, although electron-deficient ligands may lead to branched isomers (Scheme 38[72]).[10,73]



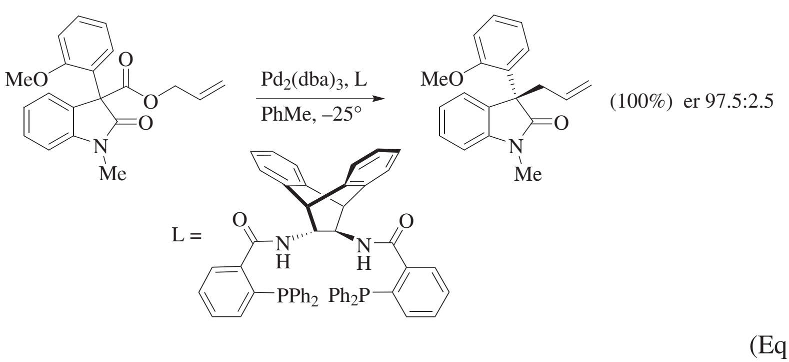
Scheme 38

The mechanism of palladium-catalyzed allylations is well known.[31] Oxidative addition of the allylic substrate to the Pd(0) complex occurs with inversion of configuration and the allylic ligand is attacked by stabilized nucleophiles *trans* to palladium without pre-coordination to the metal, again resulting in inversion of configuration. Although oxidative addition and nucleophilic attack occur with opposite stereochemical course using molybdenum and palladium catalysts, both processes thus proceed with net overall retention of configuration. Memory effects are common and may be powerful in the palladium-catalyzed allylations, in particular in the mismatched manifold.[74,75] Palladium catalysts are generally more reactive in allylic alkylations than catalysts containing molybdenum.[76] In addition to the type of substrates that undergo molybdenum-catalyzed allylations, allylic epoxides react in the presence of Pd(0) catalysts (Eq. 13).[77] Stabilized carbon nucleophiles, including enolates,[78–80] can be used as well as oxygen, nitrogen, and sulfur nucleophiles. The compatibility with functional groups is similar to that observed in molybdenum-catalyzed reactions, although silyl functional groups are cleaved under palladium catalysis and not molybdenum catalysis.



(Eq. 13)

In cases where the same product is obtained from palladium- and molybdenum-catalyzed processes, the enantioselectivities may differ. As noted earlier (Scheme 36), allylations of 3-alkyloxindoles proceed with excellent enantio- and site selectivity using a catalyst prepared from Mo(0) and ligand **1**, whereas modest enantioselectivity is observed using palladium catalysts.[56] However, highly selective decarboxylative allylations of aryl- and alkyloxindoles takes place in the presence of palladium catalysts (Eq. 14).[81]

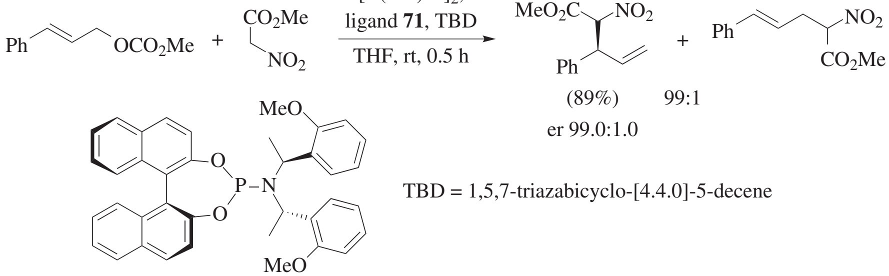


(Eq. 14)

Iridium-, ruthenium-, and tungsten-catalyzed allylic alkylations using monosubstituted allylic substrates result mainly in chiral, branched products, and thus display the same constitutional selectivity as the molybdenum-catalyzed reactions. Tungsten complexes with phosphinooxazoline ligands can be used for enantioselective substitutions using linear substrates,[82] although the enantioselectivity is lower than with molybdenum. Ligand **1** together with tungsten affords a lower yield of product than molybdenum, and the reactions are slower.[32] Reactions catalyzed by tungsten are stereospecific (Eq. 15),[83] and therefore no enantioselectivity is observed in reactions with branched racemic substrates.

(Eq. 15)

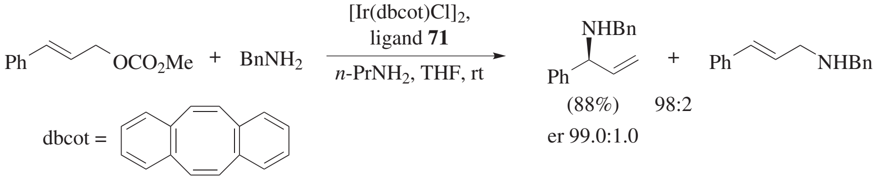
The iridium-catalyzed process[7] proceeds by an inversion-inversion mechanism.[84] A wider range of nucleophiles can be employed with iridium than with molybdenum. In addition to stabilized carbon nucleophiles (including ketone enolates[85]), both nitrogen and oxygen nucleophiles such as amines (including sulfonylamines as well as diacyl derivatives of amines), phenolates, alkoxides, and hydroxylamine derivatives can be allylated.[86] In contrast to molybdenum catalysts, iridium complexes also catalyze the allylation of nitro compounds using phosphoramidite ligands such as **71** (Eq. 16).[87] Distinct memory effects are observed in some iridium-catalyzed reactions. Thus, linear substrates with (*Z*) configuration give linear (*Z*) products. The memory effect is, however, a function of the ligand, and iridium catalysts that provide products with excellent site- and enantioselectivities are known.[70] For example, a catalyst prepared from [Ir(dibenzocyclooctatetraene)Cl]$_2$ is stable in air and affords allylation products with high enantio- and site-selectivities (Eq. 17).[88] With malonate as the nucleophile, enantioselectivities similar to those obtained with molybdenum catalysts containing, for example, ligand **1** are observed in the presence of [Ir(cod)Cl]$_2$ with phosphoramidite ligands, but the branched to linear ratios are higher with the iridium catalyst (Scheme 39).[89]



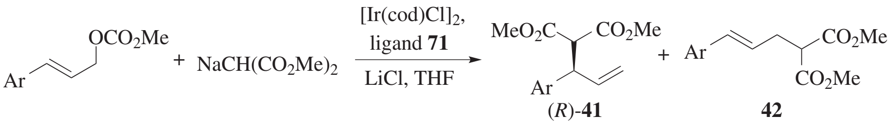
71

TBD = 1,5,7-triazabicyclo-[4.4.0]-5-decene

(Eq. 16)



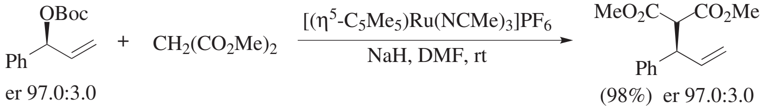
(Eq. 17)



Ar	Temp°	Yield (%)	**41/42**	er
Ph	rt	82	99:1	99.0:1.0
4-ClC$_6$H$_4$	35	90	>99:1	98.5:1.5
4-MeOC$_6$H$_4$	35	99	>99:1	98.5:1.5

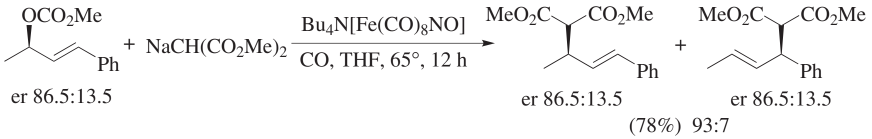
Scheme 39

Ruthenium(II)(Cp*) catalysts afford branched products from allylic alkylations, but few examples of enantioselective reactions are known.[90,91] In contrast to molybdenum and tungsten catalysts, the ruthenium complexes exhibit high reactivity with heteroatom (N, O, S) nucleophiles.[92] As in reactions with palladium, molybdenum, and tungsten catalysts, the site selectivity is not dependent on the nature of the starting substrate, although under certain conditions strong memory effects, with retained configuration of branched substrates, are observed (Eq. 18).[93] In contrast to reactions involving molybdenum catalysts, the diastereomeric ruthenium complexes formed from racemic or enantiomerically enriched substrates in the presence of chiral ligands do not equilibrate. As a consequence, products with the same enantiomeric purity as the substrates are obtained.[93] For ruthenium catalysts the site selectivity favoring branched products has been proposed to be governed by frontier orbital overlap on the basis of X-ray and computational studies.[94]

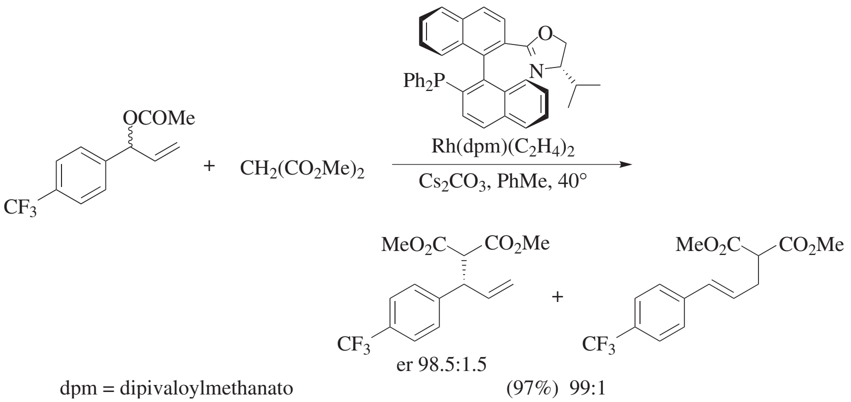


(Eq. 18)

Rhodium and iron allyl complexes isomerize slowly. Thus, the configuration is retained in branched substrates using iron (Eq. 19)[95] and rhodium.[96] Similarly, linear substrates afford predominantly linear products. Iron catalysts are attractive due to their low price and low toxicity, but can give rise to substantial memory effects, the extent of which is a function of ligand structure.[97] For rhodium catalysts the site selectivity is determined by the position of the leaving group,[98] but under certain conditions S_N2' displacement occurs.[99] However, by selecting conditions such that nucleophilic addition becomes slow compared to isomerization of the intermediate allyl complexes, high enantioselectivity may be achieved in rhodium-catalyzed reactions (Eq. 20).[100] Rhodium complexes catalyze aminations and etherifications,[96] as well as allylations of nonstabilized nucleophiles.[99,101]



(Eq. 19)



(Eq. 20)

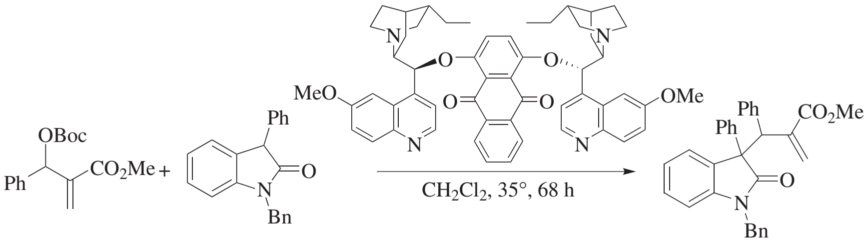
Nickel catalysts can be used for reactions with both stabilized (including amines)[102] and non-stabilized nucleophiles.[103] Allylations of nonstabilized nucleophiles,[104] such as diethylzinc[105,106] and magnesium reagents,[107] occur with high enantioselectivity using copper catalysts.[108] The reactions usually occur via S_N2'-type mechanisms and are therefore site selective. Allylic acetates, carbonates, phosphates, halides, and ethers also react under copper catalysis.[109,110]

When enantiomerically enriched branched products are desired, the most viable alternatives to molybdenum catalysts are those based on iridium, particularly iridium complexes containing phosphoramidite ligands.[111] Since molybdenum compounds are inexpensive and Mo(0) in the form of the stable $Mo(CO)_6$ can be employed together with stable ligands for in situ preparation of catalysts, molybdenum-catalyzed allylations are preferable for certain stabilized carbon nucleophiles (see Tables). An important advantage with iridium catalysts is, however, that a wider range of nucleophiles can be used.

Exceptions to the general guidelines outlined here exist as the stereochemical course is a function not only of the metal but also of other parameters, in particular the ligand structure.

Organocatalytic Allylations

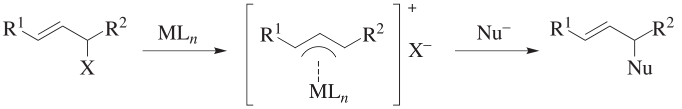
Metal-free allylations of 3-aryloxindoles using chiral, nonracemic Morita-Baylis-Hillman adducts furnish products such as oxindole **72** in up to er 98.0:2.0 and dr 87:13 (Eq. 21).[112] The enantioselectivity is comparable to that of the molybdenum-catalyzed process (compare Table 5), but higher than that reported for palladium-catalyzed allylations of aryloxindoles.[113]



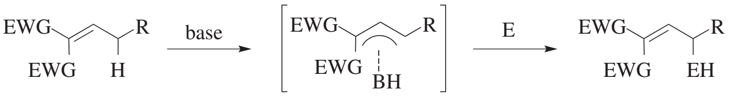
72 (82%)
er 98.0:2.0, dr 87:13

(Eq. 21)

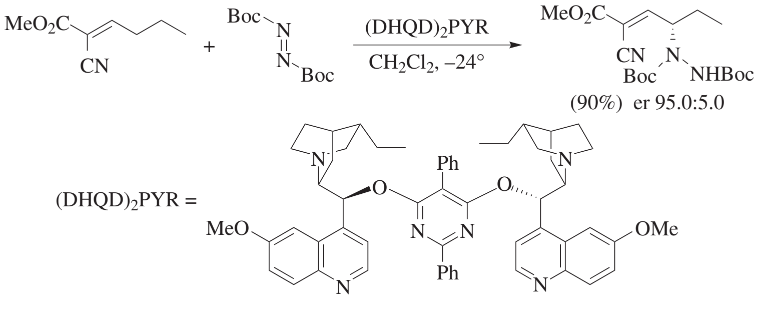
In the allylations described thus far an electrophilic allylic group reacts with a nucleophile through the intermediacy of a π-allylmetal complex (Scheme 40). Allylic derivatives can also be obtained by using reagents with reversed polarities (Scheme 41). The nucleophile is generated by abstraction of an allylic proton from an olefin; electron-withdrawing substituents are required in order to stabilize the allylic anion (Eqs. 22[114] and 23).[115] The reactions are catalyzed by chiral bases, typically cinchona alkaloid derivatives.



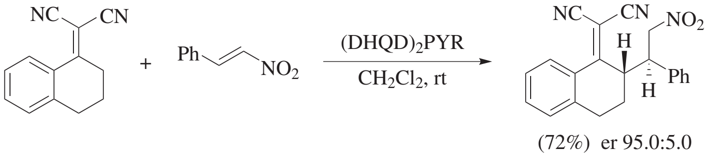
Scheme 40



Scheme 41



(Eq. 22)



(Eq. 23)

EXPERIMENTAL CONDITIONS

The complex $Mo(EtCN)_3(CO)_3$ is most commonly used as the molybdenum source. It is prepared from the crystalline, stable, and commercially available $Mo(CO)_6$ by heating in propionitrile at reflux.[116] *The procedure is hazardous, particularly on a large scale, because propionitrile is toxic and decomposes upon heating and because carbon monoxide evolves*. Comparable results from the catalytic reactions are obtained with $Mo(\eta^6\text{-}C_7H_8)(CO)_3$.[117] Both complexes are air-sensitive and require cautious handling, although the latter complex is somewhat easier to prepare and is more air-stable.[118] Both are commercially available.

The molybdenum complex is usually treated with the ligand for about an hour at 60–70° prior to the addition of the allylic substrate and the nucleophile.[21,32] The catalytic reactions are generally run at 60–80°, although occasionally room temperature or even lower temperatures are sufficient. At higher temperatures, higher yields are obtained and sometimes only a moderate decrease in enantioselectivity and lower site selectivity are observed.[32] THF and toluene are the most frequently used solvents. Carbonates are more reactive than acetates[21] and are the preferred allylic substrates; allylic phosphates have been used as substrates only in a few cases.[37,38] Catalyst loadings are generally quite high: typically 15 mol % of ligand and 10 mol % of molybdenum complex are used.

The results are essentially independent of the order of addition of the reagents: (1) concurrent addition of the substrate and deprotonated dimethyl malonate to the catalyst solution (prepared at 70° during 1 hour), (2) catalyst pretreatment with dimethyl malonate, and (3) catalyst pretreatment with substrate before addition of malonate give essentially the same results[21] when oxazoline ligands such as **8** are used.

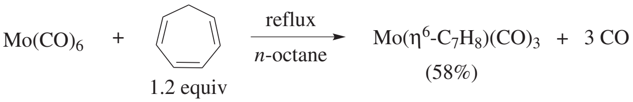
The less reactive $Mo(CO)_6$ can be used as the molybdenum source, although higher reaction temperatures or initial activation are required. Heating a 0.175 M toluene solution of $Mo(CO)_6$ with 1.5 equivalents of ligand **1** at 85–90° for 4 hours (or a THF solution at 65° for 2–3 hours) results in complete formation of a complex.[119] It is important that sufficient time is allowed for the formation of the catalyst as $Mo(CO)_6$ is able to catalyze the reaction, although at a lower rate, leading to decreased site- and enantioselectivities. Under these conditions the enantioselectivity is higher when toluene is used as the solvent; other solvents (DMF, DME, or DCE) are less effective. Results obtained under these conditions are identical to those obtained starting from $Mo(EtCN)_3(CO)_3$ or $Mo(\eta^6\text{-}C_7H_8)(CO)_3$.

Under conditions of microwave irradiation the reactions occur smoothly starting from $Mo(CO)_6$.[8] The asymmetric allylic alkylation reactions normally need to be performed under inert conditions, but microwave-mediated reactions can be run in air. Reactions are typically complete within 4–5 minutes and no activation of the catalyst is required prior to the catalytic reaction. In addition, lower amounts of catalyst (5 mol % ligand and 4 mol % molybdenum complex) are used for reactions run under microwave conditions.

EXPERIMENTAL PROCEDURES

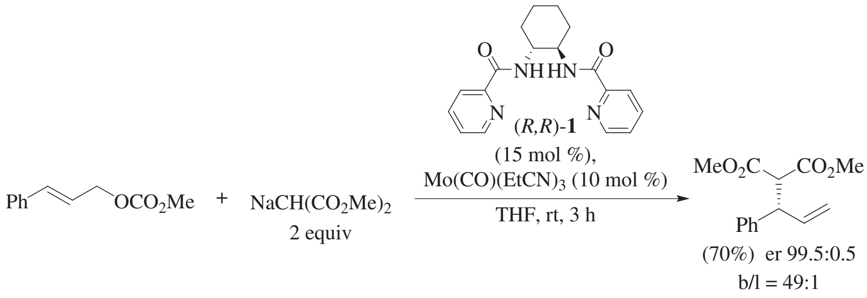
$$\mathrm{Mo(CO)_6} + 3\ \mathrm{EtCN} \xrightarrow[\text{1 d}]{\text{reflux}} \underset{(64\%)}{\mathrm{Mo(EtCN)_3(CO)_3}} + 3\ \mathrm{CO}$$

Tricarbonyltris(propionitrile)molybdenum(0).[116] *Nitriles are very toxic and the synthesis should be carried out in a well-ventilated hood. CO, which is highly toxic, is released during the reaction.* A mixture of $\mathrm{Mo(CO)_6}$ (6.0 g, 22.7 mmol) and propionitrile (60 mL) was placed into a flask equipped with a magnetic stirrer and a reflux condenser with an efficient exit for evolved CO. Heating to reflux under nitrogen gradually dissolved the hexacarbonyl complex and induced stepwise replacement of three CO ligands. After one day about one-half of the solvent was removed and $\mathrm{Et_2O}$ (30 mL) was added. Filtration afforded 5.0 g (64% yield) of $\mathrm{Mo(CO)_3(EtCN)_3}$ as light tan fine needles. Reduction of the filtrate volume to 5 mL gave a second crop (2.09 g, total yield 91%). The complex is air-sensitive and becomes dark brown within an hour. IR 1919, 1800 $\mathrm{cm^{-1}}$.

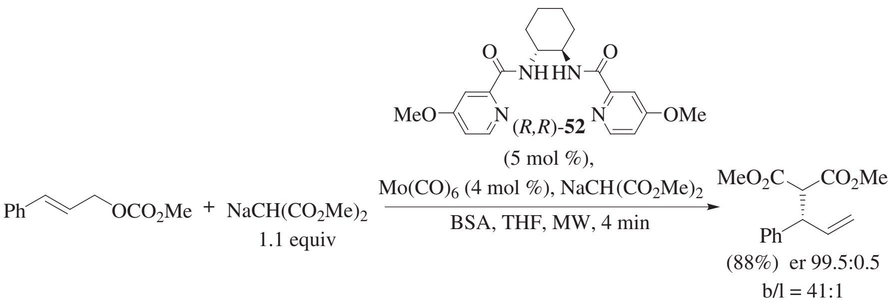


Tricarbonyl(cycloheptatriene)molybdenum(0).[117] A mixture of cycloheptatriene (11 g, 119 mmol, slight excess, used without purification) and $\mathrm{Mo(CO)_6}$ (26 g, 98.5 mmol) in *n*-octane (25 mL) was heated to reflux for 8 h. During the reaction, unreacted $\mathrm{Mo(CO)_6}$ sublimed into the condenser and needed to be scraped back into the reaction flask. After being cooled, the brown precipitate was collected by filtration and was washed with *n*-pentane (20 mL) to remove any unreacted cycloheptatriene. Evaporation of the filtrate afforded some unreacted $\mathrm{Mo(CO)_6}$, which together with that collected in the condenser amounted to 3 g. The brown residue was extracted overnight in a Soxhlet apparatus with *n*-pentane. Red hexagonal prisms precipitated to afford 14 g (58% yield based on consumed $\mathrm{Mo(CO)_6}$) of the desired product. The crystals were collected by filtration and were air-dried; they were pure enough for most purposes but could be recrystallized from *n*-hexane using an acetone–dry ice cooling bath. IR 1985, 1919, 1889 $\mathrm{cm^{-1}}$.

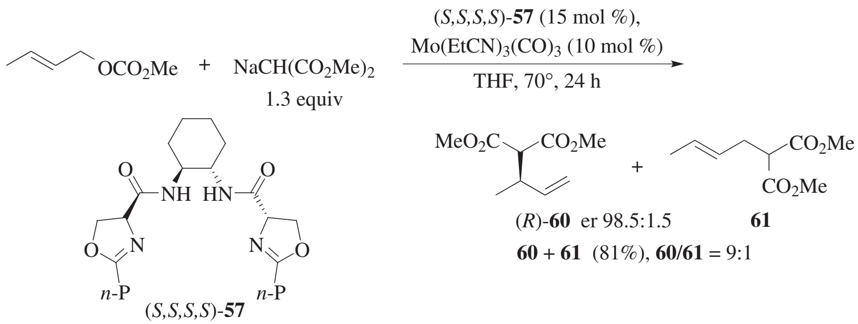
The product decomposes at 95° and sublimes rapidly at 85° under vacuum. It is very soluble in alcohol, acetone, benzene, $\mathrm{CHCl_3}$, and $\mathrm{CH_2Cl_2}$, moderately soluble in $\mathrm{Et_2O}$, and only sparingly soluble in *n*-hexane. It decomposes in $\mathrm{CCl_4}$. The solutions are sensitive to air and light, and the solid is best stored in the dark.



Dimethyl 2-[(*S*)-1-Phenyl-2-propenyl]propanedioate [Allylation of a Malonate].[32] A solution of $Mo(EtCN)_3(CO)_3$ (10 mol %) and chiral ligand (*R*,*R*)-**1** (15 mol %) in THF (1 mL) was stirred at 60° for 1 h. A solution of sodium dimethyl malonate in THF (1 mL), prepared from dimethyl malonate (578 mg, 4.37 mmol) and NaH (160 mg of 60% dispersion, 4.00 mmol in THF (10 mL), and (*E*)-3-phenyl-2-propenyl methyl carbonate (0.2 mmol) were successively added at rt. After stirring at rt for 3 h, water (2 mL) was added to quench the reaction. The mixture was extracted with Et_2O (3 × 15 mL). The combined organic layers were washed with brine (10 mL) and dried ($MgSO_4$). The solvents were evaporated and the residue was purified by chromatography on silica gel (petroleum ether/EtOAc) to afford the product (35 mg, 70% purified yield, 90% yield by GLC) as a 49:1 mixture of branched (er 99.5:0.5) and linear isomers. Branched isomer: HPLC (Daicel Chiralcel OD, heptane/PrOH, 99.5:0.5, 0.5 mL/min, 220 nm) t_R (minor, *R*) 26.89 min, t_R (major, *S*) 29.11 min; R_f 0.32 (hexane/EtOAc, 6:1); $[\alpha]_D^{20}$ – 34.2 (*c* 2.02, $CHCl_3$); IR (neat) 3031, 2954, 1737, 1435, 1263, 1197, 1163, 1027, 993, 926, 765, 702 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.32–7.19 (m, 5H), 6.05–5.93 (m, 1H), 5.15–5.07 (m, 2H), 4.14–4.08 (m, 1H), 3.87 (d, *J* = 11.0 Hz, 1H), 3.74 (s, 3H), 3.49 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 168.3, 167.9, 140.0, 137.8, 128.7, 127.9, 127.2, 116.7, 57.2, 52.5, 52.3, 49.6.



Dimethyl 2-[(*S*)-1-Phenyl-2-propenyl]propanedioate [Microwave-Assisted Allylation of a Malonate].[33] Sodium dimethyl malonate [prepared by adding dimethyl malonate (66 μL, 0.58 mmol) to a suspension of 60% NaH (2 mg, 0.050 mmol) in THF (1 mL)] was added to the ligand (*R*,*R*)-**52** (0.025 mmol) and Mo(CO)$_6$ (5 mg, 0.02 mmol) in a heavy-walled pyrex tube, followed by (*E*)-3-phenyl-2-propenyl methyl carbonate (102 mg, 0.53 mmol) in THF (0.5 mL) and BSA (156 µL, 0.63 mmol). The tube was sealed and the sample was irradiated using a single-mode cavity microwave reactor with a power of 200 W for 4 min. Directly after heating, the dark-colored reaction mixture was cooled in a water bath at rt and diluted with Et$_2$O to a volume of 10 mL, whereupon a precipitate appeared. The yellow-orange mixture was filtered, the filtrate was concentrated, and the crude product was purified by silica gel column chromatography (EtOAc/hexanes) to afford 116 mg of product (88% purified yield; >95% yield by GLC) in a 41:1 branched to linear ratio, and with er >99.5:0.5 of the major isomer. The ^{1}H and ^{13}C NMR spectra were identical to those of the compound prepared under thermal conditions (see above).[32]

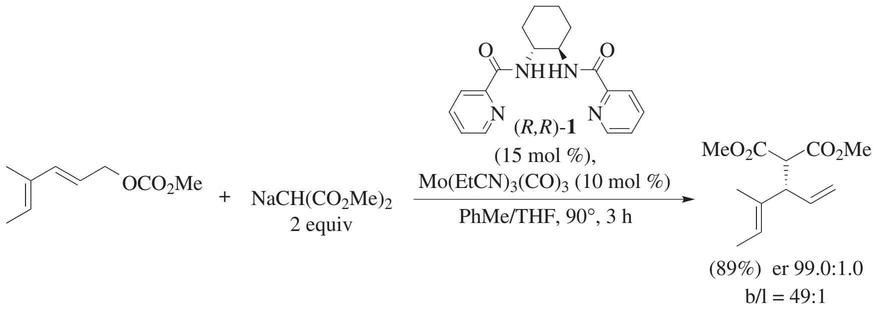


Dimethyl 2-[(*R*)-1-Methyl-2-propenyl]propanedioate [Allylation of a Malonate with an Alkyl-Substituted Allylic Carbonate].[21] A solution of ligand (*S,S,S,S*)-**57** (9.8 mg, 0.025 mmol) and Mo(EtCN)$_3$(CO)$_3$ (5.9 mg, 0.017 mmol) in freshly distilled THF (0.7 mL) was degassed and then stirred at 70° in an ampule with a J-Young valve under argon for 1 h. A solution of sodium dimethyl malonate [prepared from dimethyl malonate (40 mg, 0.3 mmol) and NaH (5.3 mg, 0.22 mmol) in THF (1.0 mL) at rt] and (*E*)-2-butenyl methyl carbonate (22.1 mg, 0.17 mmol) were then added to the reaction mixture. The solution was again degassed and then stirred at 70° for 24 h. After cooling to rt, H$_2$O (3 mL) was added. The mixture was extracted with Et$_2$O (3 ×15 mL), the combined extracts were washed with brine (5 mL) and dried (MgSO$_4$), and the solvent was evaporated. The resulting oil was purified by silica gel chromatography (pentane/BuOMe, 10:1) to afford 25.7 mg (81% yield) of a 9:1 mixture of products (*R*)-**60** and **61** as a colorless oil: R_f 0.35 (hexane/EtOAc, 4:1); GC (Restek Trx-1701, 30 m, 60–120°, 2°/min, 60 kPa H$_2$) t_R 23.2 (**60**), 27.4 ((*E*)-**61**), 28.1 ((*Z*)-**61**); GC (Chiraldex γ-CD-TA, 30 m, 50–100°, 1°/min, 90 kPa H$_2$) t_R 33.4 ((+)-(*R*)-**60**), 34.7 ((−)-(*S*)-**60**), 41.7 ((*E*)-**61**), 44.2 ((*Z*)-**61**).

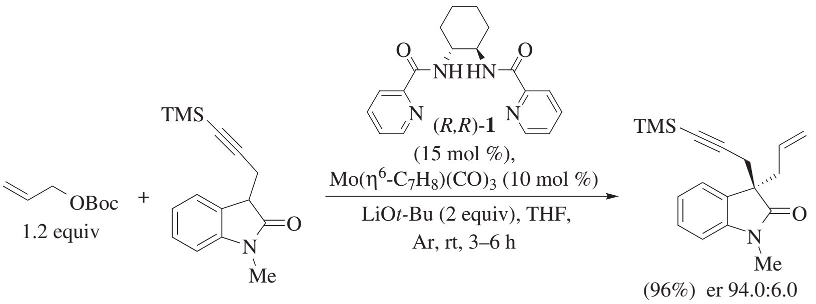
Isomer **60**: The er (98.5:1.5) and the regioselectivity were determined by GC; $[\alpha]_D^{20}$ + 19.4 (*c* 0.76, CHCl$_3$; determined using a sample with er 96.5:3.5); IR (film) 3082, 2956, 2852, 1739, 1643, 1436, 1268, 1200, 1153, 1022, 921, 802 cm^{-1}; ^{1}H

NMR (300 MHz) δ 5.77 (ddd, J = 17.1, 10.2, 8.0 Hz, CH), 5.13–5.00 (m, CH_2), 3.74 (s, MeO), 3.71 (s, MeO), 3.32 (d, J = 9.0 Hz, CHCO), 2.97–2.94 (m, MeCH), 1.10 (d, J = 6.8, Me); ^{13}C NMR (75 MHz) δ 168.7 (C=O), 168.7 (C=O), 139.7 (CH), 115.6 (CH_2), 57.6 (*C*HCO), 52.4 (MeO), 52.3 (MeO), 38.1 (Me*C*H), 18.1 (Me); EIMS (*m*/*z*): $[M + H]^+$ 187 (0.5), 155 (6), 127 (100), 111 (32), 101 (28), 95 (42). Anal. Calcd for $C_9H_{14}O_4$: C, 57.97; H, 7.63. Found: C, 58.05; H, 7.57.

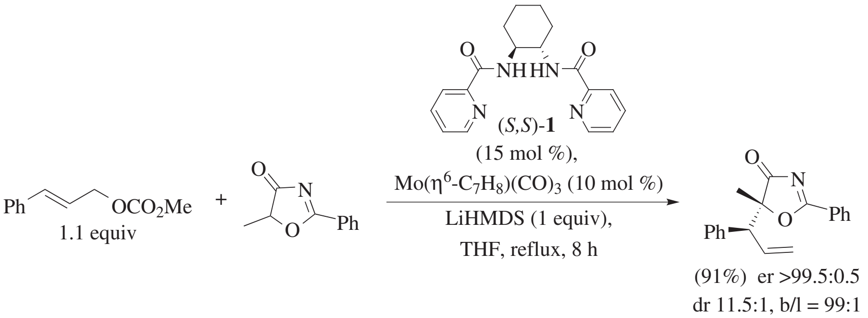
Isomer (*E*)-**61**: IR (film) 2955, 1736, 1437, 1268, 1231, 1154, 1023, 968 cm^{-1}; ^{1}H NMR (300 MHz) δ 5.61–5.49 (m, CH), 5.42–5.31 (m, CH), 3.75 (s, 2 MeO), 3.41 (t, J = 7.5 Hz, CH), 2.57 (m, CH_2), 1.64 (dd, J = 6.1, 1.0 Hz, Me); ^{13}C NMR (75 MHz) δ 169.2 (C=O), 128.4 (CH), 126.2 (CH), 52.4 (MeO), 51.9 (CH), 31.9 (CH_2), 17.8 (Me); EIMS (*m*/*z*): M^+ 186 (10), 154 (8), 132 (43), 126 (55), 123 (57), 111 (100), 101 (25), 95 (31).



Dimethyl 2-[3-(*S*,*E*)-4-Methylhexa-1,4-diene]propanedioate [Allylation of a Malonate with a Dienylic Carbonate].[49] *Thorough degassing was performed since the catalyst is sensitive to oxygen.* The reaction vessel containing $Mo(EtCN)_3(CO)_3$ (7.5 mg, 0.022 mmol) and ligand (*R*,*R*)-**1** (10.7 mg, 0.035 mmol) was evacuated and flushed with nitrogen three times and then toluene (1 mL, degassed with argon) was added. The mixture was heated at 60° for 1 h. *Note: The resultant catalyst solution should be very dark red to almost black. If the solution turned to brown, the catalyst has become deactivated and the reaction should be abandoned.* A THF solution (1 mL) of the nucleophile prepared from dimethyl malonate (63.2 mg, 0.48 mmol) and sodium hydride (60% oil dispersion, 17.4 mg, 0.44 mmol) and (*E*,*E*)-4-methylhexa-2,4-dienyl methyl carbonate (37 mg, 0.217 mmol) was added at rt and the resultant mixture was heated at 90° for 3 h. Work-up (dilution with Et_2O and washing with water) and silica gel chromatography (petroleum ether/Et_2O, 8:1) provided 43.8 mg (89% yield) of the title product: HPLC (Daicel AD column, heptane/*i*-PrOH, 99:1) $t_R(+)$ (major) 34.93 min, $t_R(-)$ (minor) 43.46 min; IR (neat) 1740, 1638, 1435, 1318 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.71 (ddd, J = 17.2, 10.1, 8.1 Hz, 1H), 5.35 (q, J = 6.4 Hz, 1H), 5.07 (d, J = 17.2 Hz, 1H), 5.04 (d, J = 10.1 Hz, 1H), 3.70 (d, J = 10 Hz, 1H), 3.68 (s, 3H), 3.66 (s, 3H), 3.43 (dd, J = 11.4, 8.1 Hz, 1H), 1.60–1.52 (m, 6H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 168.59, 136.93, 133.94, 121.71, 116.50, 54.95, 52.64, 52.33, 13.39, 13.29; HRMS (*m/z*): M^+ calcd for $C_{12}H_{18}O_4$, 226.1205; found, 226.1206.



(*R*)-3-Allyl-1-methyl-3-(3-(trimethylsilyl)prop-2-ynyl)indolin-2-one [Allylation of an Alkyloxindole].[56] *Preparation of the active catalyst solution*: A solution of ligand (*R*,*R*)-**1** (0.015 mmol) and Mo(η^6-C_7H_8)(CO)$_3$ (0.01 mmol) in freshly distilled and degassed THF (0.3 mL) was stirred at 60° in a sealed pyrex test tube under argon atmosphere. The solution turned deep purple after 3–5 min, indicating successful generation of the active catalyst. Further heating caused a black precipitate and decomposition to occur. The active catalyst is very sensitive to oxygen and moisture and should be used immediately after generation. *Preparation of the nucleophile*: A pyrex test tube containing 0.1 mmol of the oxindole was transferred to the dry box and LiO*t*-Bu (0.2 mmol) was added. The test tube was sealed, taken out of the dry box, and degassed THF (0.7 mL) was added. The resulting solution was stirred for 5 min before the solution of the active catalyst was added via cannula, followed by the addition of allyl *tert*-butyl carbonate (0.12 mmol) via a syringe. The resulting solution was stirred at rt under argon for 3–6 h until TLC indicated complete consumption of the starting oxindole. The reaction mixture was then concentrated and purified through silica gel to give the desired product (96% yield, er 94.0:6.0) as a colorless oil: Chiral HPLC (AD column, heptane/*i*-PrOH, 90:10, 6 mL/min) t_R (major) 6.55 min, t_R (minor) 7.22 min; $[\alpha]_D^{20}$ – 78.8 (*c* 2.1, $CHCl_3$); IR (film) 2958, 2178, 1716, 1613, 1493, 1469, 1376, 1250, 842 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 (dd, J = 7.5, 1.5 Hz, 1H), 7.28 (dt, J = 7.5, 1.5 Hz, 1H), 7.07 (dt, J = 7.5, 1 Hz, 1H), 6.82 (d, J = 7.5, 1H), 5.45–5.31 (m, 1H), 5.02 (dm, J = 16 Hz, 1H), 4.90 (dm, J = 16 Hz, 1H), 3.20 (s, 3H), 2.77–2.70 (m, 2H), 2.61 (dd, J = 7, 16 Hz, 1H), 2.52 (d, J = 16 Hz, 1H), 0.57 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 178.5, 143.6, 132.2, 131.2, 128.1, 123.6, 122.3, 118.8, 107.7, 78.2, 74.1, 51.2, 40.0, 27.1, 26.1, 3.5; HRMS-EI (*m*/*z*): calcd for $C_{18}H_{23}NOSi$, 297.1549; found, 297.1559.



(*R*)-5-Methyl-5-[(*S*)-(1-phenyl)-2-propenyl]-2-phenyloxazol-4(5*H*)-one [Allylation of an Oxazolidine-4-one].[38] A solution of ligand (*S*,*S*)-**1** (4.9 mg, 0.015 mmol) and $Mo(CO)_3(\eta^6\text{-}C_7H_8)$ (2.8 mg, 0.01 mmol) in freshly distilled and degassed THF (0.5 mL) was gently refluxed under argon in a pyrex test tube sealed with a rubber septum until a deep purple color developed (5–10 min). A separate tube containing 5-methyl-2-phenyloxazol-4(5*H*)-one (0.1 mmol) was evacuated and flushed with argon three times and anhydrous, degassed THF (0.5 mL) was added, followed by dropwise addition of a freshly prepared solution of LiHMDS (1 M in THF; 0.1 mL, 0.1 mmol) with stirring at 0°. The solution was stirred for 5–10 min and the resulting nucleophile was added to the catalyst. (*E*)-3-Phenyl-2-propenyl methyl carbonate (0.11 mmol) was then added at 60° using a syringe. The reaction mixture was heated at reflux for 8 h and was then poured onto a 1 N solution of 1:1 KH_2PO_4/K_2HPO_4 (pH 7, 8 mL). Dichloromethane (15 mL) was added, the phases were separated, the aqueous phase was extracted with CH_2Cl_2, and the combined organic phases were dried ($MgSO_4$). After evaporation of the solvent a crude oil was obtained which was purified by chromatography (silica gel, petroleum ether/EtOAc, 90:10, R_f 0.23), affording 26.5 mg of the desired product (91% yield, er >99.5:0.5, branched/linear 99:1, dr 11.5:1). Major diastereomer: HPLC (Daicel Chiralpac AD column, heptane/*i*-PrOH, 99:1, 1 mL/min, 254 nm): t_R (1) 27.5 min, t_R (2) 34.1 min; IR (neat) 2924, 2853, 1754, 1603, 1547, 1451, 1356, 1149, 712 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.26–8.23 (m, 2H), 7.74–7.7 (m, 1H), 7.59–7.55 (m, 2H), 7.4–7.28 (m, 5H), 5.99 (ddd, *J* = 17, 10, 8.8 Hz, 1H), 5.21–5.00 (m, 2H), 3.79 (d, *J* = 8.8 Hz, 1H), 1.41 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 193.6, 185.3, 137.8, 135.2, 133.6, 130.0, 129.0, 128.9, 128.7, 127.5, 125.7, 119.8, 90.2, 56.2, 21.2. Anal. Calcd for $C_{19}H_{17}NO_2$: C, 78.33; H, 5.88; N, 4.81. Found: C, 78.66; H, 6.71; N, 4.02.

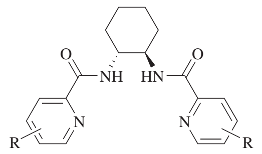
TABULAR SURVEY

The literature has been reviewed up to June 2012. The tables are divided according to the nucleophiles. Entries are ordered by increasing carbon count of the allylic substrate, excluding carbon atoms in the leaving group and typical protecting groups. Where (+) or (−) is used instead of (*R*) or (*S*), the author did not report an absolute configuration for the product. The absolute configuration of the product varies in some entries with subtables; in these cases one enantiomer is drawn with (*R*) or (*S*) marked on the structure and the associated subtable should be consulted for the absolute configuration of the product for each set of conditions. Unspecified yields, enantiomeric ratios, and absolute configurations are denoted by (—).

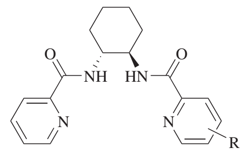
The following abbreviations that are not in the list of standard abbreviations published by the *Journal of Organic Chemistry* are used in the tables.

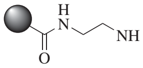
BSA	*N*,*O*-bis(trimethylsilyl)acetamide
C_7H_8	cycloheptatriene
Mes	1,3,5-trimethylbenzene
MW	microwave irradiation
PMP	4-methoxyphenyl
Ts	4-toluenesulfonyl
W	watt

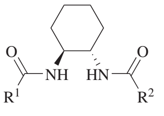
CHART 1. LIGANDS USED IN TABLES



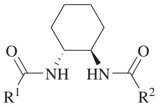
	R
1a	H
1b	2-Me
1c	4-MeO
1d	2-MeO
1e	4-*t*-Bu
1f	4-O_2N
1g	4-Cl
1h	2-Br
1i	4-pyrrolidinyl
1j	5-HO



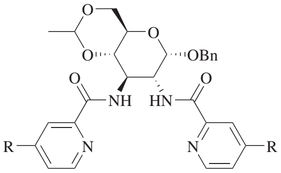
	R
2a	4-MeO
2b	4-Cl
2c	4-pyrrolidinyl
2d	4-$NH(CH_2)_2NH_2$
2e	



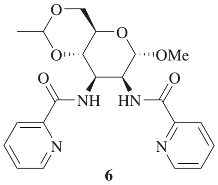
	R^1	R^2
3a	2-pyridinyl	*t*-Bu
3b	2-pyridinyl	Ph
3c	4-pyrimidinyl	4-pyrimidinyl



	R^1	R^2
4a	Ph	Ph
4b	2-pyridinyl	3-pyridinyl
4c	2-pyridinyl	2-quinolyl
4d	2-quinolyl	2-quinolyl



	R
5a	H
5b	Cl



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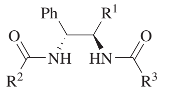
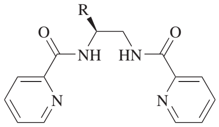
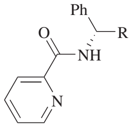


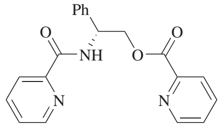
	R^1	R^2	R^3
7a	Ph	2-pyridinyl	2-pyridinyl
7b	H	2-pyridinyl	2-pyridinyl
7c	H	2-pyridinyl	Ph
7d	H	Ph	2-pyridinyl



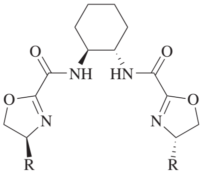
	R
8a	*i*-Pr
8b	Bn
8c	*t*-Bu



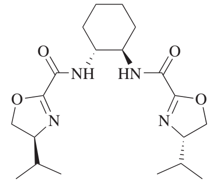
	R
9a	MeO_2C
9b	Me



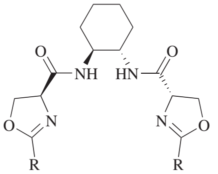
10



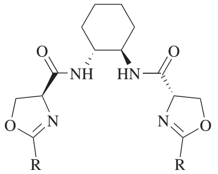
	R
11a	*i*-Pr
11b	*t*-Bu



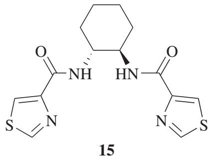
12



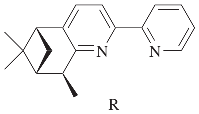
	R
13a	*n*-Pr
13b	*i*-Pr
13c	Ph



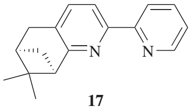
	R
14a	*n*-Pr
14b	*i*-Pr
14c	*t*-Bu
14d	Ph



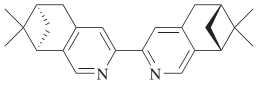
15



	R
16a	H
16b	Me



17



18

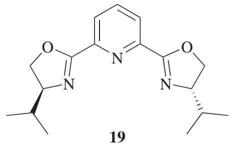


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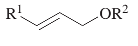
TABLE 1. ALLYLATION OF MALONATES

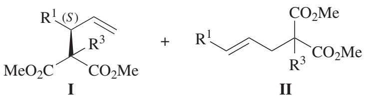
Allyl Compound and Malonate	Conditions	Product(s) and Yield(s) (%)	Refs.

C_4

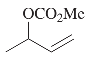


NaR^{3}C(CO$_2$Me)$_2$

Ligand (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), THF, 70°

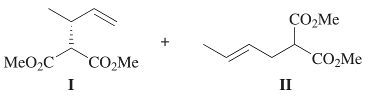


R^1	R^2	R^3	Ligand	Time (d)	**I + II**	**I/II**	er **I**	Config.	Refs.
Me	MeO$_2$C	H	*ent*-**1a**	1	(85)	5:1	97.0:3.0	(*R*)	21
Me	MeO$_2$C	H	**11a**	1	(88)	1.5:1	97.0:3.0	(*R*)	21
Me	MeO$_2$C	H	**11a**[a]	5	(80)	1.5:1	96.5:3.5	(*R*)	21
Me	MeO$_2$C	H	**11b**	1.5	(79)	2.2:1	90.0:10.0	(*R*)	21
Me	MeO$_2$C	H	**12**	5	(53)	0.6:1	63.0:37.0	(*S*)	21
Me	MeO$_2$C	H	**13a**	1	(81)	9:1	98.5:1.5	(*R*)	21
Me	MeO$_2$C	H	**13b**	1.5	(81)	9:1	97.5:2.5	(*R*)	21
Me	MeO$_2$C	H	**13c**	5	(73)	5:1	87.0:13.0	(*R*)	21
Me	MeO$_2$C	H	**14a**	2	(80)	11:1	98.0:2.0	(*S*)	21
Me	MeO$_2$C	H	**14b**	1	(86)	7:1	96.0:4.0	(*S*)	21
Me	MeO$_2$C	H	**14c**	2	(85)	1.5:1	50.0:50.0	—	21
Me	MeO$_2$C	H	**14d**	3	(76)	7:1	92.5:7.5	(*S*)	21
Me	MeO$_2$C	H	**19**	2	(69)	1.5:1	50.0:50.0	—	120
MeO	Ac	Me	*ent*-**1a**	1	(60)	>20:1	87.0:13.0	(+)	21
MeO	Ac	Me	**13a**	1	(52)	6:1	81.0:19.0	(+)	21
MeO	Ac	Me	**13b**	1	(72)	5:1	83.0:17.0	(+)	21
MeO	Ac	Me	**14a**	1	(38)	5:1	81.5:18.5	(–)	21
MeO	Ac	Me	**14b**	1	(54)	13:1	88.0:12.0	(–)	21
MeO	Ac	Me	**14c**	1	(35)	3:1	60.5:39.5	(–)	21



NaCH(CO$_2$Me)$_2$

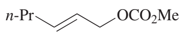
13a (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), THF, 70°, 1 d



I + II (83), **I/II** = 5:1, er **I** 90.0:10.0 (*R*)

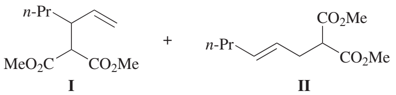
21

C_6

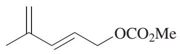


NaCH(CO$_2$Me)$_2$

Ligand (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), THF, 70°

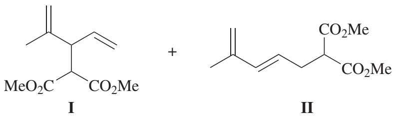


Ligand	Time (d)	**I + II**	**I/II**	er **I**	Config.	Refs.
ent-**1a**	1.5	(80)	8:1	99.0:1.0	(+)	21
13a	2	(69)	2:1	98.0:2.0	(+)	
13b	2.5	(54)	2:1	93.0:7.0	(+)	
14a	1.5	(84)	8:1	99.0:1.0	(–)	
14b	1.5	(83)	8:1	98.5:1.5	(–)	



NaCH(CO$_2$Me)$_2$

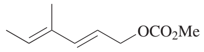
1a (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90°, 3 h



I + II (81), **I/II** = 8.1:1, er **I** 90.0:10.0

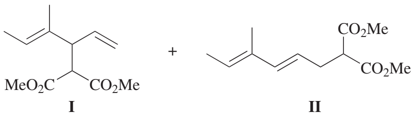
49

C_7

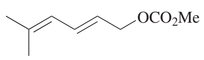


NaCH(CO$_2$Me)$_2$

Ligand (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90°

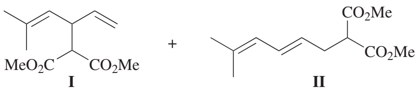


Ligand	Time (h)	**I + II**	**I/II**	er **I**	Refs.
1a	3	(89)	49:1	99.0:1.0	49
7a	6	(87)	15.7:1	98.5:1.5	



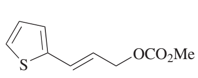
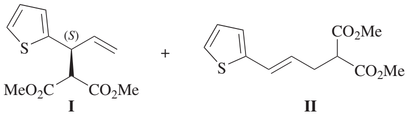
NaCH(CO$_2$Me)$_2$

Ligand (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90°, 2 h

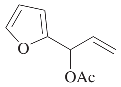
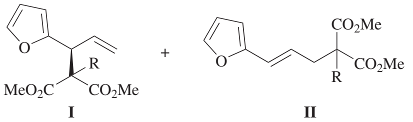


Ligand	**I + II**	**I/II**	er **I**	Refs.
1a	(96)	15.7:1	93.0:7.0	49
3c	(94)	15.7:1	95.5:4.5	

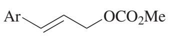
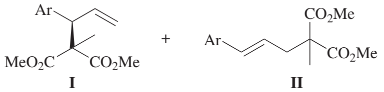
TABLE 1. ALLYLATION OF MALONATES (*Continued*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_7				
	$\mathrm{NaCH(CO_2Me)_2}$	Ligand (15 mol %), $\mathrm{Mo(\eta^6\text{-}C_7H_8)(CO)_3}$ (10 mol %), THF, 60°, 5 h		118

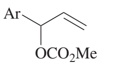
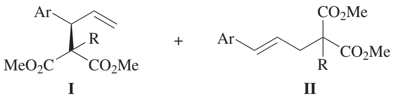
Ligand	I + II	I/II	er I	Config.
7b	(68)	10:1	95.0:5.0	(*S*)
8a	(87)	18:1	96.0:4.0	(*R*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	$\mathrm{NaRC(CO_2Me)_2}$	**1a** (15 mol %), $\mathrm{Mo(EtCN)_3(CO)_3}$ (10 mol %), THF		32

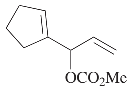
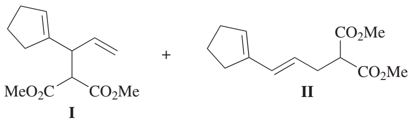
R	Temp	Time (h)	I + II	I/II	er I	Config.
Me	rt	18	(54)	99:1	97.5:2.5	(*S*)
Me	reflux	2	(65)	32:1	93.5:6.5	(*S*)
allyl	rt	12	(50)	99:1	99.0:1.0	(*S*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_{7-9}				
	$\mathrm{NaMeC(CO_2Me)_2}$	Ligand (15 mol %), $\mathrm{Mo(EtCN)_3(CO)_3}$ (10 mol %), THF, reflux		

Ar	Ligand	Time (h)	I + II	I/II	er I	Config.	Refs.
2-furyl	**1a**	2	(71)	32:1	98.5:1.5	(*S*)[b]	32
Ph	**1a**	4	(67)	24:1	99.0:1.0	(*R*)[b]	32
Ph	**7b**	12	(37)	4:1	86.5:13.5	(*R*)	118
Ph	**8b**	10	(32)	10:1	78.5:21.5	(*S*)	118

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_{7-13}				
	$\mathrm{NaRC(CO_2Me)_2}$	**1a** (15 mol %), $\mathrm{Mo(EtCN)_3(CO)_3}$ (10 mol %), THF, reflux, 2 h		32

Ar	R	I + II	I/II	er I	Config.
2-thienyl	Me	(71)	13:1	87.5:12.5	(*S*)
2-thienyl	H	(78)	19:1	94.0:6.0	(*S*)
2-pyridinyl	Me	(71)	5:1	97.0:3.0	(*S*)
2-pyridinyl	H	(69)	8:1	98.0:2.0	(*S*)
1-naphthyl	H	(82)	99:1	93.5:6.5	(*S*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_8				
	$\mathrm{NaCH(CO_2Me)_2}$	Ligand (15 mol %), $\mathrm{Mo(EtCN)_3(CO)_3}$ (10 mol %), PhMe/THF, 80–90°		49

Ligand	Time (h)	I + II	I/II	er I
1a	2	(94)	11.5:1	93.5:6.5
3c	1.5	(88)	13.3:1	93.0:7.0

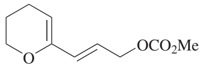
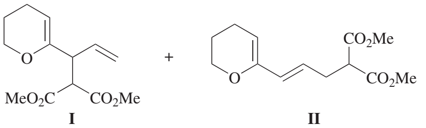
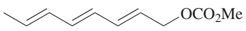
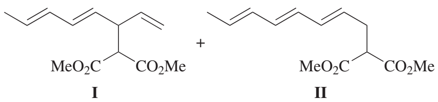
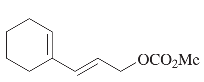
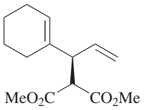
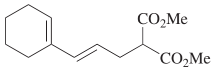
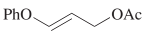
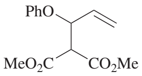
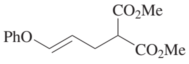
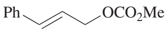
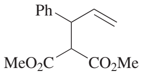
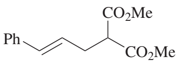
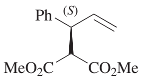
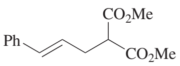
Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	$\mathrm{NaCH(CO_2Me)_2}$	**1a** (15 mol %), $\mathrm{Mo(EtCN)_3(CO)_3}$ (10 mol %), PhMe/THF, 80–90°, 1.5 h	 **I + II** (93), **I/II** = 13.3:1, er **I** 98.0:2.0	49
	$\mathrm{NaCH(CO_2Me)_2}$	**1a** (15 mol %), $\mathrm{Mo(EtCN)_3(CO)_3}$ (10 mol %), PhMe/THF, 80–90°, 3 h	 **I + II** (81), **I/II** = 10.1:1, er **I** 99.0:1.0	49

TABLE 1. ALLYLATION OF MALONATES (*Continued*)

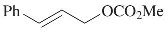
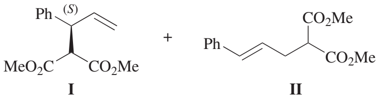
Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_9				
	$NaCH(CO_2Me)_2$	**7b** (15 mol %), $Mo(\eta^6\text{-}C_7H_8)(CO)_3$ (10 mol %), THF, 60°, 24 h	 **I** +  **II** **I + II** (59), **I/II** = 5.5:1, er **I** 93.0:7.0 (*S*)	118
	$NaCH(CO_2Me)_2$	**8a** (15 mol %), $Mo(\eta^6\text{-}C_7H_8)(CO)_3$ (10 mol %), THF, 60°, 24 h	**I + II** (61), **I/II** = 6.2:1, er **I** 93.5:6.5 (*R*)	118
	$NaCH(CO_2Me)_2$	**1a** (15 mol %), $Mo(EtCN)_3(CO)_3$ (10 mol %), PhMe/THF, 80–90°, 3 h	**I + II** (91), **I/II** = 11.5:1, er **I** 97.0:3.0	49
	$NaCH(CO_2Me)_2$	Ligand (15 mol %), $Mo(EtCN)_3(CO)_3$ (10 mol %), THF, 70°	 **I** +  **II** **I/II** > 20:1	21

Ligand	Time (d)	**I + II**	er **I**	Config.
ent-**1a**	2	(79)	96.5:3.5	(–)
13a	2	(79)	99.0:1.0	(–)
13b	2	(78)	97.5:2.5	(–)
14a	1.5	(81)	96.5:3.5	(+)
14b	2	(75)	98.0:2.0	(+)

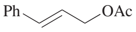
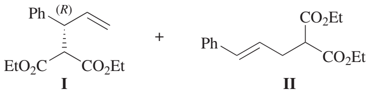
Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	$NaCH(CO_2Me)_2$	*ent*-**1a** (15 mol %), $Mo(CO)_6$ (10 mol %), PhMe, 85°, 8–12 h	 **I** +  **II** **I + II** (80), **I/II** = 19:1, er **I** 99.5:0.5	119
	$NaCH(CO_2Me)_2$	Ligand (15 mol %), $Mo(EtCN)_3(CO)_3$ (10 mol %), THF	 **I** +  **II**	

Ligand	Temp (°)	Time	**I + II**	**I/II**	er **I**	Config.	Refs.
1a	rt	3 h	(70)	49:1	99.5:0.5	(*S*)	32
1a	reflux	3 h	(88)	32:1	99.5:0.5	(*S*)	32
3a[c]	—	—	(95)	30:1	99.0:1.0	(*R*)	19
3b[c]	—	—	(90)	60:1	99.0:1.0	(*R*)	19
ent-**4a**[c]	—	—	(35)	1:1	62.0:38.0	(*R*)	19
ent-**4b**[c]	—	—	(93)	46:1	99.5:0.5	(*R*)	19
4c	—	—	(29)	19:1	99.0:1.0	(*S*)	19
4d	—	—	traces	—	—	—	19
7a[c]	—	—	(95)	19:1	99.5:0.5	(*S*)	19
7b	60	4 h	(63)	8:1	96.0:4.0	(*S*)	118
7b[c]	60	4 h	(65)	8:1	96.0:4.0	(*S*)	118
7c	60	24 h	(21)	12:1	89.0:11.0	(*S*)	118
7d[c]	60	24 h	(51)	9:1	94.5:5.5	(*S*)	28
8a	60	12 h	(68)	32:1	99.0:1.0	(*R*)	118
8b	60	4 h	(69)	13:1	94.5:5.5	(*R*)	118
8c[c]	60	72 h	(64)	13:1	79.5:20.5	(*R*)	28
9a	60	3 h	(57)	1:1	52.5:47.5	(*R*)	28
9b	60	2 d	(47)	2:1	63.5:36.5	(*R*)	28
10[c]	60	1 d	(29)	1:1	55.0:45.0	(*S*)	28
11a	70	0.5 d	(86)	14:1	99.5:0.5	(*R*)	21
13a	70	1 d	(83)	6:1	99.0:1.0	(*R*)	21
ent-**1a**	48	—	(>90)	35:1	98.5:1.5	(*R*)[d]	35

TABLE 1. ALLYLATION OF MALONATES (*Continued*)

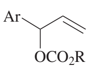
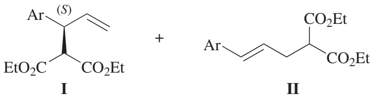
Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C9 	NaCH(CO_2Me)$_2$	Ligand (5 mol %), $Mo(CO)_6$ (4 mol %), BSA, THF, MW		

Ligand	Temp/Power	Time (min)	I + II	I/II	er I	Config.	Refs.
1a	200 W	5	(71)[e]	19:1	99.0:1.0	(*S*)	33
1a	200 W	6	(82)[e]	19:1	99.0:1.0	(*S*)	33
1a	160°	6	(80)	19:1	99.0:1.0	(*S*)	34
1b	200 W	5	(30)[e]	13:1	89.5:10.5	(*S*)	33
1c	200 W	4	(88)	41:1	>99.5:0.5	(*S*)	33
1c	200 W	5	(89)	39:1	>99.5:0.5	(*S*)	33
1d	160°	6	(0)	—	—	—	34
1e	200 W	5	(46)[e]	13:1	99.0:1.0	(*S*)	33
1f	200 W	5	(7)[e]	16:1	98.5:1.5	(*S*)	33
1f	200 W	8	(32)[e]	16:1	98.5:1.5	(*S*)	33
1f	150 W	15	(37)[e]	16:1	98.5:1.5	(*S*)	33
1g	165°	6	(89)	74:1	98.0:2.0	(*S*)	34
1h	160°	6	(0)	—	—	—	34
1i	170°	12	(91)	88:1	98.0:2.0	(*S*)	34
1j	160°	6	(0)	—	—	—	34
2a	160°	6	(90)	98:1	98.5:1.5	(*R*)	33
2b	160°	6	(89)	74:1	98.5:1.5	(*R*)	33
2c	160°	6	(89)	75:1	99.5:0.5	(*R*)	33
2d	160°	12	traces	—	—	—	33
2e	160°	30	(82)	35:1	98.5:1.5	(*R*)	33
5a	160°	6	(90)[f]	49:1	99.5:0.5	(*R*)	61
5a	160°	6	(35)[g]	8:1	99.5:0.5	(*R*)	61
5b	160°	6	(42)[e]	12:1	93.5:6.5	(*R*)	61
6	160°	6	(41)[e]	5:1	70.0:30.0	(*S*)	61

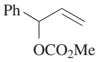
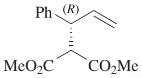
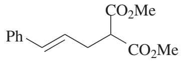
Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	NaCH(CO_2Et)$_2$	**11a** (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %)		21

Solvent	Temp (°)	Time (d)	I + II	I/II	er I	Config.
THF	70	5	(38)	9:1	99.0:1.0	(*R*)
PhMe	110	3	(84)	10:1	98.5:1.5	(*R*)

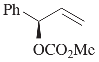
Malonate	Conditions	Product	Ligand	I + II	I/II	er I	Config.	Refs.
NaCH(CO_2Et)$_2$	Ligand–Mo(CO)$_4$ (20 mol %), $SnCl_4$, NaH, 1,4-dioxane, 80°, 24 h	I + II	**16a**	(52)	6.1:1	61.0:39.0	(*S*)	120
			16b	(0)	—	—	—	
			17	(33)	6.7:1	54.0:46.0	—	
			18	(42)	3.5:1	56.0:44.0	(*R*)	

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	NaCH(CO_2Me)$_2$	Ligand (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), THF		

Ar	R	Ligand	Temp (°)	Time (h)	I + II	I/II	er I	Config.	Refs.
Ph	Me	**1a**	rt	3	(61)	32:1	98.5:1.5	(*S*)	32
Ph	Me	**1a**	reflux	3	(70)	13:1	96.0:4.0	(*S*)	32
Ph	Me	**3a**	—	—	(88)	28:1	94.0:6.0	(*R*)	19
Ph	Me	**3b**[c]	—	—	(90)	53:1	96.0:4.0	(*R*)	19
Ph	Me	**7b**	60	4	(72)	12:1	94.0:6.0	(*S*)	118
Ph	Me	**8a**	60	12	(59)	38:1	98.5:1.5	(*R*)	118
Ph	Me	**8b**	60	4	(68)	13:1	87.0:13.0	(*R*)	118
Ph	Me	**13a**	70	24	(83)	6:1	92.0:8.0	(*R*)	21
3-$O_2NC_6H_4$	*t*-Bu	**1a**[h]	67	24	(94)	100:0	98.0:2.0	(*R*)	65

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_9				
	$NaCH(CO_2Me)_2$	Ligand (15 mol %), $Mo(\eta^6-C_7H_8)(CO)_3$ (10 mol %)	 **I** +  **II** **I** + **II** (—)	35

Ligand	Solvent	Temp (°)	**I/II**	er **I**	Config.[d]
ent-**1a**	THF	48	25:1	93.5:6.5	(*R*)
ent-**1a**	PhMe	60	46:1	98.0:2.0	(*R*)
ent-**1a**[i]	PhMe	90	32:1	98.5:1.5	(*R*)
ent-**1a**	MeCN	48	23:1	91.5:8.5	(*R*)
ent-**1a**	tetrahydropyran	48	30:1	96.0:4.0	(*R*)
ent-**1a**	tetrahydropyran	80	18:1	95.0:5.0	(*R*)
ent-**1a**	$ClCH_2CH_2Cl$	75	40:1	97.5:2.5	(*R*)
ent-**1a**	*i*-PrOAc	48	23:1	95.0:5.0	(*R*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	$NaCH(CO_2Me)_2$	Ligand (15 mol %), $Mo(\eta^6-C_7H_8)(CO)_3$ (10 mol %)	**I** + **II** (—)	35

Ligand	Solvent	Temp (°)	**I/II**	er **I**	Config.[d]
1a	THF	48	55:1	99.5:0.5	(*S*)
1a	PhMe	60	65:1	99.75:0.25	(*S*)
1a	MeCN	48	36:1	99.0:1.0	(*S*)
ent-**1a**	THF	48	12:1	85.0:15.0	(*R*)
ent-**1a**	PhMe	60	32:1	95.0:5.0	(*R*)
ent-**1a**	MeCN	48	8:1	72.0:28.0	(*R*)

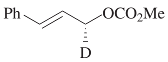
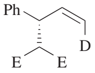
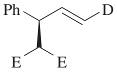
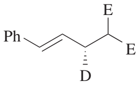
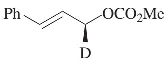
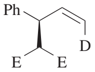
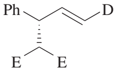
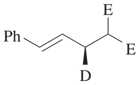
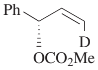
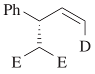
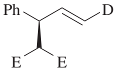
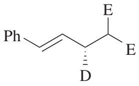
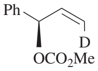
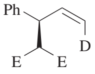
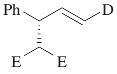
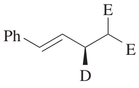
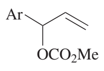
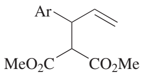
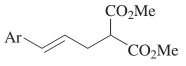
Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	$NaCH(CO_2Me)_2$	**8a** (15 mol %), $Mo(\eta^6-C_7H_8)(CO)_3$ (10 mol %), THF, 60°, 20 h	 +  +  **I** er >97.5:2.5 **II** er >97.5:2.5 **III** E = CO_2Me, **I** + **II** + **III** (—), **I/II/III** = 83.2:6.0:10.8	28
	$NaCH(CO_2Me)_2$	**8a** (15 mol %), $Mo(\eta^6-C_7H_8)(CO)_3$ (10 mol %), THF, 60°, 20 h	 +  +  **I** er 70.0:30.0 **II** er >97.5:2.5 **III** E = CO_2Me, **I** + **II** + **III** (—), **I/II/III** = 4.1:89.5:6.4	28
	$NaCH(CO_2Me)_2$	**8a** (15 mol %), $Mo(\eta^6-C_7H_8)(CO)_3$ (10 mol %), THF, 60°, 20 h	 +  +  **I** er >97.5:2.5 **II** er >97.5:2.5 **III** E = CO_2Me, **I** + **II** + **III** (—), **I/II/III** = 97.3:1.3:1.4	28
	$NaCH(CO_2Me)_2$	**8a** (15 mol %), $Mo(\eta^6-C_7H_8)(CO)_3$ (10 mol %), THF, 60°, 20 h	 +  +  **I** er 70.0:30.0 **II** er 93.5:6.5 **III** E = CO_2Me, **I** + **II** + **III** (—), **I/II/III** = 7.6:84.0:8.4	28

TABLE 1. ALLYLATION OF MALONATES (*Continued*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_9				
 Ar = Ph	$NaCH(CO_2Me)_2$	*ent*-**1a** (15 mol %), $Mo(CO)_6$ (10 mol %), PhMe, 85°, 8–12 h	 **I** +  **II** **I** + **II** (76), **I/II** = 13:1, er **I** 98.0:2.0	119
Ar = Ph	$NaCH(CO_2Me)_2$	Ligand (5 mol %), $Mo(CO)_6$ (4 mol %), BSA, THF, MW, 165°, 6 min	**I** + **II**	

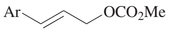
Ligand	I + II	I/II	er I	Config.	Refs.
1a	(76)	13:1	98.0:2.0	(*S*)	34
1g	(89)	69:1	93.0:7.0	(*S*)	34
5a	(82)	8:1	98.0:2.0	(*R*)	61

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)
Ar = 3-FC_6H_4	$NaCH(CO_2Me)_2$	*ent*-**1a** (15 mol %), Mo complex (10 mol %)[j]	**I** + **II**

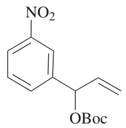
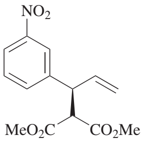
Mo Complex	Solvent	Time (h)[j]	Temp (°)	I + II	I/II	er I	Config.	Refs.
$Mo(CO)_6$	PhMe	0.75	85	(77)[k]	19:1	97.5:2.5	—	119
$Mo(CO)_6$	PhMe	4	85	(84)	19:1	98.5:1.5	—	119
$Mo(CO)_6$	PhMe	15	85	(91)[k]	11.5:1	94.5:5.5	—	119
$Mo(CO)_6$	THF	2	65	(86)[k]	11.5:1	96.0:4.0	—	119
$Mo(CO)_6$	THF	4	65	(83)[k]	8:1	96.0:4.0	—	119
$Mo(CO)_6$	THF	4	rt	(33)[k]	5.3:1	98.0:2.0	—	119
$Mo(CO)_6$	DMF	4	85	(55)[k]	6.1:1	93.5:6.5	—	119
$Mo(CO)_6$	DME	4	80	(90)[k]	5.7:1	97.5:2.5	—	119
$Mo(CO)_6$	DCE	4	80	(36)[k]	24:1	99.0:1.0	—	119
$Mo(EtCN)_3(CO)_3$	PhMe	0.5	85	(84)[k]	13.6:1	97.5:2.5	—	119
$Mo(\eta^6\text{-}C_7H_8)(CO)_3$	PhMe	0.5	85	(87)[k]	24:1	98.0:2.0	—	119
$Mo(CO)_6$	PhMe	4	85	(91)[k]	19:1	98.5:1.5	—	119
$Mo(EtCN)_3(CO)_3$	THF	0.5	65	(88)[k]	9:1	95.5:4.5	—	119
$Mo(\eta^6\text{-}C_7H_8)(CO)_3$	THF	0.5	65	(81)[k]	7.3:1	94.0:6.0	—	119
$Mo(CO)_6$	THF	4	65	(83)[k]	8.1:1	95.5:4.5	—	119
$Mo(\eta^6\text{-}C_7H_8)(CO)_3$	THF	—	48	(—)	15:1	94.0:6.0	(*R*)[d]	35
$Mo(\eta^6\text{-}C_7H_8)(CO)_3$	PhMe	—	75	(—)	30:1	98.0:2.0	(*R*)[d]	35

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
Ar = 4-ClC_6H_4	$NaCH(CO_2Me)_2$	*ent*-**2e** (5 mol %), $Mo(CO)_6$ (4 mol %), BSA, MW, 160°, 30 min	**I** + **II**	67

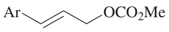
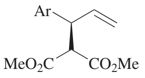
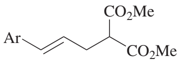
Solvent	I + II	I/II	er I	Config.
THF	(95)	27:1	74.0:26.0	(*R*)
THF/PhMe (1:1)	(98)[e]	24:1	88.0:12.0	(*R*)
THF/PhMe (1:9)	(76)[e]	25:1	94.5:5.5	(*R*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
 Ar = 4-FC_6H_4	$NaCH(CO_2Me)_2$	Ligand (15 mol %), $Mo(EtCN)_3(CO)_3$ (10 mol %), THF	**I** + **II**	19

Ligand	I + II	I/II	er I	Config.
1a	(84)	10:1	97.0:3.0	(*S*)
7a	(93)	13:1	98.0:2.0	(*S*)
7b	(92)	6:1	95.5:4.5	(*S*)
7c	(43)	9:1	88.5:11.5	(*S*)
7d	(72)	8:1	95.0:5.0	(*S*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
	$NaCH(CO_2Me)_2$	Ligand (15 mol %), $Mo(CO)_6$ (10 mol %), THF, MW, 180°, 20 min		65

Ligand		er	Config.
ent-**1a**	(92)	97.0:3.0	(*S*)
ent-**1c**	(94)	97.0:3.0	(*S*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)	Refs.
C_{9-10}				
	$NaCH(CO_2Me)_2$ $CH_2(CO_2Me)_2$	Ligand (5 mol %), $Mo(CO)_6$ (4 mol %), BSA, THF, MW, 165°, 6 min	 **I** +  **II**	34

Ar	Ligand	I + II	I/II	er I
4-ClC_6H_4	**1a**	(51)	32:1	98.0:2.0
4-ClC_6H_4	**1g**	(86)	47:1	95.0:5.0
4-$CF_3C_6H_4$	**1a**	(50)	11:1	99.5:0.5
4-$CF_3C_6H_4$	**1g**	(66)	22:1	98.0:2.0
4-$MeOC_6H_4$	**1a**	(59)	51:1	99.0:1.0
4-$MeOC_6H_4$	**1g**	(79)	57:1	97.0:3.0

TABLE 1. ALLYLATION OF MALONATES (*Continued*)

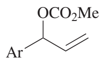
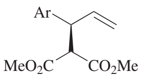
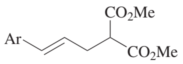
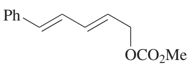
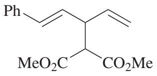
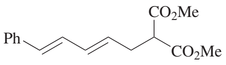
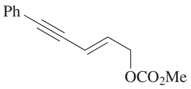
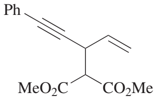
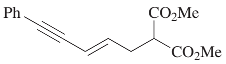
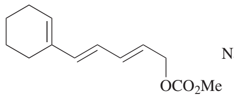
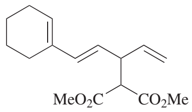
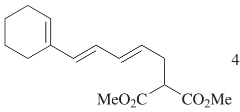
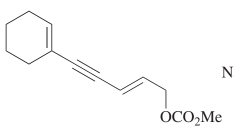
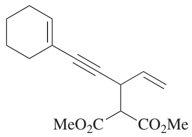
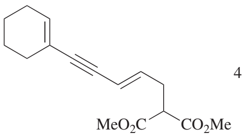
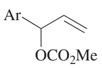
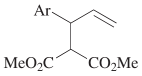
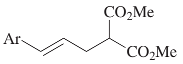
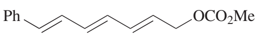
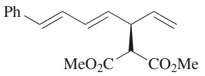
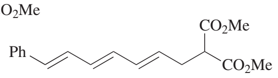
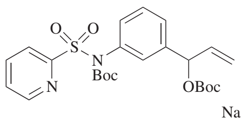
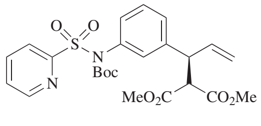
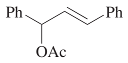
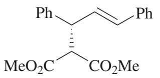
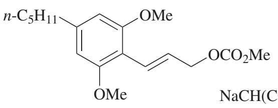
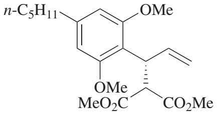
Allyl Compound and Malonate	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{9-10}  NaCH(CO$_2$Me)$_2$ Ar 4-ClC$_6$H$_4$ 4-ClC$_6$H$_4$ 4-CF$_3$C$_6$H$_4$ 4-CF$_3$C$_6$H$_4$	Ligand (5 mol %), Mo(CO)$_6$ (4 mol %), BSA, THF, MW, 165°, 6 min	 **I** +  **II** Ligand · **I + II** · **I/II** · er **I** **1a** (78) 26:1 98.0:2.0 **1g** (70) 34:1 87.0:13.0 **1a** (48) 10:1 99.0:1.0 **1g** (52) 20:1 95.0:5.0	34
C_{11}  NaCH(CO$_2$Me)$_2$	**7a** (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90°, 3 h	 **I** +  **II** **I + II** (95), **I/II** = 6.1:1, er **I** 99.0:1.0	49
 NaCH(CO$_2$Me)$_2$	**1a** (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90°, 3 h	 **I** +  **II** **I + II** (—), **I/II** = 5.3:1, er **I** 99.5:0.5	49
 NaCH(CO$_2$Me)$_2$	**1a** (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90°, 2 h	 **I** +  **II** **I + II** (70), **I/II** = 11.5:1, er **I** 98.5:1.5	49
 NaCH(CO$_2$Me)$_2$	**1a** (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90°, 3 h	 **I** +  **II** **I + II** (—), **I/II** = 7.3:1, er **I** 99.5:0.5	49
C_{13}  NaCH(CO$_2$Me)$_2$ Ar 4-*t*-BuC$_6$H$_4$ 1-naphthyl	**1a** (15 mol %), Mo(CO)$_6$ (10 mol %), PhMe, 85°, 8–12 h	 **I** +  **II** **I + II** · **I/II** · er **I** (76) 15.7:1 97.0:3.0 (80) 49:1 98.0:2.0	119
 NaCH(CO$_2$Me)$_2$	Ligand (15 mol %), Mo(EtCN)$_3$(CO)$_3$ (10 mol %), PhMe/THF, 80–90° Ligand · Time (h) **1a** 3.5 **7a** 4	 **I** +  **II** **I + II** · **I/II** · er **I** · Config. (68) 6.1:1 >99.5:0.5 (*R*) (58) 5.3:1 98.5:1.5 (*R*)	49
C_{14}  NaCH(CO$_2$Me)$_2$	**1a** (15 mol %), Mo(η^6-C$_7$H$_8$)(CO)$_3$ (10 mol %), THF, 67°	 (95) er 97.0:3.0 (*S*)	65

TABLE 1. ALLYLATION OF MALONATES (*Continued*)

Allyl Compound and Malonate		Conditions	Product(s) and Yield(s) (%)		Refs.
C_{15} 	$NaCH(CO_2Me)_2$	Ligand–$Mo(CO)_4$ (20 mol %), $SnCl_4$, NaH, 1,4-dioxane, 80°, 24 h		Ligand | (yield) | er | Config. **16b** (0) — — **18** (22) 55.0:45.0 (*R*)	120
C_{16} 	$NaCH(CO_2Me)_2$	*ent*-**1a** (7.5 mol %), $Mo(\eta^6\text{-}C_7H_8)(CO)_3$ (5 mol %),[l] THF, 65°, 30 h		(95) er 97.0:3.0 (*R*)	48

[a] This reaction employed 3.8 mol % ligand and 2.5 mol % $Mo(EtCN)_3)(CO)_3$.

[b] The apparent change in configuration between the first 2 entries in the subtable is due to a change in substituent priorities.

[c] This reaction employed 10 mol % $Mo(\eta^6\text{-}C_7H_8)(CO)_3$.

[d] The opposite absolute streochemistry of the product was erroneously reported in ref. 35.

[e] The yield was determined by gas chromatography.

[f] This reaction employed 11 mol % ligand and 10 mol % $Mo(CO)_6$.

[g] This reaction employed 4.4 mol % ligand.

[h] This reaction employed $Mo(\eta^6\text{-}C_7H_8)(CO)_3$ as the catalyst.

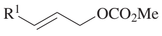
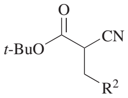
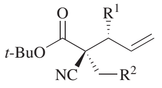
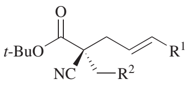
[i] This reaction employed $Mo(CO)_6$ as catalyst precursor.

[j] The catalyst was activated for 2–4 h at 65–90° prior to the catalytic reaction.

[k] The yield was determined by HPLC.

[l] The use of 15 mol % **1a** and 10 mol % Mo complex afforded the product in 95% yield and er 97.5:2.5.

TABLE 2. ALLYLATION OF CYANO ESTERS

Allyl Compound and Cyano Ester		Conditions	Product(s) and Yield(s) (%)		Refs.
C_{3-11} 		**1c** (15 mol %), $Mo(CO)_6$ (10 mol %), NaH (10 mol %), BSA (2 eq), THF, 60°, 17 h	 **I**	+  **II**	52

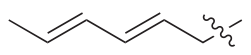
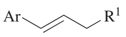
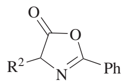
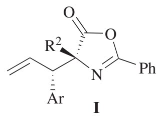
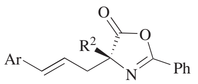
R^1	R^2	I + II	I/II	dr I	er I
H	Me	(99)	—	—	99.5:0.5
H	Et	(96)	—	—	99.0:1.0
2-thienyl	Et	(93)	>20:1	>20:1	99.0:1.0
Ph	Me	(96)	>20:1	16.8:1	96.5:3.5
Ph	Et	(93)	>20:1	12:1	97.5:2.5
Ph	Ph	(95)	>20:1	>20:1	>99.5:0.5
Ph	Bn	(93)	>20:1	>20:1	99.0:1.0
Ph	$Me(CH_2)_5$	(98)	>20:1	15.7:1	99.5:0.5
Ph		(91)	>20:1	6.5:1	98.0:2.0
Ph	MeO	(79)	>20:1	>20:1	94.0:6.0
$4\text{-}BrC_6H_4$	Et	(92)	>20:1	13.7:1	98.5:1.5
$4\text{-}FC_6H_4$	Et	(>99)	>20:1	20:1	95.5:4.5
$4\text{-}MeOC_6H_4$	Et	(85)	>20:1	12.2:1	94.5:5.5
$4\text{-}O_2NC_6H_4$	Et	(83)	>20:1	11.1:1	96.0:4.0
$3,5\text{-}Br_2C_6H_3$	Et	(94)	>20:1	14.0:1	98.5:1.5
$3,5\text{-}Br_2C_6H_3$	$4\text{-}BrC_6H_4$	(89)	>20:1	>20:1	99.5:0.5
3-(*N*-Boc)indolyl	Et	(>99)	>20:1	11:1	98.5:1.5

TABLE 3. ALLYLATION OF α-IMINO ESTERS AND α-IMINO LACTONES

Allyl Compound and α-Imino Ester or Lactone	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{7-11}  	*ent*-**1a** (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), LiHMDS, THF, 65°	 **I** +  **II**	37

Ar	R^1	R^2	Time (h)	I	dr I	er I	II
2-furyl	$MeOCO_2$	Me	4	(84)	>98:2	96.0:4.0	(4)
3-thienyl	$MeOCO_2$	Me	3	(84)	96:4	95.5:4.5	(—)
3-thienyl	$MeOCO_2$	Bn	3	(86)	>98:2	97.0:3.0	(—)
Ph	*t*-$BuOCO_2$	Me	—	(83)	96:4	99.5:0.5	(—)
Ph	$(EtO)_2PO_2$	Me	—	(80)	>98:2	99.5:0.5	(—)
Ph	$MeOCO_2$	Me	3	(92)	97:3	99.5:0.5	(—)
Ph	$MeOCO_2$	Bn	3	(92)	>98:2	98.0:2.0	(—)
Ph	$MeOCO_2$	$MeS(CH_2)_2$	4	(86)	>98:2	96.0:4.0	(6)
Ph	$MeOCO_2$	*i*-Bu	4	(85)	>98:2	98.0:2.0	(5)
Ph	$MeOCO_2$	*n*-Pr	3	(82)	>98:2	98.5:1.5	(6)
Ph	$MeOCO_2$	*i*-Pr	6	(76)	>98:2	98.0:2.0	(11)
2,4-$(MeO)_2C_6H_3$	$MeOCO_2$	Me	3	(89)	>98:2	95.0:5.0	(—)
2,4-$(MeO)_2C_6H_3$	$MeOCO_2$	Bn	3	(90)	>98:2	97.0:3.0	(—)

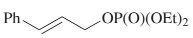
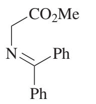
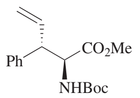
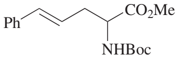
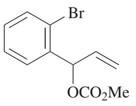
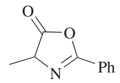
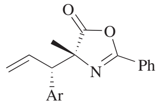
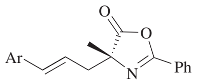
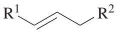
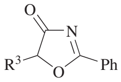
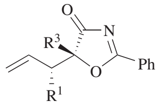
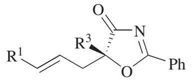
Allyl Compound and α-Imino Ester or Lactone	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9  	1. *ent*-**1a** (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), LDA, THF, 0° 2. 1 N HCl 3. $(Boc)_2O$, Et_3N	 +  **I** (67) dr 20:1, er 99.0:1.0 **II** (33)	37
 	*ent*-**1a** (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), LiHMDS, THF, 65°, 4 h	 +  **I** (82) dr >98:2, er 92.5:7.5 **II** (9)	37

TABLE 4. ALLYLATION OF OXALACTIMS

Allyl Compound and Oxalactim	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{7-11}  	*ent*-**1a** (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), base, THF, 65°, 16 h	 **I** +  **II**	38

R^1	R^2	R^3	Base	I + II	I/II	dr I	er I
Me_2C=CH	$MeOCO_2$	Me	LiHMDS	(77)	14:1	12:1	94.5:5.5
3-thienyl	$MeOCO_2$	*i*-Bu	LiHMDS	(89)	14:1	10:1	99.5:0.5
1-cyclohexenyl	$MeOCO_2$	Me	LiHMDS	(54)	12:1	12:1	99.0:1.0
Ph	$(EtO)_2PO_2$	Me	LiHMDS	(90)	7:1	8.1:1	98.0:2.0
Ph	$MeOCO_2$	Me	KHMDS	(88)	6.7:1	1.4:1	90.0:10.0
Ph	$MeOCO_2$	Me	NaHMDS	(80)	24:1	2.7:1	99.0:1.0
Ph	$MeOCO_2$	Me	LiHMDS	(91)	99:1	11.5:1	>99.5:0.5
Ph	$MeOCO_2$	*n*-Bu	LiHMDS	(86)	49:1	9:1	>99.5:0.5
Ph	$MeOCO_2$	allyl	LiHMDS	(97)	8:1	10:1	>99.5:0.5
Ph	$MeOCO_2$	*i*-Pr	LiHMDS	(70)	5.5:1	20:1	>99.5:0.5
Ph	$MeOCO_2$	*c*-C_6H_{11}	LiHMDS	(74)	9:1	12:1	>99.5:0.5
Ph	$MeOCO_2$	Bn	LiHMDS	(84)	>95:5	7.4:1	>99.5:0.5
2,4-$(MeO)_2C_6H_3$	$MeOCO_2$	Me	LiHMDS	(82)	12:1	18:1	>99.5:0.5

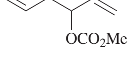
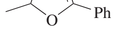
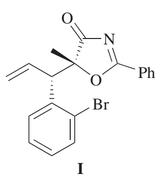
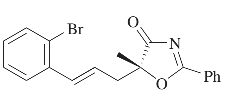
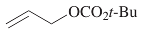
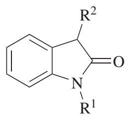
Allyl Compound and Oxalactim	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9  	*ent*-**1a** (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), LiHMDS, THF, 65°, 16 h	 **I** +  **II** **I** + **II** (78), **I**/**II** = 27:1, dr **I** 24:1, er **I** 99.5:0.5	38

TABLE 5. ALLYLATION OF OXINDOLES

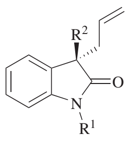
Allyl Compound and Oxindole	Conditions	Product(s) and Yield(s) (%)	Refs.

C_3



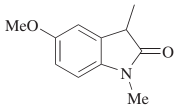


1a (15 mol %),
Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %),
LiO*t*-Bu (2 eq), THF, rt, 3–6 h

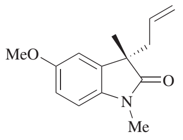


56

R^1	R^2		er
Me	Me	(98)	91.0:9.0
Me	Me	(99)	90.5:9.5
Bn	Me	(93)	87.5:12.5
Me	Bn	(95)	96.5:3.5
MOM	Bn	(95)	93.5:6.5
Bn	Bn	(92)	93.5:6.5
allyl	Bn	(99)	94.0:6.0
Me	*i*-Pr	(96)	95.5:4.5
Bn	*i*-Pr	(98)	92.5:7.5
Me	$NCCH_2$	(99)	96.5:3.5
allyl	$NCCH_2$	(98)	96.5:3.5
Me	2-(BocHN)$C_6H_4CH_2$	(96)	97.5:2.5
Bn	$Me_2C{=}CHCH_2$	(95)	90.0:10.0
Me	$MeC{\equiv}CCH_2$	(95)	90.0:10.0
MOM	$MeC{\equiv}CCH_2$	(96)	87.5:12.5
Bn	$MeC{\equiv}CCH_2$	(98)	87.0:13.0
Me	$TMSC{\equiv}CCH_2$	(96)	94.0:6.0
Me	$TBSO(CH_2)_2$	(94)	87.5:12.5



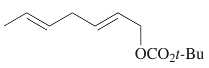
1a (15 mol %),
Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %),
base, THF

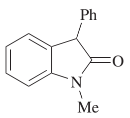


56

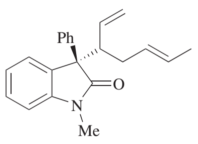
Base	Temp		er
KHMDS	67°	(—)	69.0:31.0
NaHMDS	67°	(—)	80.0:20.0
LiHMDS	67°	(75–92)	87.5:12.5–89.0:11.0
s-BuLi	67°	(—)	85.5:14.5
LiHMDS	rt	(45)	90.0:10.0
LiHMDS/LiO*t*-Bu	rt	(95)	90.5:9.5
LiHMDS (2 eq)	rt	traces	—
LiO*t*-Bu (2 eq)	rt	(95–98)	90.0:10.0–91.0:9.0
LiO*t*-Bu (2 eq)	4°	(95)	91.0:9.0
LiO*t*-Bu (2 eq)	–10°	(90)	86.5:13.5

C_7



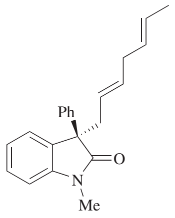


1a (15 mol %),
Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %),
NaO*t*-Bu (1.1 eq), THF, 60°



I

\+



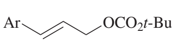
II

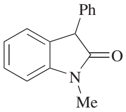
I + **II** (84), **I**/**II** = 6:1, dr **I** 6:1, er **I** 95.5:4.5

39

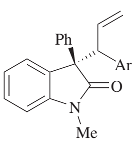
Allyl Compound and Oxindole	Conditions	Product(s) and Yield(s) (%)	Refs.

C_{7-9}



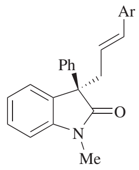


1a (15 mol %),
Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %),
NaO*t*-Bu (1.1 eq), THF, 60°



I

+

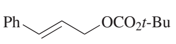


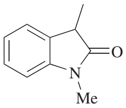
II

39

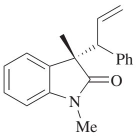
Ar	**I** + **II**	**I**/**II**	dr **I**	er **I**
2-furyl	(92)	12:1	6:1	95.5:4.5
2-thienyl	(88)	13:1	8:1	95.0:5.0
4-(TBSO)C_6H_4	(90)	19:1	8:1	94.5:5.5
2-(BocHN)C_6H_4	(89)	19:1	19:1	96.5:3.5
3,4-$Cl_2C_6H_3$	(87)	6:1	5.5:1	94.5:5.5

C_9



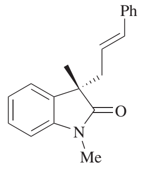


Ligand **1a** (15 mol %),
Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %),
LiO*t*-Bu (1 eq), THF, rt, 8 h



I

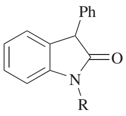
+



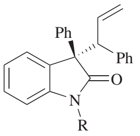
II

45

I + **II** (—), **I**/**II** = 2:1, dr **I** 1.2:1, er **I** —

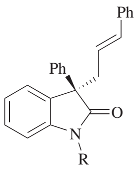


Ligand (15 mol %),
Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %),
base (1.1 eq), THF, 2–8 h



I

+

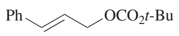


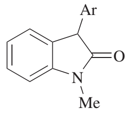
II

R	Ligand	Base	Temp	**I** + **II**	**I**/**II**	dr **I**	er **I**	Refs.
Boc	**1a**	NaO*t*-Bu	60°	(91)	5:1	5:1	96.5:3.5	39
MOM	**1a**	NaO*t*-Bu	60°	(90)	19:1	7:1	96.0:4.0	39
Bn	**1a**	NaO*t*-Bu	60°	(85)	17:1	9:1	95.0:5.0	39
Me	**1a**	NaO*t*-Bu	60°	(88)	18:1	8:1	96.0:4.0	39
Me	**1a**	NaO*t*-Bu	60°	(—)	16:1	—	—	45
Me	**1a**	LiO*t*-Bu	rt	(—)	4:1	8:1	97.5:2.5	45
Me	**1c**	LiO*t*-Bu	rt	(—)	2.5:1	5.5:1	—	45
Me	*ent*-**3c**	LiO*t*-Bu	rt	(—)	2.5:1	5:1	—	45
Me	**15**	LiO*t*-Bu	rt	(—)	4:1	7:1	—	45
Me	**7a**	LiO*t*-Bu	rt	(—)	1.2:1	3:1	—	45
Me	*ent*-**7d**	LiO*t*-Bu	rt	(—)	5:1	4:1	—	45
Me	**1a**	KO*t*-Bu	rt	(—)	10:1	5:1	97.0:3.0	45
Me	**1a**	NaO*t*-Bu	rt	(89)	16:1	9:1	96.0:4.0	45
Me	**1a**	NaO*t*-Bu	0°	(—)	16:1	9:1	96.0:4.0	45
Me	**1a**	NaO*t*-Bu	–78°	(40)	1:1	2:1	95.5:4.5	45

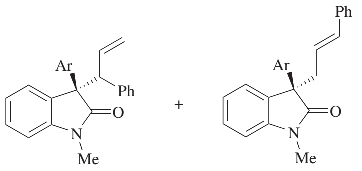
Allyl Compound and Oxindole	Conditions	Product(s) and Yield(s) (%)	Refs.

C_9





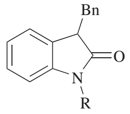
Ligand (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), NaO*t*-Bu (1.1 eq), THF, 60°, 2–8 h



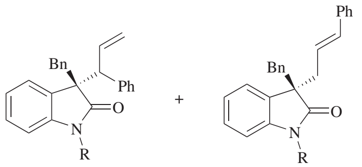
I + **II**

39

Ar	Ligand	**I** + **II**	**I**/**II**	dr **I**	er **I**
4-FC_6H_4	**1a**	(90)	16:1	6:1	95.5:4.5
4-ClC_6H_4	**1a**	(88)	13:1	5.5:1	97.5:2.5
4-NCC_6H_4	**1a**	(84)	7:1	4.5:1	94.5:5.5
4-NCC_6H_4	**1c**	(85)	18:1	4:1	96.0:4.0
4-$MeOC_6H_4$	**1a**	(92)	18:1	8:1	96.0:4.0
4-$Me_2NC_6H_4$	**1a**	(87)	17:1	6:1	96.0:4.0
2-MeC_6H_4	**1a**	(90)	17:1	19:1	97.0:3.0
1-naphthyl	**1a**	(88)	15:1	19:1	97.5:2.5
2-naphthyl	**1a**	(90)	15:1	6:1	95.0:5.0
2-thienyl	**1a**	(90)	0:1	—	50.0:50.0
N-Me-3-indolyl	**1a**	(82)	0:1	—	—
2-Ph-5-thiazolyl	**1a**	(86)	0:1	—	—
3-Me-2-thienyl	**1a**	(95)	11:1	19:1	96.0:4.0
N-Me-2-Ph-3-indolyl	**1a**	(65)	9:1	19:1	97.0:3.0
2,4-Me_2-5-thiazolyl	**1a**	(84)	2.5:1	19:1	96.0:4.0
2,4-Me_2-5-thiazolyl	**1c**	(86)	16:1	19:1	96.5:3.5
2,4-Ph_2-5-oxazolyl	**1a**	(83)	16:1	19:1	98.0:2.0
N-Ts-3-indolyl	**1a**	(63)	10:1	19:1	98.5:1.5



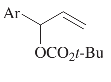
1a (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), base, THF, 60°, 2 h

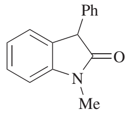


I + **II**

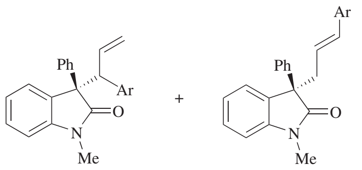
45

R	Base (eq)	**I** + **II**	**I**/**II**	dr **I**	er **I**
Me	NaO*t*-Bu (1)	(92)	2:1	1.2:1	96.0:4.0
AcO	NaO*t*-Bu (1)	(0)	—	—	—
2-pyridinyl	NaO*t*-Bu (1)	(89)	14:1	1:1	—
t-BuO_2C	NaO*t*-Bu (1)	(85)	12:1	3:1	99.0:1.0
EtO_2C	NaO*t*-Bu (1)	(86)	15:1	5:1	99.5:0.5
MeO_2C	NaO*t*-Bu (1)	(60)	15:1	7:1	99.0:1.0
MeO_2C	NaO*t*-Bu (0.1), BSA (1.2)	(88)	15:1	7:1	99.0:1.0
MeO_2C	NaO*t*-Bu (0.1), BSA (1.2)[a]	(83)	15:1	7:1	99.0:1.0





Ligand (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), NaO*t*-Bu, THF, 60°, 2 h



I + **II**

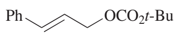
45

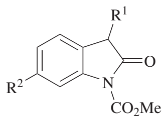
Ar	Ligand	**I** + **II**	**I**/**II**	dr **I**	er **I**
Ph	**1a**	(88)	10:1	6:1	91.0:9.0
Ph	**1c**	(85)	15:1	9:1	96.5:3.5
3,4-$Cl_2C_6H_3$	**1a**	(90)	6:1	5:1	90.0:10.0
3,4-$Cl_2C_6H_3$	**1c**	(87)	8:1	6:1	94.5:5.5
4-(TBSO)C_6H_4	**1a**	(89)	12:1	6.5:1	90.5:9.5
4-(TBSO)C_6H_4	**1c**	(89)	15:1	8:1	94.5:5.5

TABLE 5. ALLYLATION OF OXINDOLES (*Continued*)

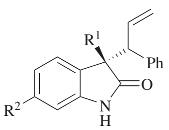
Allyl Compound and Oxindole	Conditions	Product(s) and Yield(s) (%)	Refs.

C_9



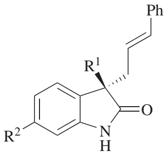


1. **1a** (15 mol %), Mo(η^6-C_7H_8)(CO)$_3$ (10 mol %), NaO*t*-Bu (1 eq), THF, 60°, 2 h
2. NaOH/MeOH, 30 min



I

\+



II

45

R^1	R^2	**I** + **II**	**I**/**II**	dr **I**	er **I**
Me	H	(93)	>15:1	7:1	99.0:1.0
Et	H	(90)	>15:1	10:1	99.5:0.5
i-Pr	H	(90)	>19:1	>19:1	98.5:1.5
i-Pr	Cl	(87)	>15:1	>19:1	99.0:1.0
i-Pr	MeO	(90)	>15:1	>19:1	98.0:2.0
allyl	H	(89)	>15:1	8:1	99.5:0.5
TBSO(CH_2)$_2$	H	(83)	11:1	7:1	98.5:1.5
t-BuO_2CCH_2	H	(84)	12:1	4:1	98.5:1.5
Bn	H	(85)	>15:1	7:1	99.0:1.0

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[a] This reaction employed 2.5 mol % Mo(η^6-C_7H_8)(CO)$_3$.

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CHAPTER 2

THE WACKER OXIDATION

Brian W. Michel, Laura D. Steffens, and Matthew S. Sigman

Department of Chemistry, University of Utah, 315 S 1400 E, Salt Lake City, UT 84112-0850

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sigman@chem.utah.edu

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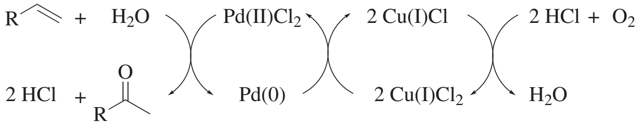
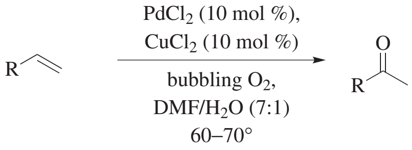
INTRODUCTION

The Wacker oxidation is both an industrially viable and synthetically useful transformation to access methyl ketones from terminal alkenes that generally uses a Pd(II) catalyst and co-oxidant (Scheme 1). This reaction has a rich history dating back to the discovery of the stoichiometric conversion of ethylene into acetaldehyde mediated by an acidic, aqueous solution of $PdCl_2$.[1] For more than a half century, this report received little attention until chemists at the Consortium für Elektrochemische Industrie, the research organization for Wacker Chemie, reported what is now termed the Wacker process using catalytic amounts of Pd(II) and stoichiometric amounts of Cu(II) under acidic, aqueous, aerobic conditions (Scheme 1).[2] The motivation for the development of this process was to avoid a difficult two-step hydration–oxidation of ethylene into acetaldehyde. The mechanistic and technical details of the Wacker process are in themselves very impressive, but the focus of this chapter will be applications of this general transformation in synthetic chemistry.

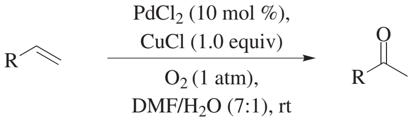


Scheme 1

Most organic molecules have limited solubility in water, which is often used as the sole solvent in the Wacker process. Therefore, an important practical advance for synthetic applications of the Wacker oxidation was the discovery that dimethyl formamide (DMF) is a viable co-solvent for most substrates (Scheme 2).[3] This modification, termed the "Clement modification", set the foundation for the disclosure of the most commonly applied Wacker oxidation conditions, referred to as the Tsuji–Wacker oxidation, which has found extensive application in synthesis. The method includes the use of catalytic amounts of $PdCl_2$ and 1 equivalent of CuCl under balloon pressure of molecular oxygen and in a 7:1 solvent mixture of DMF/H_2O (Scheme 3).[4] Although these conditions are generally a good starting point for evaluating a new substrate for the Wacker oxidation, numerous modifications of this method have been described.



Scheme 2



Scheme 3

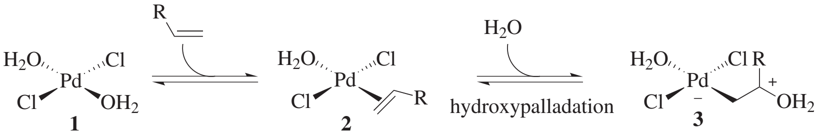
This chapter will first summarize the current mechanistic understanding, particularly emphasizing the aspects relevant to practical use. The coverage then continues with an overview of the scope and limitations of the Tsuji–Wacker oxidation conditions, describing compatible functional groups and substrate classes. The "Scope and Limitations" section will also include substrates (mainly terminal alkenes functionalized at the allylic position) that do not selectively yield the standard ketone product under standard Tsuji–Wacker conditions. Mechanistically distinct variants employing peroxides instead of water as the nucleophile will also be presented as these methods yield ketone products selectively when applied to these difficult substrate classes. Finally, this survey includes the use of alternative nucleophiles involving both inter- and intramolecular additions of alcohols and amines. An overview of alternative reaction conditions is discussed in the "Experimental Conditions" section. In view of the breadth of this topic and the focus on synthetic applications, reports of process improvements of unfunctionalized, low-molecular-weight alkenyl substrates are not included. Several reviews are available on the Wacker oxidation and related Pd-catalyzed alkene functionalization reactions and these reports should be referred to for a more detailed overview of specific topics.[5−22]

MECHANISM AND STEREOCHEMISTRY

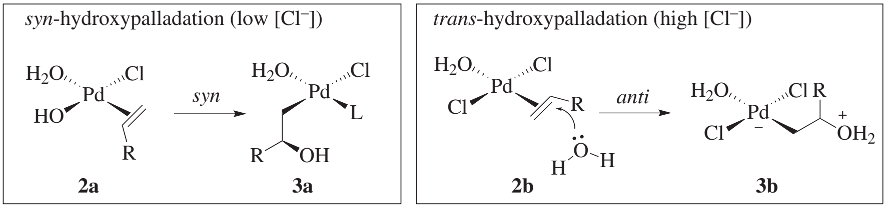
Because of both the industrial importance and synthetic utility, the mechanism of the Wacker oxidation has been extensively investigated. These studies have resulted in both diverse and conflicting analyses and a review on this topic has been published.[8]

Water as the Nucleophile

In a simplified mechanistic scheme, the reaction begins by coordination of the alkene to a $PdCl_2$ aqua complex **1**. Most studies suggest that the rate-limiting step is the addition of water to the resultant Pd-coordinated alkene **2**, often referred to as hydroxypalladation (Scheme 4).[5−8] The first issue in this step is whether the addition of water is an intra- or intermolecular process, often referred to as *syn*- and *anti*-hydroxypalladation, respectively (Scheme 5).[5−8] *Syn*-hydroxypalladation can be considered a formal migratory insertion wherein the Pd(II) and a coordinated hydroxide add to the same side of the alkene (**2a**→**3a**) and is proposed to be the operative mechanism under certain reaction conditions. Chloride ion concentration has a significant impact on the perceived mechanism of hydroxypalladation as chloride ion is likely to be a competitive anionic ligand with hydroxide in the system.[23,24] In fact, kinetic analysis at low chloride ion concentration suggests a *syn*-hydroxypalladation due to an observed inverse second-order dependence on chloride ion and an inverse first-order dependence on acid concentration.[25,26] This behavior is consistent with dissociation of both anionic ligands to allow for coordination of hydroxide.[27] In contrast, at high chloride ion concentration *anti*-hydroxypalladation, the outersphere addition of a water molecule to the coordinated alkene (**2b**→**3b**), is consistent with kinetic analysis, where an inverse first-order dependence of chloride ion and no dependence on proton concentration is observed.[8,28,29] In either case, the subsequent organometallic step is proposed to be β-hydride elimination (Scheme 6, **4**→**5**).[8]



Scheme 4



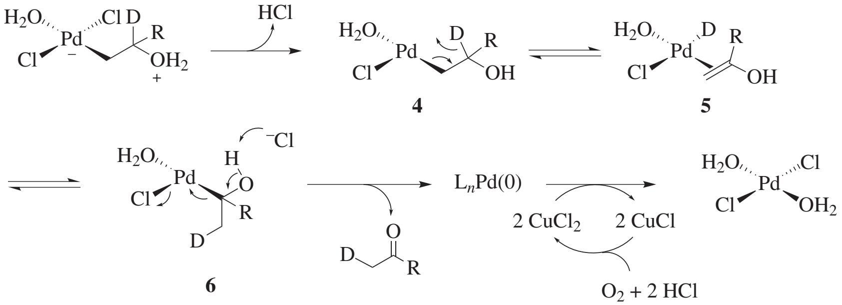
$$\text{rate} = k_{\text{obs}} \frac{[\text{PdCl}_4^{2-}]\,[\text{C}_2\text{H}_4]}{[\text{Cl}^-]^2\,[\text{H}^+]}$$

consistent with syn addition

$$\text{rate} = k_{\text{obs}} \frac{[\text{PdCl}_4^{2-}]\,[\text{C}_2\text{H}_4]}{[\text{Cl}^-]}$$

consistent with anti addition

Scheme 5



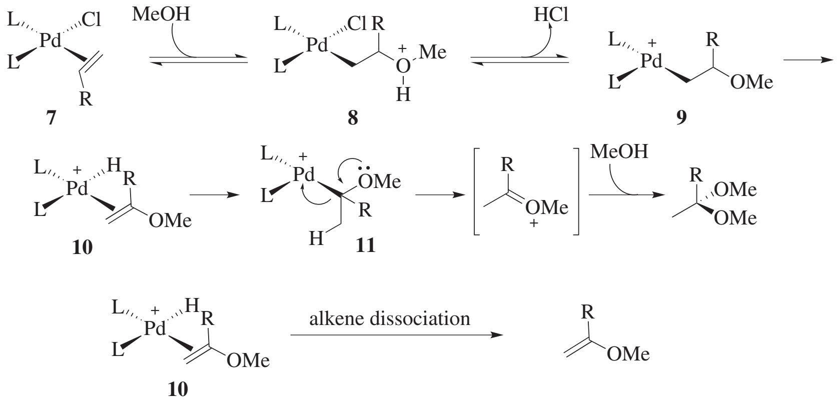
Scheme 6

The original studies of the Wacker oxidation show, through deuterium isotopic labeling experiments, that the substrate hydrogens are conserved in the resulting carbonyl product, strongly suggesting that the enol does not dissociate from the metal (Scheme 6).[2,30,31] Instead, the coordinated enol **5** reinserts into the Pd–D bond leading to the isomeric Pd–alkyl **6**. β-Hydride elimination of the alcoholic hydrogen has been proposed to then afford the product. However, recent computational studies suggest chloride-assisted deprotonation of the alcohol in **6** leading to elimination and concomitant reduction of Pd(II) to Pd(0).[32–34] Since the direct oxidation of Pd(0) to Pd(II) is presumably slower than the substrate-based organometallic sequence, the addition of Cu salts facilitates this redox cycle via the rapid oxidation of CuCl with HCl and molecular oxygen. The role of copper is poorly defined, as bimetallic complexes have been implicated as potential catalytic species in the Wacker and related processes.[35–38]

Considering that the stereochemical information is lost upon β-hydride elimination, it may seem that the ultimate mode of hydroxypalladation is inconsequential in applications to synthesis. However, the product distribution of particular substrate classes suggests that both *syn*- and *anti*-hydroxypalladation may be operative.[39–41] Additionally, this phenomenon could be the origin of product mixtures consisting of ketone (Markovnikov) and aldehyde (anti-Markovnikov) products observed from terminal alkene oxidation, which clearly impacts the overall yields and alters synthetic strategies.[39–41] This experimental observation will be addressed in the “Scope and Limitations” section of the pertinent substrate classes.

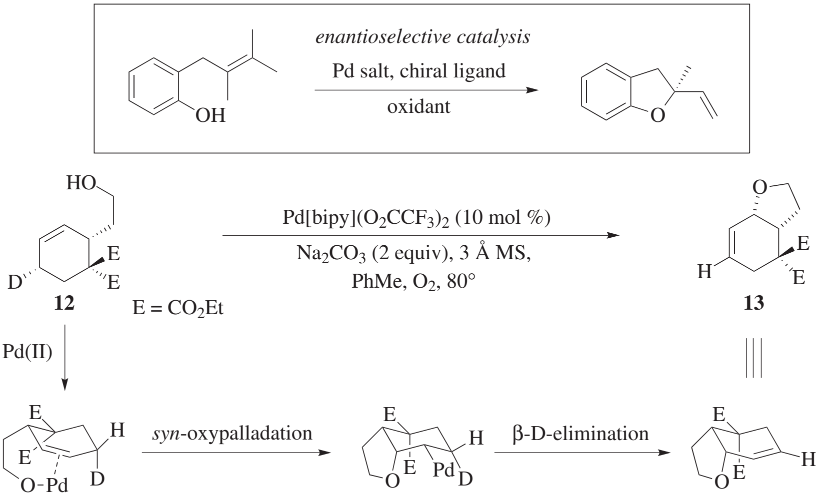
Alcohol Nucleophiles

In processes closely related to the Wacker oxidation, alcohols can add to palladium-bound alkenes to produce acetals, vinyl ethers, or allylic ethers. The proposed mechanism of these reactions is similar to the Wacker oxidation described above. Specifically, nucleophilic attack of methanol on an alkene ligated to Pd complex **7** forms the product of alkoxypalladation **8**. After proton transfer and loss of HCl to yield **9**, the resultant palladium–alkyl species undergoes β-hydride elimination to provide palladium-bound enol ether **10**, which upon dissociation from the metal accounts for the observation of vinyl ether products (Scheme 7).[42] Alternatively, acetal formation is proposed to occur by internal reaction of the coordinated enol ether with the Pd–H in complex **10** via reinsertion to yield the intermediate **11**. The presumed elimination of palladium from species **11** forms an oxocarbenium ion that is then trapped by an additional molecule of methanol forming an acetal. Transformation of a vinyl ether into an acetal through in situ formation of a Pd–H bond has been demonstrated.[42] A similar mode of reaction can be proposed for amine nucleophiles where enamines are often formed.[43,44]



Scheme 7

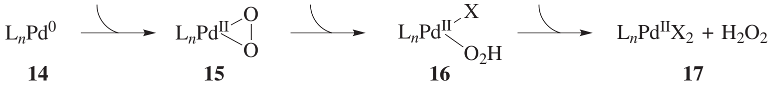
Allylic ethers generally result from a more specialized substrate class in which the alcohol nucleophile is tethered to the alkene. This reaction class is referred to as the Wacker cyclization and can occur with a broad range of alcohol, phenol, carboxylic acid, and nitrogenous nucleophiles. This unique case can set a stereogenic center and has been rendered enantioselective with use of an appropriate chiral ligand (Scheme 8).[45] Additionally, the stereochemical course of the nucleopalladation is not lost in the process allowing for careful mechanistic studies to determine the mode of nucleophilic addition. In most cases involving both phenols and primary alcohols as the nucleophiles (e.g. conversion of **12** to **13**, Scheme 8), a *syn*-oxypalladation is consistent with isotopic labeling experiments.[45,46] However, it should be noted that addition of chloride ion can again alter the mechanism of hydroxypalladation, presumably through inhibiting pre-coordination of the tethered nucleophile.[46]



Scheme 8

Direct O_2-Coupled Oxidations

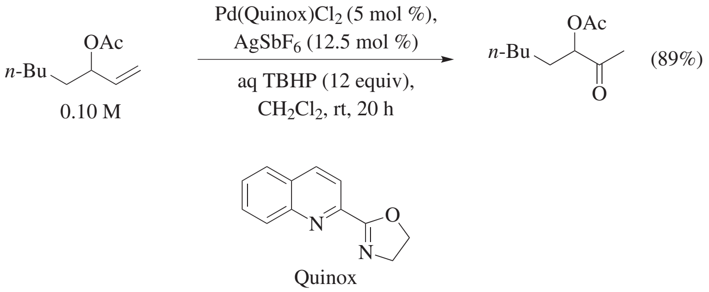
A limited number of reports describe Wacker oxidation systems wherein no co-oxidant is used and Pd(0) is directly reoxidized to Pd(II) by molecular oxygen.[47–50] This modification is accomplished through the use of either increased O_2 pressure in DMA[49] or the inclusion of a ligand, such as the bidentate amine (−)-sparteine.[48] It is generally thought that the reoxidation process proceeds through a Pd(II)-peroxo species **15** produced from a formal oxidative addition of O_2 to Pd(0) complex **14** (Scheme 9).[51] Sequential protonolysis of **15** and hydroperoxo species **16** reveals the active Pd(II) catalyst **17** with concomitant formation of hydrogen peroxide (which may also engage in Wacker-type reactions, see below). An advantage of direct O_2-coupled systems is the elimination of Cu-salts that increase the acidity and ion concentration of the reaction medium and complicate mechanistic studies.[38]



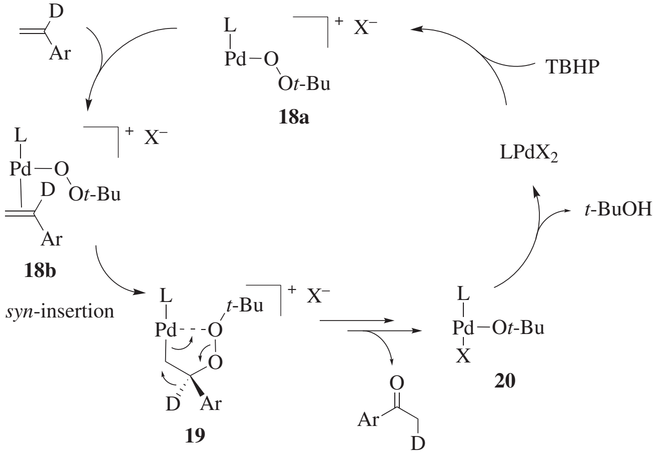
Scheme 9

Peroxide Nucleophiles

The transformation of terminal alkenes to methyl ketones can be accomplished with peroxides such as *tert*-butyl hydroperoxide (TBHP) as the oxygen atom source (Scheme 10).[22,52–55] An interesting caveat to this mechanistically distinct means of achieving the Wacker oxidation is that the redox chemistry is proposed to occur exclusively on the peroxide ligand with palladium remaining in the 2^+ oxidation state throughout the catalytic cycle (Scheme 11).[53,56,57] Kinetic analysis supports a mechanism wherein the in situ formed peroxypalladium species **18a** coordinates to the alkene to yield **18b**, which then undergoes a *syn*-peroxypalladation resulting in a pseudo-palladacyclic species **19**.[56,57] Cleavage of the O–O bond along with a concomitant hydride shift is proposed to provide the methyl ketone product and a palladium alkoxide species **20** that can reform the precatalyst **18a** by ligand substitution with another equivalent of peroxide.[22]



Scheme 10

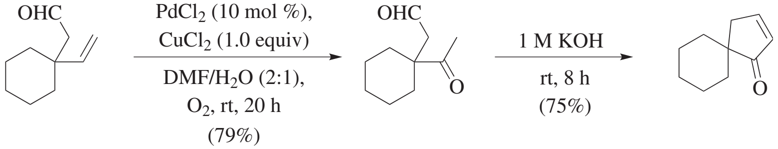


Scheme 11

SCOPE AND LIMITATIONS

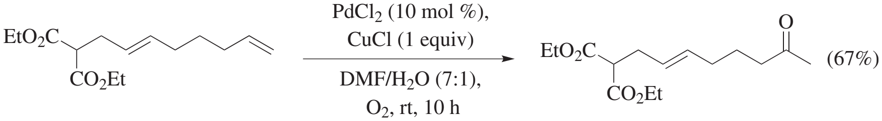
General Functional-Group Tolerance

Oxygen-Containing Functional Groups. Substrates bearing oxygen-containing functional groups are well-tolerated, except when they are in close proximity to the reacting double bond (see section below). Substrates bearing carbonyl moieties elsewhere, such as aldehydes, are oxidized efficiently and are frequently precursors to subsequent cyclization–condensation reactions (Scheme 12).[58]

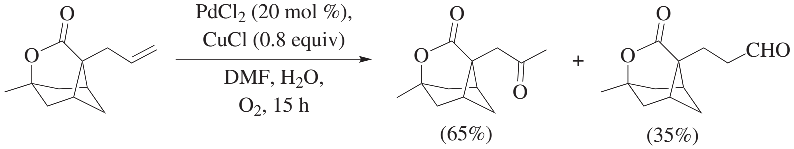


Scheme 12

Carbonyl compounds such as ketones, carboxylic acids, and esters are also compatible functional groups, including instances of β-dicarbonyls bearing an acidic α-proton (Scheme 13).[59] It is also worth noting that only the terminal alkene is oxidized in this diene substrate, which is the outcome typically observed. Aldehydes resulting from anti-Markovnikov oxypalladation are frequently observed from substrates bearing Lewis basic groups in close proximity to the reacting double bond. This product type is less frequently observed when the Lewis basic atom is distal from the alkene (further than the homoallylic position). Nonetheless, significant amounts of aldehyde product are occasionally observed from the Tsuji–Wacker oxidation of such substrates, where conformational constraints may also influence selectivity (Scheme 14).[60]

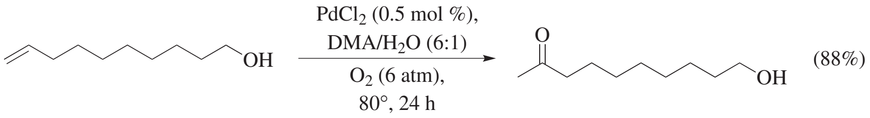


Scheme 13

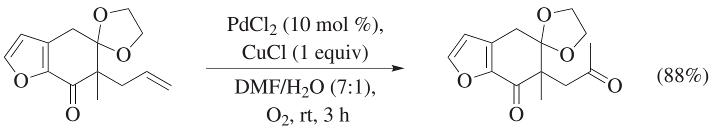


Scheme 14

Under Tsuji–Wacker type conditions alcohols are not oxidized (Scheme 15),[61] despite relatively similar conditions to Pd-catalyzed alcohol oxidations.[62] This result is indicative of the preference for palladium to interact with the π-bond of an alkene, as compared to the lone pair of an alcohol (a common solvent for Wacker oxidations). This phenomenon can be further highlighted in the selective reaction of the alkene even in highly oxygenated substrates, which do not require extended reaction times or high catalyst loadings (Scheme 16).[63]

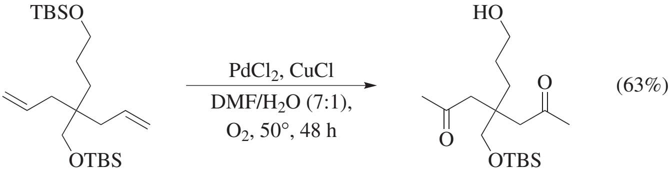


Scheme 15



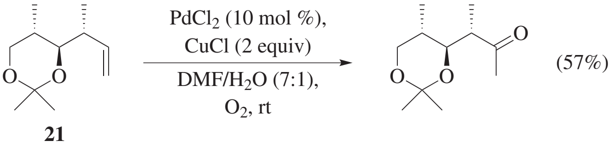
Scheme 16

As noted earlier, the acidic conditions of the Wacker oxidation can cause the reaction of acid-sensitive functional groups such as silyl ethers. For example, one of the TBS-protected primary hydroxyl groups in a substrate undergoes concomitant deprotection using increased reaction time and modestly elevated temperatures (Scheme 17).[64] The acid-induced reaction of certain functional groups can be mitigated by the use of less acidic Cu salts.

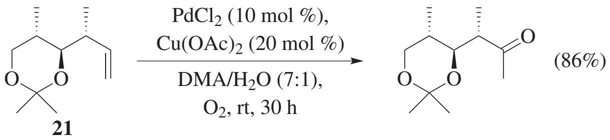


Scheme 17

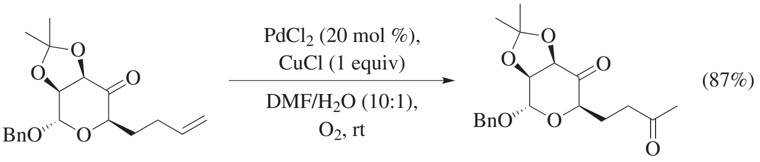
In fact, the counterion associated with the copper salt used in the Wacker oxidation influences the overall acidity of the reaction medium and the ion concentration (most commonly chloride). The counterion effect can be detrimental in synthetic applications as the acidic aqueous conditions are incompatible with certain functional groups. For example, the acidic conditions arising from the use of CuCl (resulting in HCl) along with the requisite aqueous solvent are reported to hydrolyze acetals in some instances, ultimately resulting in a reduced chemical yield of the desired product (Scheme 18).[65] Therefore, a modification of the Tsuji–Wacker procedure has been developed utilizing $Cu(OAc)_2$ in place of CuCl, which results in the formation of HOAc rather than HCl. The use of this modification is beneficial for reaction of substrate **21** (Scheme 19), and has been adopted as a common modification of the Tsuji–Wacker oxidation.[65] It should be noted, however, that acetals, and in particular acetonides, are not always incompatible with conditions employing CuCl salts (Scheme 20).[66]



Scheme 18

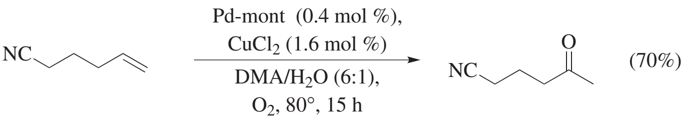


Scheme 19



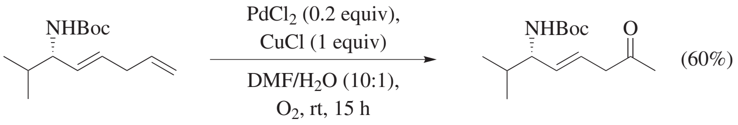
Scheme 20

Nitrogen-Containing Functional Groups. Some nitrogen-based functional groups are compatible with the Tsuji–Wacker oxidation conditions. As an example, a mixture of palladium and montmorillonite (Pd-mont) is used to impart heterogeneity to the Wacker oxidation for catalyst recycling, although the conditions are otherwise similar to the standard Tsuji–Wacker oxidation. Although not necessarily a function of the heterogeneous nature of this system, oxidation of an alkene substrate bearing a nitrile is observed (Scheme 21).[61] It should be noted that it is possible to easily separate the catalyst from the product for reuse.[61]

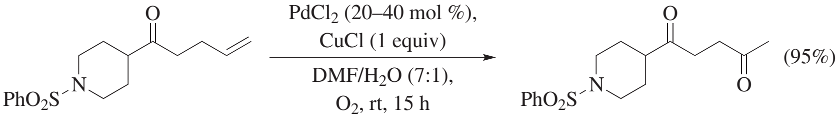


Scheme 21

Amides, carbamates, or other similarly protected amines having attenuated nucleophilicity are well-tolerated in the Tsuji–Wacker oxidation (Scheme 22).[67] Similarly, alkenyl substrates bearing sulfonamides are oxidized in good yields and under standard conditions (Scheme 23).[68,69] However, basic amine derivatives, such as alkyl amines, are not successfully oxidized under Tsuji–Wacker conditions.

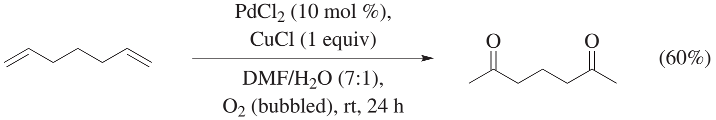


Scheme 22

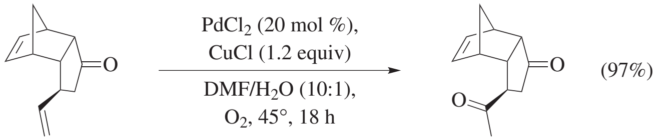


Scheme 23

Substrates with Multiple Alkenes. The reaction of multiple terminal alkenes in the same substrate has been demonstrated using Tsuji–Wacker oxidation conditions (Scheme 24).[70] The presence of two differentially substituted alkenes in the same substrate raises a number of interesting considerations, although terminal alkenes generally react faster than internal alkenes as illustrated in Scheme 25 where the substrate contains both an internal *cis*-disubstituted alkene and a terminal alkene (see also Scheme 13).

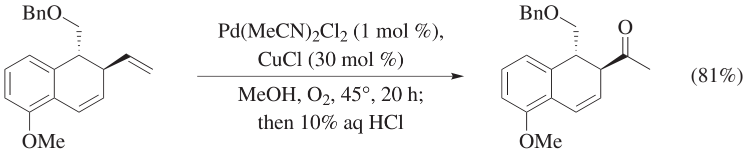


Scheme 24

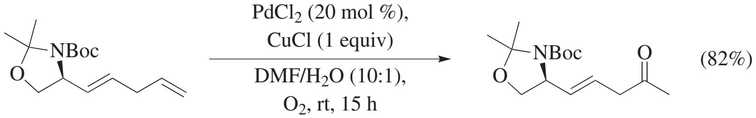


Scheme 25

Despite the reported ability of Pd(II) to catalyze alkene isomerization along an alkyl chain,[71] 1,4-dienes can be selectively oxidized at the terminal alkene. The 1,4-diene in Scheme 26 is selectively oxidized in methanol at the terminal alkene in preference to the internal styrenyl alkene.[72] This reaction presumably provides the dimethyl acetal initially, which is readily converted into the methyl ketone upon workup with 10% HCl solution. Other functionalized 1,4-dienes have been successfully oxidized with no isomerization of the initial product to the α,β-unsaturated ketone (Scheme 27).[67]

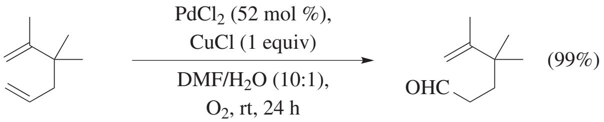


Scheme 26

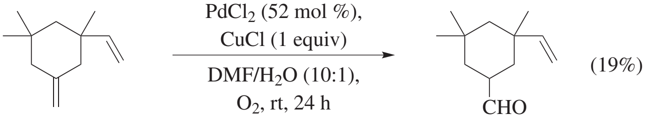


Scheme 27

However, selective and predictable reaction of a terminal alkene in the presence of a second alkene is not always observed. In the specialized substrates where a 1,1-disubstituted alkene is present proximal to the terminal alkene, anti-Markovnikov oxidation is observed (Scheme 28).[73] These anomalies may result from metal coordination by both alkenes, ultimately having the effect of disfavoring Markovnikov oxypalladation. The use of high palladium loadings is presumably a contributing factor as bidentate alkene complexes likely form prior to oxypalladation. Opposite selectively is observed in some cases in which the 1,1-disubstituted exocyclic alkene reacts preferentially over a more hindered terminal alkene, albeit in poor yield (Scheme 29).

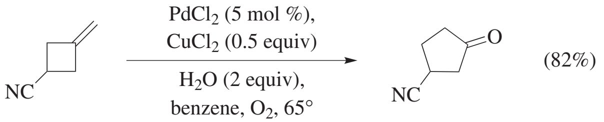


Scheme 28

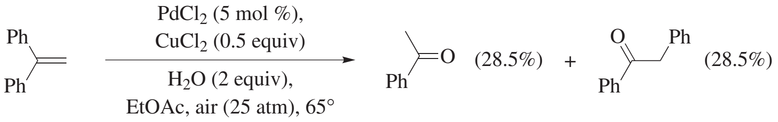


Scheme 29

Other instances of 1,1-disubstituted alkenes that provide unusual products have been reported. For example, methylenecyclobutanes undergo ring expansion to provide cyclopentanones under the acidic conditions of the Wacker oxidation (Scheme 30).[74] The alkene, 1,1-diphenylethylene, provides an equimolar ratio of products derived from a formal phenyl shift and an unexplained loss of one phenyl group upon oxidation (Scheme 31).[74] It is possible that the interesting reactions observed for the 1,1-disubstituted alkene substrates shown here are a result of formal positive charge generation upon Pd coordination to the alkene and subsequent carbocation-related rearrangements. It should also be noted that these reactions employ modified conditions with benzene or ethyl acetate as the solvent.

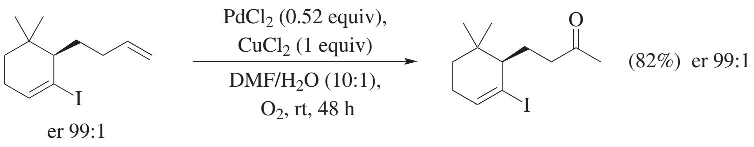


Scheme 30



Scheme 31

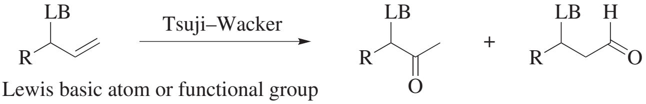
While Pd(0) is an intermediate in the Wacker oxidation and is often visible as deposited Pd-black to the experimentalist during the course of a reaction, products arising from Pd(0) processes are typically not observed. Thus, a terminal alkene undergoes selective oxidation and a vinyl iodide remains intact (Scheme 32).[75]



Scheme 32

Presence of Proximal Heteroatoms

Allylic Alcohols and Protected Variants. Substrates that bear proximal Lewis basic heteroatoms (e.g., substrates with oxygen- or nitrogen-containing functional groups in the allylic or homoallylic position) often undergo oxidation under Tsuji–Wacker oxidation reaction conditions in an unpredictable fashion to give product mixtures consisting of ketones (Markovnikov) and aldehydes (anti-Markovnikov) (Scheme 33).[40] Although this topic has recently been reviewed,[40] a discussion of the information pertinent to selection of optimal conditions is provided.



LB = Lewis basic atom or functional group

Scheme 33

Allyl acetate displays the disparity in product distributions generally observed under various common reaction conditions. The distribution can be shifted to favor product **22** or **23** depending on the choice of solvent and additives (Scheme 34).[54,76,77] The problem of site selectivity in this substrate class is hypothesized to arise from a secondary coordination of the substrate to Pd(II), which may perturb the mode of oxypalladation.[40] The challenge of selective oxidation of this substrate class has been overcome recently though the use of ligand modulation and a peroxide oxidant (see below).[22]

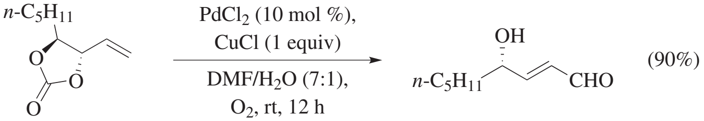
22 **23**

Cond	Pd Catalyst (mol %)	Additive(s) (mol %)	Solvent(s)
A	$PdCl_2$ (2.5)	$CuCl_2$ (10), CuCl (5), NaCl (5)	MeCN, *t*-BuOH
B	$PdCl_2$ (2.5)	$CuCl_2$ (10), CuCl (5), NaCl (5)	$4\text{-}O_2NC_6H_4CN$, *t*-BuOH
C	$Pd(MeCN)_2Cl_2$ (10)	CuCl (10)	HMPA (2 eq), CH_2Cl_2
D	$Pd(MeCN)_2Cl_2$ (10)	$CuCl_2$ (10)	aq THF

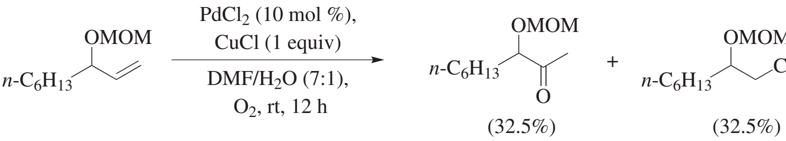
				Yield (%)	
Cond (*cont.*)	O_2 (psi)	Temp (°)	Time (h)	**22 + 23**	**22/23**
A	40	50	1	56	14:84
B	40	50	1	75	27:73
C	—	rt	2–12	76	36:64
D	—	rt	2–12	76	95:5

Scheme 34

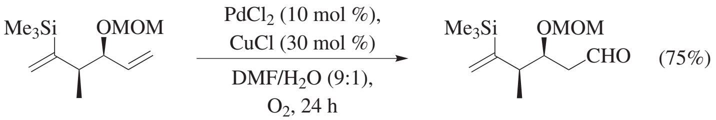
An allylic carbonate provides the α,β-unsaturated aldehyde product upon oxidation using standard Tsuji–Wacker oxidation conditions (Scheme 35).[39] This product is proposed to arise from anti-Markovnikov oxidation and subsequent β-elimination of CO_2. In a further investigation of this effect, it was found that a MOM-protected alcohol provides an equimolar amount of the ketone and aldehyde products (Scheme 36).[39] Only the aldehyde product is reported for a similar substrate that is oxidized under slightly modified conditions (Scheme 37), highlighting the difficulty in determining the origin of the product distribution.[78]



Scheme 35

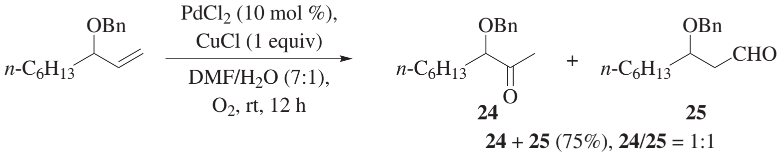


Scheme 36

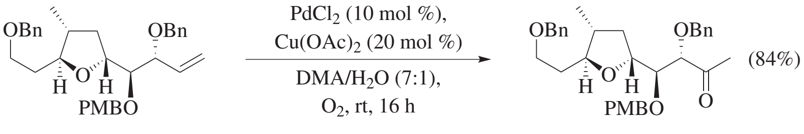


Scheme 37

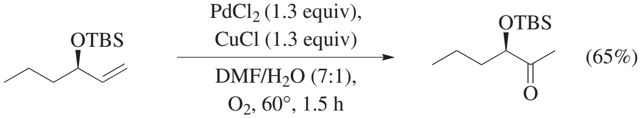
Benzyl ethers of allylic alcohols also lead to variable product distributions. For example, a 1:1 mixture of ketone **24** and aldehyde **25** is observed in the oxidation of a simple allylic benzyl ether (Scheme 38).[39] However, a more complex substrate gives predominately the methyl ketone product using $Cu(OAc)_2$ instead of CuCl (Scheme 39).[79] Bulky silyl-ether-protected allylic alcohols are typically well-behaved in that the alkene is converted into the methyl ketone product upon oxidation. Only the methyl ketone is obtained from a simple substrate (Scheme 40), although it should be noted that a superstoichiometric amount of palladium is used to effect this transformation.[80]



Scheme 38

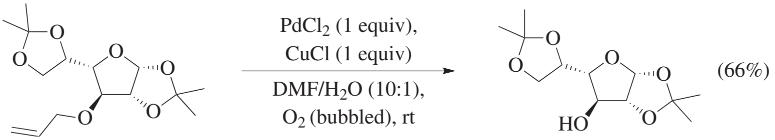


Scheme 39



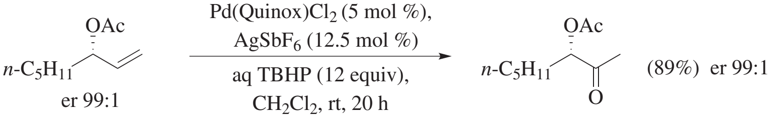
Scheme 40

Alcohols protected as the allyl ethers can be deprotected by Pd(0) catalysis under acidic conditions through the formation of a π-allyl palladium intermediate.[81] Alternatively, oxidative conditions employing $PdCl_2$ have also been reported for allyl group cleavage (Scheme 41).[82] Presumably this transformation occurs through an anti-Markovnikov oxidation of the alkene to the aldehyde and subsequent β-elimination to give the alcohol or isomerization to the enol ether and formation of a mixed acetal, which can subsequently undergo hydrolysis.

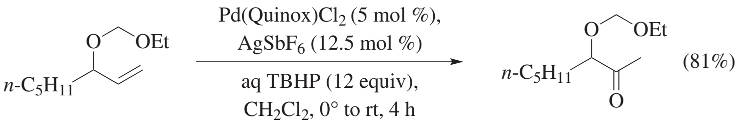


Scheme 41

In contrast to the Tsuji–Wacker oxidation, the use of Pd(Quinox) as the catalyst in combination with TBHP as the oxidant leads to the predictable formation of the Markovnikov product with various allylic alcohol derivatives (Scheme 42).[83] It should be noted that the enantiomeric ratio in the substrate is fully retained in the product. An allylic alcohol bearing an acetal protecting group is also selectively oxidized solely to the methyl ketone product (Scheme 43).[83]

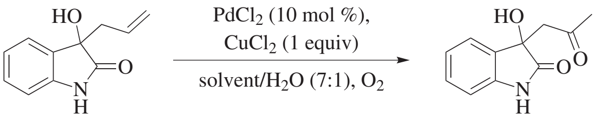


Scheme 42



Scheme 43

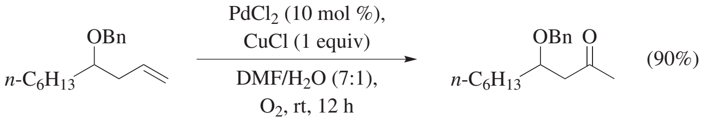
Homoallylic Alcohols and Protected Variants. Homoallylic alcohols and protected derivatives can also afford aldehydes, although rarely as the only oxidation product. Selection of proper conditions is required to achieve high yields of the methyl ketone. When a hindered homoallylic alcohol is subjected to the standard Tsuji–Wacker conditions, no reaction is observed after seven days (Scheme 44).[84] However, changing the solvent to dioxane and elevating the temperature provides the ketone in good yield after just one hour.



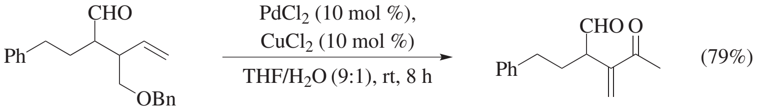
Solvent	Temp	Time	Yield (%)
DMF	rt	7 d	0
dioxane	50°	1 h	88

Scheme 44

Alkenes bearing protected homoallylic alcohols are generally, although not always, oxidized primarily to the methyl ketone (Scheme 45).[39] A sequence of aldehyde allylation to form the homoallylic alcohol and Wacker oxidation leads to aldol type products. When the ketone product has a β-substituent, elimination may be observed, which in particular has been reported for the substrates such as the one shown in Scheme 46.[85] It should also be noted that THF is utilized as the cosolvent in this case, although it is not clear the extent to which solvent choice favors β-elimination and how much is dependent on the structure of the product.

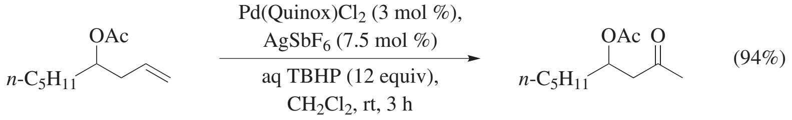


Scheme 45

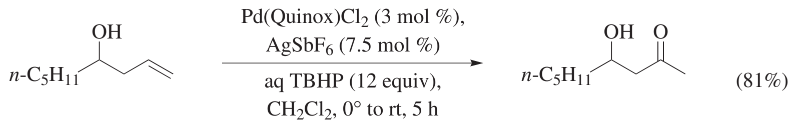


Scheme 46

As observed with allylic alcohol derivatives, homoallylic esters are cleanly oxidized in high yields using the Pd(Quinox)–TBHP system (Scheme 47).[86] Additionally, no protecting groups on the alcohol are required for selective oxidation of this substrate type (Scheme 48).[86]

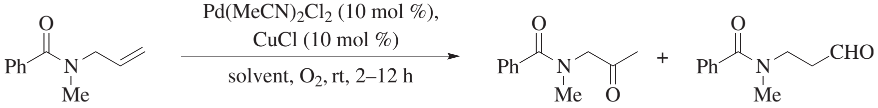


Scheme 47



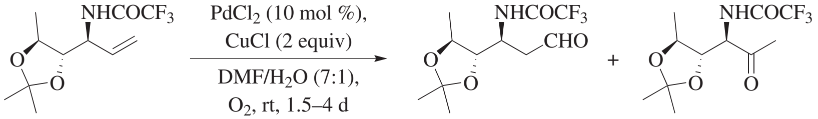
Scheme 48

Protected Allylic Amines. Some nitrogen functional groups are more Lewis basic than their oxygen counterparts and as a result protected allylic- and homoallylic nitrogen moieties have a similar or greater propensity to direct an oxypalladation in an anti-Markovnikov sense. For example, when a nitrogen atom is present as an allylic amide, the ratio of aldehyde to ketone product can be substantially modified (Scheme 49). It has been demonstrated that the use of HMPA in a solvent such as 1,2-dichloroethane can increase the selectivity for the aldehyde product, although the origin of this observation is not well-understood (Schemes 49 and 50).[77,87]



Solvent	Yield (%)	
THF, H_2O (15 wt %)	58	3.7
DCE, HMPA (2 equiv)	5.2	47

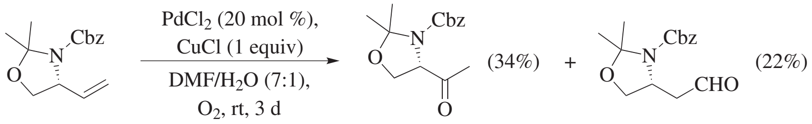
Scheme 49



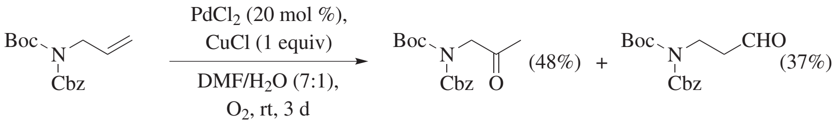
	Yield (%)	
Equiv HMPA	Aldehyde + Ketone	Aldehyde/Ketone
0	85	75:25
2	64	82:18

Scheme 50

A Cbz-protected allylic amine provides a 3:2 mixture of ketone to aldehyde using standard Tsuji–Wacker oxidation conditions (Scheme 51).[88] A similar product distribution is observed with *N*-Cbz, *N*-Boc allylamines (Scheme 52).[88]

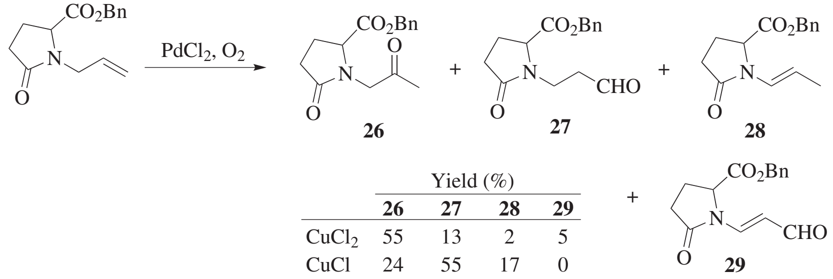


Scheme 51



Scheme 52

The nature of the copper salt can also influence the ratio of ketone and aldehyde products for substrates bearing allylic Lewis basic groups, as illustrated by the distribution of products **26–29** in Scheme 53.[89] With $CuCl_2$, the methyl ketone **26** is the favored product in the Wacker oxidation of the homoallylic amide, but the aldehyde **27** is the predominant product when CuCl is used. These results may indicate that at higher chloride ion concentration the secondary substrate coordination to palladium is less favorable because chloride ion competes for the binding site on palladium.[89]

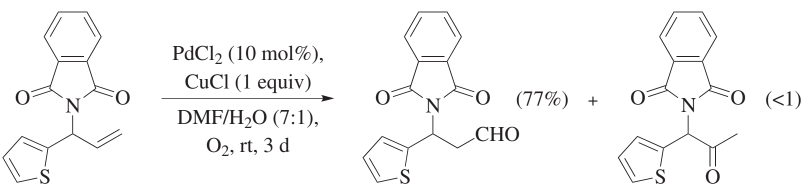


26 **27** **28** **29**

	Yield (%)			
	26	**27**	**28**	**29**
$CuCl_2$	55	13	2	5
CuCl	24	55	17	0

Scheme 53

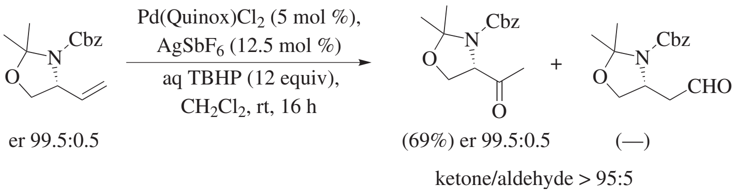
The propensity for certain protecting groups to bias the oxypalladation in an anti-Markovnikov sense has been exploited in a protocol for an aldehyde-selective Wacker oxidation. This process is general for a broad scope of alkene substrates bearing an allylic phthalimide functional group (Scheme 54).[41]



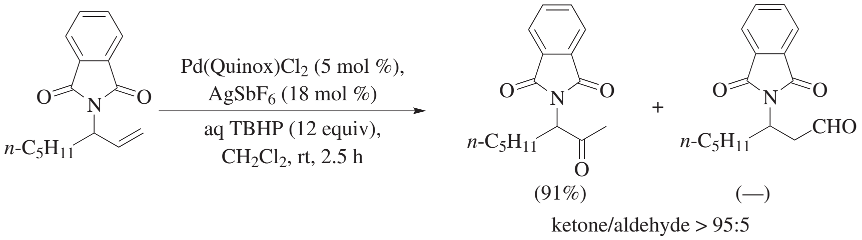
aldehyde/ketone > 95:5

Scheme 54

Consistent with the results using allylic alcohol derivatives, the oxidation of terminal alkene substrates bearing protected allylic amines using Pd(Quinox)-TBHP as the oxidation system results in the formation of the methyl ketone product in high yields and with excellent site selectivity compared to the standard Tsuji–Wacker oxidation (Scheme 55).[88] Even allylic phthalimide-bearing substrates (discussed above) that favor anti-Markovnikov oxidation under Tsuji–Wacker oxidation conditions[41] are oxidized to the methyl ketone product with high selectivity and yield (Scheme 56).[88]

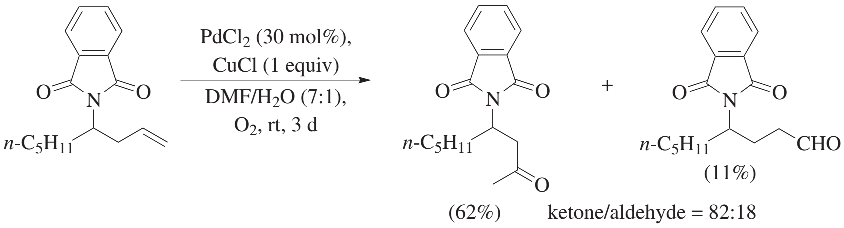


Scheme 55

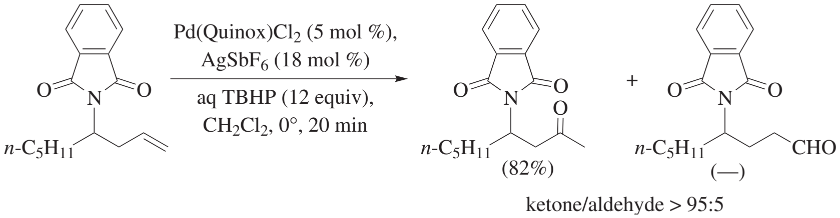


Scheme 56

Protected Homoallylic Amines and Related Variants. The influence of Lewis basic functional groups is attenuated as the group is moved further from the alkene. Homoallylic nitrogen moieties typically do not lead to significant amounts of aldehyde products. A phthalimide group that is able to impart high aldehyde selectivity when allylic to the alkene provides predominately the ketone product when located at the homoallylic position (Scheme 57).[88] Improved selectivity is observed using Pd(Quinox)-TBHP as the oxidation system in the evaluation of the same substrate as well as shorter reaction times and lower catalyst loadings (Scheme 58).

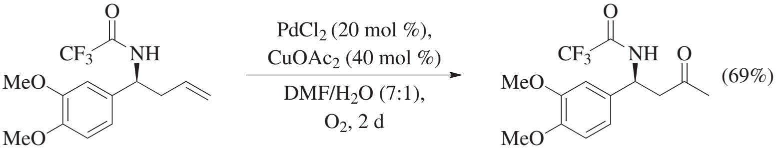


Scheme 57



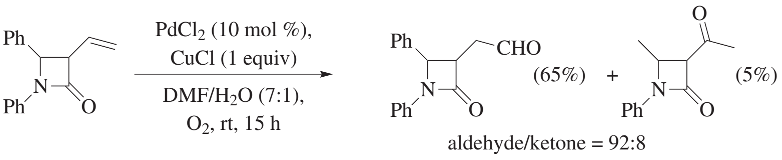
Scheme 58

Nitrogen-containing functional groups other than phthalimide generally impart selectivity for the ketone product. For example, a trifluoroacetamide is reported to provide only the methyl ketone (Scheme 59).[90]

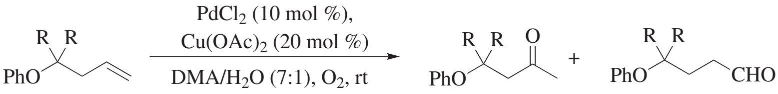


Scheme 59

Other Functional Groups that Provide Aldehydes. When using Tsuji–Wacker conditions, a lactam substrate provides predominately the aldehyde product arising from anti-Markovnikov oxypalladation rather than the methyl ketone (Scheme 60).[91] Interestingly, homoallylic fluorine atoms are reported to perturb the methyl ketone selectivity in a series of substrates, as evidenced by the ratios of products **30** and **31** (Scheme 61).[92] It is difficult to determine to what extent this result is due to an inductive effect, which would destabilize the partial positive charge distribution in the palladium-bound alkene, or if a secondary metal coordination exists to influence oxypalladation. In contrast, an enantiomerically enriched allylic fluoride is converted to the methyl ketone product using Pd(Quinox)–TBHP as the oxidation system without any erosion of the enantiomeric enrichment (Scheme 62).[93] Modestly increased catalyst loadings are required, most likely due to the electron-poor nature of the alkene.



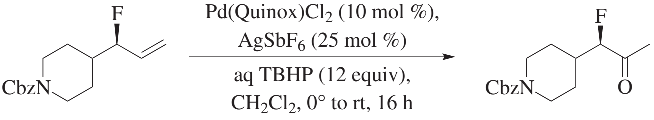
Scheme 60



30 (—) **31** (—)

R	**30/31**
H	90:10
F	30:70

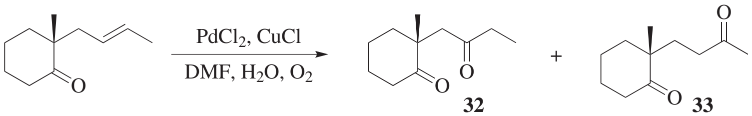
Scheme 61



er 96.5:3.5 (91%) er 96.5:3.5

Scheme 62

Influence of Proximal Heteroatoms on Internal Alkene Oxidation. As might be expected, simple internal alkenes do not undergo site-selective oxypalladation under Wacker oxidation conditions, most likely because of a lack of electronic bias between the two potential sites for oxypalladation.[50,94] More functionalized substrates can react with greater site selectivity, although in this case the adjacent ketone may direct oxypalladation, as shown by the predominance of ketone **32** over ketone **33** in Scheme 63.[95] The majority of selective oxidations of internal alkenes involve electronically biased substrates.

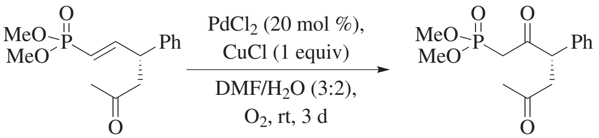


32 **33**

32 + **33** (57%), **32/33** = 91:9

Scheme 63

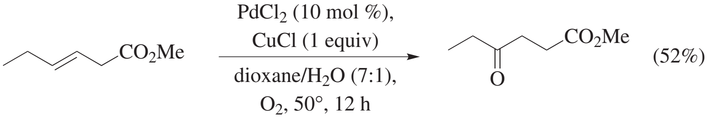
Internal alkene substrates bearing proximal heteroatoms tend to undergo site-selective oxidation more readily than unfunctionalized substrates; thus, oxidation of these substrates has found greater application in synthesis. Alkenes that are Michael-acceptors are oxidized at the β-position, consistent with the anticipated site for nucleophilic attack. The oxidation of vinyl phosphonates to provide diketophosphonates with high site selectivity demonstrates this preference (Scheme 64).[96]



(81%)

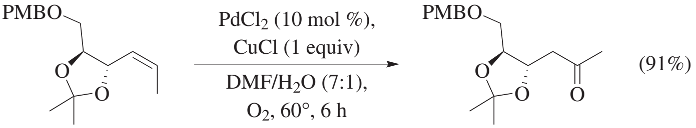
Scheme 64

For non-activated alkenes, selectivity arises if a significant electronic perturbation is present (i.e., a strong electron-withdrawing group is proximal to one side), or a functional group that may have the ability to interact as a Lewis base with palladium is present. For disubstituted alkene substrates, oxidation tends to occur at the site expected to have the most partial positive character (Scheme 65).[97]

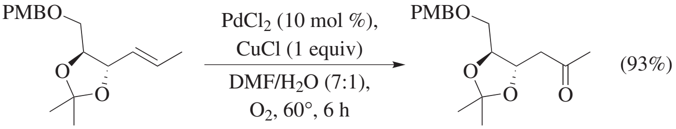


Scheme 65

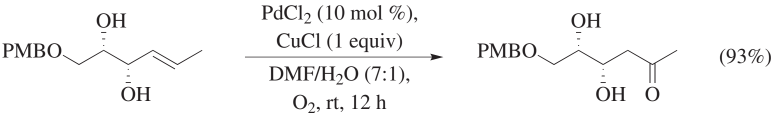
For internal alkenes bearing allylic alcohols or protected analogs, oxidation generally occurs distal to the oxygen. This result is observed for both the *cis*- and *trans*-isomers of an allylic acetonide substrate (Schemes 66 and 67).[39] An interesting observation is reported for the analogous diol substrate in which the *trans*-alkene isomer provides oxidation distal to the alcohol (Scheme 68).[39] However, when the corresponding *cis*-alkene is subjected to the same oxidation conditions, the more uncommon oxidation proximal to the oxygen atoms is observed (Scheme 69).[39] The origin of this change in reaction outcome is not obvious.[39]



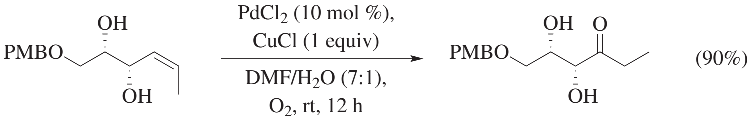
Scheme 66



Scheme 67

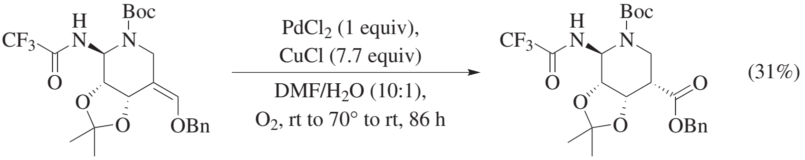


Scheme 68



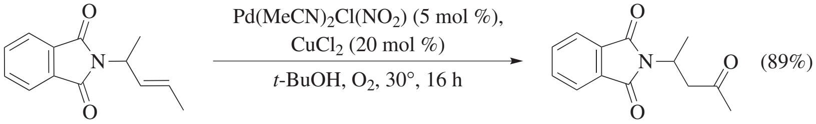
Scheme 69

Trisubstituted alkenes do not react under Wacker oxidation conditions.[98] Enol ether substrates undergo oxidation at the carbon bearing the oxygen, consistent with oxypalladation at the most electrophilic site (Scheme 70).[99] In the depicted example, alkene geometry does not affect the product outcome (other isomer not depicted).

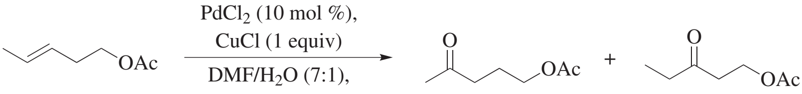


Scheme 70

The excellent directing ability of an allylic phthalimide substituent is again evident for internal alkenes (Scheme 71).[41] Having a directing functional group more distal to the alkene reduces its impact on selectivity (Scheme 72).[100] Although both ketone isomers **34** and **35** are observed in the oxidation of the (*E*)-pentenyl acetate substrate, methyl ketone **34** predominates.



Scheme 71



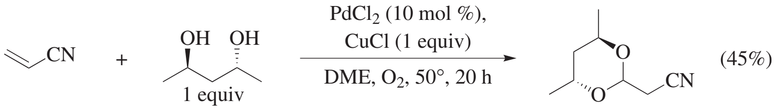
34 **35**

34 + **35** (80%), **34**/**35** = 91:9

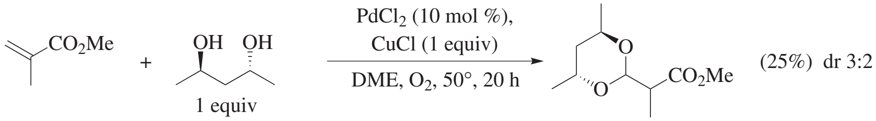
Scheme 72

Wacker-Type Oxidations that do not Yield Carbonyl Compounds

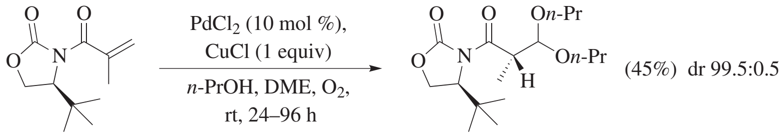
Acetal-Forming Reactions. The use of anhydrous alcoholic solvents under standard Wacker oxidation conditions produces acetals as the oxidation products. Stoichiometric amounts of alcohols can also be employed in aprotic organic solvents. Michael acceptor substrates undergo oxidation in the presence of a diol nucleophile to provide a cyclic acetal (Scheme 73).[101] When a new stereogenic center is generated, the use of a chiral diol imparts only modest diastereoselectivity (Scheme 74).[102] In contrast, the use of a chiral auxiliary on the alkene can lead to products with good to excellent diastereoselectivity (Scheme 75).[103]



Scheme 73

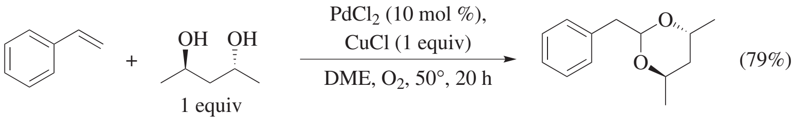


Scheme 74

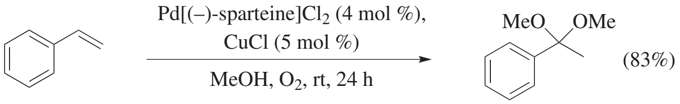


Scheme 75

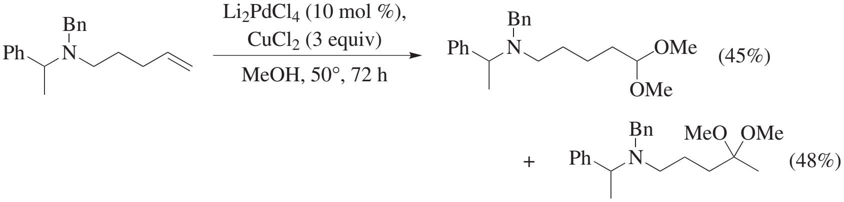
In the context of acetal-forming reactions, alkene substrates that are not Michael acceptors or activated alkenes undergo oxidation and frequently provide the anti-Markovnikov oxidation product. However, these substrates typically require a functional group that may control the direction of the anti-Markovnikov oxidation (such as a styrene) (Scheme 76).[102] Interestingly, the use of a well-defined palladium complex overrides the inherent substrate control, where Markovnikov addition to a styrene is observed (Scheme 77).[42] When the directing group is distal to the alkene, a mixture of Markovnikov and anti-Markovnikov oxidation products is observed (Scheme 78).[104]



Scheme 76

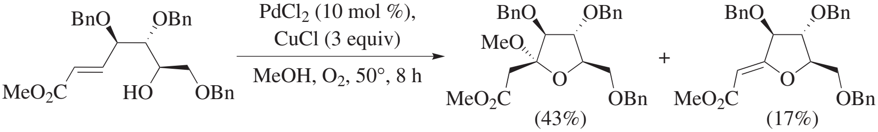


Scheme 77



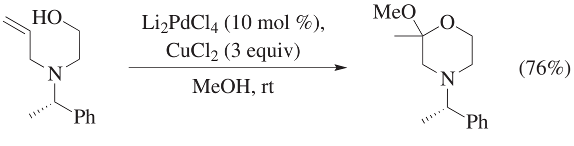
Scheme 78

If the alkene substrate contains a tethered nucleophile, a mixed acetal product derived from cyclization can be observed. Again, Michael acceptor substrates undergo oxidation at the β-position, although the product can be prone to β-elimination providing a mixture of products (Scheme 79).[105]

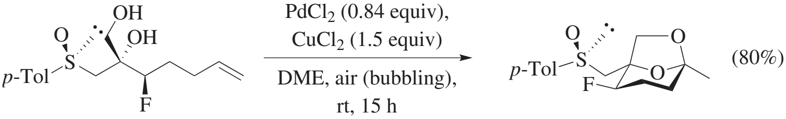


Scheme 79

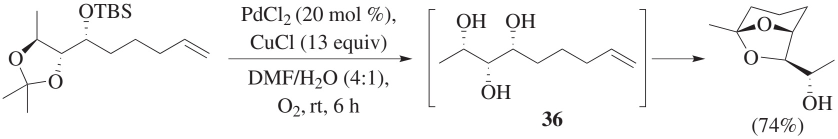
Simple terminal alkene substrates with a single tethered nucleophile tend to undergo oxidation to provide the favored (Markovnikov) cyclization product (Scheme 80).[106] Substrates have also been designed with internal diols capable of cyclizing onto a pendant alkene using Wacker oxidation conditions (Scheme 81).[107] A large excess of CuCl is used to effect a global deprotection in situ to generate triol **36**, which undergoes Markovnikov oxidative cyclization to provide an acetal product (Scheme 82).[108]



Scheme 80

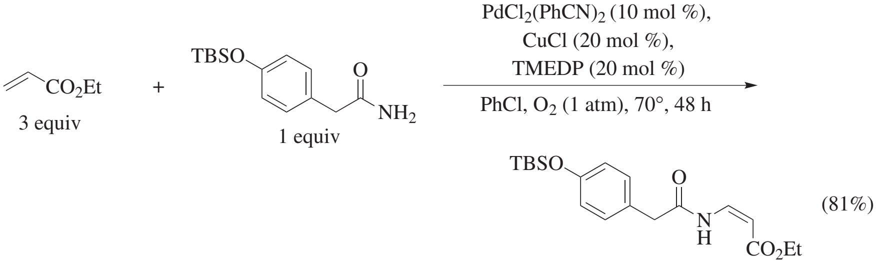


Scheme 81



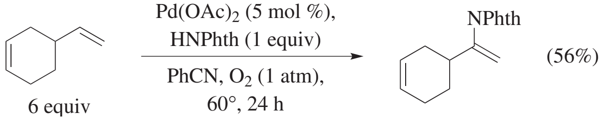
Scheme 82

Intermolecular Aza-Wacker Reactions. Nitrogen-based functional groups can add to a palladium-bound double bond yielding enamines. Interestingly, the addition of amides to Michael acceptors using Pd(II)-catalyzed oxidative conditions results in (*Z*)-enamide products (Scheme 83).[109] It should be noted that the reported yield is based on the amide as the limiting reagent.



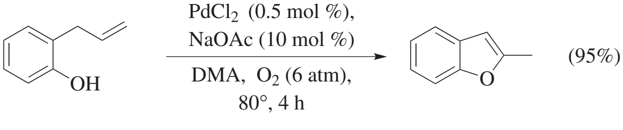
Scheme 83

Sulfonamides and phthalimides add to non-activated alkenes in a Markovnikov fashion (Scheme 84).[110] The alkene is used in excess for these reactions.

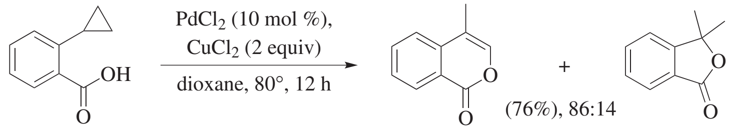


Scheme 84

Wacker Cyclizations. The intramolecular attack of a tethered nucleophile onto a palladium-bound alkene, followed by subsequent β-hydride elimination, is commonly referred to as the Wacker cyclization.[111] Primary alcohols, carboxylic acids, and phenols are viable oxygen nucleophiles for this process (Scheme 85).[49] Phenylcyclopropanes have been used as alkene surrogates, although a mixture of products results (Scheme 86).[112]

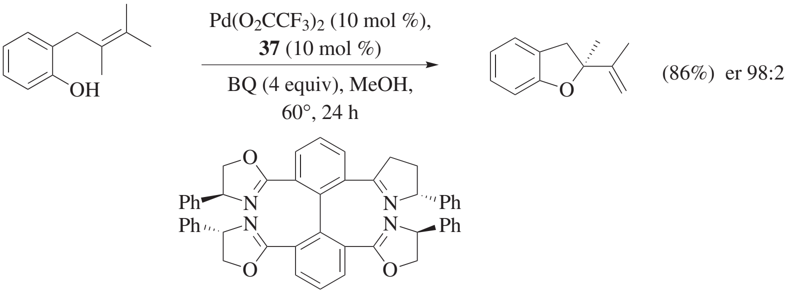


Scheme 85



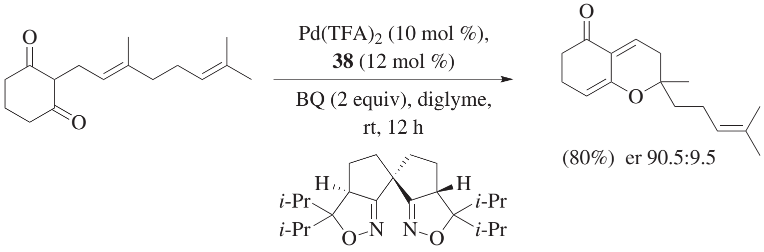
Scheme 86

As discussed in the "Mechanism and Stereochemistry" section, when β-hydride elimination takes place adjacent to the carbon that undergoes nucleophilic attack, the stereochemical course of the nucleophilic addition is not ablated in the process. Consequently, the use of chiral ligands can result in enantioselective Wacker cyclizations. Ligand **37** induces excellent enantioselectivity for the cyclization of phenolic substrates bearing tetrasubstituted alkenes (Scheme 87).[113] An interesting example has been reported for an asymmetric Wacker cyclization employing ligand **38** in which the oxygen nucleophile is an enol (Scheme 88).[114]



37

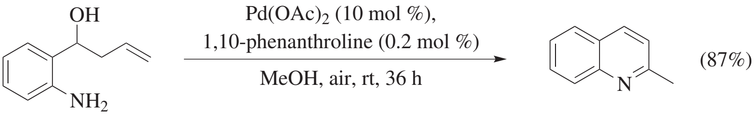
Scheme 87



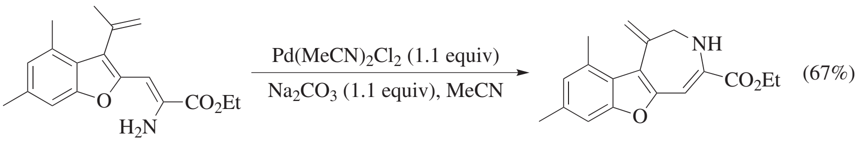
38

Scheme 88

Aza-Wacker Cyclizations. Analogous aza-Wacker cyclization reactions have been reported that provide access to functionalized nitrogen heterocycles. A variety of aniline, amide, carbamate, and sulfonamide nitrogens can act as nucleophiles in this process. Pyrrole, indole, pyridine, and quinoline derivatives can be accessed through this reaction class (Scheme 89).[115] An interesting cyclization induced by a stoichiometric amount of palladium involving an enamine nitrogen forming a 7-membered ring has been reported (Scheme 90).[116]

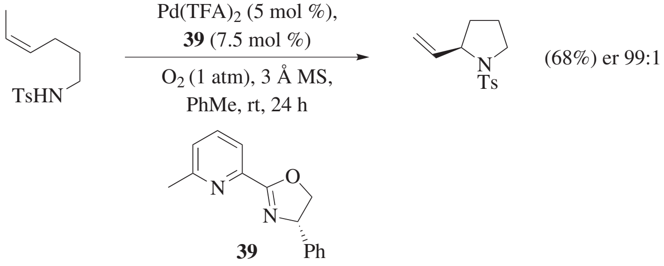


Scheme 89

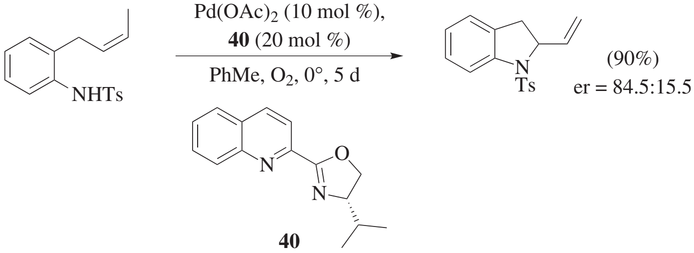


Scheme 90

Asymmetric variants of the aza-Wacker cyclization have also been reported. The pyridyl oxazoline ligand **39** promotes the reaction with high enantiomeric ratios for the cyclization of the alkene substrates bearing a tethered sulfonamide (Scheme 91).[117] A similar ligand **40** is able to provide modest er values from *N*-sulfonylaniline derivatives (Scheme 92).[118]



Scheme 91



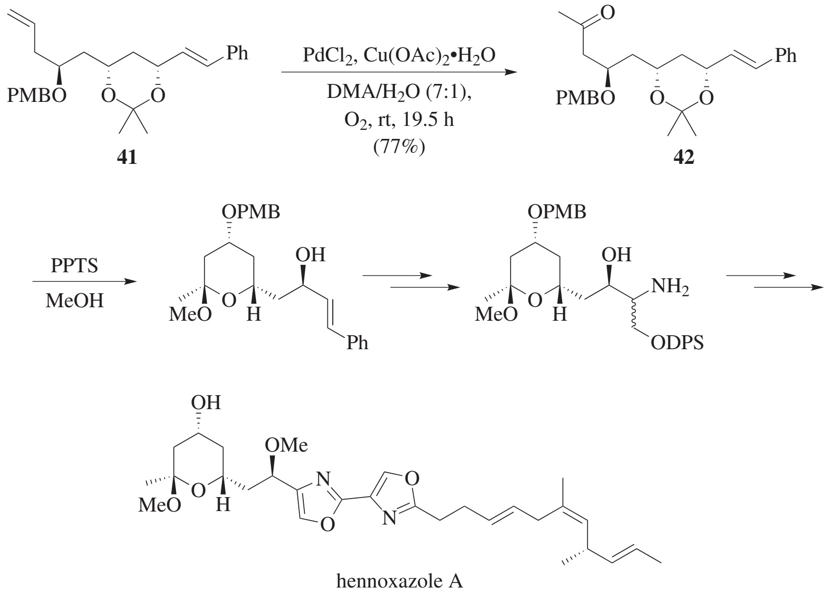
Scheme 92

APPLICATIONS TO SYNTHESIS

The Wacker oxidation converts a terminal alkene, an easily installed functional group that is generally stable when subjected to a wide variety of strongly basic and nucleophilic conditions, to a methyl ketone that can undergo subsequent nucleophilic attack and/or can be selectively deprotonated for participation in enolate-based reactions. As a result, the Wacker oxidation has been widely used in target-oriented synthesis. A few significant examples are discussed in this section.

Synthesis of (−)-Hennoxazole A

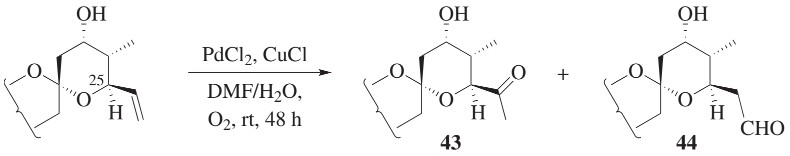
In the total synthesis of (−)-hennoxazole A, a Wacker oxidation provides a methyl ketone that undergoes subsequent mixed acetal formation with an internal nucleophile.[119] In this event, the Wacker oxidation converts substrate **41** into ketone **42** in 77% yield (Scheme 93).



Scheme 93

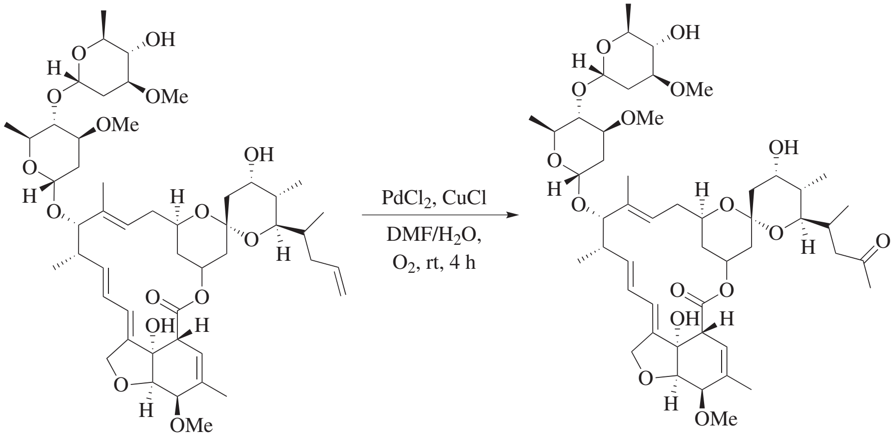
Synthesis of Avermectin Derivatives

In the preparation of polar avermectin analogues for study of structure-activity relationships, the Wacker oxidation is used to oxidize alkenyl derivatives at the C25 position (Scheme 94).[120] When the vinyl group is directly attached to the C25 position, a mixture of ketone and aldehyde products, **43** and **44**, is observed. An elongated attachment of the terminal alkene in analog **45** provides only the methyl ketone product (Scheme 95).[120] Successful application of the Wacker oxidation to substrates bearing multiple internal and trisubstituted alkenes such as **45** further highlights the selectivity of the Wacker oxidation for the reaction of terminal double bonds.



43 + **44** (60%), **43/44** = 62:38

Scheme 94



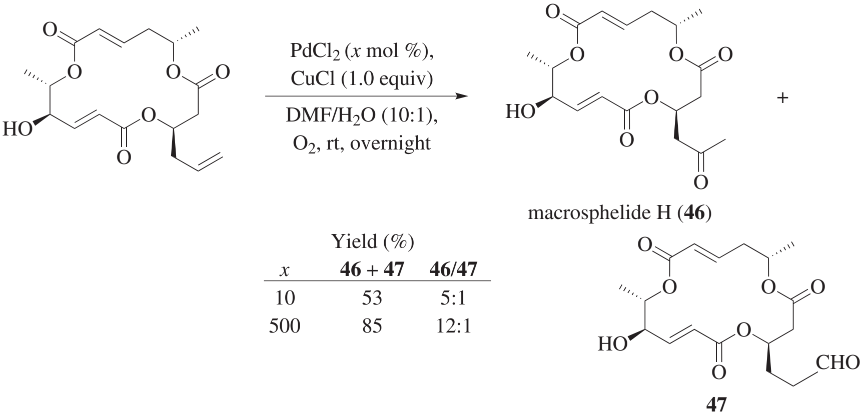
45

(80%)

Scheme 95

Synthesis of Macrosphelide H

A Wacker oxidation is an obvious transformation for the synthesis of macrosphelide H, which contains a methyl ketone moiety.[121,122] Therefore, the Wacker oxidation of the direct precursor is employed for the ultimate step in the synthesis (Scheme 96).[121,122] Standard Tsuji–Wacker oxidation conditions result in a slow reaction and incomplete conversion to a 5:1 mixture of the target macrosphelide H (**46**) and the corresponding aldehyde **47**. The use of five equivalents of $PdCl_2$ and careful monitoring of the reaction provides a 12:1 mixture of ketone and aldehyde in 85% yield. The substrate was recovered in 10% yield. Longer reaction times could not be employed as decomposition of the substrate occurred.



macrosphelide H (**46**)

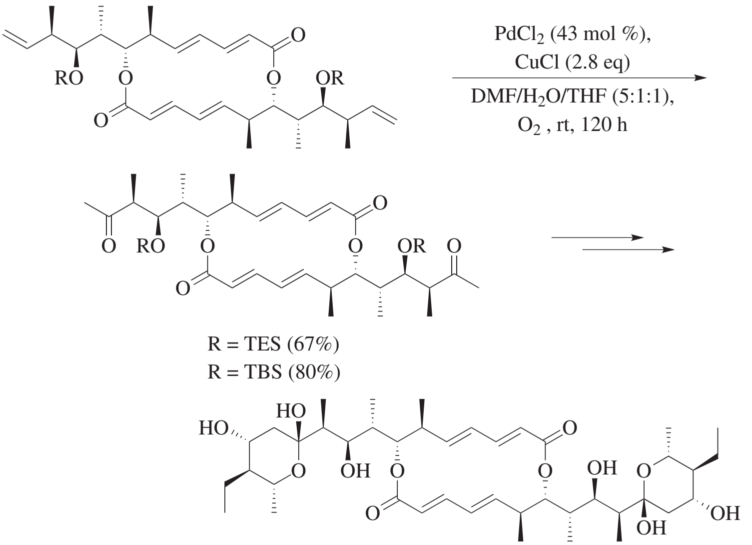
47

	Yield (%)	
x	**46 + 47**	**46/47**
10	53	5:1
500	85	12:1

Scheme 96

Formal Synthesis of Elaiolide

The formal synthesis of elaiolide is achieved through a late-stage double Wacker oxidation of the terminal alkene substrate bearing a homoallylic alcohol protected as the triethylsilyl ether (Scheme 97).[123] The substrate is cleanly converted to the bis(methyl) ketone as the only reported product. A better yield of the ketone is achieved in the presence of a TBS ether in the substrate. Of note, the internal, electron-poor alkenes are not reported to undergo significant oxidation under these conditions.



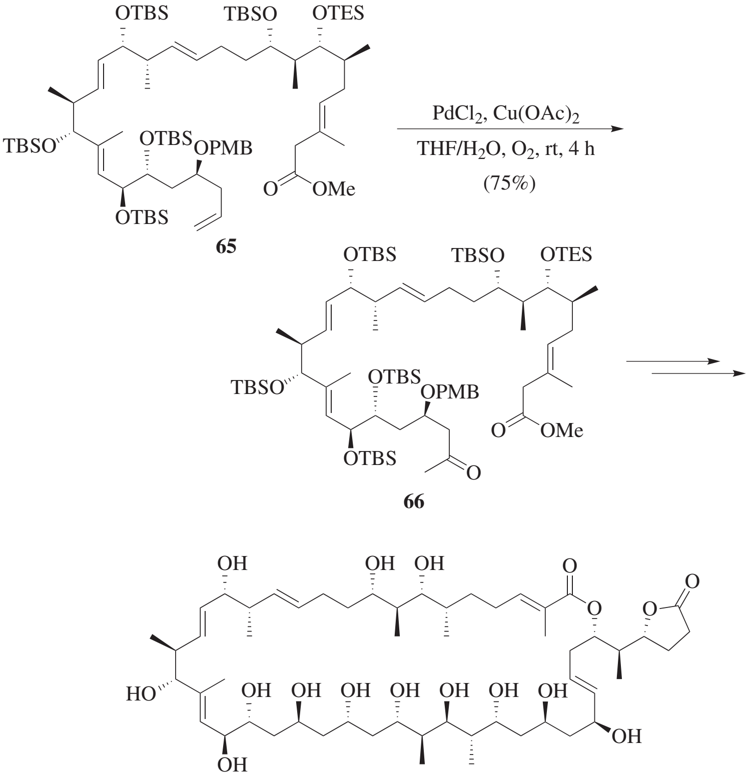
R = TES (67%)
R = TBS (80%)

elaiolide

Scheme 97

Synthesis of Oasomycin A

The synthesis of the C1-C28 fragment of oasomycin A is accomplished using a late-stage Wacker oxidation of a highly functionalized substrate (Scheme 98).[124] The reaction is performed in a mixed THF–water solvent system with $Cu(OAc)_2$ as the co-oxidant. The resulting ketone is subsequently used to generate an enolate for an aldol reaction.



65

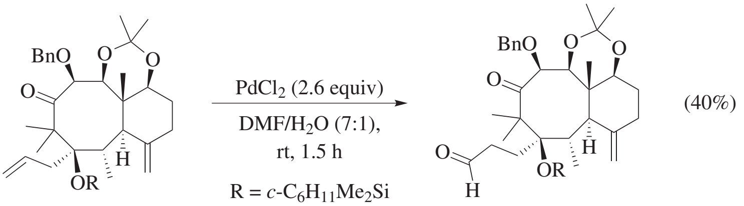
66

oasomycin A

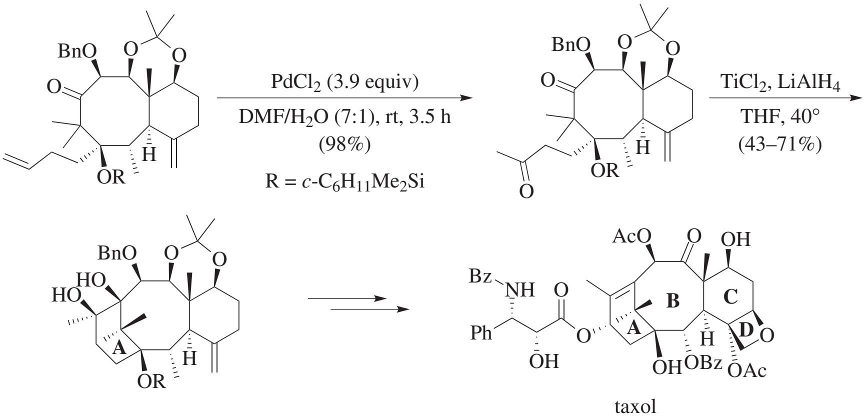
Scheme 98

Synthesis of Taxol

In application of the Wacker oxidation at a late stage of a complex multistep synthesis, the substrate is often significantly more valuable than the palladium salts used. For this reason, it is not uncommon to see superstoichiometric amounts of palladium being used to elicit the oxidation of an alkene. This approach is applied in a total synthesis of taxol.[125] Oxidation of the substrate containing a dimethylcyclohexylsilyl-ether-protected homoallyic alcohol affords the aldehyde (Scheme 99).[125] This outcome is contrary to results with a model system in which the methyl ketone is formed.[126,127] Calculations indicated that the internal position is sterically shielded as compared to the terminal position, which is proposed to be the origin of anti-Markovnikov oxidation in this case. An alternative strategy is thus employed for construction of this ring system involving the Wacker oxidation of a more accessible alkene (Scheme 100), which is smoothly oxidized to the methyl ketone, followed by subsequent intramolecular pinacol coupling to afford the **A** ring of taxol.



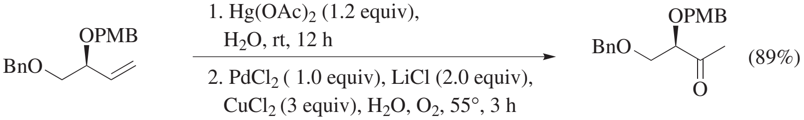
Scheme 99



Scheme 100

COMPARISON WITH OTHER METHODS

As has been described at various points in this chapter, some substrate classes (particularly when a proximal Lewis basic functional group is present) are not selectively oxidized to the methyl ketone under standard Wacker conditions. A two-step oxymercuration–transmetalation sequence that uses a stoichiometric amount of mercuric acetate and palladium chloride with superstoichiometric quantities of copper salts has been employed to generate the methyl ketone (Scheme 101).[128] While this clearly is an unattractive procedure, it has been used in past syntheses as a necessary means to effect the desired conversion of a terminal alkene into a methyl ketone. Recent reports of ligand-modulated Wacker systems, which are proposed to proceed through a *syn*-peroxypalladation should render the oxymercuration–transmetalation procedure obsolete, as this enhanced Wacker method can selectively oxidize substrates bearing allylic oxygen functional groups to the methyl ketone products.



Scheme 101

EXPERIMENTAL CONDITIONS

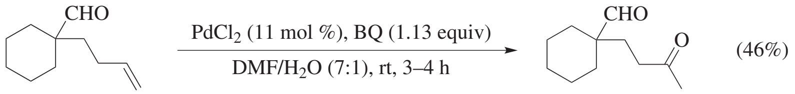
Tsuji–Wacker Oxidation

The most common conditions for effecting the Wacker oxidation employ a mixed solvent system of DMF and water (7:1 ratio), $PdCl_2$ (10 mol %), CuCl (1 equivalent), and an atmosphere of O_2, which is typically introduced with a balloon similar to a hydrogenation reaction. Countless variations to these standard conditions are known, which unfortunately cannot be readily rationalized. Therefore, the most common modifications will be addressed here. Organic solvents other than DMF can be used in the Wacker oxidation. Because of the need for water, viable solvent alternatives tend to be water miscible solvents such as DMA, dioxane, and THF. Since the Wacker oxidation reaction is sensitive to the nature of the substrate, some substrates bearing various functional groups react at different rates. Slow-reacting substrates can be oxidized at higher temperatures and catalyst loadings.

Although molecular oxygen is typically introduced via establishing an O_2 atmosphere and vigorous stirring of the reaction mixture, sparging of O_2 through the reaction mixture has also been reported. *CAUTION: Organic solvents are highly flammable under an O_2 atmosphere and explosions are possible in the presence of metal salts*. As discussed in the "Scope and Limitations" section, the selection of a Cu salt additive can impact the product distribution. CuCl is the most common Cu salt because Cu(I) is not only rapidly oxidized to Cu(II) under aerobic conditions, but also minimizes the chloride ion concentration, which can slow the reaction rate.[6] $Cu(OAc)_2$ is commonly substituted for use with acid-sensitive substrates.[65] In the Wacker oxidation, efficient redox coupling between palladium, copper, and molecular oxygen is necessary. However, since copper is typically present in large excess relative to palladium and the oxidation of Cu(I) to Cu(II) is efficient, vigorous stirring is generally sufficient to maintain the necessary concentration of Pd(II). As CuCl is the standard Cu salt used, a 30-minute period of vigorous stirring under an O_2 atmosphere prior to substrate addition is used to oxidize Cu(I) to Cu(II).

Benzoquinone

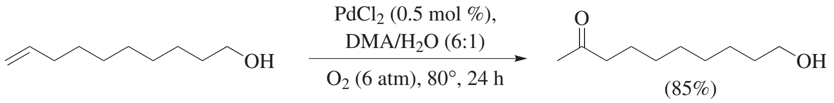
Benzoquinone (BQ) is a common reoxidant for Pd(0) in the Wacker oxidation as well as in other Pd(II)-mediated reactions. BQ presumably acts as an oxidant by nucleophilic attack of Pd(0) to the protonated quinone species.[129] This modification has been executed both stoichiometrically and catalytically in combination with a terminal oxidant. In general, the use of BQ does not significantly influence the reaction outcome as compared to using the standard Tsuji–Wacker conditions (Scheme 102).[130]



Scheme 102

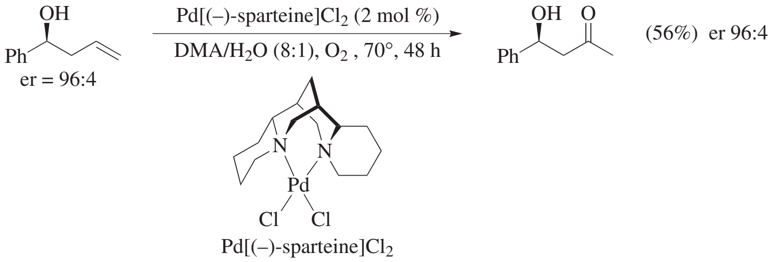
Direct O_2-Coupled Oxidations

A limited number of reports describe the direct reoxidation of Pd(0) to Pd(II) in the Wacker oxidation without the need for a cooxidant.[47,131] The use of dimethylacetamide (DMA) as the primary solvent under elevated oxygen pressure and high temperature has been reported and the scope of the system has been evaluated.[49] Some functional groups such as alcohols are compatible with these conditions (Scheme 103). Internal alkenes can also be oxidized.[50] Supercritical CO_2[132] and ethylene carbonate[133] are also viable solvents for this process.

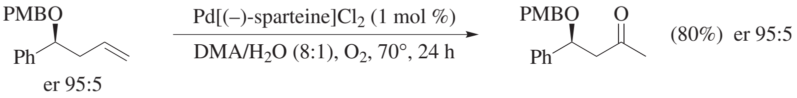


Scheme 103

Ligand modulation has also been successfully employed as a means to facilitate direct reoxidation of Pd(0) to Pd(II) with molecular oxygen. The use of the diamine ligand, (−)-sparteine, allows for the direct O_2-coupled Wacker oxidation of a variety of substrates, including allylic alcohols and their protected variants, at ambient pressures of O_2 and elevated temperatures (Schemes 104 and 105).[48]

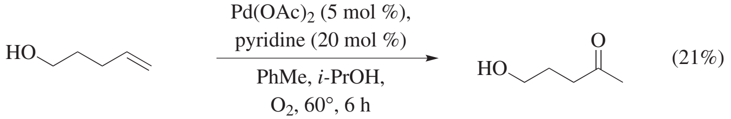


Scheme 104



Scheme 105

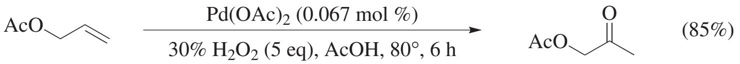
As a unique example, hydrogen peroxide is proposed to result from a palladium hydride generated from the palladium-mediated oxidation of isopropyl alcohol and subsequent insertion of molecular oxygen into the Pd–H bond to yield a Pd–O_2H species (Scheme 106).[134] This intermediate is proposed to ultimately follow a peroxide-mediated Wacker-type mechanism.



Scheme 106

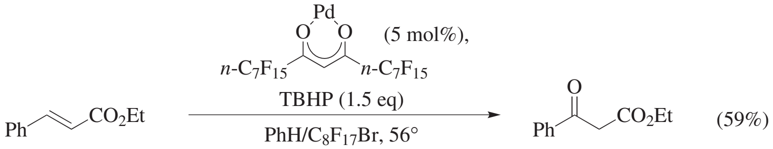
Peroxide-Mediated Reactions

Hydrogen peroxide or TBHP can promote highly selective Wacker oxidations. The use of hydrogen peroxide has led to catalytic systems with very low loadings of palladium. However, these systems have found limited applications (Scheme 107).[54,135]



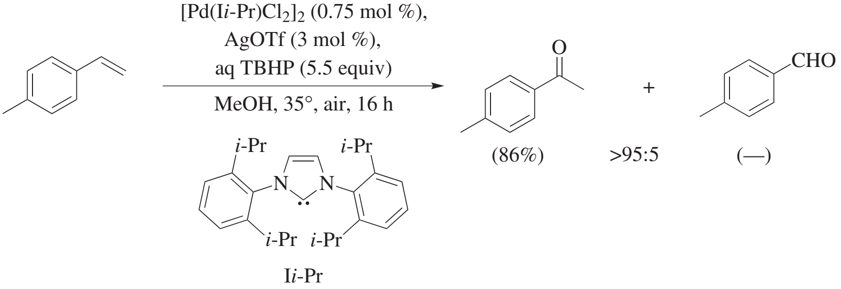
Scheme 107

Catalytic systems that utilize *tert*-butylhydroperoxide (TBHP) have been evaluated more extensively. A catalytic system that utilizes TBHP in a perfluorinated solvent has been developed. Similar to the Tsuji–Wacker oxidation, β-keto ester products are formed from the oxidation of α,β-unsaturated carbonyl compounds (Scheme 108).[136]



Scheme 108

Ligand modulation has been crucial for the development of peroxide-mediated reactions. For example, *N*-heterocyclic carbenes have been used as ligands for the TBHP-mediated oxidation of styrene derivatives (Scheme 109).[56] This system provides good yields of acetophenones with limited amounts of oxidative cleavage arising from anti-Markovnikov oxidation, which is often a problem in the Wacker oxidation of these substrates.[137,138]



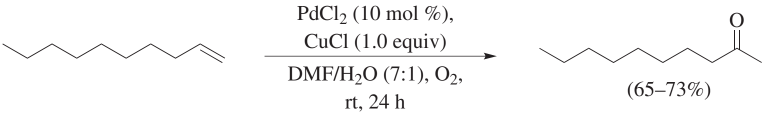
Scheme 109

The use of the ligand Quinox with Pd(II) and TBHP constitutes a highly active and selective system for the Wacker oxidation as described throughout the "Scope and Limitations" section.[22] This catalyst system has shown wide functional-group compatibility comparable to that of the Tsuji–Wacker oxidation. Better site selectivity and rates can be achieved by using the alkyl peroxide TBHP along with the Pd(Quinox)Cl$_2$ complex for substrates that are slow to react or give unpredictable product mixtures using water as the oxygen atom source. Standard reaction conditions use between 1–5 mol % of the commercially available Pd(Quinox)Cl$_2$ complex (or the complex can be prepared in situ) along with twice the molar amount of AgSbF$_6$ to remove the chloride counterions and render the palladium center more electrophilic. Since an excess of aqueous 70% TBHP (12 equivalents) is generally used, the compatible solvents CH$_2$Cl$_2$ or 1,2-dichloroethane can be used without prior drying. Additionally, the reaction does not require an inert atmosphere, so a loosely capped vessel is sufficient to prevent solvent evaporation. Some substrates react very rapidly under these conditions and therefore it is recommended to initiate these reactions with the flask in an ice bath. *CAUTION: The concentration of TBHP upon evaporation of the solvent to provide the crude product mixture is potentially dangerous. Therefore, a mild reducing agent, such as aqueous* Na$_2$SO$_3$, *is used to consume the remaining peroxide in the reaction mixture prior to work up.*

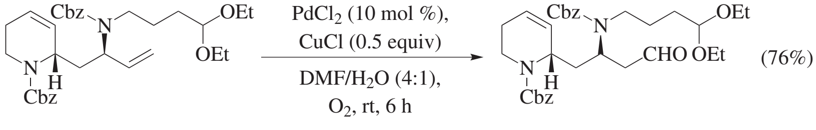
Additives and Specialized Systems

A significant number of additives are utilized to enhance or modify Wacker oxidation systems. Heteropolyacids are used in hydroquinone-O$_2$ redox as well as in direct O_2-coupled redox systems, although these methods are not widely used in synthetic applications.[139,140] Numerous reports that use β-cyclodextrin exist, including use in conjunction with heteropolyacids.[141,142] Ionic liquids are used as solvents in the Wacker oxidation.[143] Immobilization of palladium is also reported.[61]

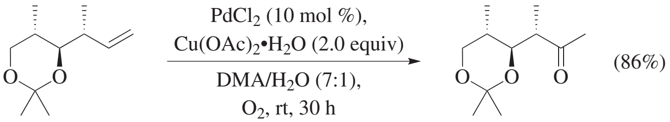
EXPERIMENTAL PROCEDURES



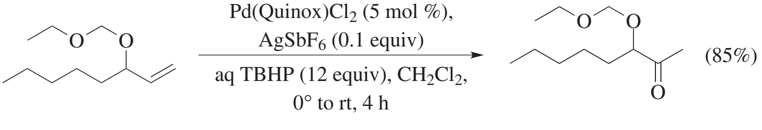
2-Decanone (Tsuji–Wacker Oxidation).[4] A 100-mL, 3-necked, round-bottomed flask was fitted with a magnetic stirring bar and a pressure-equalizing dropping funnel containing 1-decene (4.2 g, 30 mmol, 1.0 equiv). The flask was charged with a mixture of $PdCl_2$ (0.53 g, 3 mmol, 0.1 equiv), CuCl (2.97 g, 30 mmol, 1.0 equiv) and aqueous DMF (DMF/H_2O = 7:1, 24 mL). With the other outlets securely stoppered and wired down, an oxygen-filled balloon was placed over one neck, and the mixture was stirred at rt to allow oxygen uptake. After 1 h, the 1-decene (4.2 g, 30 mmol) was added over 10 min, and the solution was stirred vigorously at rt under an oxygen balloon. The color of the solution turned from green to black within 15 min and returned gradually to green. After 24 h, the mixture was poured into cold 3 N HCl (100 mL) and extracted with five 50 mL portions of ether. The extracts were combined and washed successively with 50 mL of saturated aqueous $NaHCO_3$ solution, 50 mL of brine, and then dried over anhydrous magnesium sulfate. The solvent was removed by evaporation and the residue was distilled using a 15 cm Vigreux column to give 2-decanone as a colorless oil (3.0–3.4 g, 65–73%): bp 43.5° (1 mm Hg); IR (neat) 1722 cm^{-1}; ^1H NMR (CCl_4) δ 2.37 (t, $J = 7$ Hz, 2H), 2.02 (s, 3H), 0.7–1.8 (m, 15H).



(3*R*,4*S*)-3-[*N*-Benzyloxycarbonyl-(4,4-diethoxybutyl)amino]-4-(*N*-benzyloxycarbonyl-1,2,5,6-tetrahydropyridin-2-yl)butyraldehyde (Generation of an Aldehyde from a Terminal Alkene).[144] (2*S*,8*R*)-*N*-Benzyloxycarbonyl-2-[2-*N*-benzyloxycarbonyl-(4,4-diethoxybutyl)amino]-but-3-enyl-1,2,5,6-tetrahydropyridine (650 mg, 1.15 mmol) was dissolved in DMF/H_2O (4:1, 20 mL) under an oxygen atmosphere. $PdCl_2$ (20.0 mg, 0.115 mmol, 10 mol %) and CuCl (57.0 mg, 0.576 mmol. 0.5 equiv) were added and the suspension was stirred for 6 h. MTBE (100 mL) was then added and the mixture was dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue was chromatographed on silica gel using MTBE/hexane (1:1) to yield the aldehyde product as a clear oil (510 mg, 76%): $[\alpha]_D^{20}$ + 51.8 (*c* 1, $CHCl_3$); IR (film) 3033, 2972, 2929, 2899, 1695, 1424, 1308, 1241, 1111, 1060, 699 cm^{-1}; ^{1}H NMR (500 MHz, C_6D_6) δ 9.43 (sbr, 1H), 7.30–7.00 (m, 10H), 5.68–5.58 (m, 1H), 5.51 (m, 1H), 5.19–5.01 (m, 4H), 4.54–4.39 (m, 3H), 4.19–3.99 (m, 1H), 3.52 (m, 2H), 3.40–3.25 (m, 3H), 3.19–3.07 (m, 1H), 2.77–2.33 (m, 3H), 2.02–1.53 (m, 8H), 1.48 (dm, J = 18 Hz, 1H), 1.11 (t, J = 7 Hz, 6H); ^{13}C NMR (C_6D_6) δ 198.7 (CH), 155.8 (Cq), 155.0 (Cq), 137.3 (Cq), 128.4–127.5 (8C), 125.5 (CH), 102.7 (CH), 102.6 (CH), 102.4 (CH), 67.0 (CH), 67.0 (CH_2), 66.9 (CH_2), 60.9 (CH_2), 60.8 (CH_2), 60.4 (CH_2), 49.8 (CH_2), 49.7 (CH_2), 47.2 (CH), 45.6 (CH_2), 45.9 (CH_2), 37.9 (CH_2), 37.1 (CH_2), 31.4 (CH_2), 24.9 (CH_2), 24.8 (CH_2), 24.5 (CH_2), 15.3 (CH_3); LRMS (*m/z*) (%): $[M{-}C_2H_5O]^+$ 535 (18), 399 (30), $[C_5H_{10}NZ]^+$ 216 (28), $[C_9H_{18}O_2N]^+$ 172 (82), $[C_7H_7]^+$ 91 (100); HRMS (*m/z*): $[M - C_2H_5O]^+$ calcd for $C_{31}H_{39}N_2O_6$, 535.2808; found, 535.2810. Anal. Calcd for $C_{33}H_{44}N_2O_7$: C, 68.25; N, 4.82; H, 7.64. Found: C, 68.38; N, 5.12; H, 7.61.

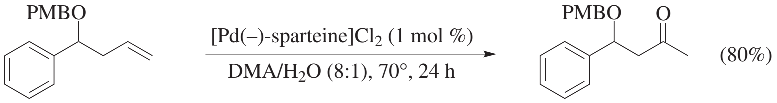


(*S*)-3-((4*S*,5*S*)-2,2,5-Trimethyl-1,3-dioxan-4-yl)butan-2-one (Wacker Oxidation Using Cu(OAc)$_2$).[145] A suspension of the alkene (5.33 g, 29.0 mmol, 1.0 equiv), $PdCl_2$ (0.51 g, 2.9 mmol, 0.1 equiv), and $Cu(OAc)_2{\bullet}H_2O$ (11.6 g, 58 mmol, 2.0 equiv) in DMA (50 mL) and water (7 mL) was placed under oxygen (1 atm), and the green mixture was stirred at rt for 30 h. The mixture was diluted with ether (50 mL), filtered through Celite employing ether (3 × 20 mL) to wash the filter cake, poured into water (100 mL), and the water layer was extracted with ether (3 × 20 mL). The organic phase was washed with brine (3 × 50 mL), dried over Na_2SO_4, and concentrated. Adsorption of the residue on silica gel and gradient flash chromatography (hexanes to 3:1 hexanes/ethyl acetate) furnished the title product as a colorless oil (4.89 g, 86%). A similar yield (84%) was obtained using 0.2 equiv of $Cu(OAc)_2{\bullet}H_2O$: $[\alpha]_D^{23}$ 0 (c 2.93, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.64 (dd, J = 11.6, 5.1 Hz, 1H), 3.57 (dd, J = 10.2, 3.9 Hz, 1H), 3.43 (dd, J = 11.6, 10.5 Hz, 1H), 2.64 (apparent qd, J = 7.1, 3.9 Hz), 2.14 (s, 3H), 1.77–1.67 (m, 1H), 1.39 (s, 3H), 1.34 (s, 3H), 1.18 (d, J = 7.1 Hz, 3H), 0.76 (d, J = 6.7 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 211.3, 98.4, 77.1, 65.8, 50.3, 32.4, 29.2, 28.9, 18.9, 13.4, 12.9; HRMS–Cl (NH_3) (*m/z*): $[M + H]^+$ calcd for $C_{11}H_{21}O_3$, 201.1490; found 201.1495.

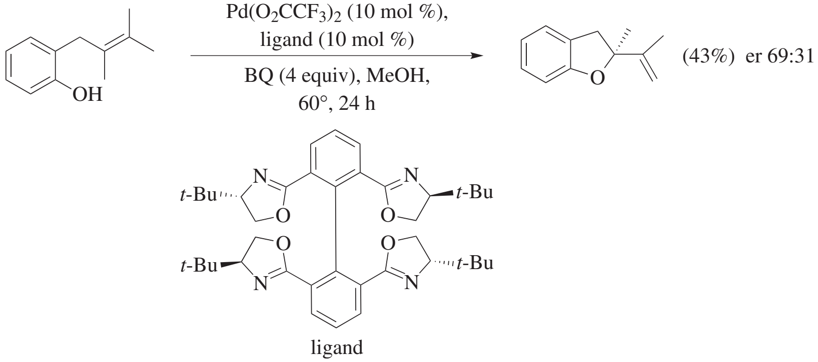


3-(Ethoxymethoxy)octan-2-one (Peroxide-Mediated Wacker Oxidation).[83] In the dark, $AgSbF_6$ (34.3 mg, 0.10 mmol, 0.1 equiv), Pd(quinox)Cl_2 complex

(18.7 mg, 0.05 mmol, 0.05 equiv), and a magnetic stirring bar were added to a 25-mL round-bottomed flask. CH_2Cl_2 (2.3 mL) was added to the flask and the mixture was stirred for 15 min. The mixture was then diluted with CH_2Cl_2 (6 mL) and aq TBHP (1.7 mL, 12 mmol, 12 equiv, 70 wt %) solution was added. The resulting mixture was stirred for an additional 10 min, cooled in an ice bath, and 3-(ethoxymethoxy)-oct-1-ene (187 mg, 1.0 mmol, 1.0 equiv) was added with stirring. After 5 min, the ice bath was removed and the reaction mixture was allowed to slowly warm to rt. After 4 h, TLC analysis indicated complete consumption of starting material and the reaction was quenched with a saturated aqueous solution of Na_2SO_3 (15 mL) to consume excess TBHP. The mixture was transferred to a separatory funnel and diluted with hexanes (25 mL). The aqueous layer was separated and back-extracted with hexanes (25 mL). The combined organic extracts were washed with water (4 × 25 mL), brine (50 mL), dried ($MgSO_4$), and concentrated under reduced pressure. The crude material was purified by silica gel flash chromatography eluting with a mixed solvent system of 15% Et_2O in hexanes to provide the title product as a colorless oil (172 mg, 85%): R_f 0.27 (25% Et_2O in hexanes); IR (neat) 2955 (m), 2931 (m), 2873 (m), 1715 (s), 1352 (m), 1097 (m), 1027 (s), 846 (w) cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 4.69 (dd, J = 6.8, 7.8 Hz, 2H), 3.99 (dd, J = 5.9, 7.8 Hz, 1H), 3.66–3.56 (m, 2H), 2.17 (s, 3H), 1.70–1.61 (m, 2H), 1.43–1.23 (m, 6H), 1.19 (t, J = 7.8 Hz, 3H), 0.88 (t, J = 6.8 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 210.3, 95.1, 82.9, 64.2, 32.1, 31.8, 26.2, 25.0, 22.7, 15.2, 14.2; HRMS–ESI/APCI (m/z): $[M + Na]^+$ calcd for $C_{11}H_{22}O_3Na$, 225.1467; found 225.1468.



4-((4-Methoxybenzyl)oxy)-4-phenylbutan-2-one (Direct O_2-Coupled Wacker Oxidation).[48] In a 75-mL Schlenk flask equipped with a magnetic stirring bar, [Pd(−)-sparteine]Cl_2 (3.3 mg, 0.008 mmol, 0.01 equiv) and 4 mL of an 8:1 (v/v) mixture of DMA and H_2O were combined. The flask was placed in an oil bath heated at 70° and the mixture was stirred to dissolve the catalyst (~10 min), at which time the flask was cooled to rt. A condenser was then attached to the flask and a three-way joint fitted with a balloon of O_2 was installed on the condenser. The flask was evacuated, refilled with O_2 three times, and the mixture was stirred vigorously at rt (~10 min). Using a syringe, the alkene (215 mg, 0.8 mmol, 1 equiv) was added at rt. Following substrate addition, the reaction flask was placed into a 70° oil bath. The reaction mixture was stirred vigorously under a balloon of O_2. After 24 h, the flask was removed from the oil bath and condenser walls were rinsed with 2 mL of Et_2O. The reaction mixture was transferred to a separatory funnel and washed twice with 4 mL of 1 N HCl. The aqueous layers were combined, back extracted three times with 4 mL of Et_2O, the organic layers were combined, washed with 5 mL of brine and dried (Na_2SO_4). The product was purified by flash column chromatography (20% Et_2O/pentane) to afford the title product as a clear oil (182 mg, 80%): IR (neat) 2933, 1721, 1612, 1516, 1454, 1357, 1302, 1253, 1173, 1087, 1038, 822, 755, 702, 548 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.41–7.27 (m, 5H), 7.22–7.14 (d, $J = 8.8$ Hz, 2H), 6.89–6.82 (d, $J = 8.8$ Hz, 2H), 4.88–4.82 (dd, $J = 4.4$, 9.1 Hz, 1H), 4.37–4.19 (dd, $J = 11.0$, 36.1 Hz, 2H), 3.8 (s, 3H), 3.08–2.97(dd, $J = 9.1$, 15.9 Hz, 2H), 2.65–2.56 (dd, $J = 4.3$, 15.8 Hz, 2H), 2.13 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 206.8, 159.4, 141.5, 130.4, 129.8, 128.9, 128.2, 126.9, 114.0, 77.5, 70.6, 55.5, 52.3, 31.2; MS–EI (*m/z*): M^+ calcd for $C_{18}H_{20}O_3$, 284.14; found, 284.05.



(*S*)-2-Isopropenyl-2-methyl-2,3-dihydrobenzofuran (Wacker Cyclization).[113] To a solution of palladium bis(trifluoroacetate) (14.0 mg, 0.04 mmol) and 2,2′,6,6′-tetra[(4′*S*)-*tert*-butyloxazolin-2′-yl]-1,1′-biphenyl (13.8 mg, 0.02 mmol) in MeOH (1.0 mL) was added *p*-benzoquinone (181.6 mg, 1.68 mmol) and 2-(2,3-dimethyl-2-butenyl)phenol (74.0 mg, 0.42 mmol) in MeOH (0.5 mL) at rt. The reaction mixture was stirred at 60° for 24 h, concentrated under vacuum, and the residue was chromatographed on silica gel (EtOAc/petroleum ether) to give (*S*)-2-isopropenyl-2-methyl-2,3-dihydrobenzofuran as a colorless oil (31.5 mg, 43%, er 69:31): $[\alpha]_D^{26} - 32.4$ (*c* 1.45, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 7.15–7.10 (m, 2H), 6.83 (m, 1H), 6.79 (d, $J = 7.2$ Hz, 1H), 5.09 (m, 1H), 4.84 (m, 1H), 3.26 (d, $J = 15.2$ Hz, 1H), 3.02 (d, $J = 16.0$ Hz, 1H), 1.83 (dd, $J = 0.8$, 1.6 Hz, 3H), 1.55 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.9, 147.7, 128.0, 126.5, 124.9, 120.0, 109.9, 109.4, 89.7, 41.3, 26.0, 18.7. The er was determined by GC on a Chirasil-DEX CB column (110° isothermal).

TABULAR SURVEY

The tabular survey in this chapter covers Wacker oxidations of terminal and internal alkenes, as well as reactions that are closely related from a mechanistic point of view. The dates covered range from the inception of the catalytic reaction in 1959 through November 2012. The tables are organized by substrate type and within each table they are listed in order of increasing carbon number. The carbon count excludes protecting groups and most groups on heteroatoms, except when they define the substrate, as in, for example, terminal alkenes with allylic or homoallylic heteroatoms.

The oxidation of terminal alkenes is separated into substrates that do not bear heteroatom functionality at the allylic and/or homoallylic position (Table 1A) and those that do (Table 1B). Table 2 presents the oxidation of internal alkene substrates and is similarly separated according to the proximity of heteroatoms (Tables 2A and 2B, respectively). Table 3 presents the oxidation of alkene substrates that do not result in carbonyl products, such as the formation of acetals from external nucleophiles (Table 3A), the formation of acetals from internal nucleophiles (Table 3B), and internal nitrogen-based nucleophiles (Table 3C). Table 4 presents Wacker cyclizations where hydride elimination follows the internal nucleophilic attack of an oxygen (Table 4A) or nitrogen (Table 4B) nucleophile.

Very simple substrates such as straight-chain alkenes bearing no functional groups (e.g., 1-butene) have been omitted from the Tabular Survey as there are numerous conditions to perform this transformation.

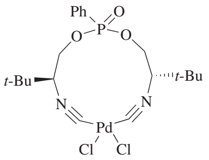
The notation “(—)” indicates that no yield was reported. Also, many examples do not report explicit conditions or simply state “Wacker Oxidation”, which is assumed to be similar to the standard Tsuji–Wacker conditions.

The following abbreviations (not included in “*The Journal of Organic Chemistry* Standard Abbreviations and Acronymns”) are used in the Tabular Survey:

bmim	1-butyl-3-methylimidazolium
BQ	*p*-benzoquinone
BOM	benzyloxymethyl
dba	dibenzylideneacetone
EOA	ethyl orthoacetate
HQ	*p*-hydroquinone
I*i*Pr	2,6-diisopropylphenyllimidazolium (see ligand table)
mont	montmorillonite
MS	molecular sieves
NPMoV	molybdovanadophosphate
Ns	*o*-nitrobenzenesulfonyl
Pa	Pascals
Pc	phthalocyanine
PEG	polyethylene glycol
phth	phthaloyl
PMP	4-methoxyphenyl
PS-BQ	polystyrene-supported benzoquinone
PTSA	*p*-toluenesulfonic acid
Quinox	quinoline-2-oxazoline ligand (see ligand table)
TAc	trichloroacetyl
TBAP	tetrabutylammonium perchlorate

TBDPS	*tert*-butyldiphenylsilyl
TEMDP	tetraethyl methylenediphosphonate
TEMPO	(2,2,6,6-tetramethylpiperidin-1-yl)oxy
TES	triethylsilyl
TMU	*N*,*N*,*N′*,*N′*-tetramethylurea
p-Tol	*p*-tolyl

CHART 1. LIGANDS AND CATALYST COMPLEXES USED IN THE TABLES



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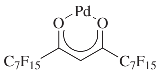

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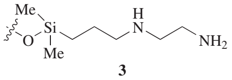
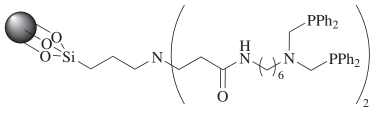


3

montmorillonite supported ligand



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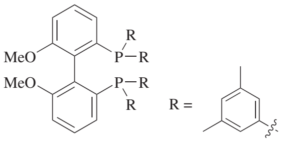
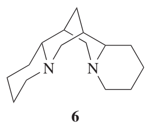
G1–C6 ligand



5

(*R*)-(+)-2,2'-bis[di(3,5-xylyl)phosphino]-6,6'-dimethoxy-1,1'-biphenyl: (*R*)-xylyl-MeO-BIPHEP



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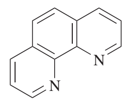
(–)-sparteine



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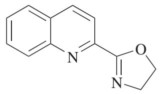
1,10-phenanthroline



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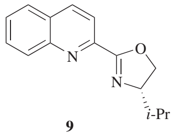
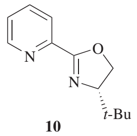
Quinox



9

i-Pr-Quinox



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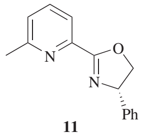
t-Bu-Pyrox



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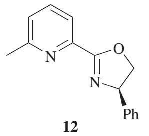

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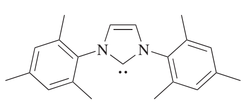

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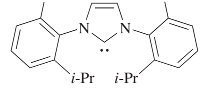
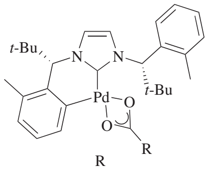
IMes

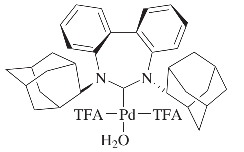


14

I*i*-Pr



	R
15a	Me
15b	CF_3



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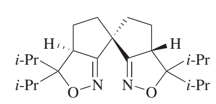

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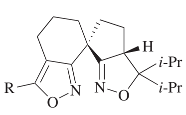
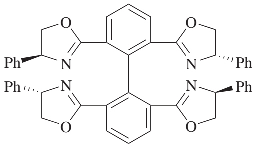


	R
18a	Br
18b	Ph
18c	4-$MeOC_6H_4$
18d	4-$Me_2NC_6H_4$
18e	4-$MeO_2CC_6H_4$
18f	4-FC_6H_4
18g	1-naphthyl
18h	9-anthryl
18i	2,6-xylyl
18j	2-biphenyl
18k	2-$CF_3C_6H_4$
18l	3,5-$(CF_3)_2C_6H_3$
18m	*t*-Bu



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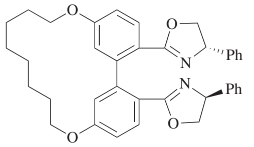

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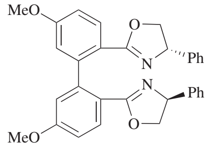

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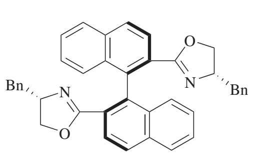

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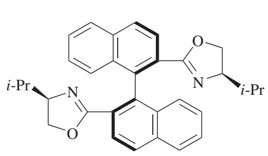

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TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES

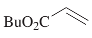
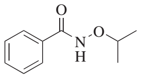
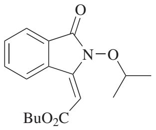
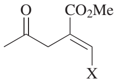
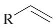
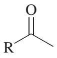
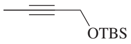
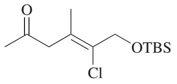
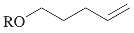
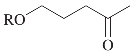
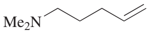
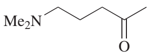
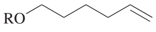
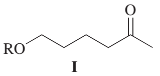
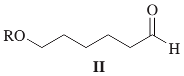
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_3			
 (2 eq)	 (1 eq), $Pd(OAc)_2$ (5 mol %), BQ (20 mol %), AcOH, O_2 (1 atm), 110°	 (46)	146
$MeO_2C{-}C{\equiv}C{-}H$	1. $Pd(PhCN)_2X_2$ (3 mol %), additive (1 eq), DME, 0° to rt, 6 h 2. CuCl (1 eq), DME/H_2O, O_2, rt, 24 h	 X Additive Br allyl bromide (74) Cl allyl chloride (75)	147
$C_{4–11}$			
	$Pd(OAc)_2$ (10 mol %), TEMPO (30 mol %), $NaClO_4$ (0.05 M), CH_3CN/H_2O (7:1), rt, divided cell, (Pt)–(Pt), 5 mA, 3 F/mol	 R $MeO_2C(CH_2)_8$ (83) $Ph(CH_2)_2$ (71) $CHO(CH_2)_8$ (75) $BnO(CH_2)_2$ (63)	148
C_4			
	1. Allyl chloride (1 eq), $Pd(PhCN)_2Cl_2$ (3 mol %), DME, 0° to rt, 6 h 2. CuCl (1 eq), DME/H_2O, O_2 rt, 24 h	 (66)	147
C_5			
	$Pd(OAc)_2$ (5 mol %), py (20 mol %), toluene, alcohol, O_2	 R Alcohol Temp (°) Time (h) H propan-2-ol 60 6 (21) THP butan-2-ol 75 8 (70) TBS propan-2-ol 60 16 (71) Bz butan-2-ol 75 8 (78)	134
	$PdCl_2$ (5 mol %), $CuCl_2$ (10 mol %), NaCl (1 eq), HCl (2 eq), H_2O, O_2, 60°, 3.5 h	 (85)	149
C_6			
	$PdCl_2$ (10 mol %), CuCl (1 eq), $(bmim)BF_4$ (4.2 eq), H_2O, O_2, 60°	 +  **I** **II** R Time (h) **I** **II** **I/II** THP 64 (62) (—) 74:12.6 TBS 58 (60) (—) 73.1:10.3	143

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

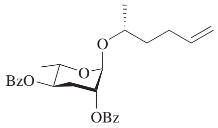
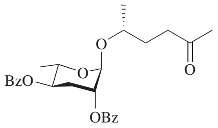
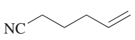
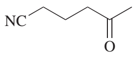
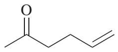
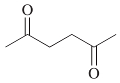
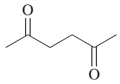
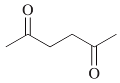
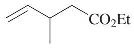
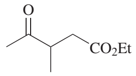
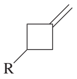
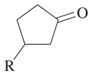
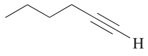
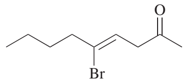
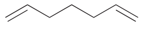
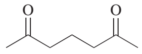
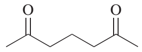
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	$Pd(OAc)_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (7:1), air, rt, 18 h	 (89)	150
	Pd-mont **3** (0.4 mol %), $CuCl_2$ (1.6 mol %), DMA/H_2O (6:1), O_2, 80°, 15 h	 (70)	61
	$Pd(OAc)_2$ (5 mol %), polypyrrole (20 mg/mmol), MeCN, H_2O (150 mol %), 40°, 90 h	 (62)	151
	$Pd(OAc)_2$ (5 mol %), polyaniline (20 mg/mmol), $MeCN/H_2O$ (1:15), 70°, 24 h	 (22)	152
	$PdCl_2$ (10 mol %), $CuCl_2$ (20 mol %), acetoximine (20 mol %), acetone, O_2, 50°, 21 h	 (26)	153
	$PdCl_2$ (10 mol %), $CuCl_2$ (10 mol %), H_2O, 70°, 3 h	 (—)	154
	$PdCl_2$ (5 mol %), $CuCl_2$ (0.5 eq), H_2O (2 eq), benzene, O_2	 R / Temp Me / 0° / (75) NC– / 65° / (82) $AcNHCH_2$ / rt / (65)	74
	1. $Pd(PhCN)_2Br_2$ (3 mol %), allyl bromide (1 eq), DME, 0° to rt, 6 h 2. CuCl (1.0 eq), DME/H_2O, O_2, rt, 24 h	 (70)	147
C_7			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2 (bubbled), rt, 24 h	 (60)	70
	$Pd(OAc)_2$ (5 mol %), NPMoV (35 mg/2 mmol), $MeSO_3H$ (10 mol %), additive (20 mol %), HQ (20 mol %), $EtOH/H_2O$ (19:1), O_2, 5 h	 Additive NH_4Cl (59) NaCl (69)	139

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

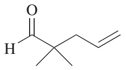
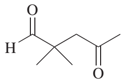
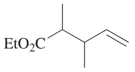
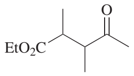
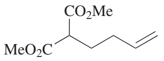
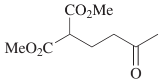
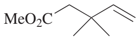
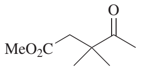
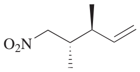
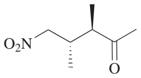
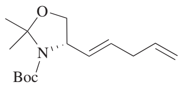
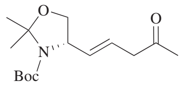
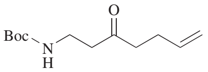
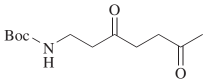
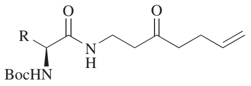
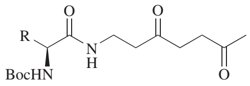
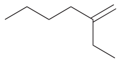
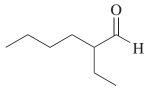
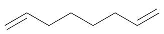
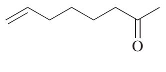
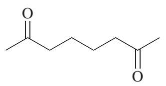
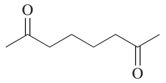
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C$_7$			
	Pd(CH$_3$CN)$_2$Cl(NO$_2$) (0.4 mol %), CuCl$_2$ (3.2 mol %), *N*,*N*-diethylpivaloylamide/*t*-BuOH, O$_2$, 8 h	 (100)	155
	PdCl$_2$ (10 mol %), CuCl$_2$ (10 mol %), DME/H$_2$O (20:1), O$_2$, 80°, 5–6 h	 (90)	154
	Pd(OAc)$_2$ (4 mol %), BQ (20 mol %), DMSO/H$_2$O (7:1), Et$_4$NBF$_4$, Pt-anode, rt	 (69)	156
	[Pd(P(*t*-Bu)$_2$H)(μ-P(*t*-Bu)$_2$)]$_2$ (2 mol %), THF, O$_2$, 50°	 (75)	157
	—	 (—)	158
	PdCl$_2$ (0.2 eq), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$, rt	 (82)	67
	PdCl$_2$ (20–40 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt	 (—)	68
	PdCl$_2$ (30 mol %), CuCl (2 eq), DMF/H$_2$O (7:1), O$_2$, rt	 R Me (85) Bn (80)	159
C$_8$			
	RhCl$_3$•3H$_2$O (0.8 mol %), Cu(ClO$_4$)$_2$(HMPA)$_4$ (1.6 mol %), EtOH, O$_2$ (860 mmHg), 40°, 4 h	 (0)	160
	RhCl$_3$•3H$_2$O (0.8 mol %), Cu(ClO$_4$)$_2$(HMPA)$_4$ (1.6 mol %), EtOH, O$_2$ (860 mmHg), 40°, 4 h	 (61)	160
	Pd(OAc)$_2$ (5 mol %), NPMoV (35 mg/2 mmol), MeSO$_3$H (10 mol %), additive (20 mol %), HQ (20 mol %), EtOH/H$_2$O (19:1), O$_2$, 5 h	 Additive NH$_4$Cl (41) NaCl (58)	139
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$ (bubbled), rt, 24 h	 (47)	70

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

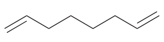
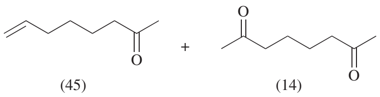
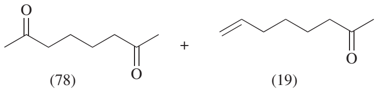
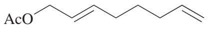
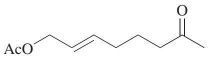
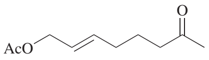
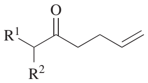
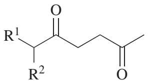
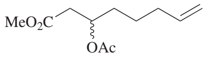
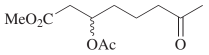
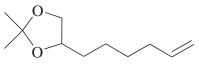
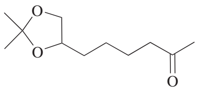
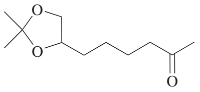
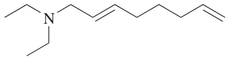
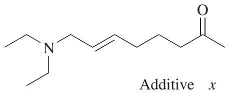
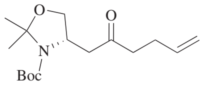
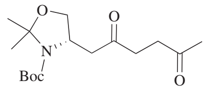
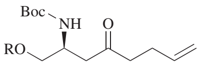
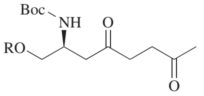
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_8			
	$Pd(OAc)_2$ (1 mol %), BQ (3 mol %), H_2O_2 (1.1 eq), AcOH, 50°, 12–18 h	 (45) + (14)	161
	$PdCl_2$ (0.5 mol %), DMA/H_2O (6:1), O_2 (6 atm), 80°, 40 h	 (78) + (19)	49
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, rt	 (77)	140
	$Pd(OAc)_2$ (4 mol %), BQ (20 mol %), DMSO/H_2O (7:1), Et_4NBF_4, Pt-anode, rt	 (75)	156
	$PdCl_2$ (14 mol %), BQ (1.01 eq), H_2O, 70°, 3 h	 R^1 R^2 Me Me (47) Et H (43)	162
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2	 (90)	163
	Pd[(–)-sparteine]Cl_2 (2.5 mol %), DMA/H_2O (4:1), air, 70°, 24 h	 (62)	48
	Pd(Quinox)Cl_2 (2 mol %), $AgSbF_6$ (5 mol %), aq TBHP (12 eq), CH_2Cl_2, 0° to rt, 0.5 h	 (95)	83
	Na_2PdCl_4 (20 mol %), HCl (3 eq), H_2O, additive (*x* eq), 60°	 Additive *x* Time (h) H_2O_2 6 0.5 (82) BQ 1 — (—)	164
	$PdCl_2$ (16 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 (58)	165
	$PdCl_2$ (16 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 R H (29) TBS (14)	165

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

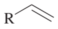
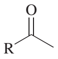
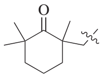
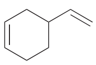
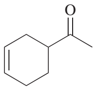
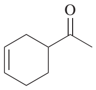
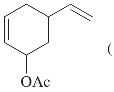
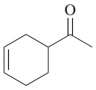
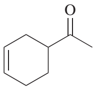
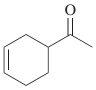
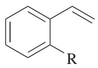
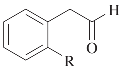
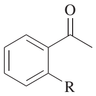
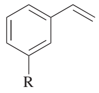
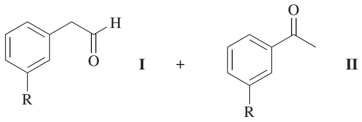
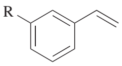
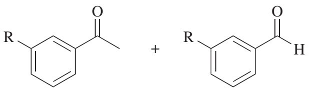
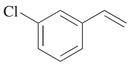
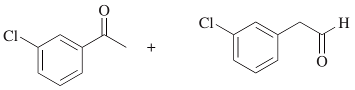
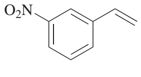
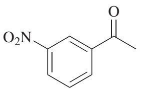
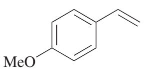
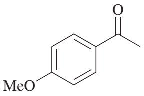
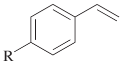
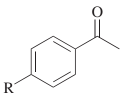
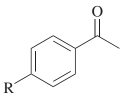
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{8-12}			
	**1** (5 mol %), DMA/H_2O (6:1, 0.125 M), O_2 (1 atm), 70°	 R Time (h) n-C_6H_{13} 24 (98^a, 75) $HO(CH_2)_9$ 48 (97^a, 77) c-C_6H_{11} 48 (84^a, —) Bn 48 (75^a, —) $MeO_2C(CH_2)_8$ 48 (98^a, —)  48 (92^a, 71)	166
C_8			
	$Pd(OAc)_2$ (5 mol %), py (20 mol %), toluene/i-BuOH (1:1), O_2, 75°, 12 h	 (75)	134
	$Pd(OAc)_2$ (1 mol %), BQ (3 mol %), H_2O_2 (1.1 eq), AcOH, 50°, 12–18 h	 (23) +  (13)	161
	$Pd(MeCN)_2Cl(NO_2)$ (8 mol %), benzene, O_2, 60°	 (50–70)	167
	$PdSO_4$ (2.15 mol %), α-cyclodextrin (2.5 mol %), $CuSO_4$ (25 mol %), $H_9PV_6Mo_6O_{40}$ (25 mol %), H_2O (4 mol %), 80°	 (42)	142
	$[Pd(P(t\text{-}Bu)_2H)(\mu\text{-}P(t\text{-}Bu)_2)]_2$ (2 mol %), THF, O_2, 50°	 (55)	157
C_{8-9}			
	$PdCl_2$ (2 eq), DMF/H_2O (x :1), rt, 5 h	 **I** +  **II** R x **I + II** **I/II** F 10 (78) >25:1 Br 10 (—) >25:1 MeO — (95) 17.4:1.0 Me — (89) >25:1	138

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

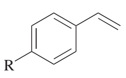
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{8-9}			
	$PdCl_2$ (2 eq), DMF/H_2O (10:1), rt	 **I** + **II** R / Time (h) / **I + II** / **I/II** Cl / 5 / (80) / >25:1 O_2N / 18 / (54) / 16.2:1.0 Me / 5 / (50) / 5:1	138
	$[Pd(Ii\text{-}Pr)Cl_2]_2$ (*x* mol %), AgOTf (*y* mol %), TBHP (5.5 eq), MeOH, 35°, air	 **I** + **II** R / *x* / *y* / Time (h) / **I** / **II** / **I/II** Cl / 0.75 / 3 / 48 / (80) / (—) / >150:1 O_2N / 2.25 / 12 / 24 / (79) / (—) / >150:1 Me / 0.75 / 3 / 32 / (83) / (—) / 22:1	56
C_8			
	$PdCl_2$ (10 mol %), CuCl (1 eq), $(bmim)BF_4$ (4.2 eq), H_2O, O_2, 60°, 24 h	 **I** (88) **I/II** = 97.5:2.4 **II** (—)	143
	Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (12.5 mol %), aq TBHP (12 eq), CH_2Cl_2, 0° to rt, 17 h	 (60)	83
	$PdCl_2$ (1 eq), DMF/H_2O (1:1), 100°	 (—)	94
C_{8-9}			
	$PdCl_2$ (5.8 mol %), CuCl, PEG, O_2 (2 MPa), 60°, 24 h	 R Cl (72) MeO (85) Me (87)	132
	$PdCl_2$ (2 mol %), NaOAc (10 mol %), ethylene carbonate, H_2O, O_2 (10 atm)	 R / Temp (°) / Time (h) Cl / 80 / 12 / (29) Cl / 100 / 24 / (56) MeO / 100 / 24 / (86) Me / 100 / 24 / (82)	133

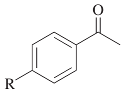
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{8-14}



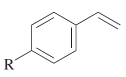
2 (5 mol %), TBHP (1.5 eq), benzene/$C_8F_{17}Br$, 56°



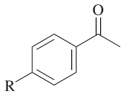
R	
MeO	(76)
AcO	(84)
CF_3	(76)
i-Pr	(78)
Ph	(80)

Refs. 136

C_{8-9}



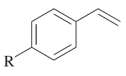
Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (12.5 mol %), aq TBHP (12 eq), CH_2Cl_2, 0° to rt



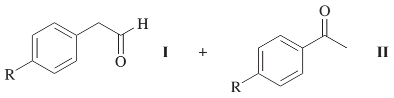
R	Time (min)	
BocHN	60	(83)
Me	50	(88)

Refs. 83

C_{8-12}



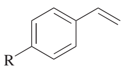
$PdCl_2$ (2 eq), DMF/H_2O (*x*:1), rt



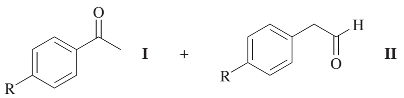
R	*x*	Time (h)	I + II	I/II
Cl	10	18	(56)	>25:1
MeO	—	5	(83)	9.5:1.0
Me	—	5	(61)	7.1:1.0
CF_3	10	18	(69)	>25:1
t-Bu	10	5	(82)	8.7:1.0

Refs. 138

C_{8-9}



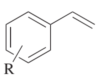
$PdCl_2$ (10 mol %), CuCl (1 eq), (bmim)BF_4 (4.2 eq), H_2O, O_2, 60°



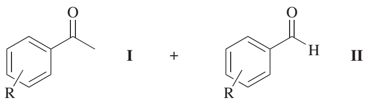
R	Time (h)	I	II	I/II
Cl	30	(82)	(—)	94.1:4.2
Br	24	(85)	(—)	96.2:3.1
MeO	28	(85)	(—)	95.1:3.5
Me	24	(80)	(—)	80:18

Refs. 143

C_{8-12}



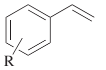
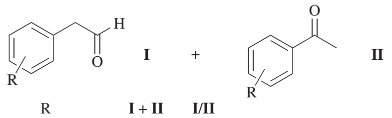
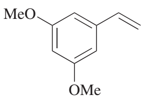
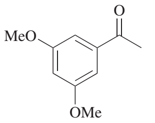
Catalyst **1** (5 mol %), DMA/H_2O (6:1, 0.125 M), O_2 (1 atm), 70°



R	Time (h)		I/II
H	70	(84)[a]	17:1
3-Cl	96	(72)[a]	7:1
4-Cl	96	(98)[a]	7:1
4-Br	96	(50)[a]	9:1
4-MeO	48	(>99)[a]	21:1
4-Me	40	(>99)[a]	26:1
2-vinylnaphthalene	70	(88)[a]	11:1

Refs. 166

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{8-12}			
	$Pd(MeCN)_2Cl_2$ (2.5 mol %), H_2O (1 eq), BQ (1.15 eq), *t*-BuOH, 85°	 R — I + II — I/II H — (83) — 98:2 4-F — (74) — 99:1 4-Cl — (92) — 99:1 4-Br — (90) — 99:1 3-O_2N — (96) — >99:1 4-O_2N — (96) — 99:1 2-Me — (90) — 96:4 4-Me — (81) — 97:3 3,5-$(CF_3)_2$ — (72) — 99:1 4-MeO_2C — (59) — 96:4 4-*t*-Bu — (42) — 98:2	168
C_8			
	**2** (5 mol %), TBHP (1.5 eq), benzene/$C_8F_{17}Br$, 56°	 (80)	136

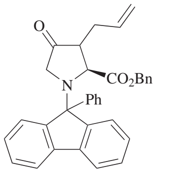
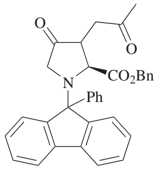
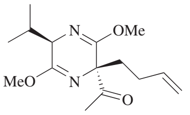
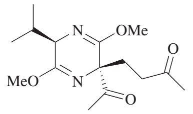
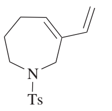
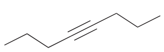
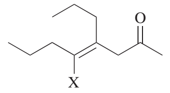
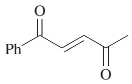
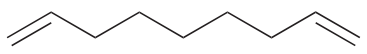
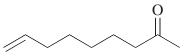
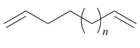
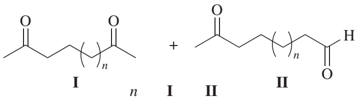
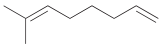
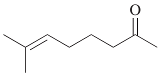
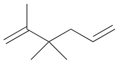
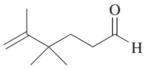
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
 dr 5:1	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 (81) dr 5:1	169
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 10 h	 (83)	170
	$PdCl_2$, CuCl, DMF/H_2O, O_2	(—)	171
	1. $Pd(PhCN)_2X_2$ (3 mol %), additive (1 eq), DME, 0° to rt, 6 h 2. CuCl (1.0 eq), O_2, DME/H_2O, rt, 24 h	 Additive — X allyl bromide (80) — Br allyl chloride (77) — Cl	147
$\mathrm{Ph}-\equiv-\mathrm{H}$	1. $Pd(PhCN)_2X_2$ (3 mol %), additive (1 eq), DME, 0° to rt, 6 h 2. CuCl (1.0 eq), O_2, DME/H_2O, rt, 24 h	 Additive — X allyl bromide (77) — Br allyl chloride (73) — Cl	147

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C$_9$ 	Pd(dba)/**4** (0.5 mol %), TBHP (1.1 eq), 55°, 24 h	 (40)	172
C$_{9–10}$ 	$PdCl_2$ (4 mol %), β-cyclodextrin (2.4 mol %), $CuCl_2$ (40 mol %), H_2O, O_2, 65°, 24–48 h	 n I II 3 (56) (7) 4 (100) (0)	141
C$_9$ 	$Pd(OAc)_2$ (5 mol %), NPMoV (17.5 mg/mmol), $MeSO_3H$ (10 mol %), additive (20 mol %), HQ (20 mol %), EtOH/H_2O (19:1), O_2	 Additive NH_4Cl (92) NaCl (97)	139
	$PdCl_2$ (52 mol %), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt, 24 h	 (99)	73

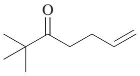
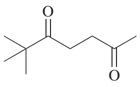
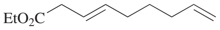
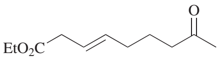
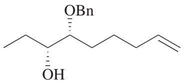
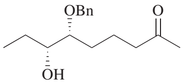
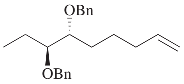
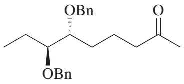
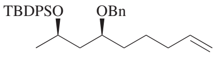
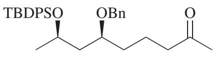
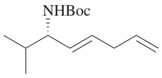
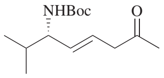
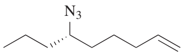
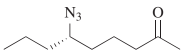
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (14 mol %), BQ (1.01 eq), H_2O, 70°, 3 h	 (49)	162
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (8:1), O_2, rt, 5 h	 (87)	173
	$PdCl_2$ (5 mol %), CuCl (5 eq), DMF/H_2O (4:1), O_2, rt, 2.5 h	 (85)	174
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (10:1.2), O_2, rt	 (81)	175
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (2 eq), DMA/H_2O (7:1), O_2, 20°, 66 h	 (78)	176
	$PdCl_2$ (0.2 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt	 (60)	67
	$PdCl_2$ (20 mol %), NMP/H_2O (8.5:1), O_2 (1 atm), rt, 24 h	 (85)	177

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

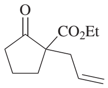
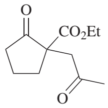
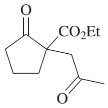
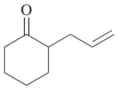
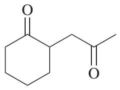
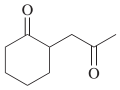
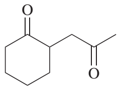
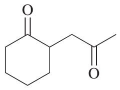
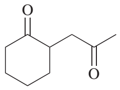
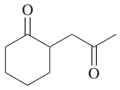
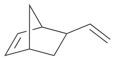
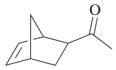
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_9			
	$PdCl_2$ (19 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 (71)	178
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMF/H_2O (7:1), O_2, rt, 2 d	 (73)	65
	$PdCl_2$ (0.5 mol %), DMA/H_2O (6:1), O_2 (6 atm), 80°, 24 h	 (88)	49
	$Pd(OAc)_2$ (5 mol %), py (20 mol %), toluene/butan-2-ol (1:1), O_2, 60°, 6 h	 (26)	134
	Pd-mont **3** (0.4 mol %), $CuCl_2$ (1.6 mol %), DMA/H_2O (6:1), O_2, 80°, 12 h	 (83)	61
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (8:1), O_2, rt, 2 h	 (68)	178
	$Pd(OAc)_2$ (5 mol %), Fe(Pc) (5 mol %), HQ (15 mol %), $HClO_4$ (5 mol %), DMF/H_2O (89:11), O_2, rt	 (85)	179
	$Pd(OAc)_2$ (5 mol %), Fe(Pc) (5 mol %), HQ (15 mol %), O_2, 20°, 2 h	 (85)	180
	Pd(dba)/**4** (0.5 mol %), TBHP (1.1 eq), 55°, 24 h	 (22)	172

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

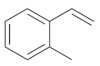
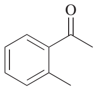
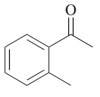
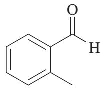
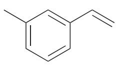
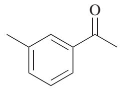
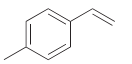
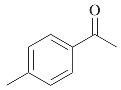
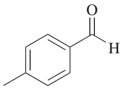
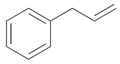
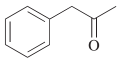
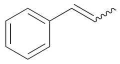
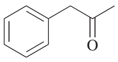
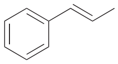
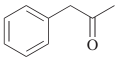
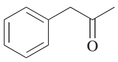
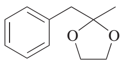
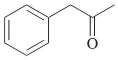
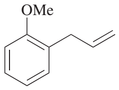
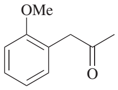
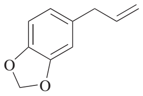
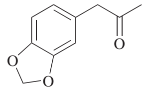
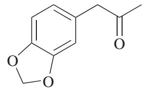
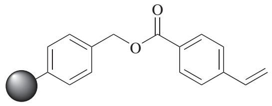
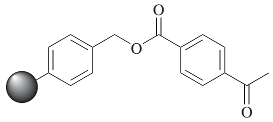
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	$PdCl_2$ (2 mol %), NaOAc (10 mol %), ethylene carbonate, H_2O, O_2 (10 atm), 100°, 24 h	 (53)	133
	$[Pd(Ii\text{-}Pr)Cl_2]_2$ (0.75 mol %), AgOTf (3 mol %), aq TBHP (5.5 eq), MeOH, air, 35°, 48 h	 +  **I** (79) **II** (—) **I/II** = 36:1	56
	$PdCl_2$ (2 mol %), NaOAc (10 mol %), ethylene carbonate, H_2O, O_2 (10 atm), 100°, 24 h	 (83)	133
	$[Pd(Ii\text{-}Pr)Cl_2]_2$ (0.75 mol %), AgOTf (3 mol %), aq TBHP (5.5 eq), MeOH, air, 35°, 48 h	 +  **I** (86) **II** (—) **I/II** = 22:1	56
	$PdSO_4$ (2.15 mol %), $CuSO_4$ (25 mol %), α-cyclodextrin (2.5 mol %), $H_9PV_6Mo_6O_{40}$ (25 mol %), H_2O (4 mol %), 80°, 6 h	 (56) +  (34)	142
	$PdCl_2$ (4 mol %), β-cyclodextrin (2.4 mol %), $CuCl_2$ (40 mol %), H_2O, O_2, 65°, 24–48 h	 (17) +  (83)	141
	5 wt % $Pd(OAc)_2/C$ (5 mol %), NPMoV (17.5 mg/mmol), NH_4Cl (5 mol %), $MeSO_3H$ (10 mol %), EtOH/H_2O (19:1), O_2	 (35) + recovered alkenes (53)	139
	$PdCl_2$ (10 mol %), CuCl (1 eq), $HO(CH_2)_2OH$, DME, O_2, 50°, 20 h	 (40) +  (14)	181
	$PdCl_2$ (0.5 mol %), DMA/H_2O (6:1), O_2 (6 atm), 80°, 40 h	 (85)	49
	$PdCl_2$ (2 mol %), $Cu(OAc)_2/H_2O$ (3 eq), LiCl (0.3 eq), DMF, air, 100°, 3 h	 (40)	182

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C$_9$			
	Pd(OAc)$_2$ (divided, 5 mol %), MeCN/H$_2$O (7:1), Et$_4$NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (57)	183
	PdCl$_2$ (undivided, 5 mol %), MeCN/H$_2$O (7:1), Et$_4$NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (85)	183
	PdCl$_2$ (10 mol %), CuCl$_2$ (30 mol %), air		184

Resin	Solvent		Resin Appearance
XAD 16	aq NaOH/dioxane	(7)^b	gray
XAD 2010	aq NaOH/dioxane	(11)^b	gray
XAD 1180	aq NaOH/dioxane	(5)^b	gray
Merrifield	TFA/CH$_2$Cl$_2$	(0)^b	unchanged
R&H	aq NaOH/dioxane	(8)^b	gray

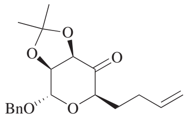
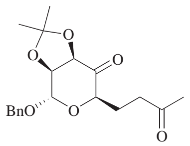
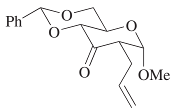
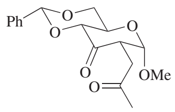
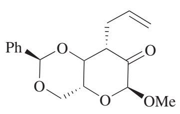
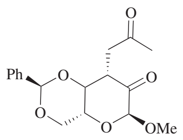
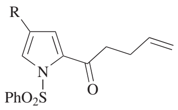
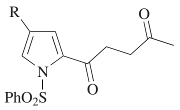
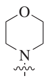
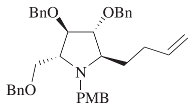
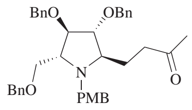
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	PdCl$_2$ (20 mol %), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$, rt	 (87)	66
	PdCl$_2$ (10 mol %), CuCl$_2$ (1 eq), DMF/H$_2$O (1:1), O$_2$, rt, 5 h	 (92)	185
	PdCl$_2$, CuCl$_2$, DMF/H$_2$O (1:1), O$_2$, rt, 4h	 (85)	186
	PdCl$_2$ (20 mol %) , CuCl (1 eq), DMF/H$_2$O (7:1) , O$_2$, rt	 R MeO (81) Me$_2$N (25) BnMeN (65)  (80)	69
	PdCl$_2$ (0.5 eq), CuCl (1.1 eq), DMF/H$_2$O (3:1), O$_2$, rt, 6 h	 (73)	187

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

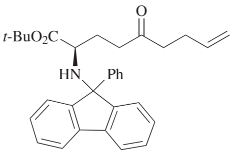
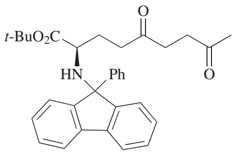
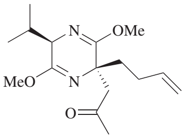
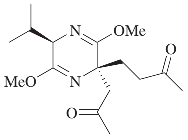
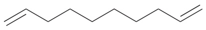
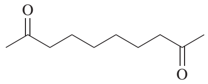
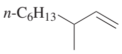
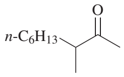
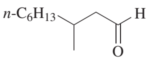
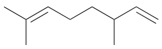
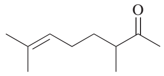
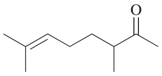
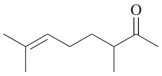
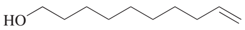
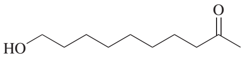
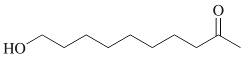
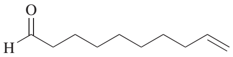
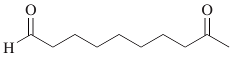
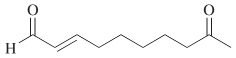
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_9			
	$PdCl_2$ (20–40 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt	 (—)	68
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 10 h	 (75)	170
C_{10}			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 (>99)	70
	$Pd(MeCN)_2Cl(NO_2)$ (13 mol %), $CuCl_2$ (53 mol %), *t*-BuOH, O_2, 30°, 3.2 h	 (15) +  (3)	188
	$Pd(OAc)_2$ (5 mol %), NPMoV (17.5 mg/ mmol), $MeSO_3H$ (10 mol %), additive (20 mol %), HQ (20 mol %), EtOH/H_2O (19:1), O_2	 Additive NH_4Cl (82) NaCl (82)	139
	$PdCl_2$ (7 mol %), CuCl (25 mol %), DMF/H_2O (5:1), O_2	 (—)	189
	$PdCl_2$, BQ, DMF/H_2O	 (—)	189
	$PdCl_2$ (0.5 mol %), DMA/H_2O (6:1), O_2 (6 atm), 80°, 24 h	 (85)	49
	$PdCl_2$ (0.4 mol %), $CuCl_2$ (1.6 mol %), DMA/H_2O (6:1), O_2, 80°, 4 h	 (88)	61
	$Pd(OAc)_2$ (divided, 5 mol %), MeCN/H_2O (7:1), Et_4NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (46) +  (22)	183

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

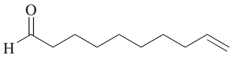
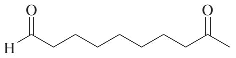
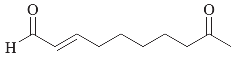
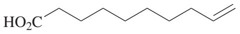
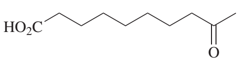
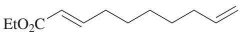
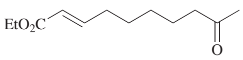
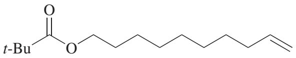
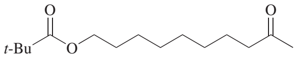
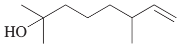
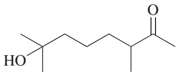
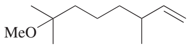
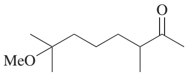
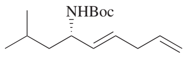
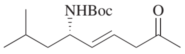
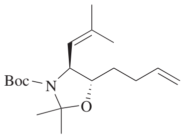
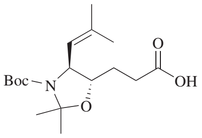
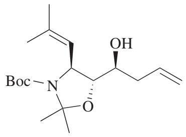
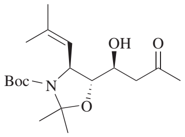
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
	$PdCl_2$ (undivided, 5 mol %), $MeCN/H_2O$ (7:1), Et_4NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (74) +  (4)	183
	$PdCl_2$ (12 mol %), $CuCl_2$ (16 mol %), DMF/H_2O (12.5:1), O_2, 60–70°, 0.5 h	 (70)	190
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (100:1), O_2, 10 h	 (67)	191
	**2** (5 mol %), TBHP (3.5 eq), benzene/$C_8F_{17}Br$, 56°	 (73)	136
	Pd[(–)-sparteine]Cl_2 (2 mol %), DMA/H_2O (4:1), O_2, 70°, 24 h	 (79)	48
	$PdCl_2$, CuCl, aq DMF	 (—)	189
	$PdCl_2$ (0.2 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt	 (57)	67
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, NaOCl, rt	 (74)	192
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, NaOCl, rt	 (53)	192

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

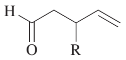
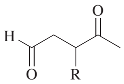
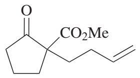
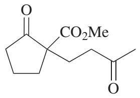
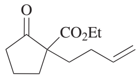
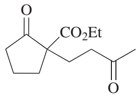
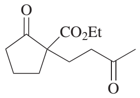
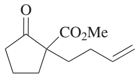
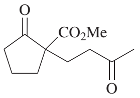
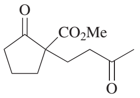
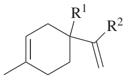
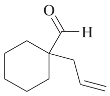
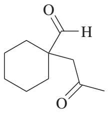
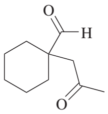
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10-17}			
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (10:1.2), O_2, rt	 R c-C_5H_9 (70) 4-$MeOC_6H_4$ (74) 4-MeC_6H_4 (85) c-C_8H_{15} (74) c-$C_{12}H_{23}$ (76)	193
C_{10}			
	$Pd(OAc)_2$ (4 mol %), BQ (20 mol %), $DMSO/H_2O$ (7:1), Et_4NBF_4, Pt-anode, rt	 (76)	156
	$PdCl_2$ (19 mol %), CuCl (1 eq), DMF/H_2O (8:1), O_2, rt, 9 h	 (61)	178
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), O_2, rt, 2 d	 (87)	65
	$Pd(OAc)_2$ (divided, 5 mol %), $MeCN/H_2O$ (7:1), Et_4NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (89)	183
	$PdCl_2$ (undivided, 5 mol %), $MeCN/H_2O$ (7:1), Et_4NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (60)	183
	$Pd(MeCN)_2Cl(NO_2)$ (8 mol %), benzene, O_2, 60°	R^1 R^2 H Me (0) Me H (0)	167
	$PdCl_2$ (11 mol %), BQ (1.13 eq), DMF/H_2O (7:1), rt, 3–4 h	 (54)	130
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), O_2, rt, 2 d	 (71)	65

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

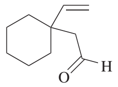
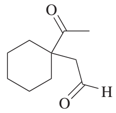
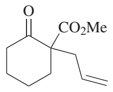
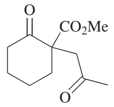
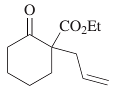
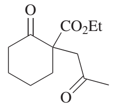
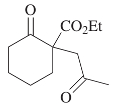
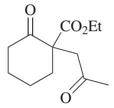
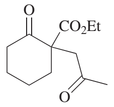
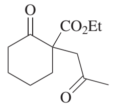
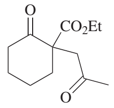
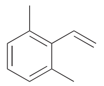
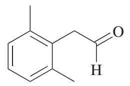
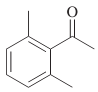
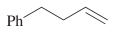
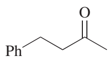
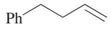
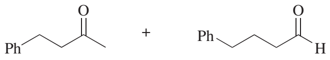
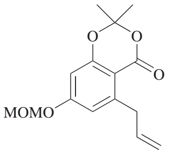
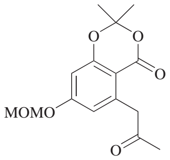
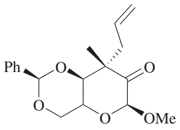
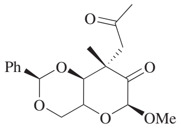
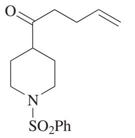
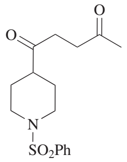
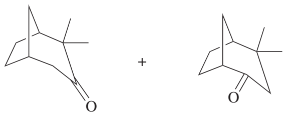
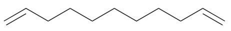
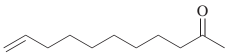
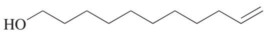
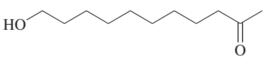
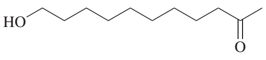
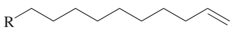
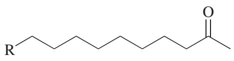
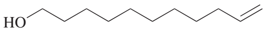
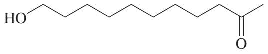
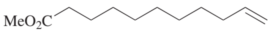
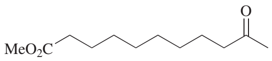
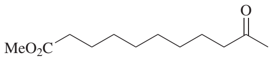
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{10}			
	$PdCl_2$ (0.1 eq), $CuCl_2$ (1.0 eq), DMF/H_2O (2:1), O_2, rt, 20 h	 (79)	58
	$Pd(OAc)_2$ (4 mol %), BQ (20 mol %), DMSO/H_2O (7:1), Et_4NBF_4, Pt-anode, rt	 (82)	156
	$Pd(OAc)_2$ (15 mol %), Fe(Pc) (5 mol %), $HClO_4$ (5 mol %), HQ (15 mol %), DMF/H_2O (89:11), O_2, 20°, 8 h	 (82)	179
	$PdCl_2$ (2 mol %), BQ (20 mol %), DMF/H_2O (8:1), $LiClO_4$, rt, 1.0 V	 (79)	194
	$PdCl_2$ (5 mol %), BQ (1.1 eq), DMF/H_2O (8:1), rt	 (87)	194
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), rt, 2 d	 (91)	65
	$Pd(OAc)_2$ (5 mol %), Fe(Pc) (5 mol %), HQ (15 mol %), O_2, rt	 (82)	180
	$PdCl_2$ (17 mol %), CuCl (0.83 eq), DMF/H_2O (8:1), O_2, rt, 8 h	 (77)	178
	$PdCl_2$ (2 eq), DMF/H_2O (10:1), rt, 5 h	 +  **I** **I** + **II** (82), **I/II** > 25:1 **II**	138
	Pd(dba)/**4** (0.5 mol %), TBHP (1.1 eq), 55°, 24 h	 (59)	172

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$, DMA/H_2O (7:1), O_2	 **I** **I** + **II** (—), **I**/**II** = 99:1 **II**	92
	$PdCl_2$, CuCl, O_2	 (72)	195
	$PdCl_2$, $CuCl_2$, DMF/H_2O (1:1), O_2, rt, 4 h	 (—)	196
	$PdCl_2$ (20–40 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt	 (95)	68
	$PdCl_2$ (5 mol %), $CuCl_2$ (0.5 eq), H_2O (2 eq), *i*-PrOH, O_2, 65°	 **I** **I** + **II** (—), **I**/**II** = 3:1 **II**	74
C_{11}			
	$PdSO_4$ (2.15 mol %), $CuSO_4$ (25 mol %), α-cyclodextrin (2.5 mol %), $H_9PV_6Mo_6O_{40}$ (25 mol %), H_2O (4 mol %), 80°, 8 h	 (36) + isomeric starting material (34)	142
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2	 (—)	197
	Pd[(–)-sparteine]Cl_2 (1 mol %), DMA/H_2O (4:1), air, 70°, 18 h	 (71)	48

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*			
C_{11}			
	Pd(Quinox)Cl$_2$ (x mol %), AgSbF$_6$ (y mol %), aq TBHP (12 eq), CH$_2$Cl$_2$, 0° to rt	 R x y Time (min) HOCH$_2$ 2 5 35 (98) HOCH$_2$ 1 2.5 40 (91) ClCH$_2$ 2 5 80 (89) MeO$_2$C 2 5 35 (82)	83
	Pd(OAc)$_2$ (1 mol %), py (20 mol %), toluene, *i*-PrOH, O$_2$, 60°, 27 h	 (71)	134
	Pd(OAc)$_2$ (5 mol %), polyaniline (20 mg/mmol), MeCN/H$_2$O (1:15), O$_2$, 70°, 24 h	 (34)	152
	Pd-mont **3** (0.4 mol %), CuCl$_2$ (1.6 mol %), DMA/H$_2$O (6:1), O$_2$, 80°, 4 h	 (86)	61

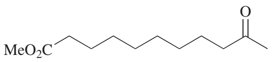
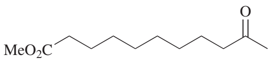
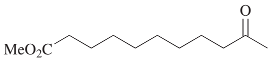
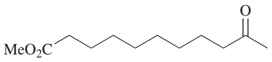
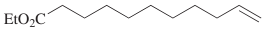
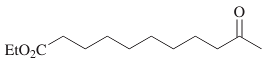
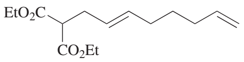
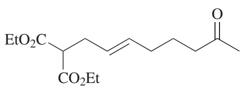
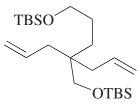
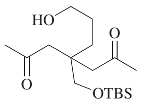
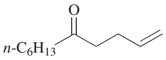
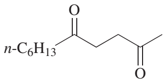
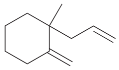
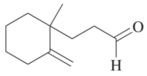
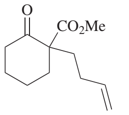
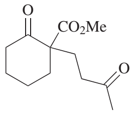
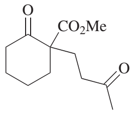
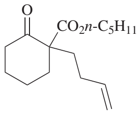
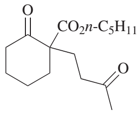
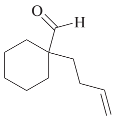
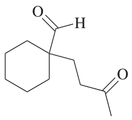
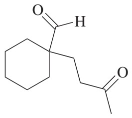
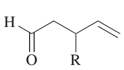
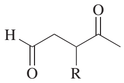
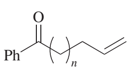
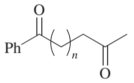
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(OAc)$_2$ (5 mol%), polypyrrole, MeCN (1 ml/mmol), H$_2$O (150 mol %), O$_2$, 40°, 90 h	 (37)	151
	2 (5 mol %), TBHP (3.5 eq), benzene/C$_8$F$_{17}$Br, 56°	 (77)	136
	PdCl$_2$, (0.5 mol %), DMA/H$_2$O (6:1), O$_2$ (6 atm), 80°, 40 h	 (92)	49
	Pd[(–)-sparteine]Cl$_2$ (2 mol %), DMA/H$_2$O (4:1), air, 70°, 24 h	 (73)	48
	PdCl$_2$ (10 mol %), CuCl (20 mol %), acetoxime (20 mol %), acetone, O$_2$, 50°, 21 h	 (35)	153
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt, 10 h	 (67)	59

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{11}			
	$PdCl_2$, CuCl, DMF/H_2O (7:1), O_2, 50°, 48 h	 (63)	64
	$PdCl_2$ (18 mol %), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt, 6 h	 (69)	178
	$PdCl_2$ (52 mol %), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt, 24 h	 (60)	73
	$Pd(OAc)_2$ (divided, 5 mol %), MeCN/H_2O (7:1), Et_4NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (93)	183
	$PdCl_2$ (undivided, 5 mol %), MeCN/H_2O (7:1), Et_4NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (90)	183
	$PdCl_2$ (15 mol %), CuCl (0.76 eq), DMF/H_2O (8:1), O_2, rt, 20 h	 (58)	178
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), O_2, rt, 2 d	 (62)	65
	$PdCl_2$ (11 mol %), BQ (1.13 eq), DMF/H_2O (7:1), rt, 3–4 h	 (46)	130
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (10:1.2), O_2, (shaken under pressure), rt	 R: c-C_6H_{11} (82) Ph (73)	193
$C_{11–12}$			
	$PdCl_2$ (14 mol %), BQ (1.01 eq), H_2O, 70°, 3 h	 n: 1 (50) 2 (25)	162

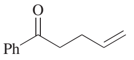
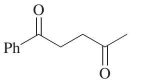
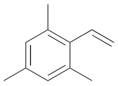
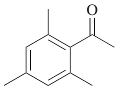
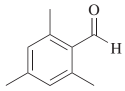
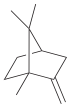
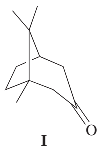
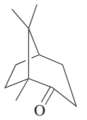
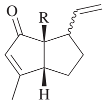
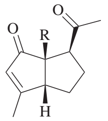
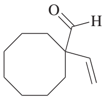
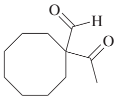
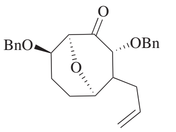
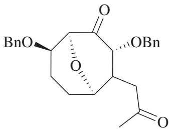
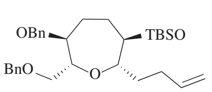
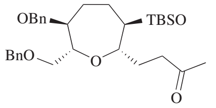
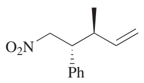
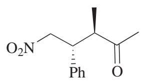
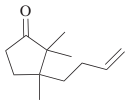
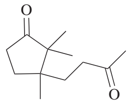
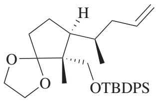
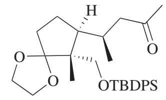
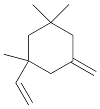
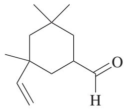
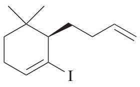
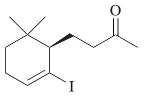
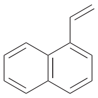
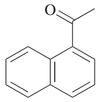
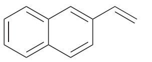
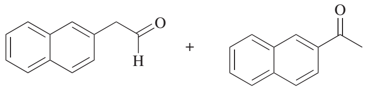
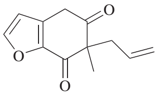
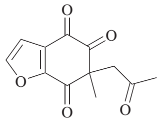
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{11}			
	$PdCl_2$ (20–40 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, overnight	 (—)	68
	[Pd(I*i*-Pr)Cl_2]$_2$ (0.75 mol %), AgOTf (3 mol %), aq TBHP (5.5 eq), MeOH, air, 35°, 24 h	 +  **I** (71) **I**/**II** > 150:1 **II** (—)	56
	$PdCl_2$ (5 mol %), $CuCl_2$ (0.5 eq), H_2O (2 eq), *i*-PrOH, O_2, 65°	 +  **I** **II** **I** + **II** (20), **I**/**II** = 3:1	74
C_{11-12}			
 dr 2:3	$PdCl_2$, (1 eq), BQ (2.5 eq), DMF/H_2O (40:1), 70°	 R H (99) *n*-$C_5H_{11}O_2C$ (99)	198
C_{11}			
	$PdCl_2$ (0.1 eq), CuCl (1 eq), DMF/H_2O (2:1), O_2, rt, 20 h	 (80)	58
	$PdCl_2$ (2.6 eq), DMF/H_2O (7:1), 0°, 3 h	 (94)	199
	$PdCl_2$ (20 mol %), Cu(OAc)$_2$ (2 eq), DMF/H_2O (7:1), O_2, rt, 1.5 d	 (92)	200
C_{12}			
	—	 (—)	158
	$PdCl_2$, CuCl, H_2O, O_2	 (71)	201

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{12}			
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (8.5:1), rt, 18 h	 (91)	202
	$PdCl_2$ (52 mol %), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt, 24 h	 (19)	73
 er 99.0:1.0	$PdCl_2$ (0.52 eq), $CuCl_2$ (1 eq), DMF/H_2O (10:1), O_2, rt, 48 h	 (82) er 99.0:1.0	75
	**2** (5 mol %), TBHP (1.5 eq), benzene/$C_8F_{17}Br$, 56°	 (75)	136
	$PdCl_2$ (2 eq), DMF/H_2O (10:1), rt, 5 h	 **I** **I** + **II** (38), **I**/**II** = 13.1:1.0 **II**	138
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3 h	 (58)	63

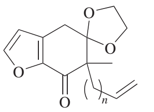
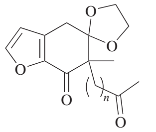
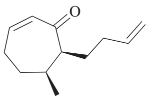
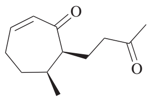
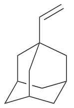
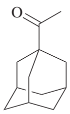
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{12–13}$			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3 h	 *n* 1 (88) 2 (87)	63
C_{12}			
	$PdCl_2$ (*x* mol %), CuCl (*y* eq), DMF/H_2O (7:1), O_2, rt	 *x* *y* Time (h) *cis*/*trans* 15 1.5 24 (—) 94:6 20 2 — (—) 94:6	203
	$PdCl_2$ (*x* eq)		
		x Solvent Temp (°) 2 $DMF/H_2O/THF$ (4:1:1) — (59)	138
		1 DMF/H_2O (1:1) 100 (—)	94

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

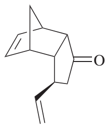
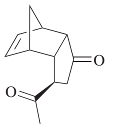
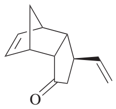
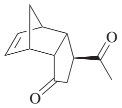
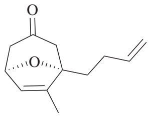
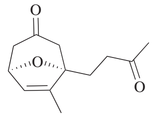
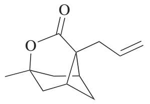
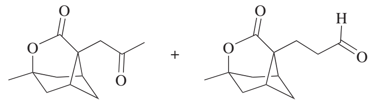
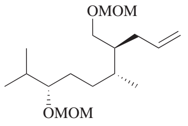
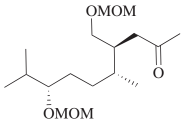
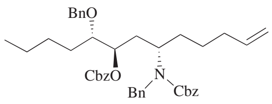
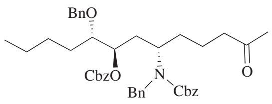
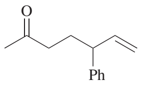
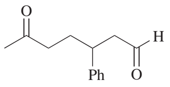
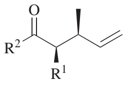
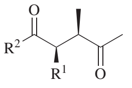
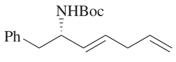
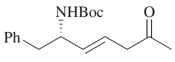
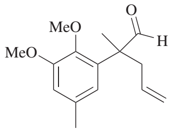
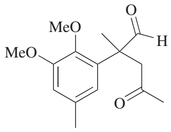
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C$_{12}$			
	PdCl$_2$ (20 mol %), CuCl (1.2 eq), DMF/H$_2$O (10:1), O$_2$, 45°, 18 h	 (97)	204
	PdCl$_2$ (20 mol %), CuCl (1.2 eq), DMF/H$_2$O (10:1), O$_2$, 50°, 18 h	 (84)	204
	PdCl$_2$ (6 mol %), CuCl (1 eq), DMA/H$_2$O (1:1), O$_2$, 5 d	 (72)	205
	PdCl$_2$ (20 mol %), CuCl (0.8 eq), DMF, H$_2$O, O$_2$, 15 h	 (65) (35)	60
C$_{13}$			
	PdCl$_2$ (6.8 mol %), CuCl (1 eq), DMF/H$_2$O (10:1.2), O$_2$, rt, 16 h	 (84)	206
	PdCl$_2$, CuCl, DMF/H$_2$O, O$_2$, 80°	 (91)	207
	PdCl$_2$ (8 mol %), BQ (1.1 eq), DMF/H$_2$O (7:1), rt, 2.5 h	 (49)	162
C$_{13-16}$			
	PdCl$_2$, CuCl, DMF/H$_2$O, air	 R^1 R^2 Me 3,4-(MeO)$_2$C$_6$H$_3$ (81) Me 4-MeOC$_6$H$_4$ (96) n-C$_3$H$_7$ 4-MeOC$_6$H$_4$ (86) Ph n-C$_4$H$_9$ (78)	208
C$_{13}$			
	PdCl$_2$ (0.2 eq), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$, rt	 (49)	67
	PdCl$_2$, CuCl, O$_2$, DMF, H$_2$O, rt, 16 h	 (77)	209

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

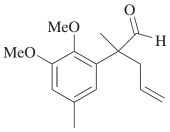
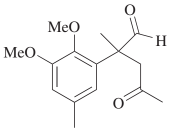
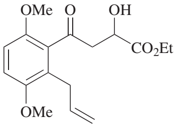
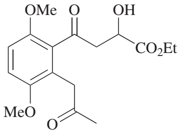
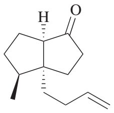
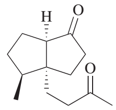
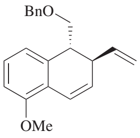
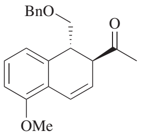
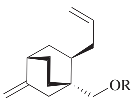
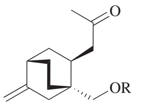
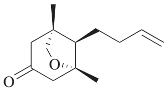
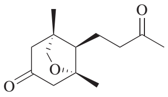
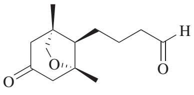
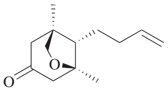
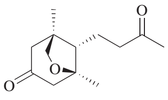
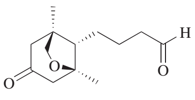
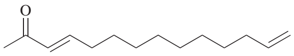
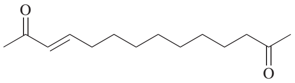
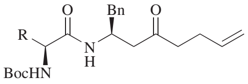
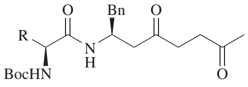
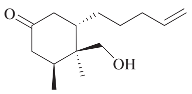
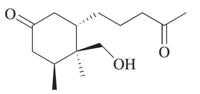
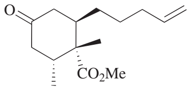
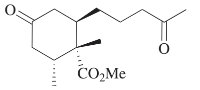
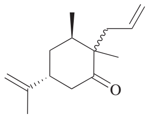
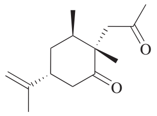
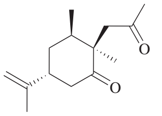
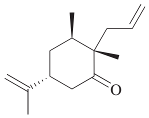
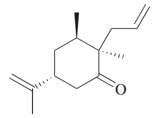
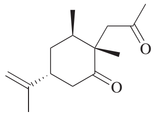
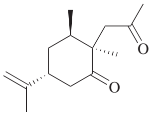
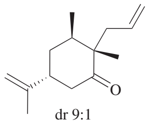
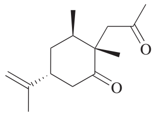
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{13}			
	$PdCl_2$ (0.2 eq), CuCl (3 eq), DMF/H_2O (2:1), O_2, rt, 1 h	 (77)	210
	$PdCl_2$ (10 mol %), $CuCl_2$ (1.0 eq), DMF/H_2O (1:1), O_2, 70°, 2 h	 (67)	211
	$PdCl_2$, CuCl, H_2O, DMF, O_2, 20°	 (81)	212
	$Pd(MeCN)_2Cl_2$ (1 mol %), CuCl (30 mol %), MeOH, O_2, 45°, 20 h	 (81)	72
	$PdCl_2$ (0.25 eq), CuCl (1.5 eq), DMF/H_2O (6.6:1), O_2, rt, 24 h	 R SEM (50) PMB (81)	213
	$PdCl_2$ (11 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3 d	 (64) +  (6)	214
	$PdCl_2$ (11 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3 d	 (64) +  (6)	214
C_{14}			
	$PdCl_2$ (10 mol %), $CuCl_2$ (20 mol %), acetoxime (20 mol %), acetone, O_2, 50°, 21 h	 (26)	153
	$PdCl_2$ (30 mol %), CuCl (2 eq), DMF/H_2O (7:1) , O_2, rt	 R Me (80) Bn (80)	159

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{14}

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$, CuCl, DMF, H_2O, O_2	 (58)	215
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2	 (65)	216
 dr 9:1	$PdCl_2$ (7 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2, rt, 24 h	 (70) +  (7.7)	217
 +  dr 9:1	$PdCl_2$ (6.8 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2, rt, 25 h	 (70) +  (12.9)	218
 dr 9:1	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (10:1.2), O_2, rt	 (—)	219

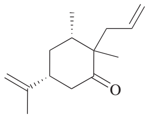
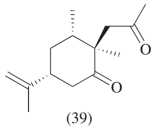
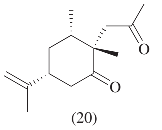
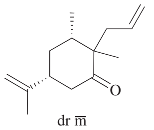
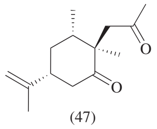
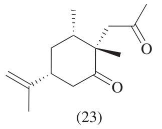
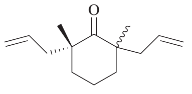
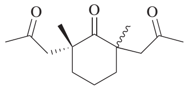
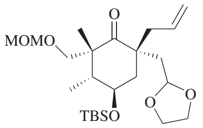
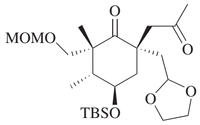
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
 dr 2:1	$PdCl_2$ (5 mol %), CuCl (74 mol %), DMF/H_2O (4.2:1), O_2, rt, 24 h	 (39) +  (20)	220
 dr m̄	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (10:1.2), O_2, rt, 5 h	 (47) +  (23)	221
	$PdCl_2$ (0.6 eq), $CuCl_2$ (1 eq), DMF/H_2O (10:1), O_2, rt, 48 h	 (48)	222
	$PdCl_2$ (25 mol %), CuCl (2 eq), DMF/H_2O (9:1), O_2, rt, 8 h	 (80)	208

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

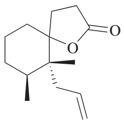
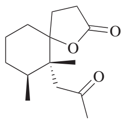
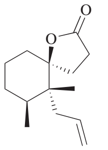
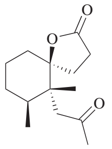
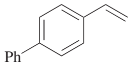
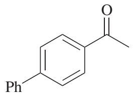
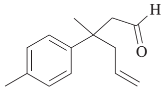
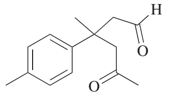
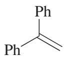
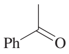
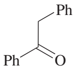
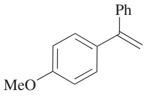
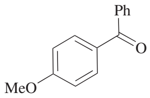
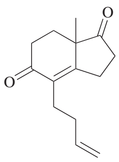
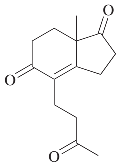
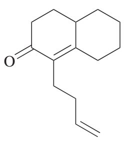
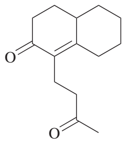
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{14}			
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (19 mol %), DMA/H_2O (7:1), O_2, rt, 3 d	 (60)	223
	$PdCl_2$ (10 mol %), CuCl (10 mol %), DMF, H_2O, O_2, 24 h	 (70)	224
	Catalyst **2** (5 mol %), TBHP (1.5 eq), benzene/$C_8F_{17}Br$, 56°	 (80)	136
	$PdCl_2$ (5 mol %), CuCl (0.7 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 (49)	225
	$PdCl_2$ (5 mol %), $CuCl_2$ (0.5 eq), H_2O (2 eq), EtOAc, air (25 atm), 65°	 (28.5) +  (28.5)	74
	$PdCl_2$ (5 mol %), $CuCl_2$ (0.5 eq), H_2O (2 eq), EtOAc, air (25 atm), 65°	 (62.5)	74
	$PdCl_2$ (x mol %), CuCl (y eq), aq DMF, O_2	 x y 10 1 (77) — — (—)	226 227
	$PdCl_2$ (17 mol %), CuCl (1.7 eq), aq DMF, O_2, rt, 24 h	 (83)	226

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

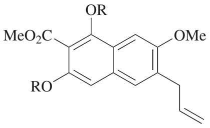
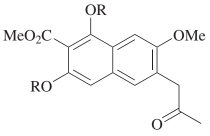
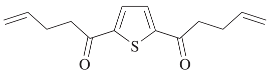
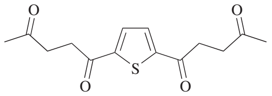
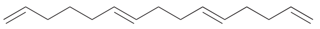
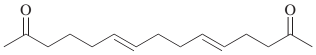
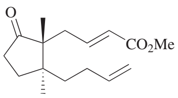
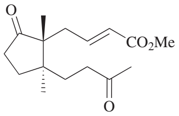
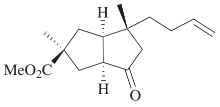
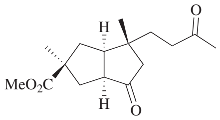
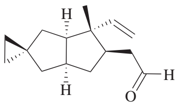
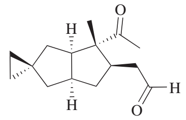
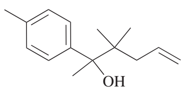
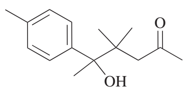
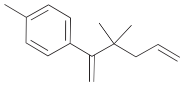
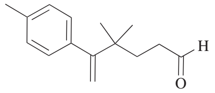
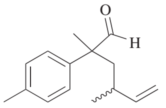
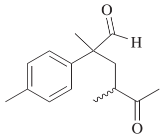
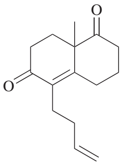
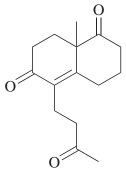
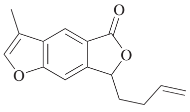
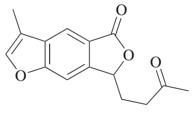
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{14}			
	PdCl$_2$ (*x* eq), CuCl (*y* eq), DMF/H$_2$O (7:1), O$_2$, 12 h	 R *x* *y* Me 1.1 2.0 (43) Piv 1.05 1.1 (63)	228
	PdCl$_2$ (40 mol %), CuCl (2 eq), THF/H$_2$O (4:1), O$_2$, ultrasound	 (—)	229
C_{15}			
	PdCl$_2$, CuCl, O$_2$	 (—)	230
	PdCl$_2$, CuCl, H$_2$O, O$_2$	 (88)	201
	PdCl$_2$ (0.1 mol %), CuCl, DMF/H$_2$O, O$_2$, rt, 5 h	 (92)	231
	PdCl$_2$, CuCl, DMF/H$_2$O, O$_2$	 (—)	232
	PdCl$_2$ (52 mol %), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$, rt, 24 h	 (—)	73
	PdCl$_2$ (52 mol %), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$, rt, 24 h	 (73)	73

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{15}			
 dr 3:2	PdCl$_2$ (10 mol %), CuCl$_2$ (10 mol %), DME/H$_2$O (9:1), O$_2$, rt, 2 h	 (82) dr 1:1	233
	PdCl$_2$, CuCl, aq DMF, O$_2$	 (75)	226
	PdCl$_2$ (5 mol %), CuCl (1 eq), aq DMF, O$_2$, rt, 2 h	 (94)	234

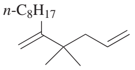
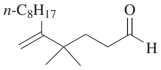
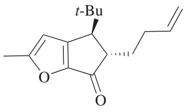
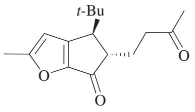
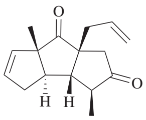
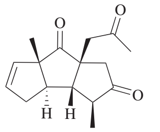
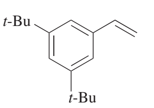
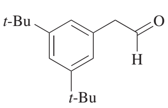
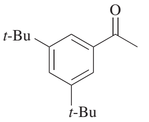
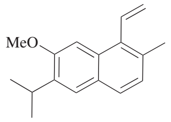
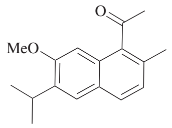
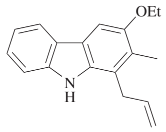
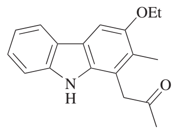
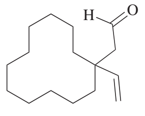
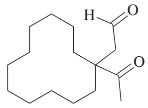
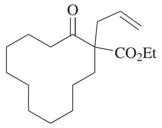
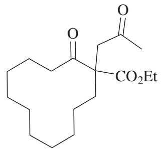
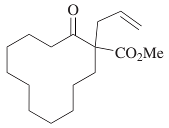
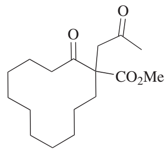
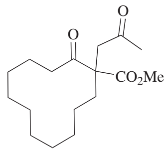
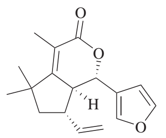
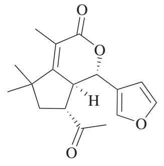
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{16}			
	PdCl$_2$ (52 mol %), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$, rt, 24 h	 (75)	73
	PdCl$_2$, CuCl, DMF, H$_2$O, O$_2$	 (80)	235
	PdCl$_2$ (87 mol %), CuCl (6.2 eq), DMF/H$_2$O (40:1), O$_2$, rt, 2 h	 (62)	236
	PdCl$_2$ (2 eq), DMF/H$_2$O (10:1), rt, 5 h	 +  **I** **I** + **II** (—), **I**/**II** = 6.4:1.0 **II**	138

Table 1A. Wacker Oxidation of Terminal Alkenes (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{16}			
	PdCl$_2$, CuCl, O$_2$, THF/H$_2$O, rt, 12 h	 (71)	237
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt	 (81)	238
	PdCl$_2$ (0.1 eq), CuCl (1.0 eq), DMF/H$_2$O (2:1), O$_2$, rt, 20 h	 (76)	58
	PdCl$_2$ (20 mol %), CuCl (1 eq), DMF/H$_2$O (8:1), O$_2$, rt, 20 h	 (74)	178
	Pd(OAc)$_2$ (divided, 5 mol %), MeCN/H$_2$O (7:1), Et$_4$NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (79)	183
	PdCl$_2$ (undivided, 5 mol %) MeCN/H$_2$O (7:1), Et$_4$NOTs-(Pt)-(Pt) (0.5 M), rt, 2.0–3.0 F/mol electricity	 (48)	183
C_{17}			
	PdCl$_2$ (20 mol %), CuCl (1 eq), DMF/H$_2$O (10:1.2), O$_2$, rt	 (96)	239

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

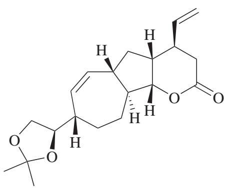
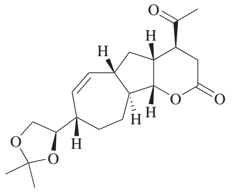
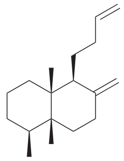
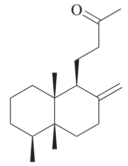
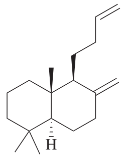
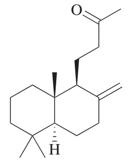
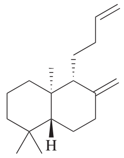
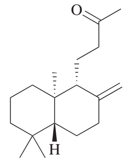
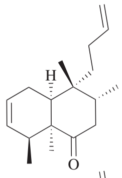
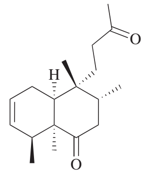
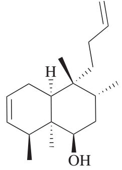
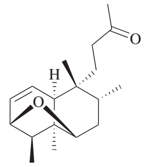
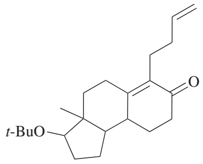
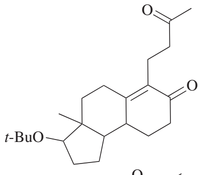
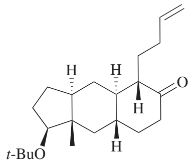
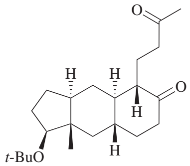
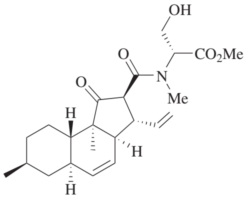
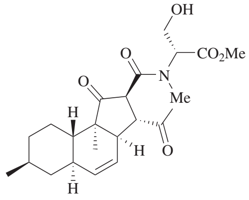
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{17}			
	$PdCl_2$, CuCl, DMF/H_2O (4:1), O_2, rt, 6 h	 (92)	240
C_{18}			
	$PdCl_2$ (0.33 eq), CuCl (1 eq), aq DMF, O_2	 (63)	241
	$PdCl_2$ (0.1 eq), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt	 (88)	242
	$PdCl_2$ (0.1 eq), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt	 (89)	242
	$PdCl_2$, CuCl, DMF/H_2O, O_2, rt, 1.5 h	 (85)	243
	$PdCl_2$, CuCl, DMF/H_2O, O_2, rt, 3 h	 (67)	243
	$PdCl_2$, CuCl, aq DMF, O_2	 (78)	226
	$PdCl_2$, CuCl, DMF/H_2O (9:1), O_2, rt	 (77)	244
	$PdCl_2$ (25 mol %), CuCl (1.5 eq), DMF/H_2O (10:1, 1.2 eq), O_2, rt, 12 h	 (79)	245

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

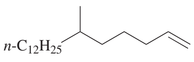
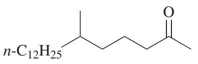
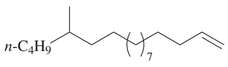
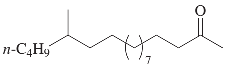
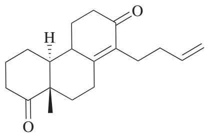
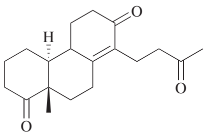
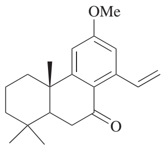
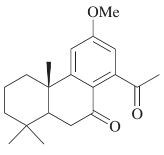
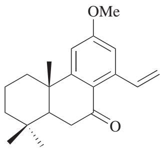
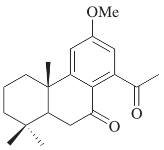
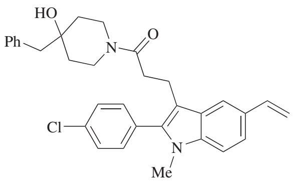
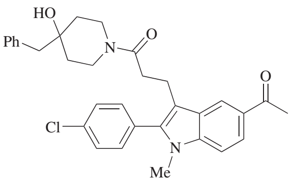
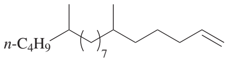
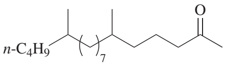
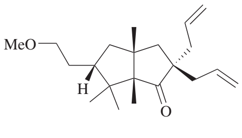
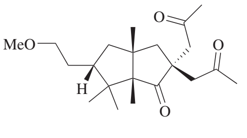
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{19}			
	$PdCl_2$, CuCl, DMF/H_2O, O_2	 (70)	246
	$PdCl_2$, CuCl, DMF/H_2O, O_2	 (76)	246
	$PdCl_2$ (10 mol %), CuCl (1 eq), aq DMF, O_2	 (84)	192
	$PdCl_2$ (6.5 eq), DMF/H_2O, 4 h	 (trace)	247
	Hg(OAc) (1 eq), THF/H_2O, 10 min; then $PdCl_2$ (1 eq), 4 h	 (trace)	247
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 (65)	248
C_{20}			
	$PdCl_2$, CuCl, DMF/H_2O, O_2	 (70)	246
	$PdCl_2$ (50 mol %), CuCl (5 eq), THF/H_2O, O_2, rt, 4 h	 (85)	249

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

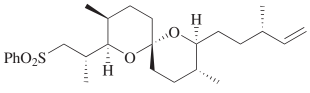
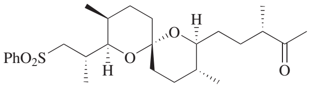
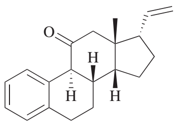
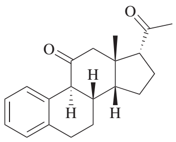
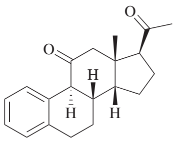
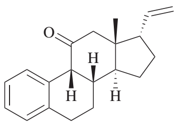
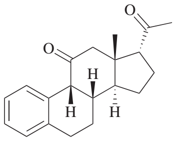
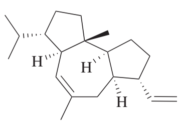
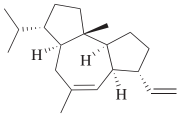
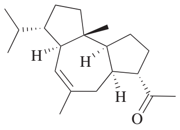
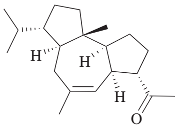
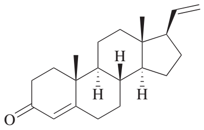
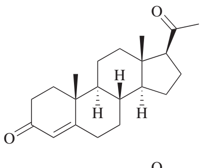
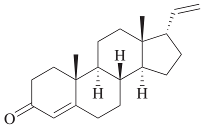
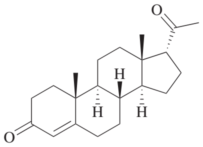
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{20}			
	$PdCl_2$ (19 mol %), CuCl (1.9 eq), DMF/H_2O (7:1), O_2, rt, 40 h	 (85)	250
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2	 +  **I** (45) **I/II** =3:1 **II** (—)	251
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2	 (45)	251
 1.3:1 + 	$PdCl_2$ (40 mol %), CuCl (5 eq), DMF/H_2O (10:1), O_2, rt, 3 d	 +  (46) (37)	252
C_{21}			
	—	 (22)	253
	—	 (70)	253

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

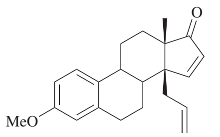
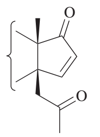
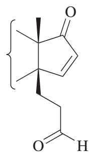
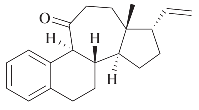
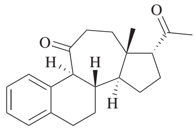
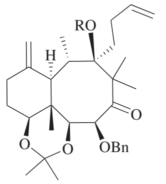
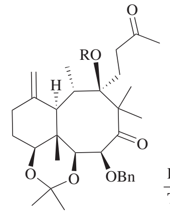
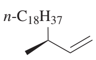
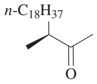
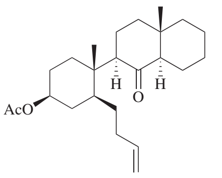
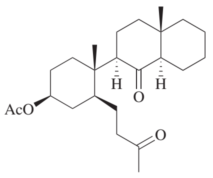
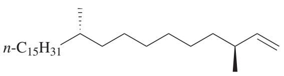
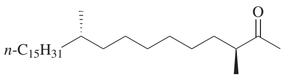
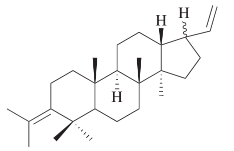
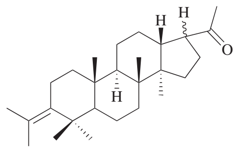
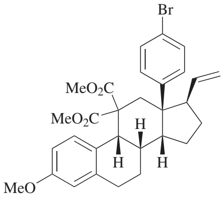
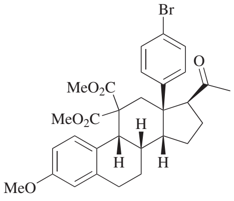
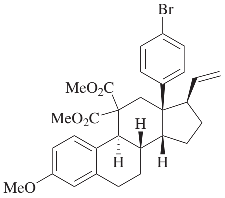
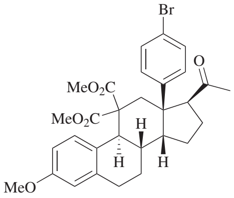
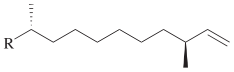
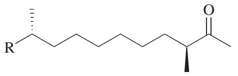
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{21}			
	$PdCl_2$ (0.5 eq), CuCl (2.6 eq), DMF/H_2O (10:1), O_2, 65°, 1.5 h	 (45.5) +  (45.5)	254
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2	 (45)	251
	$PdCl_2$ (*x* eq), DMF/H_2O (7:1), rt	 R | *x* | Time (h) TBS | 4.5 | 3.5 | (85) *c*-$C_6H_{11}(Me)_2Si$ | 3.9 | 3.5 | (98) (*c*-$C_6H_{11})_2MeSi$ | 6.6 | 1.5 | (98)	125
C_{22}			
	$PdCl_2$ (23 mol %), CuCl (1.2 eq), THF/H_2O (8:1), O_2, 60°, 6 h	 (74)	255
	$PdCl_2$, CuCl, DMF, O_2, rt, 24 h	 (—)	256
C_{27}			
	$PdCl_2$ (1 eq), $Cu(OAc)_2$•H_2O (2 eq), DMA/H_2O (7:1), O_2, rt, 2 d	 (51)	257
	$PdCl_2$ (23 mol %), CuCl (62 mol %), DMF/H_2O (10:1), O_2, 60°, 3 h	 (85)	258

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)		Refs.
C_{27}				
	Pd(OAc)$_2$ (10 mol %), HClO$_4$, BQ (1.2 eq), MeCN, H_2O, rt, 48 h		(62)	259
	Pd(OAc)$_2$ (10 mol %), HClO$_4$, BQ (1.2 eq), MeCN, H_2O, rt, 48 h		(58)	259
$C_{28–30}$				
	PdCl$_2$ (x eq), Cu(OAc)$_2$•H_2O (y eq), DMA/H_2O (z :1), O_2, rt, 3 d			257

R	x	y	z	
n-$C_{17}H_{35}$	1.2	2.3	6	(57)
BnO(CH$_2$)$_{16}$	2	3.3	11	(70)
BnO(CH$_2$)$_{18}$	0.9	1.6	6	(45)

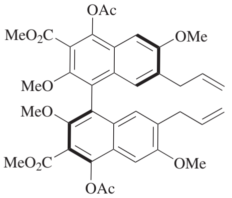
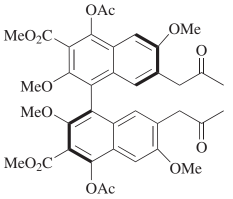
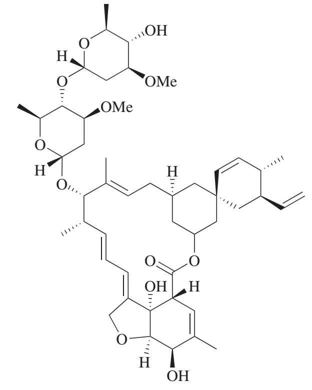
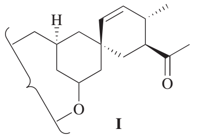
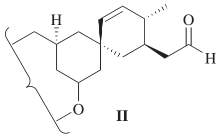
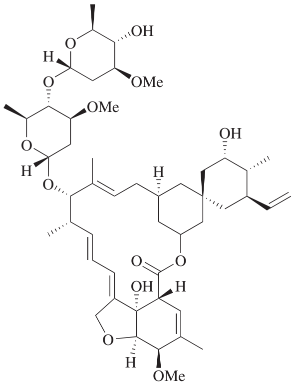
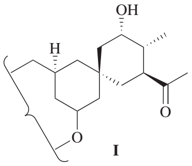
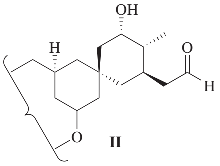
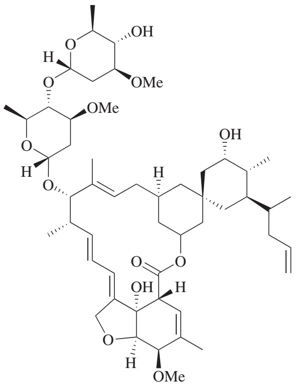
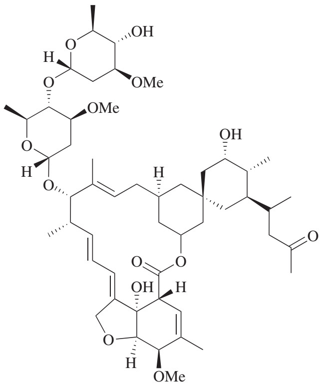
Alkene	Conditions	Product(s) and Yield(s) (%)		Refs.
C_{28}				
	PdCl$_2$ (4.1 eq), CuCl (20 eq), DMF/H_2O (7:1), O_2, 12 h		(55)	228
C_{34}				
	PdCl$_2$, CuCl, DMF/H_2O, O_2, rt, 4 h	 **I** +  **II** **I** + **II** (60), **I**/**II** = 5:3		120

TABLE 1A. WACKER OXIDATION OF TERMINAL ALKENES (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{34}			
	$PdCl_2$, CuCl, DMF/H_2O, O_2, rt, 4 h	 **I** +  **II** **I** + **II** (60), **I**/**II** = 5:3	120
C_{37}			
	$PdCl_2$, CuCl, DMF/H_2O, O_2, rt, 4 h	 (80)	120

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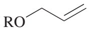
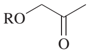
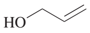
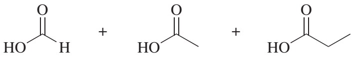
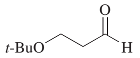
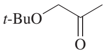
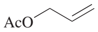
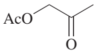
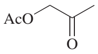
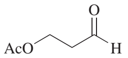
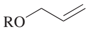
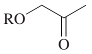
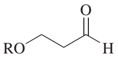
[a] This value is the % conversion.

[b] The yield was determined by HPLC.

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3 	Pd/**3** (0.02 mol %), H_2O_2, additive, 80°, 1 h	 R Additive H none (97) Ac AcOH (94)	135
	$Pd(OAc)_2$ (0.067 mol %), H_2O_2 (30%, 5 eq), 80°, 6 h	 (30) (33) (35)	54
	$Pd(MeCN)_2Cl(NO_2)$ (7 mol %), $CuCl_2$ (36 mol %), *t*-BuOH, O_2, 30°, 18 min	 (51) +  (22)	188
	$Pd(OAc)_2$ (0.067 mol %), H_2O_2 (30%, 5 eq), ROH, 80°, 6 h	 R *t*-Bu (7) Ac (85)	54

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (2.5 mol %), $CuCl_2$ (10 mol %), CuCl (5 mol %), NaCl (5 mol %), additive, *t*-BuOH, O_2 (40 psi), 50°	 **I** +  **II**	
		Additive **I** **II** MeCN (8) (48)	76
		4-$O_2NC_6H_4CN$ (20) (55)	54
	$Pd(MeCN)_2Cl_2$ (10 mol %), CuCl (10 mol %), additive (2 eq), O_2, rt, 2–12 h	 **I** +  **II**	77

R	Additive	Solvent	I	II
Ac	HMPA	CH_2Cl_2	(27)	(49)
EtO_2C	HMPA	CH_2Cl_2	(29)	(27)
Ac	none	aq THF	(72)	(3.8)
EtO_2C	none	aq THF	(59)	(0)

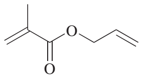
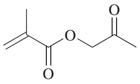
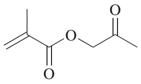
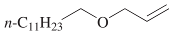
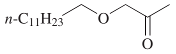
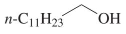
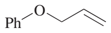
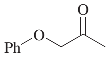
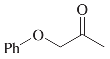
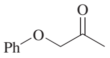
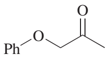
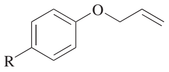
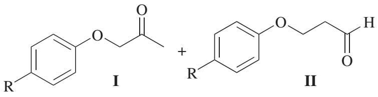
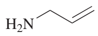
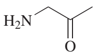
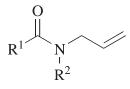
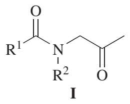
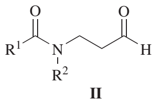
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$Pd(OAc)_2$ (5 mol %, divided), $MeCN/H_2O$ (7:1), 0.5 M Et_4NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity	 (64)	183
	$PdCl_2$ (5 mol %, undivided), $MeCN/H_2O$ (7:1), 0.5 M Et_4NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity	 (64)	183

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3			
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2 (bubbled)	 (52) +  (45)	82
	$Pd(OAc)_2$ (5 mol %), Fe(Pc) (5 mol %), HQ (15 mol %), O_2 , rt	 (47)	180
	$Pd(OAc)_2$ (5 mol %), Fe(Pc) (5 mol %), $HClO_4$ (5 mol %), HQ (15 mol %), DMF/H_2O (89:11), O_2, 20°, 5 h	 (47) + PhOH (—)	179
	$PdCl_2$ (10 mol %), CuCl (20 mol %), acetoxime (20 mol %), acetone, O_2, 50°, 21 h	 (23) + PhOH (19)	153
	2 (5 mol %), TBHP (3.5 eq), benzene, $C_8F_{17}Br$, 56°	 (58)	136
	$PdCl_2$ (10 mol %), CuCl (1 eq), $(bmim)BF_4$ (4.2 eq), H_2O, O_2, 60°, 33 h		143

R	I	II	I /II
H	(70)	(—)	83.4:8.8
Me	(80)	(—)	90.2:6.9

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (0.005 M), $CuCl_2$ (0.01 M), NaCl, HCl, H_2O, O_2, 60°, 100 h	 (42)	260
	$Pd(MeCN)_2Cl_2$ (10 mol %), CuCl (10 mol %), HMPA (2 eq), O_2, rt, 2–12 h	 + 	77

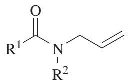
R^1	R^2	Solvent	I	II
Me	Me	DCE	(8.7)	(49)
Me	Ph	DCE	(6.8)	(61)
Ph	Me	DCE	(5.2)	(47)
Ph	Me	DME	(18)	(53)
—$(CH_2)_3$—		DCE	(6)	(49)
—$(CH_2)_4$—		DCE	(5)	(45)
—$(CH_2)_5$—		DCE	(6.2)	(56)

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

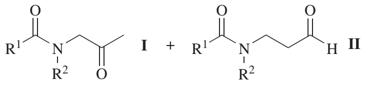
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

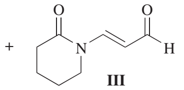
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_3



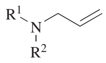
Pd$(MeCN)_2Cl_2$ (10 mol %),
$CuCl_x$ (10 mol %),
O_2, rt, 2–12 h



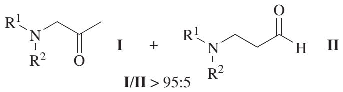


77

R^1	R^2	Solvent	x	**I**	**II**	**III**
Me	Me	aq THF	2	(47)	(3.5)	(—)
Me	Ph	aq THF	2	(52)	(4.6)	(—)
Ph	Me	aq THF	2	(58)	(3.7)	(—)
Ph	Me	DME	1	(42)	(16)	(—)
—$(CH_2)_3$—		aq THF	2	(69)	(2.9)	(18)
—$(CH_2)_4$—		aq THF	2	(63)	(11)	(—)
—$(CH_2)_5$—		aq THF	2	(71)	(15)	(—)



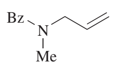
Pd(Quinox)Cl_2 (5 mol %),
$AgSbF_6$ (12.5 mol %),
aq TBHP (12 eq), CH_2Cl_2



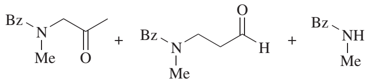
I/II > 95:5

88

R^1	R^2	Temp	Time	**I**	**II**
Boc	H	0° to rt	2.5 h	(74)	(—)
Cbz	H	0° to rt	50 min	(81)	(—)
Boc	Boc	rt	2.5 h	(93)	(—)
Boc	Cbz	rt	2.5 h	(95)	(—)



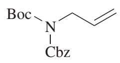
Pd(Quinox)Cl_2 (5 mol %),
$AgSbF_6$ (12.5 mol %),
aq TBHP (12 eq), CH_2Cl_2, rt, 16 h



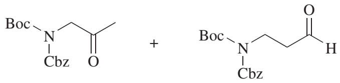
I (—) **II** (—) **III** (—)

I/II/III = 64:17:19

88



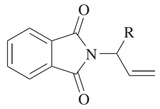
$PdCl_2$ (20 mol %), CuCl (1 eq),
DMF/H_2O (7:1), O_2, rt, 3 d



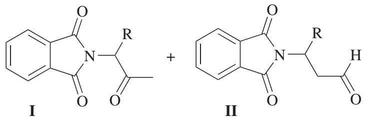
I (48) **I/II** = 57:43 **II** (37)

88

C_{3-8}



Pd(Quinox)Cl_2 (5 mol %),
$AgSbF_6$ (18 mol %),
aq TBHP (12 eq), CH_2Cl_2



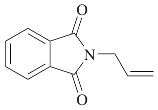
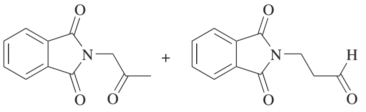
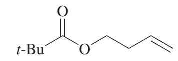
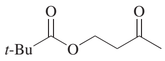
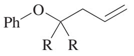
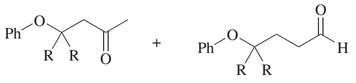
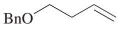
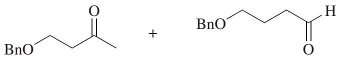
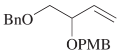
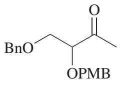
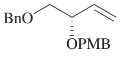
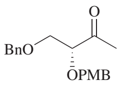
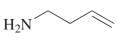
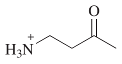
I **II**

88

R	Temp	Time (h)	**I**	**II**	**I/II**
H	0° to rt	0.33	(91)	(—)	>95:5
n-C_5H_{11}	rt	2.5	(91)	(—)	>95:5

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

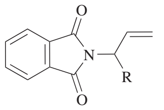
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3			
	$PdCl_2$ (40 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3 d	 **I** (34) **I/II** = 40:60 **II** (50)	88
C_4			
	**2** (5 mol %), TBHP (3.5 eq), benzene, $C_8F_{17}Br$, 56°	 (54)	136
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), O_2	 **I** **II** R **I/II** H 90:10 F 30:70	92
	$PdCl_2$ (10 mol %), CuCl (1 eq), (bmim)BF_4 (4.2 eq), H_2O, O_2, 60°, 25 h	 **I** (80) **I/II** = 91:7.5 **II** (—)	143
	Pd[(–)-sparteine]Cl_2 (5 mol %), DMA/H_2O (4:1), O_2, 70°, 48 h	 (34)	48
 er > 99.5:0.5	Pd[(–)-sparteine]Cl_2 (5 mol %), DMA/H_2O (4:1), O_2, 70°, 48 h	 (37) er > 99.5:0.5	48
	$PdCl_2$ (5 mol %), $CuCl_2$ (10 mol %), NaCl (1 eq), HCl (2 eq), H_2O, O_2, 60°, 3 h	 (80)	149

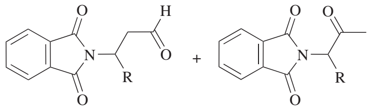
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

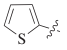
$C_{4–9}$



$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 3 d

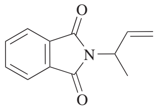


I + **II**

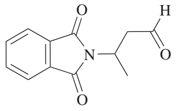
R	I	II	I/II
Me	(94)	(—)	>99:1
n-C_5H_{11}	(91)	(—)	>95:5
Ph	(95)	(—)	>99:1
$BnOCH_2$	(93)	(—)	>99:1
	(77)	(—)	>99:1

41

C_4

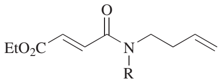


$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt

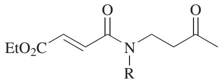


(87)

261

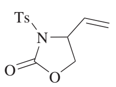


$PdCl_2$, CuCl, DMF/H_2O, O_2

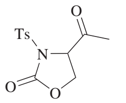


R	
Bn	(86)
Ph_3C	(78)

262

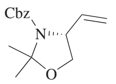


$PdCl_2$ (5 mol %), CuCl (1.0 eq), DMF/H_2O (9:1), 80°, 16 h



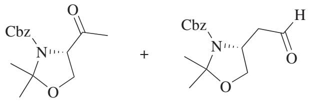
(81)

243



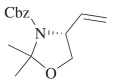
er 99.5:0.5

Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (12.5 mol %), aq TBHP (12 eq), CH_2Cl_2, rt, 16 h

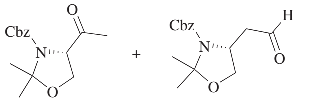


I (69) er 99.5:0.5 + **II** (—) **I/II** > 95:5

88



$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3 d

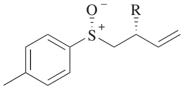
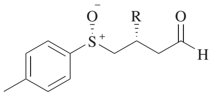
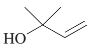
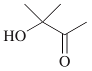
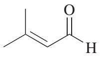
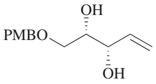
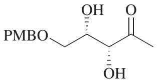
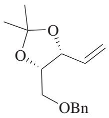
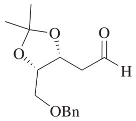
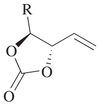
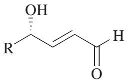
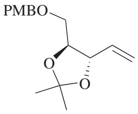
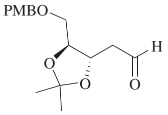
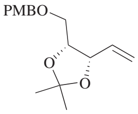
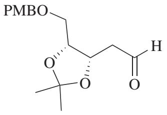
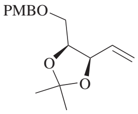
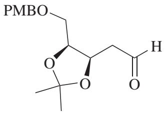


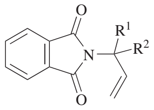
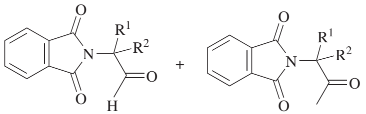
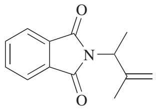
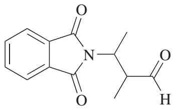
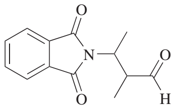
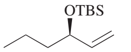
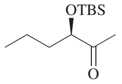
I (34) + **II** (22) **I/II** = 60:40

88

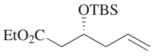
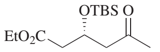
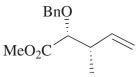
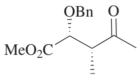
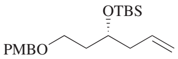
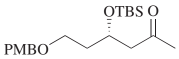
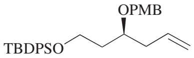
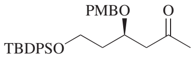
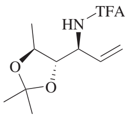
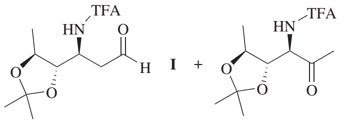
TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_4			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (x:1), O_2, 65°	 R — x — Time (h) TBSO — — — (89) TsHN 7 5 (84)	98
C_5			
	$PdCl_2$ (2 mol %), quinone, H_2O	 (37) +  (8)	264
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 12 h	 (90)	39
	$PdCl_2$ (20 mol %), CuCl, DMF/H_2O (7:1), O_2, 60°, 18 h	 (38)	265
C_{5-9}			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 12 h	 R $PMBOCH_2$ (95) n-C_5H_{11} (90)	39
C_5			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 60°, 6 h	 (93)	39
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 60°, 24 h	 (83)	39
	$PdCl_2$ (20 mol %), CuCl, DMF/H_2O (7:1), O_2	 (low)	265

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
$C_{5–7}$			
	Pd(MeCN)$_2$Cl(NO$_2$) (5 mol %), CuCl$_2$ (20 mol %), *t*-BuOH, O$_2$, 16 h	 **I** + **II**	41
C_5			
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, 3 d	 (—)	41
	Pd(MeCN)$_2$Cl(NO$_2$) (5 mol %), CuCl$_2$ (20 mol %), *t*-BuOH, O$_2$, 16 h	 (—)	41
C_6			
	PdCl$_2$ (1.3 eq), CuCl (1.3 eq), DMF/H$_2$O (7:1), O$_2$, 60°, 1.5 h	 (65)	80

R^1	R^2	I	II	I/II
Me	Me	(74)	(—)	94:6
s-Bu	H	(93)	(—)	>99:1

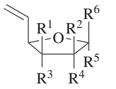
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	PdCl$_2$ (20 mol %), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$, rt, overnight	 (96)	266
	PdCl$_2$ (10 mol %), CuCl (1 eq), H$_2$O/acetone (6:1), O$_2$ (5 bar), 70°, 4 h	 (77)	267
	PdCl$_2$, CuCl, DMF/H$_2$O, O$_2$, rt, 6 h	 (89)	268
	PdCl$_2$ (10 mol %) , CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$ (bubbled), rt, 12 h	 (86)	268, 269
	PdCl$_2$ (10 mol %), CuY (2 eq), additive, DMF/H$_2$O (7:1), O$_2$, rt	 **I** + **II**	87

Y	Additive	I	II	I/II
(AcO)$_2$	none	(45)	(38)	54:46
Cl$_2$	none	(52)	(28)	65:35
Cl	none	(64)	(21)	75:25
Cl	HMPA	(64)	(—)	82:18

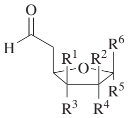
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

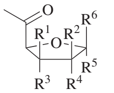
C_6



PdCl$_2$ (20 mol %), CuCl (1 eq), solvent/H$_2$O (7:1), O$_2$

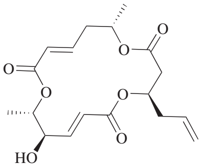


I +

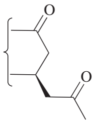


II 270

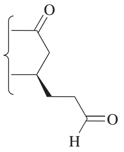
R^1	R^2	R^3	R^4	R^5	R^6	Solvent	Time (h)	**I**	**II**
—OC(Me)$_2$O—		H	H	BnO	H	MeCN	87	(87)	(—)
BzO	H	H	TBSO	MeO	MeO	DMF	82	(82)	(—)
AcO	H	H	AcO	BnO	BnO	MeCN	86	(86)	(—)
AcO	H	H	—OC(Me)$_2$O—		H	MeCN	85	(85)	(—)
H	H	—OC(Me)$_2$O—		H	BnO	MeCN	76	(76)	(—)
H	H	AcO	AcO	H	BnO	MeCN	89	(89)	(—)
H	H	HO	—OC(Me)$_2$O—		H	DMF	68	(34)	(34)



PdCl$_2$ (x), CuCl (y), DMF/H$_2$O (z), O$_2$



I +



II

x	*y*	*z*	Temp	Time (h)	**I + II**	**I/II**	Recovered SM		
10 mol %	1 eq	7–10:1	rt	overnight	(53)	5:1	(33)	A, B	122, 121
5 eq	—	7–10:1	0°	3	(24)	12:1	(63)	A	122
5 eq	—	7–10:1	rt	3.5	(85)	12:1	(10)	A	122
5 eq	—	7–10:1	rt	overnight	(0)	—	(0)	A	122
5 eq	—	7:1	rt	4	(81)	12:1	(—)	B	121

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

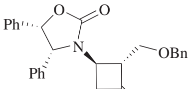
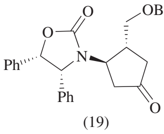
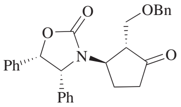
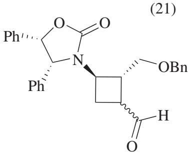
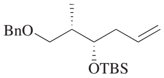
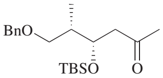
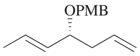
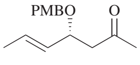
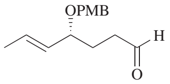
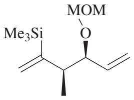
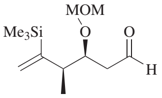
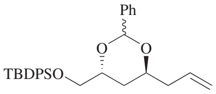
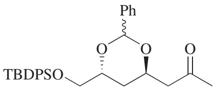
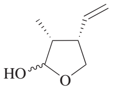
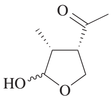
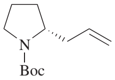
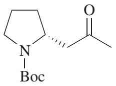
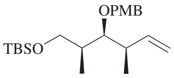
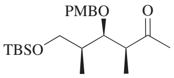
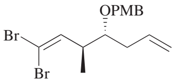
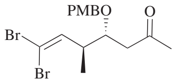
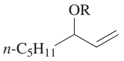
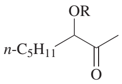
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_6			
	$PdCl_2$ (20 mol %), CuCl (1.1 eq), $HClO_4$, $MeCN/H_2O$ (7:1), O_2	 (19) +  (21) +  (4)	271
C_7			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 9 h	 (85)	272, 273
	$PdCl_2$ (8 mol %), CuCl, DMF/H_2O (8:1), O_2, rt, 16 h	 +  **I** (38) **I/II** = 4:1 **II** (9)	274
	$PdCl_2$ (10 mol %), CuCl (30 mol %), DMF/H_2O (9:1), O_2, 24 h	 (75)	78
	$PdCl_2$ (10 mol %), $CuCl_2$ (1 eq), DMF/H_2O (19:1), O_2, 45°, 15 h	 (74)	275
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), O_2, rt, 4 d	 (41)	276
	$PdCl_2$ (8 mol %), CuCl (2.2 eq), DMF/H_2O (2:1), reflux, 2 h	 (56)	277
C_8			
	$PdCl_2$ (10 mol %), CuCl, DMF/H_2O, O_2	 (60)	278

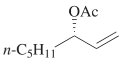
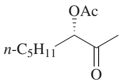
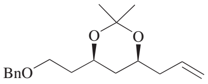
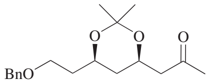
TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

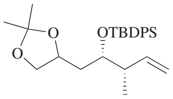
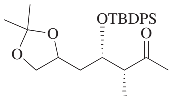
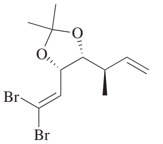
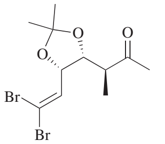
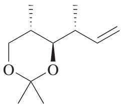
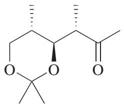
Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

C_8

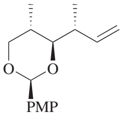
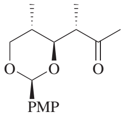
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$, CuCl, DMF/H_2O, O_2	 (64)	279
	Pd(Quinox)Cl_2 (*x* mol %), $AgSbF_6$ (*y* mol %), aq TBHP (12 eq), CH_2Cl_2		83

R	*x*	*y*	Temp	Time (h)	
Ac	5	12.5	rt	20	(89)
$EtOCH_2$	5	12.5	0° to rt	4	(81)
TBS	2	15	0° to rt	4.5	(77)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
 er 99.0:1.0	Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (12.5 mol %), aq TBHP (12 eq), CH_2Cl_2, rt, 20 h	 (99) er 99.0:1.0	83
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$•H_2O (20 mol %), DMF/H_2O (7:1), O_2, rt, 6 h	 (77)	280

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (20 mol %), CuCl (1.1 eq), DMF/H_2O (7:1), O_2, 50°	 (85)	281, 282
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 24 h	 (65–70)	283
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (*x*), DMA/H_2O (7:1), O_2, rt		

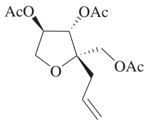
x	Time (d)		Refs.
2 eq	1	(86)	145
20 mol %	2	(84)	65

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (27 mol %), CuCl (2.7 eq), DMF/H_2O (4:1), O_2, rt, 24 h	 (56)	145

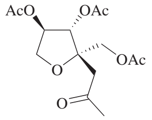
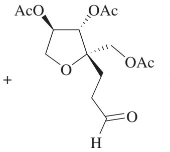
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_8

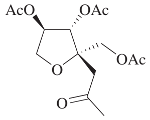
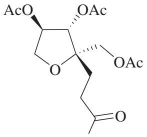


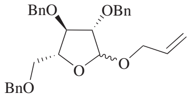
PdCl$_2$ (x eq), THF/H$_2$O (10:1)


I +

II

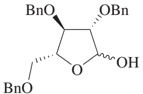
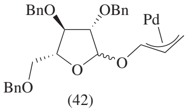
x	Temp	Time (h)	I	II	Refs.
1.1	—	—	(66)	(24)	284
1.5	rt	3	(67)	(25)	255

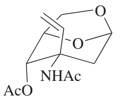
PdCl$_2$ (15 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt to 45°


(69) +

(13) — 286

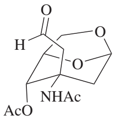


PdCl$_2$ (1 eq), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$ (bubbled)

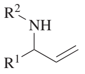

(26) +

(42) — 82



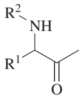
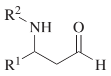
PdCl$_2$ (20 mol %), Cu(OAc)$_2$ (40 mol %), DMF/H$_2$O (3:1), O$_2$ (bubbled), 8 d


(21) — 287

$C_{8–9}$

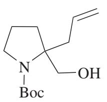


Pd(Quinox)Cl$_2$ (5 mol %), AgSbF$_6$ (12.5 mol %), aq TBHP (12 eq), CH$_2$Cl$_2$, rt, 2.5 h

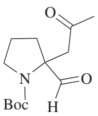

I +

II — 88

R^1	R^2	I	II	I/II
n-C$_5$H$_{11}$	Cbz	(67)	(7)	90:10
n-C$_5$H$_{11}$	Ns	(88)	(—)	>95:5
Ph	Ts	(90)	(—)	>95:5

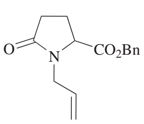
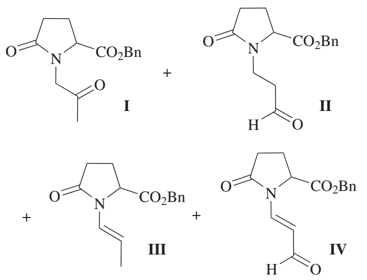
C_8



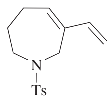
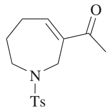
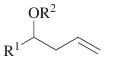
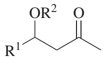
1. DMSO, (COCl)$_2$, CH$_2$Cl$_2$, 60°; then Et$_3$N
2. PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt


(72) — 288

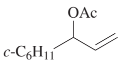
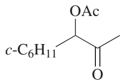
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

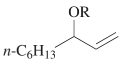
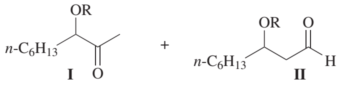
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_8			
	PdCl$_2$, CuCl$_x$, O$_2$		89

x	**I**	**II**	**III**	**IV**
2	(55)	(13)	(2)	(5)
1	(24)	(55)	(17)	(0)

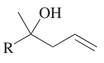
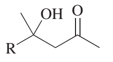
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	PdCl$_2$, CuCl, DMF/H$_2$O, O$_2$	 (0)	289
C_9			
	Pd(Quinox)Cl$_2$ (3 mol %), AgSbF$_6$ (7.5 mol %), aq TBHP (12 eq), CH$_2$Cl$_2$		86

R^1	R^2	Temp	Time (h)	
n-C$_5$H$_{11}$	H	0° to rt	5	(81)
n-C$_5$H$_{11}$	Ac	rt	3	(94)
Ph	H	0° to rt	24	(0)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(Quinox)Cl$_2$ (5 mol %), AgSbF$_6$ (12.5 mol %), aq TBHP (12 eq), CH$_2$Cl$_2$, rt, 17 h	 (89)	83

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt		39

R	**I + II**	**I/II**
MOM	(65)	1:1
Bn	(75)	~1:1

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{9-11}			
	Pd(Quinox)Cl$_2$ (x mol %), AgSbF$_6$ (y mol %), aq TBHP (12 eq), CH$_2$Cl$_2$		86

R	x	y	Temp	Time (h)	
n-C$_4$H$_9$	5	12.5	0° to rt	5	(83–84)
Ph	5	12.5	rt	8	(44)
Ph	10	25	rt	8	(79)

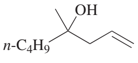
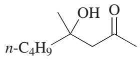
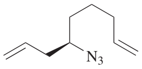
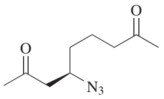
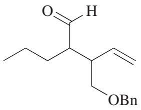
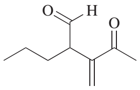
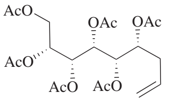
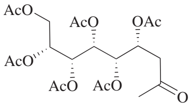
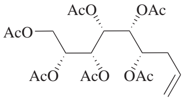
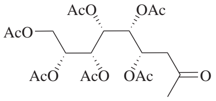
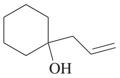
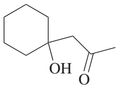
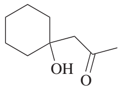
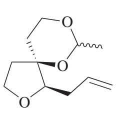
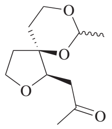
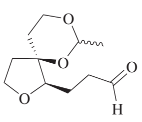
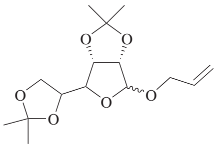
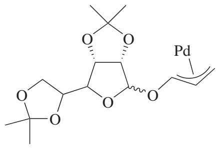
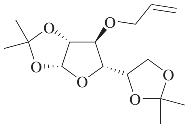
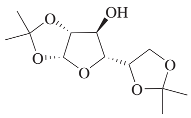
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt, 30 h	 (26)	86

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

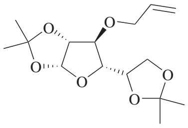
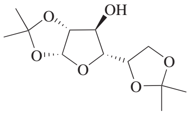
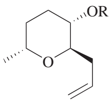
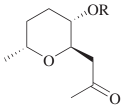
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	$PdCl_2$ (40 mol %), NMP/H_2O (10:1), O_2 (1.25 bar), rt	 (70)	177
	$PdCl_2$ (10 mol %), $CuCl_2$ (10 mol %), THF/H_2O (9:1)	 (64)	85
	$PdCl_2$ (1.2 eq), THF/H_2O (10:1), rt, 3 h	 (82)	290
	$PdCl_2$ (1.2 eq), THF/H_2O (10:1), rt, 3 h	 (86)	290
	Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (12.5 mol %), aq TBHP (12 eq), CH_2Cl_2, 0° to rt, 6.5 h	 (71)	86

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 30 h	 (34)	86
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2, 24 h	 +  **I** (64) **I**/**II** = 8:1 **II** (—)	291
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2 (bubbled)	 (94)	82
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), rt, 1–6 h	 (90–92)	292

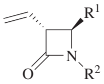
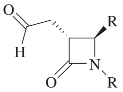
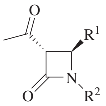
Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

C$_9$

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2 (bubbled)	 (66)	82
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (x :1), O_2, rt		

R	x	Time (h)		Refs.
H	12	1.5	(92)	293
4-$O_2NC_6H_4CO$	10	—	(83)	294

C$_{9–14}$

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$, CuCl, O_2	 (major) +  (minor)	295

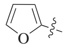
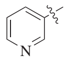
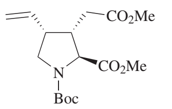
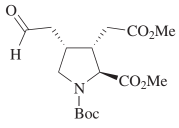
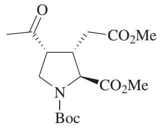
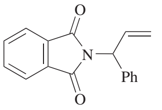
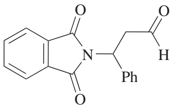
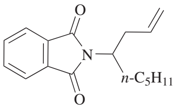
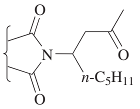
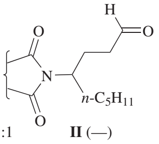
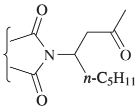
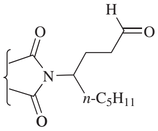
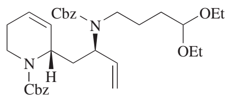
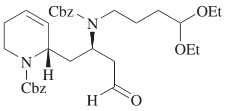
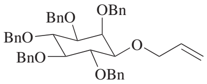
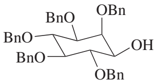
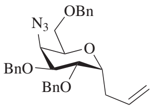
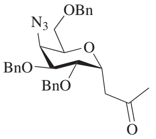
R^1	R^2	
Ph	Ph	*trans*
Ph	*p*-anisyl	*trans*
Bz	*p*-anisyl	*cis/trans* 70:30
Bz	Ph(Me)CH	*cis*
p-anisyl	*p*-anisyl	*trans*
	HO(Me)CH(PNBO$_2$C)CH	*cis*
	*p*-anisyl	*trans*
trans-cinnamyl	HO(Me)CH(PNBO$_2$C)CH	*cis/trans* 90:10

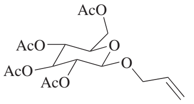
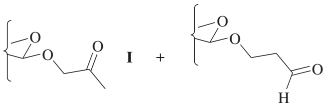
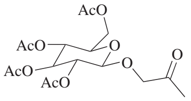
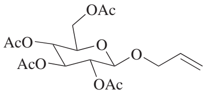
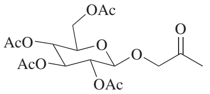
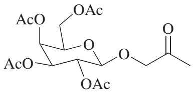
TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	—	 (major) +  (minor)	296
 er 98.0:2.0	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 3 d	 (95) er 98.0:2.0	41
	Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (18 mol %), CH_2Cl_2, aq TBHP (12 eq), 0° to rt, 20 min	 +  **I** (82) **I/II** > 95:1 **II** (—)	88

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (30 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3 d	 +  **I** (62) **I/II** = 85:15 **II** (11)	88
	$PdCl_2$ (10 mol %), CuCl (0.5 eq), DMF/H_2O (4:1), O_2, rt, 6 h	 (76)	144
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), rt, 1–6 h	 (88–93)	292
	$PdCl_2$ (47 mol %), $CuCl_2$ (2.5 eq), DMF/H_2O (10:1), air, 2 d	 (86)	297

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	$PdCl_2$, CuCl, DMF/H_2O (1:1), O_2	 **I** + **II** **I** + **II** ("almost quant."), **I/II** = 1.4:1	298
	$Hg(OAc)_2$, Li_2PdCl_2, THF/H_2O (3:1), 65°, 3 h	 (94)	298
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (85)	82
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (81)	82

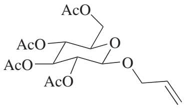
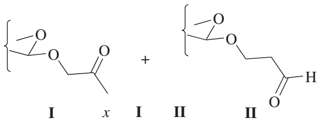
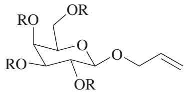
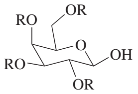
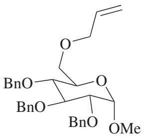
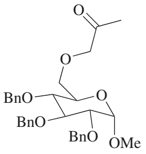
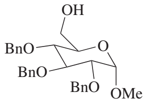
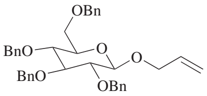
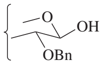
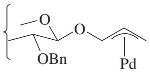
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (25 mol %), CuCl (3 eq), DMF/H_2O (*x*:1), O_2, 45°, 3 h	 **I** + **II** *x* **I** **II** 6 (70) (30) 1 (50) (50)	298
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), rt, 1–6 h	 R Ac (90–92) Bn (90–92)	292
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2 (bubbled)	 (30) +  (32)	82
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2 (bubbled)	 (15) +  (68)	82

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

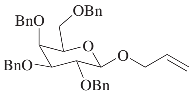
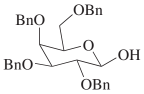
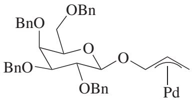
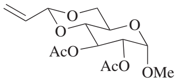
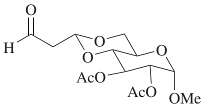
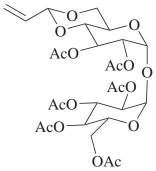
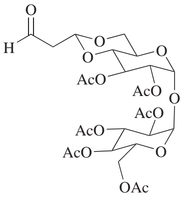
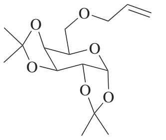
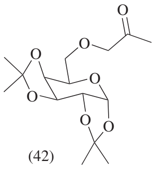
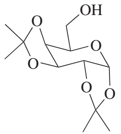
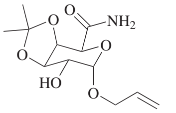
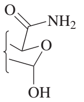
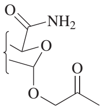
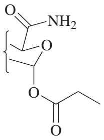
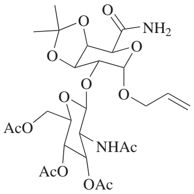
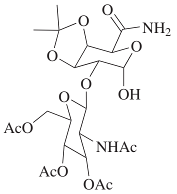
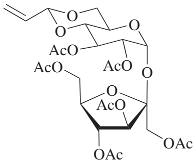
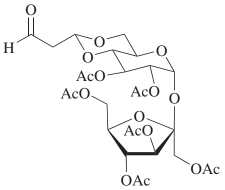
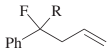
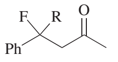
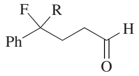
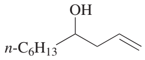
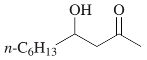
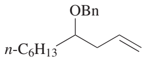
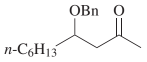
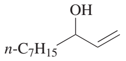
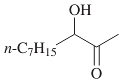
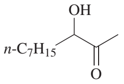
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	PdCl$_2$ (1 eq), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$ (bubbled)	 (12) +  (52)	82
	PdCl$_2$ (20 mol %), BQ (1 eq), DMF, 18–24 h; then H$_2$O (10 v/v %)	 (80)	299
	PdCl$_2$ (20 mol %), BQ (1 eq), DMF, 18–24 h; then H$_2$O	 (80)	299
	PdCl$_2$ (1 eq), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$ (bubbled)	 (42) +  (35)	82
	PdCl$_2$ (0.25 eq), CuCl (3 eq), DMF/H$_2$O (1:1), O$_2$, 45°, 3 h	 (43) +  (24) +  (15)	298
	PdCl$_2$, CuCl, DMF/H$_2$O (1:1), O$_2$; then Me$_3$CN, Et$_3$N, *h*ν	 (67)	298
	PdCl$_2$ (20 mol %), BQ (1 eq), DMF, 18–24 h; then H$_2$O	 (55)	299

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), O_2	 **I** +  **II** R I/II H 74:26 F 40:60	92
	$PdCl_2$ (10 mol %), BQ (3 eq), DMF/H_2O (50:1), rt, 8 h	 (68)	300
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt	 (90)	39
	$Pd(OAc)_2$ (5 mol %, divided), MeCN/H_2O (7:1), 0.5 M Et_4NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity	 (70)	183
	$PdCl_2$ (5 mol %, undivided), MeCN/H_2O (7:1), 0.5 M Et_4NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity	 (41)	183

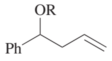
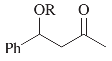
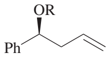
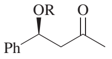
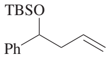
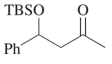
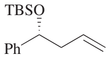
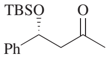
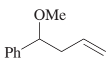
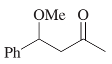
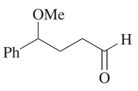
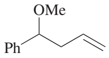
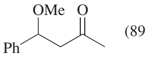
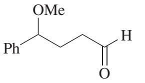
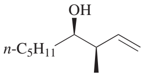
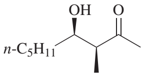
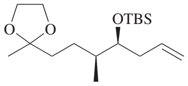
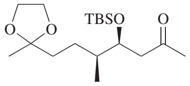
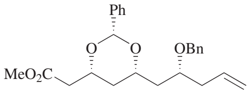
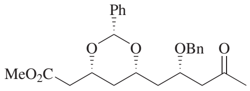
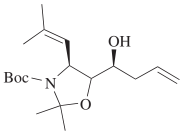
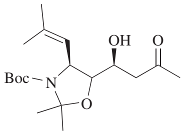
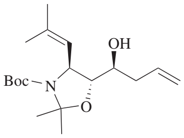
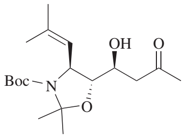
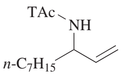
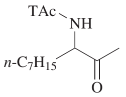
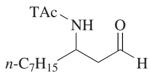
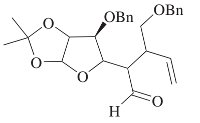
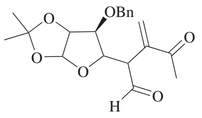
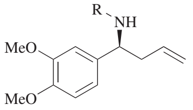
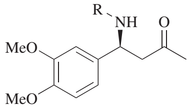
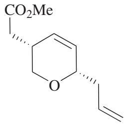
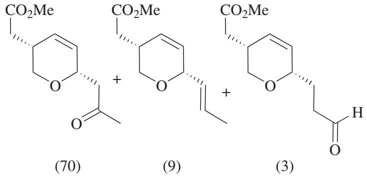
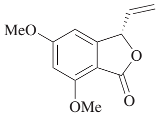
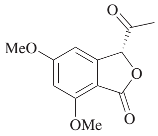
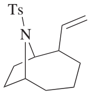
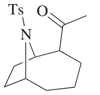
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd[(–)-sparteine]Cl_2 (*x* mol %), DMA/H_2O (*y* :1), O_2 , 70°	 R *x* *y* Time (h) H 2 8 48 (69) TBS 2 4 24 (87) PMB 1 8 24 (80)	48
	Pd[(–)-sparteine]Cl_2 (*x* mol %), DMA/H_2O (8:1), O_2 , 70°		48
	R er *x* Time (h) er H 96.0:4.0 2 48 (56) 96.0:4.0 TBS 96.5:3.5 2 24 (85) 96.5:3.5 PMB 95.0:5.0 1 24 (80) 95.0:5.0		
	Pd(Quinox)Cl_2 (2 mol %), $AgSbF_6$ (5 mol %), aq TBHP (12 eq), CH_2Cl_2, 0° to rt, 35 min	 (92)	83
 er 96.0:4.0	Pd(Quinox)Cl_2 (2 mol %), $AgSbF_6$ (5 mol %), aq TBHP (12 eq), CH_2Cl_2, rt	 (99) er 96.0:4.0	83
	$Pd(OAc)_2$ (5 mol %, divided), MeCN/H_2O (7:1), 0.5 M Et_4NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity	 (82) +  (10)	183

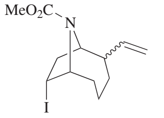
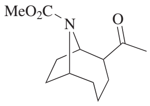
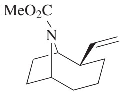
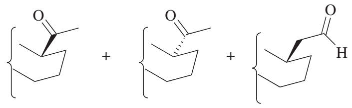
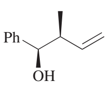
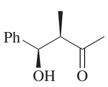
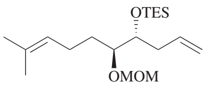
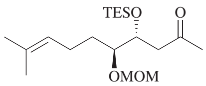
TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
	$PdCl_2$ (5 mol %, undivided), MeCN/H_2O (7:1), 0.5 M Et_4NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity	 (89) +  (—)	183
	Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (12.5 mol %), aq TBHP (12 eq), CH_2Cl_2, rt, 8 h	 (57)	86
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 3.5 h	 (60)	272
	$PdCl_2$ (62.5 mol %), CuCl (1.6 eq), DMF/H_2O (7:1), 60–70°, 3 h	 (72)	301
	$PdCl_2$ (11 mol %), CuCl (1.2 eq), DMF/H_2O (7:1), rt, 2.5 h	 (86)	302
	$PdCl_2$, CuCl, DMF/H_2O, O_2, rt; then NaOCl	 (53)	192
	Pd(Quinox)Cl_2 (5 mol %), $AgSbF_6$ (12.5 mol %), aq TBHP (12 eq), CH_2Cl_2, rt, 23 h	 +  **I** (67) **I/II** > 95:5 **II** (—)	88
	$PdCl_2$ (10 mol %), $CuCl_2$ (10 mol %), THF/H_2O (9:1)	 (50)	85

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

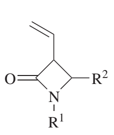
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
	$PdCl_2$ (20 mol %), $CuOAc_2$ (40 mol %), DMF/H_2O (7:1) , O_2, 2 d	 R CF_3CO (69) Bz (88)	90
	$PdCl_2$ (12 mol %), CuCl (23 mol %), DMF/H_2O (2:1), O_2, rt, 37 h	 (70) (9) (3)	303
	$PdCl_2$ (50 mol %), CuCl (1.3 eq), DMF/H_2O (6:1), O_2 (bubbled), rt, 2 h	 (86)	304
	$PdCl_2$ (0.2 eq), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt	 (71)	305

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	1. Bu_3SnH, AIBN, benzene, MeOH 2. $PdCl_2$, $CuCl_2$, DMF/H_2O	 (55)	306
 dr 19:1	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF, H_2O, O_2	 (32) (32) (5)	307
C_{11}			
	$PdCl_2$, $CuCl_2$, DMF/H_2O, O_2	 (87–92)	308
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMF/H_2O (7:1), O_2 (1 atm), rt, 48 h	 (77)	195

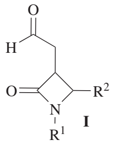
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{11-14}



PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt



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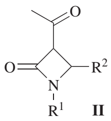
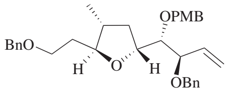


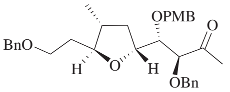
91

R^1	R^2	I	II
Ph	Ph	(65)	(5)
PMP	PMP	(60)	(5)
PMP	PhOC	(70)	(0)
PMP	PhCH=C(Me)	(60)	(4)

C_{11}

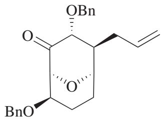


PdCl$_2$ (10 mol %), Cu(OAc)$_2$ (0.2 eq), DMA/H$_2$O (7:1), O$_2$, rt, 16 h

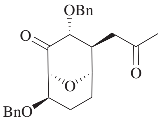


(84)

79

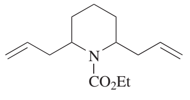


PdCl$_2$ (2 eq), DMF/H$_2$O (7:1), rt, 3 h

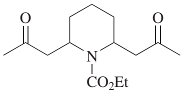


(94)

199

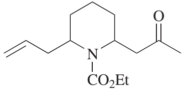


Pd(OAc)$_2$ (5 mol %, divided), MeCN/H$_2$O (7:1), 0.5 M Et$_4$NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity



I (74)

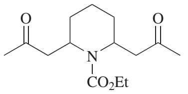
+



II (16)

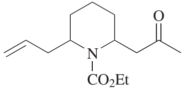
183

PdCl$_2$ (5 mol %, undivided), MeCN/H$_2$O (7:1), 0.5 M Et$_4$NOTs-(Pt)-(Pt), rt, 2.0–3.0 F/mol electricity



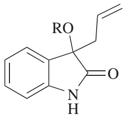
I (72)

+

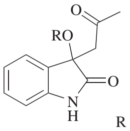


II (0)

183



PdCl$_2$ (10 mol %), CuCl$_2$ (1 eq), solvent/H$_2$O (7:1), O$_2$



84

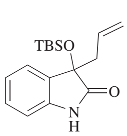
R	Solvent	Temp	Time	
H	DMF	rt	7 d	(0)
H	dioxane	50°	5 h	(88)
TBS	dioxane	50°	5 h	(88)

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

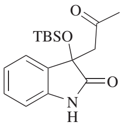
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{11}



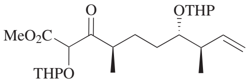
Na_2PdCl_4 (20 mol %),
TBHP (1.5 eq),
$AcOH/H_2O$ (1:1), O_2, 50°, 5 h



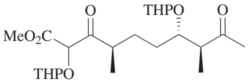
(71)

84

C_{12}

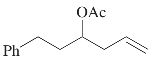


$PdCl_2$ (1.2 eq), aq $NaHPO_4$,
THF/DMF (5:1), 24 h

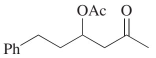


(84)

309

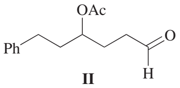


$PdCl_2$ (*x*), additive,
solvent/H_2O (*y* :1), O_2



I

+

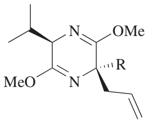


II

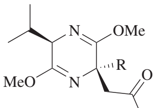
121

x	Additive	Solvent	*y*	Temp	Time	**I + II**	**I/II**
10 mol %	CuCl (1 eq)	DMF	10	rt	overnight	(91)	6:1
10 mol %	CuCl (1 eq)	DMF	10	0°	24 h	(65)	6:1
10 mol %	$Cu(OAc)_2$ (20 mol %)	DMA	7	rt	24 h	(93)	6:1
10 mol %	$Cu(OAc)_2$ (2 eq)	DMA	7	rt	24 h	(95)	6:1
4.5 eq	none	DMF	7	rt	4 h	(84)	15:1

C_{12-13}

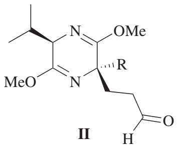


$PdCl_2$ (10 mol %), CuCl (1 eq),
DMF/H_2O (7:1), O_2, rt, 10 h



I

+

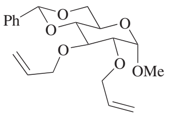


II

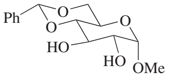
170

R	I	II
MeCO	(55)	(18)
$MeCOCH_2$	(<5)	(64)

C_{12}



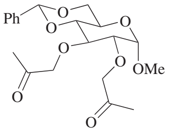
$PdCl_2$ (1 eq), CuCl (1 eq),
DMF/H_2O (10:1), rt, 1–6 h



(90–92)

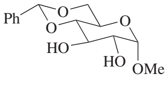
292

$PdCl_2$ (1 eq), CuCl (1 eq),
DMF/H_2O (10:1), O_2 (bubbled)



(24)

+



(46)

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TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

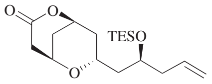
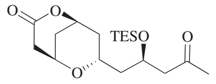
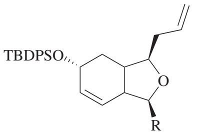
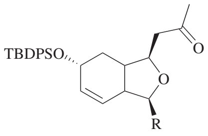
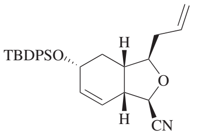
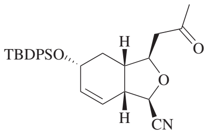
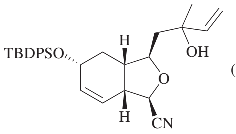
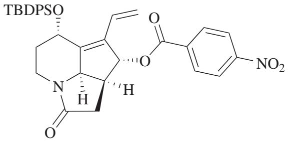
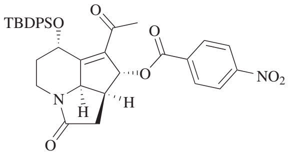
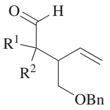
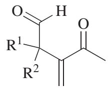
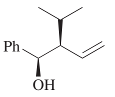
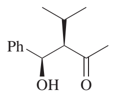
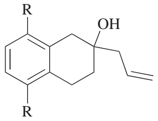
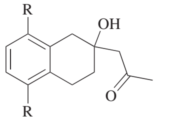
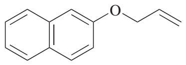
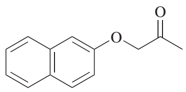
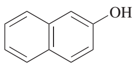
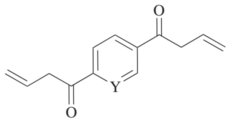
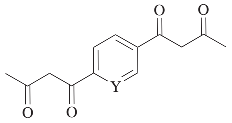
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{12}			
	$PdCl_2$ (30 mol %), $Cu(OAc)_2$ (60 mol %), DMF/H_2O (7:1), O_2, rt, 24 h	 (66)	310
	$PdCl_2$ (x mol %), CuCl (y eq), DMF/H_2O (7:1), O_2	 R — x — y — Time (d) MeO_2C — 12 — 1.3 — 1 — (57) NC– — 23 — 0.91 — 4 — (86)	311
	$PdCl_2$, CuCl, DMF, H_2O, O_2	 (86)	312
	1. $PdCl_2$, CuCl, DMF, H_2O, O_2 2. $CH_2CHMgBr$, $CeCl_3$, THF	 (75)	313
	—	 (—)	314
$C_{13–15}$			
	$PdCl_2$ (10 mol %), $CuCl_2$ (10 mol %), THF/H_2O (9:1)	 R^1 — R^2 n-C_7H_{15} — H — (79) 4-MeC_6H_4 — Me — (70) $Ph(CH_2)_2$ — H — (79) n-C_9H_{19} — H — (79)	85
C_{13}			
	$PdCl_2$, $CuCl_2$, DMF, H_2O, O_2	 (87–92)	308

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{13}			
	PdCl$_2$, CuCl, aq DMF, O$_2$	 R: H (61) MeO (71)	315
	PdCl$_2$ (1 eq), CuCl (1 eq), DMF/H$_2$O (10:1), O$_2$ (bubbled)	 (51) +  (43)	82
$C_{13–14}$			
	PdCl$_2$ (40 mol %), CuCl (2 eq), THF/H$_2$O (4:1), O$_2$, ultrasound	 Y: CH (—) N (74)	229

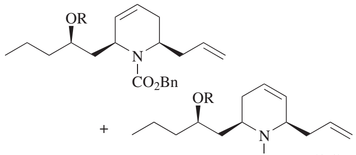
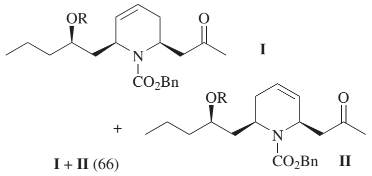
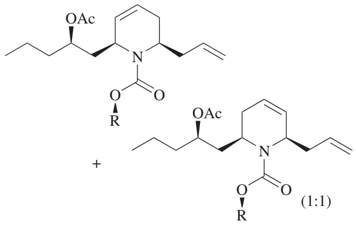
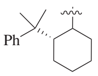
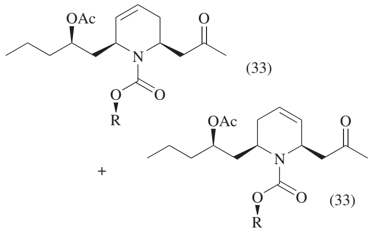
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{13}			
 (1:1) R = 4-O$_2$NC$_6$H$_4$CO	PdCl$_2$ (10 mol %), CuCl (0.5 eq), DMF/H$_2$O (6:1), O$_2$, rt, 7 h	 **I** + **II** **I** + **II** (66)	316
 (1:1)	PdCl$_2$ (50 mol %), CuCl (1 eq), DMF/H$_2$O (6:1), O$_2$, 12 h R = 	 (33) + (33)	316

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

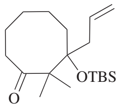
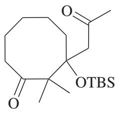
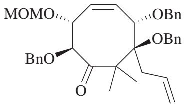
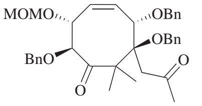
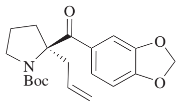
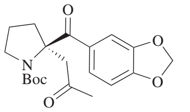
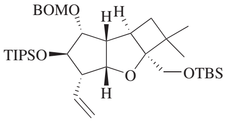
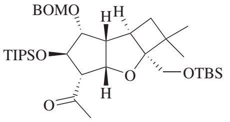
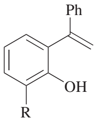
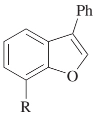
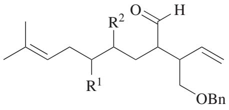
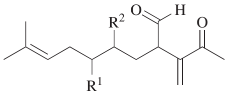
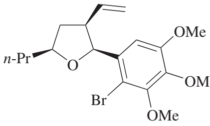
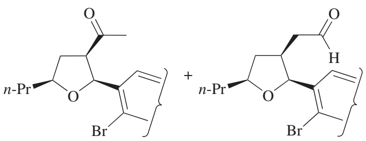
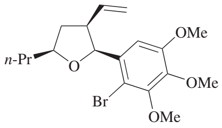
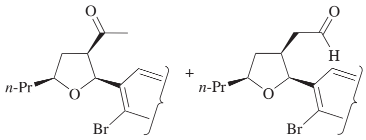
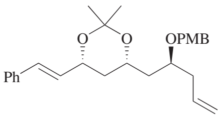
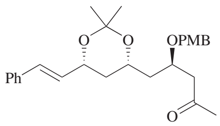
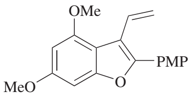
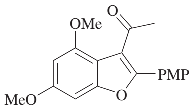
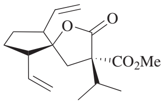
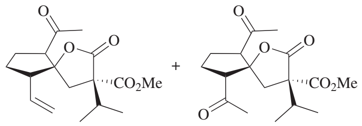
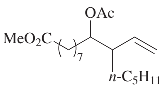
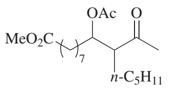
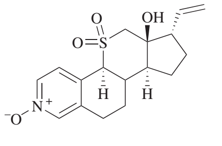
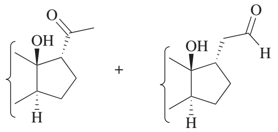
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*			
C_{13}			
	PdCl$_2$ (20 mol %), CuCl (1 eq), DMF/H$_2$O (10:1.2), O$_2$, rt	 (62)	127
	PdCl$_2$ (20 mol %), CuCl (1 eq), DMF/H$_2$O (10:1.2), O$_2$, rt	 (84)	126
C_{14}			
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, rt	 (72)	288
	PdCl$_2$, CuCl, DMF/H$_2$O (10:1), O$_2$, 20°, 4 d	 (94)	317
$C_{14–18}$			
	PdCl$_2$	 R H (—) Me (—) *t*-Bu (—)	318
C_{15}			
	PdCl$_2$ (10 mol %), CuCl$_2$ (10 mol %), THF/H$_2$O (9:1)	 R^1 R^2 H Me (94) Me H (78)	85
	PdCl$_2$ (10 mol %), DMF/H$_2$O, O$_2$	 **I** **I** + **II** (73), **I**/**II** = 1:1 **II**	319

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

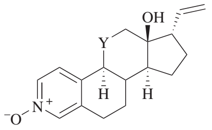
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{15}			
	$PdCl_2$ (10 mol %), BQ, $HClO_4$ $MeCN/H_2O$	 **I** **I** + **II** (80), **I**/**II** = 3:1 **II**	319
C_{16}			
	$PdCl_2$ (10 mol %), $Cu(OAc)_2$ (20 mol %), DMA/H_2O (7:1), O_2, rt, 19.5 h	 (77)	119
	$PdCl_2$ (10 mol %), CuCl (10 mol %), DMF/H_2O (7:1), O_2, 65°, 4 h	 (93)	320
	$Pd(OAc)_2$ (10 mol %), BQ (0.5 eq), $MeCN/H_2O$ (7:1), $HClO_4$	 (—) major (—) minor	321
C_{17}			
	$PdCl_2$ (10 mol %), BQ (3 eq), DMF (2 % H_2O), rt, 43 h	 (35)	300
	$Pd(OAc)_2$, BQ, $HClO_4$, H_2O, rt, 3 h	 **I** (67) **II** (7) **I**/**II** = 9:1	322

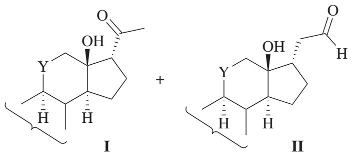
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{17}

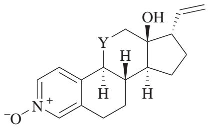


$Pd(OAc)_2$ (10 mol %), BQ (1 eq), $HClO_4$ (0.3 M), $MeCN/H_2O$ (7:1), rt, 3 h

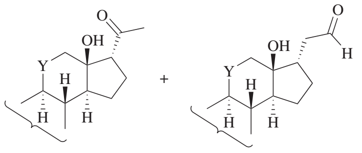


Y	I	II	I/II
O	(68)	(17)	4:1
O_2S	(63)	(11)	6:1

323



$Pd(OAc)_2$ (10 mol %), BQ (0.91 eq), $HClO_4$ (0.3 M), $MeCN/H_2O$ (7:1), rt, 2 h

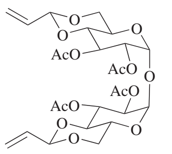


I **II**

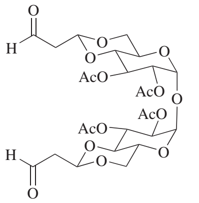
Y	I	II
OSe	(72)	(10)
OTe	(64)	(15)

324

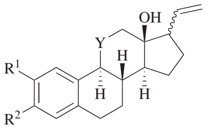
C_{18}



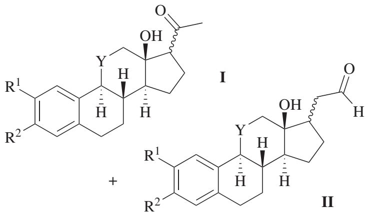
$PdCl_2$ (20 mol %), BQ (1 eq), DMF, 18–24 h; then H_2O



(50–80) 299



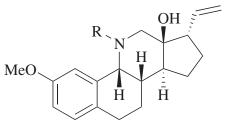
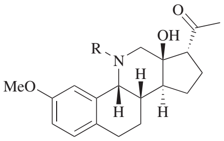
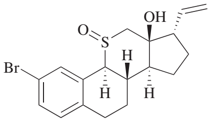
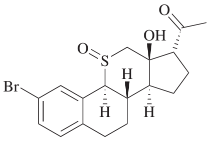
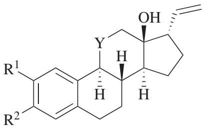
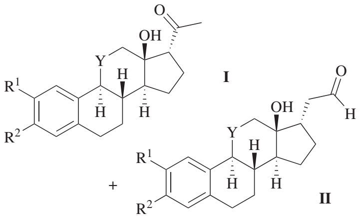
$Pd(OAc)_2$ (*x* mol %), BQ (*y* eq), $HClO_4$, $MeCN/H_2O$ (7:1), rt



R^1	R^2	Y	*x*	*y*	Time (h)	I	II	Refs.
MeO	H	O	—	—	3	(56)	(14)	325
H	MeO	O	—	—	3	(56)	(14)	325
MeO	H	OS	10	1	12	(58)	(11)	326

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{18}			
	$Pd(OAc)_2$, BQ, $HClO_4$, MeCN, H_2O	 R Me (76) Et (70) Bn (74)	327
	$Pd(OAc)_2$ (10 mol %), BQ (1 eq), $HClO_4$ (0.3 M), $MeCN/H_2O$ (7:1), rt, 3 h	 (70)	328
	$Pd(OAc)_2$ (10 mol %), BQ (*x* eq), $HClO_4$ (*y* M), $MeCN/H_2O$ (7:1), rt		

R^1	R^2	Y	*x*	*y*	Time (h)	**I**	**II**	Refs.
H	MeO	OS	1	—	3	(81)	(15)	328
H	MeO	O_2S	1	—	3	(64)	(10)	328
MeO	H	OSe	0.91	0.3	2	(75)	(12)	324
MeO	H	OTe	0.91	0.3	2	(66)	(8)	324

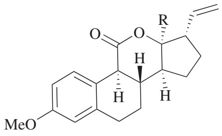
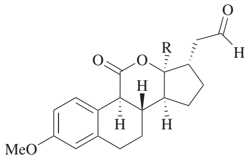
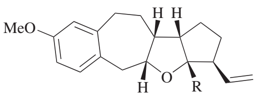
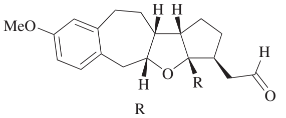
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{19}			
	$Pd(OAc)_2$ (0.1 M), BQ (0.9 M), $HClO_4$ (0.3 M), $MeCN/H_2O$ (7:1), 20°	 R CF_3 (80) CHF_2 (85)	329

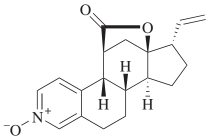
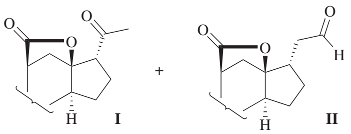
TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C$_{19}$

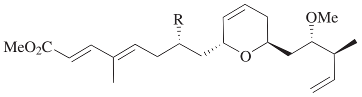
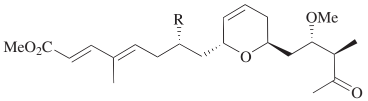
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(OAc)$_2$ (0.1 M), BQ (0.9 M), HClO$_4$ (0.3 M), MeCN/H$_2$O (7:1), 20°		330

R	
CF$_3$	(74)
CHF$_2$	(82)

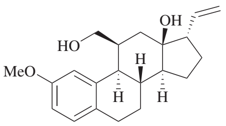
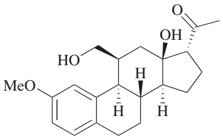
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Catalyst (*x* mol %), BQ (*y* eq), HClO$_4$, rt, 3 h		

Catalyst	*x*	*y*	Solvent	**I + II**	**I/II**	Refs.
Pd(OAc)$_2$	10	1	MeCN/H$_2$O (7:1)	(78)	8:1	323
PdCl$_2$(OAc)$_2$	–	–	H$_2$O	(78)	8:1	331

C$_{20}$

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	PdCl$_2$ (20 mol %), CuCl (*x* eq), DMF/H$_2$O (*y*:1), O$_2$, 20°		

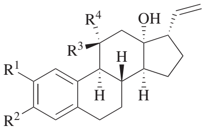
R	*x*	*y*	Time (h)		Refs.
H	1	10	48	(85)	332
TBSO	2	7	72	(84)	333

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq), HClO$_4$ (1.8 eq), MeCN/H$_2$O (7:1), 20°, 1.5 h	 (0)	334

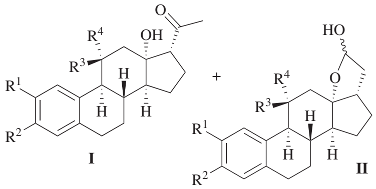
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

$C_{20–21}$

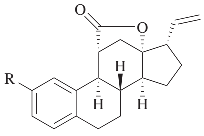


Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq), HClO$_4$ (x)

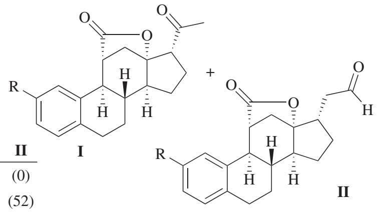


R^1	R^2	R^3	R^4	x	Solvent	Temp (°)	Time (h)	I	II	Refs.
H	H	H	MeO_2C	0.3 M	MeCN	—	—	(55)	(37)	335
H	H	H	MeO_2C	1.8 eq	$MeCN/H_2O$ (7:1)	20	1.5	(46)	(37)	334
H	H	H	$BnOCH_2$	1.8 eq	$MeCN/H_2O$ (7:1)	20	1.5	(60)	(39)	334
H	H	MeO_2C	MeO_2C	1.8 eq	$MeCN/H_2O$ (7:1)	20	1.5	(46)	(37)	334
MeO	H	H	MeO_2C	1.8 eq	$MeCN/H_2O$ (7:1)	20	1.5	(58)	(22)	334
MeO	MeO	H	MeO_2C	0.3 M	MeCN	—	—	(54)	(38)	335
MeO	MeO	H	MeO_2C	1.8 eq	$MeCN/H_2O$ (7:1)	20	1.5	(54)	(22)	334

C_{20}

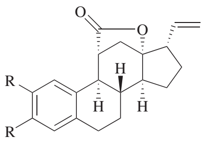


Pd(OAc)$_2$ (1 eq), BQ (1 eq), HClO$_4$, $MeCN/H_2O$ (7:1), rt, 2 h

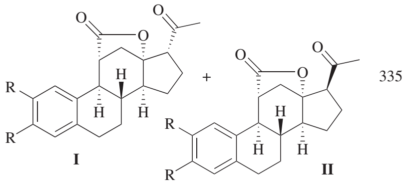


R	I	II
F	(68)	(0)
HO	(0)	(52)

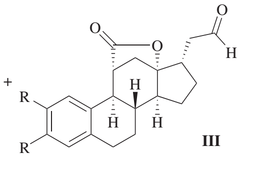
336



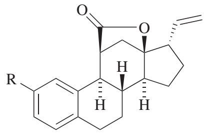
Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq), HClO$_4$ (0.3 M), MeCN



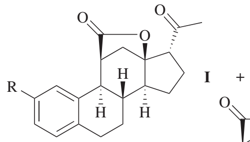
R	I	II	III
H	(35)	(10)	(34)
MeO	(39)	(14)	(38)

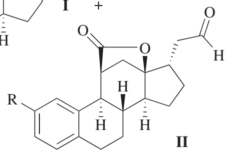


335



Pd(OAc)$_2$ (1 eq), BQ (1 eq), HClO$_4$, $MeCN/H_2O$ (7:1), rt, 2 h





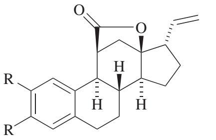
R	I	II
F	(81)	(0)
HO	(86)	(0)

336

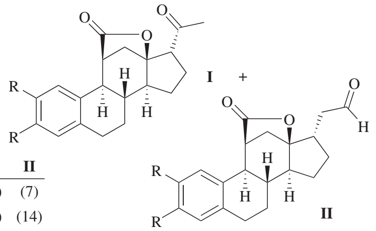
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{20}

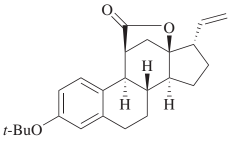


Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq),
HClO$_4$ (0.3 M), MeCN

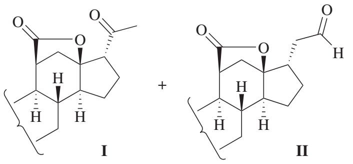


R	I	II
H	(85)	(7)
MeO	(79)	(14)

335

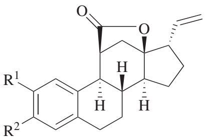


Pd(OAc)$_2$, BQ, HClO$_4$, H$_2$O, rt, 1.5 h

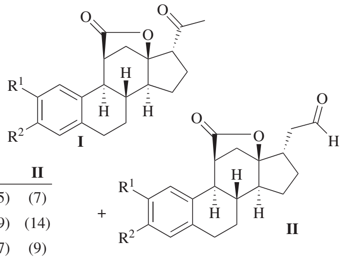


I + **II** (56), **I**/**II** = 10:1

337

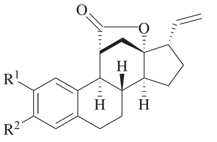


Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq),
HClO$_4$ (1.8 eq),
MeCN/H$_2$O (7:1), 20°, 1.5 h

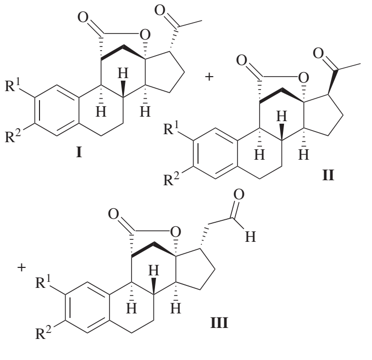


R^1	R^2	I	II
H	H	(85)	(7)
MeO	H	(79)	(14)
MeO	MeO	(77)	(9)

334



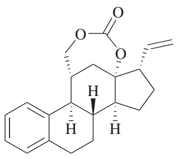
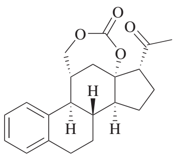
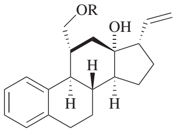
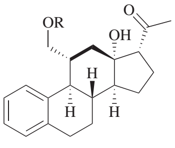
Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq),
HClO$_4$ (1.8 eq),
MeCN/H$_2$O (7:1), 20°, 1.5 h



R^1	R^2	I	II	III
H	H	(35)	(10)	(35)
MeO	H	(35)	(8)	(28)
MeO	MeO	(35)	(10)	(30)

334

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

<table>
<tr><th>Alkene</th><th>Conditions</th><th>Product(s) and Yield(s) (%)</th><th>Refs.</th></tr>
<tr><td>C_{20}</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq), HClO$_4$ (x)</td><td><table><tr><th><i>x</i></th><th>Solvent</th><th>Temp (°)</th><th>Time (h)</th><th></th></tr><tr><td>0.3 M</td><td>MeCN</td><td>—</td><td>—</td><td>(0)</td></tr><tr><td>1.8 eq</td><td>MeCN/H$_2$O (7:1)</td><td>20</td><td>1.5</td><td>(0)</td></tr></table></td><td>335
334</td></tr>
<tr><td></td><td>PdOAc$_2$ (10 mol %), BQ (0.5 eq), HClO$_4$ (1.8 eq), MeCN/H$_2$O (7:1), 20°, 1.5 h</td><td>I
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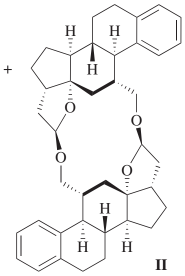
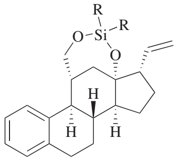
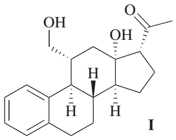
II<table><tr><th>R</th><th>I</th><th>II</th></tr><tr><td>H</td><td>(45)</td><td>(19)</td></tr><tr><td>TBS</td><td>(46)</td><td>(4)</td></tr></table></td><td>334</td></tr>
<tr><td></td><td>Pd(OAc)$_2$ (10 mol %), BQ (0.5 eq), HClO$_4$ (1.8 eq), MeCN/H$_2$O (7:1), 20°, 1.5 h</td><td>I
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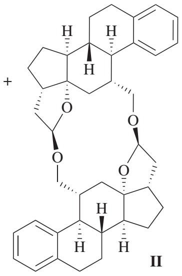
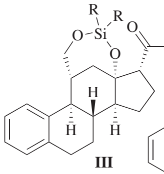
II<table><tr><th>R</th><th>I</th><th>II</th><th>III</th><th>IV</th></tr><tr><td>Me</td><td>(51)</td><td>(18)</td><td>(0)</td><td>(0)</td></tr><tr><td>Ph</td><td>(45)</td><td>(0)</td><td>(7)</td><td>(11)</td></tr></table>+
III
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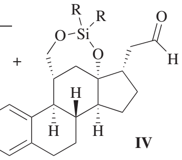IV</td><td>334</td></tr>
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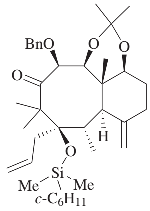
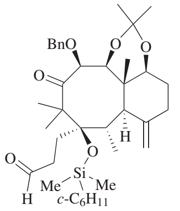
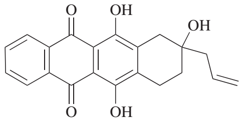
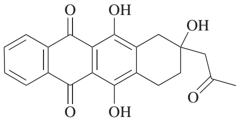
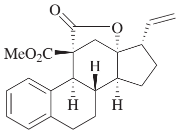
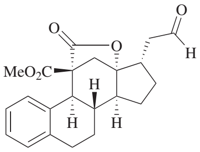
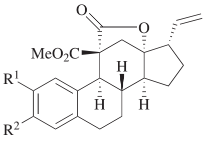
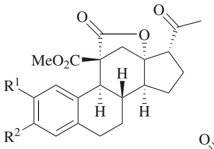
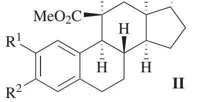
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{20}			
	$PdCl_2$ (2.6 eq), DMF/H_2O (7:1), rt, 1.5 h	 (40)	125
C_{21}			
	$PdCl_2$, CuCl, aq DMF, O_2	 (85)	315
	$Pd(OAc)_2$ (10 mol %), BQ (0.5 eq), $HClO_4$ (0.3 M), MeCN	 (38)	335
	$Pd(OAc)_2$ (10 mol %), BQ (0.5 eq), $HClO_4$ (1.8 eq), $MeCN/H_2O$ (7:1), 20°, 1.5 h	 + **I**  **II**	334

R^1	R^2	**I**	**II**
H	H	(0)	(37)
MeO	H	(38)	(45)
MeO	MeO	(24)	(28.5)

TABLE 1B. WACKER OXIDATION OF TERMINAL ALKENES WITH ALLYLIC OR HOMOALLYLIC HETEROATOMS (*Continued*)

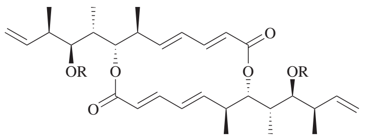
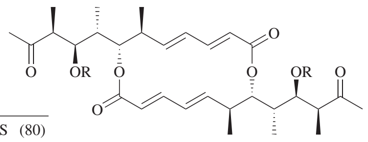
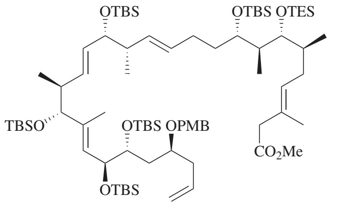
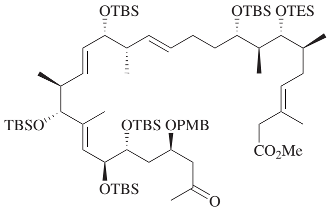
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{30}			
	$PdCl_2$ (43 mol %), CuCl (2.8 eq), DMF/H_2O/THF (5:1:1), O_2 (bubbled), rt	 R TBS (80) TES (67)	123
C_{34}			
	$PdCl_2$, $Cu(OAc)_2$, THF/H_2O	 (75)	124

TABLE 2A. WACKER OXIDATION OF INTERNAL ALKENES

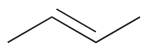
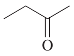
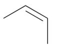
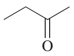
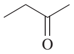
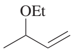
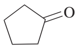
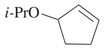
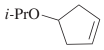
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_4			
	$PdCl_2$ (4 mol %), $CuCl_2$ (40 mol %), α-cyclodextrin (2.4 mol %), H_2O, O_2 (bubbling), 65°, 24–48 h	 (70)	141
	$PdCl_2$ (4 mol %), $CuCl_2$ (40 mol %), α-cyclodextrin (2.4 mol %), H_2O, O_2 (bubbling), 65°, 24–48 h	 (76)	141
	$RhCl_3$ (0.2 mol %), $Cu(ClO_4)_2$•$6H_2O$ (0.3 mol %), EtOH, O_2 (2 atm), 80°, 4 h	 (76) +  (10)	160
C_5			
	$RhCl_3$ (0.8 mol %), $Cu(ClO_4)_2$•$6H_2O$ (1.6 mol %), H_2O, *i*-PrOH, O_2 (860 mmHg), 40°, 4 h	 (4) +  (24) +  (6)	160

TABLE 2A. WACKER OXIDATION OF INTERNAL ALKENES (*Continued*)

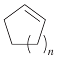
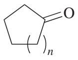
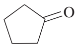
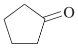
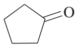
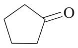
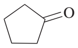
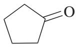
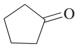
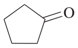
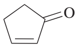
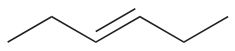
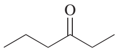
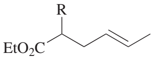
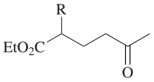
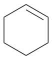
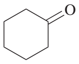
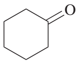
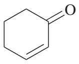
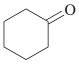
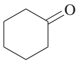
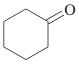
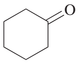
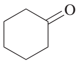
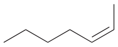
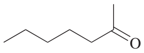
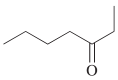
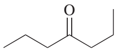
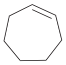
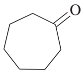
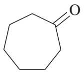
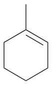
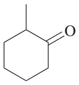
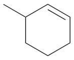
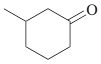
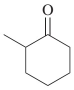
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
***Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the* bold *numbers*.**			
C_{5-8}			
	Pd(II) salt (*x* mol %), $H_3PMo_6W_6O_{40}$ (13 mol %), *c*-C_6H_{12}/H_2O (3:10), O_2, 30°	 *n* Pd(II) salt *x* Time (h) 1 $PdSO_4$ 3 6 (100) 2 $PdSO_4$ 3.3 10 (70.3) 2 $PdCl_2$ 3.3 24 (4.1) 2 $Pd(NO_3)_2$ 3.3 23 (63.9) 2 $Pd(OAc)_2$ 3.3 24 (12.1) 3 $PdSO_4$ 3 22 (10) 4 $PdSO_4$ 3 6 trace	338
C_5			
	$Pd(DMA)_2Cl_2$ (0.5 mol %), EtOH, O_2 (860 mmHg), 30°, 8 h	 (19.3)	339
	$Pd(Et_2NAc)_2Cl_2$ (0.5 mol %), EtOH, O_2 (860 mmHg), 30°, 8 h	 (20.1)	339
	$PdCl_2$ (2 mol %), EtOH, O_2 (860 mmHg), 30°, 8 h	 (20.1)	339
	$Pd(PhCN)_2Cl_2$ (0.5 mol %), CuCl (3 mol %), THF, O_2, 30°, 8 h	 (9)	340
	$Pd(OAc)_2$ (2 mol %), BQ (20 mol %), DMSO/H_2O (7:1), Et_4NBF_4, Pt-anode, rt	 (75)	156
	$PdCl_2$ (1 mol %), $CuCl_2$ (4.6 mol %), EtOH, O_2 (490.3 kPa), 50°, 2 h	 (96)	341
	$Pd(MeCN)_2Cl_2$ (10 mol %), CuCl (10 mol %), HMPA (200 mol %), CH_2Cl_2, 50°	 (47)	342
	$Pd(OAc)_2$ (10 wt %), NPMoV/C (15 wt %) (100 mg/mmol), MeCN/H_2O (9:1), O_2, 50°, 6 h	 (85) +  (1)	343
C_6			
	$PdCl_2$ (5 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 10 h	 (98)	50
C_{6-7}			
 	$PdCl_2$ (10 mol %), $CuCl_2$ (10 mol %), DME/H_2O (20:1), O_2 (bubbled), 80°, 5–6 h	 R H (50–60) Me (50–60)	154

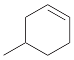
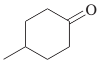
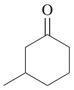
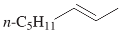
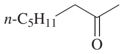
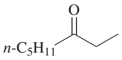
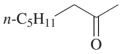
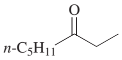
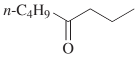
TABLE 2A. WACKER OXIDATION OF INTERNAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

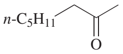
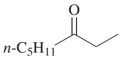
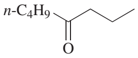
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	$Pd(OAc)_2$ (5 mol %), BQ (30 mol %), DMSO/H_2O (7:1), Et_4NBF_4, Pt-anode, rt	 (83)	156
	$PdCl_2$ (20 mol %), DMA/H_2O (10:1), O_2 (3 atm), 70°, 10 h	 (73) +  (17)	50
	$Pd(OAc)_2$ (2 mol %), BQ (90 mol %), $HClO_4$	 Temp rt (102) 60° (102)	344
	$Pd(OAc)_2$ (5 mol %), HQ (20 mol %), NPMoV (17.5 mg/mmol), O_2, 60°, 4 h	 (58)	345
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 (75)	261
	$PdSO_4$ (1 mol %), $H_3PMo_6W_6O_{40}$ (4 mol %), O_2, 30°	 Solvent — Time (h) H_2O/Et_2O (10:3) — 18 (90.0) H_2O/MeNHCHO (10:3) — 5 (96.1)	338

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (1 mol %), $CuCl_2$ (4 mol %), EtOH, O_2, 30°, 22 h	 (73.8)	338
C_7			
	$Pd(OAc)_2$ (2 mol %), BQ (90 mol %), $HClO_4$, 60°	 (58) +  (32) +  (7)	344
	$Pd(OAc)_2$ (2 mol %), BQ (90 mol %), $HClO_4$, 60°	 (76)	344
	$RhCl_3$ (0.8 mol %), $Cu(ClO_4)_2(HMPA)_4$ (1.6 mol %), *i*-PrOH, H_2O, O_2 (860 mmHg), 40°, 4 h	 (22)	160
	$PdSO_4$ (1.3 mol %), $H_3PMo_6W_6O_{40}$ (3 mol %), *c*-C_6H_{12}/H_2O (3:10), O_2, 30°, 8 h	 (0)	338
	$PdSO_4$ (1.3 mol %), $H_3PMo_6W_6O_{40}$ (3 mol %), *c*-C_6H_{12}/H_2O (3:10), O_2, 30°, 8 h	 (12.9) +  (7.6)	338

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_7			
	$PdSO_4$ (1.3 mol %), $H_3PMo_6W_6O_{40}$ (3 mol %), c-C_6H_{12}/H_2O (3:10), O_2, 30°, 8 h	 (0.8) +  (1.7)	338
C_8			
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 (62) +  (25)	261
	$Pd(OAc)_2$ (1 mol %), BQ (x mol %), additive, 0.90 V, 1000 Coulombs, $[HClO_4]$ = y M, MeCN/H_2O (7:1)	 +  +  **I** **II** **III** **I**/**II**/**III** = 60:30:10	346

x	Additive	y	Temp	Time (min)	**I** + **II** + **III**
10	TBAP	0.015	22°	85	(51)
20	TBAP	0.015	rt	90	(68)
20	TBAP	0.12	rt	38	(67)
20	$NaHClO_4$	0.12	22°	75	(76)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$Pd(OAc)_2$ (2 mol %), BQ (90 mol %), $HClO_4$, 10 min	 +  +  **I** **II** **III**	344

Temp	**I**	**II**	**III**
rt	53	26	5
60°	40	47	11

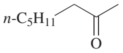
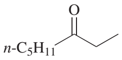
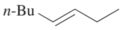
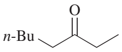
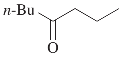
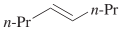
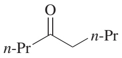
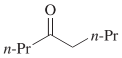
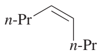
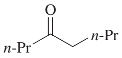
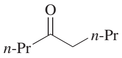
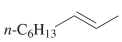
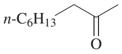
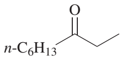
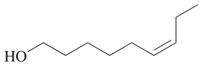
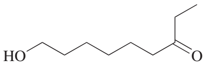
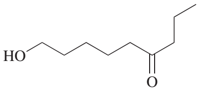
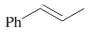
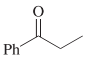
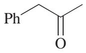
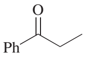
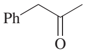
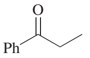
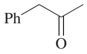
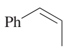
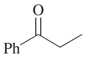
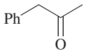
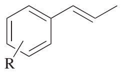
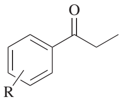
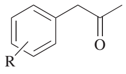
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (5 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 10 h	 (62) +  (36)	50
	$PdCl_2$ (5 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 10 h	 (54) +  (44)	50
	$PdCl_2$ (5 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 10 h	 (91)	50
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 (78)	261

TABLE 2A. WACKER OXIDATION OF INTERNAL ALKENES (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_8			
	$PdCl_2$ (5 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 10 h	 (83)	50
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 (70)	261
C_9			
	$[Pd(P(t\text{-}Bu)_2H)(\mu\text{-}P(t\text{-}Bu)_2)]_2$ (2 mol %), THF, O_2, 50°	 (28) +  (28)	157
	$PdCl_2$ (10 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 10 h	 (47) +  (45)	50
	$PdCl_2$ (50 mol %), CuCl (3 eq), DMF/H_2O (1:1), O_2, 50°, 72 h	 **I** (—) +  **II** (—) **I/II** = 3:1	347

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$[Pd(I\textit{i}\text{-}Pr)Cl_2]_2$ (0.75 mol %), AgOTf (3 mol %), TBHP (5.5 eq), MeOH, 35°, 48 h	 **I** (—) +  **II** (—) **I/II** = 2.3:1	56
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), MeCN/H_2O (7:1), rt	 (45.5) +  (45.5)	261
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), MeCN/H_2O (7:1), rt	 (53) +  (38)	261
C_{9-10}			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (1:1), O_2, 50°, 24 h	 **I** +  **II**	94

R	**I/II**
H	1:7.5
2-MeO	1:2.7
4-MeO	1:2.0
2,4-$(MeO)_2$	1:2.1
2,4,6-$(MeO)_3$	2.3:1
4-Me	1:3.8
4-CF_3	<1:19

TABLE 2A. WACKER OXIDATION OF INTERNAL ALKENES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

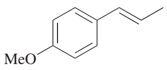
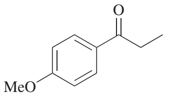
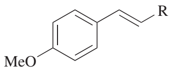
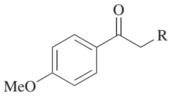
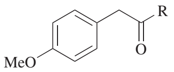
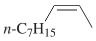
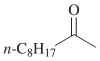
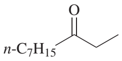
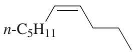
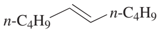
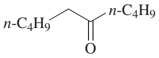
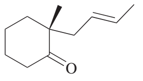
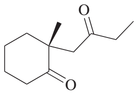
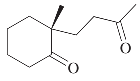
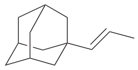
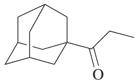
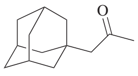
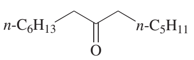
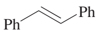
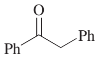
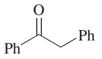
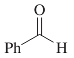
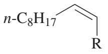
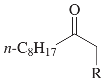
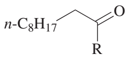
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 (84)	261
$C_{9–12}$			
	$PdCl_2$ (1 eq), DMF/H_2O (1:1), 100°	 **I** +  **II** R — **I/II** Me — 1:10 *t*-Bu — 2.2:1	94
C_{10}			
	$[Pd(P(t\text{-Bu})_2H)(\mu\text{-}P(t\text{-Bu})_2)]_2$ (2 mol %), THF, O_2 (1 atm), 50°	 (27) +  (18)	157
	$PdCl_2$ (4 mol %), $CuCl_2$ (50 mol %), α-cyclodextrin (2.4 mol %), H_2O, O_2 (bubbling), 65°, 24–48 h	decanones (31) + decene isomers (69)	141
	Pd[(–)-sparteine]Cl_2 (2 mol %), DMA/H_2O (4:1), air (balloon), 70°, 24 h	(—)	48
	$PdCl_2$ (5 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 10 h	 (86)	50
C_{11}			
	$PdCl_2$, CuCl, DMF, H_2O, O_2	 +  **I** — **I** + **II** (57), **I/II** = 91:9 — **II**	95
C_{13}			
	$PdCl_2$ (1 eq), DMF/H_2O (1:1), 100°	 +  **I** (—) — **I/II** = 1:2.2 — **II** (—)	94

TABLE 2A. WACKER OXIDATION OF INTERNAL ALKENES (*Continued*)

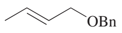
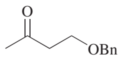
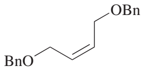
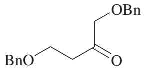
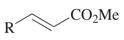
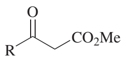
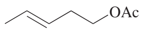
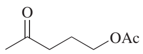
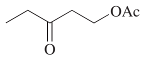
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{14}			
	$PdCl_2$ (5 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 20 h	 (81)	50
	**2** (5 mol %), TBHP (1.5 eq) benzene/$C_8F_{17}Br$, 56°	 (73)	136
	$[Pd(Ii\text{-}Pr)Cl_2]_2$ (1.25 mol %), AgOTf (4 mol %), TBHP (5.5 eq), MeOH, 35–50°, 48 h	 **I** +  **II** **I** + **II** (42), **I**/**II** = 42:35	56
C_{18}			
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 **I** +  **II**	261

R	I	II
$HO_2C(CH_2)_7$	(41)	(41)
$MeO_2C(CH_2)_7$	(42)	(42)
$HO(CH_2)_8$	(38)	(38)

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_4			
	$PdCl_2$ (10 mol %), additive (1 eq), solvent/H_2O (7:1), O_2, 6 h		100
	$Pd(OAc)_2$ (10 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 (73)	261
$C_{4–9}$			
	Na_2PdCl_4 (20 mol %), 70% TBHP in *t*-BuOH (1.2–2.0 eq), AcOH/H_2O (1:1), 50°		55
C_5			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 50°	 **I** +  **II** **I** + **II** (80), **I**/**II** = 91:9	100

Additive	Solvent	Temp	
CuCl	DMF	50°	(67)
BQ	THF	rt	(54)

R	
Me	(83)^a, (—)
n-Pr	(96)^a, (78)
i-Pr	(96)^a, (64)
i-Bu	(80)^a, (68)
n-C_6H_{13}	(—)^a, (75)

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

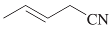
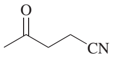
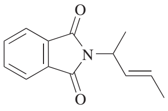
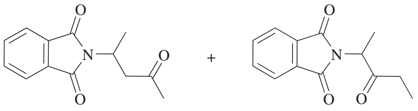
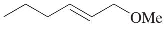
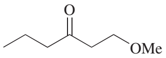
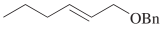
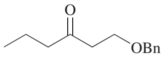
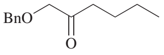
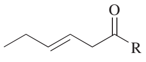
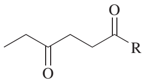
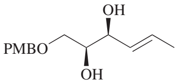
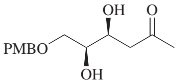
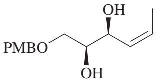
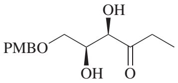
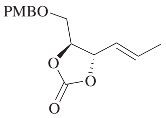
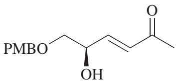
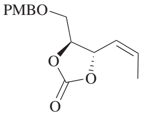
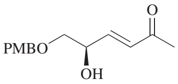
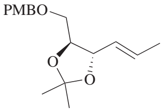
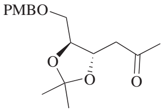
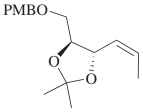
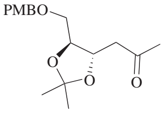
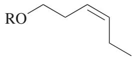
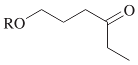
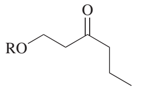
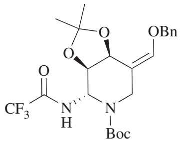
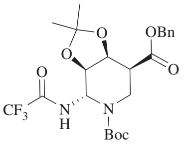
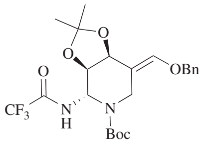
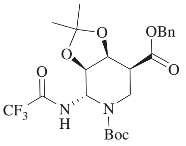
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_5			
	$PdCl_2$ (10 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 20 h	 (94)	50
	$Pd(MeCN)_2Cl(NO_2)$ (5 mol %), $CuCl_2$ (20 mol %), *t*-BuOH, O_2, 16 h	 **I** (89) **I/II** >99:1 **II** (—)	41
C_6			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 50°, 8 h	 (65)	100
	$PdCl_2$ (20 mol %), DMA/H_2O (10:1),O_2 (3 atm), 80°, 20 h	 (91) +  (4)	50
$C_{6–7}$			
	$PdCl_2$ (10 mol %), CuCl (1 eq), dioxane/H_2O (7:1), O_2, 50°, 12 h	 R: MeO (52) Me (45)	97
C_6			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 12 h	 (93)	39
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 12 h	 (90)	39
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 12 h	 (90)	39
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, rt, 12 h	 (91)	39
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 60°, 6 h	 (93)	39
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 60°, 6 h	 (91)	39

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	$Pd(OAc)_2$ (5 mol %), BQ (1 eq), HBF_4 (0.27 M), DMA/MeCN/H_2O (3.5:3.5:1), rt	 **I** +  **II**	261
	$PdCl_2$ (1 eq), CuCl (7.7 eq), DMF/H_2O (10:1), O_2, rt to 70° to rt	 (31)	99
	$PdCl_2$ (1 eq), CuCl (7.7 eq), DMF/H_2O (10:1), O_2, rt to 70° to rt	 (15)	99

R	I	II
Bz	(73)	(18)
2-hydoxybenzoyl	(75)	(19)

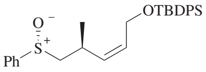
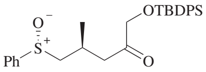
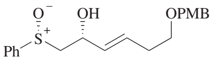
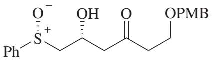
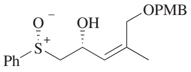
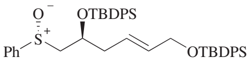
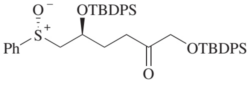
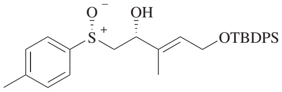
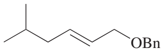
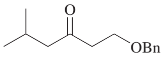
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°, 12 h	 (81)	98
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (1:1), O_2, 50°, 4 h	 (70)	348
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°	(—)	98
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°, 12 h	 (73)	98
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°	(0)	98
C_7			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 50°, 12 h	 (76)	100

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

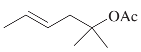
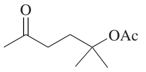
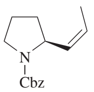
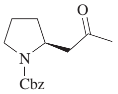
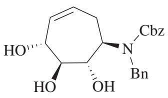
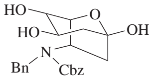
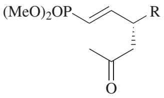
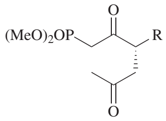
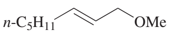
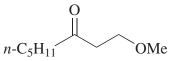
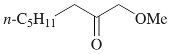
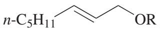
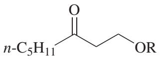
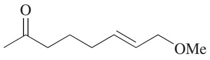
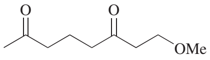
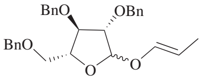
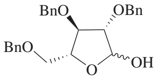
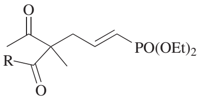
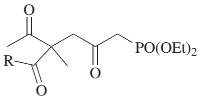
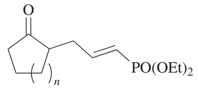
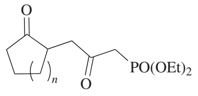
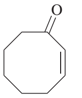
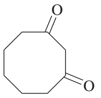
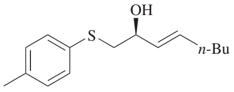
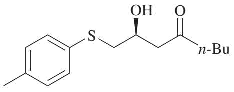
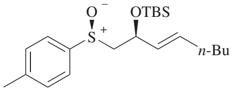
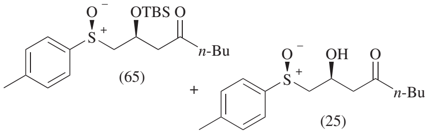
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_7			
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 50°	 (42)	100
	$PdCl_2$, CuCl, DMF/H_2O, O_2, 72°, 48 h	 (76)	349
	$PdCl_2$ (10 mol %), CuCl, DMF/H_2O, O_2, 50°	 (70)	350
$C_{7–12}$			
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (3:2), O_2, rt, 3 d	 R Me (80) $CH_3CH(OBn)CH_2$ (65) *i*-Bu (86) *n*-C_5H_{11} (80) *c*-C_6H_{11} (83) Ph (81)	96
C_8			
	$PdCl_2$ (10 mol %), DMA/H_2O (10:1), O_2 (3 atm), 80°, 20 h	 (80) +  (5)	50
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 50°, 12 h	 R Me (60) Ac (42)	100
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2, 50°, 12 h	 (64)	100
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (76)	82
$C_{8–9}$			
	Na_2PdCl_4 (37 mol %), TBHP (12 eq), *i*-PrOH, 60°, 15 h	 R EtO (67) Me (67)	351

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{8-10}			
	Na_2PdCl_4 (37 mol %), TBHP (12 eq), *i*-PrOH, 60°, 15 h	 *n* 1 (93) 2 (87) 3 (91)	351
C_8			
	$PdCl_2$ (10 mol %), TBHP (3 eq), AcOH/H_2O (1:1), 50°	 (37)	352
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°, 8 h	 (76)	98
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°, 12 h	 (65) + (25)	98

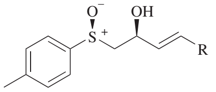
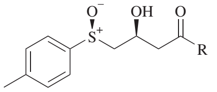
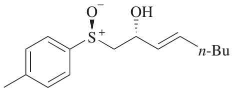
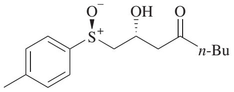
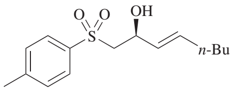
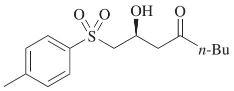
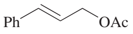
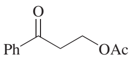
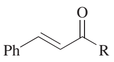
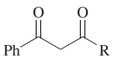
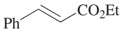
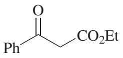
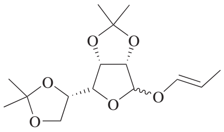
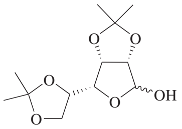
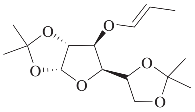
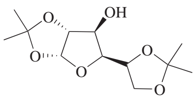
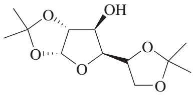
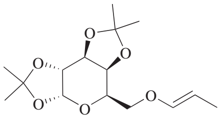
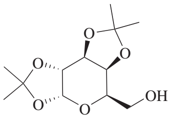
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{8-12}			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°, 12 h	 R / Time (h) *n*-Bu 12 (95) $BnCH_2$ — (89)	98
C_8			
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°, 12 h	 (95)	98
	$PdCl_2$ (10 mol %), CuCl (1 eq), DMF/H_2O, O_2, 65°, 8 h	 (83)	98
C_9			
	$Pd(OAc)_2$ (10 mol %), BQ (1 eq), HBF_4 (0.27 M), MeCN/H_2O (7:1), rt	 (80)	261
C_{9-10}			
	Pd–mont **3** (0.02 mol %), H_2O_2, AcOH, 80°	 R / Time (min) H 40 (98) Me 35 (98)	135

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	**2** (5 mol %), TBHP (1.5 eq), benzene/$C_8F_{17}Br$, 56°	 (59)	136
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (90)	82
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (81)	82
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O (10:1), rt, 1–6 h	 (88–93)	292
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (97)	82

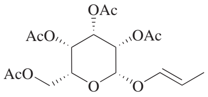
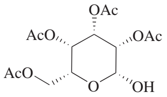
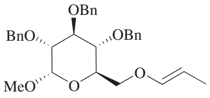
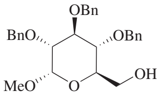
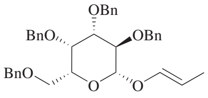
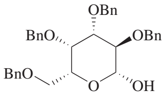
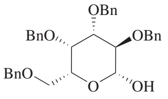
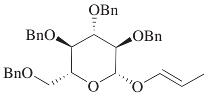
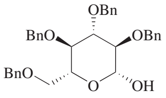
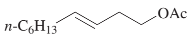
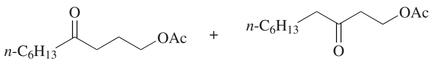
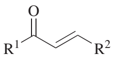
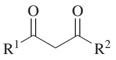
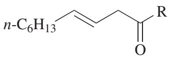
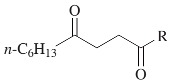
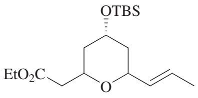
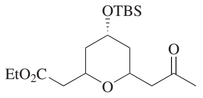
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (1 eq), CuCl (1 eq), DMF/H_2O, rt, 1–6 h	 (88–93)	292
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (75)	82
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (10:1), O_2, rt, 1–15 min	 (88–93)	292
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (86)	82
	$PdCl_2$ (20 mol %), CuCl (20 mol %), DMF/H_2O (10:1), O_2 (bubbled)	 (85)	82

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C$_{10}$			
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, 50°, 12 h	 **I** **I** + **II** (73), **I**/**II** = 88:12 **II**	100
	Na$_2$PdCl$_4$ (20 mol %), 70% TBHP in t-BuOH (1.2–2.0 eq), AcOH/H$_2$O (1:1), 50°	 R^1 R^2 Me n-C$_6$H$_{13}$ (59) Ph Me (59)	55
C$_{10–11}$			
	PdCl$_2$ (10 mol %), CuCl (1 eq), dioxane/H$_2$O (7:1), O$_2$, 50°, 12 h	 R MeO (61) Me (61)	97
C$_{10}$			
	PdCl$_2$ (20 mol %), CuCl (1.2 eq), DMF/H$_2$O (7:1), air (bubbled), rt, 48 h	 (86)	353

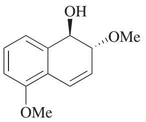
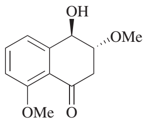
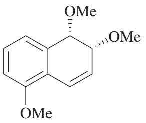
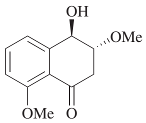
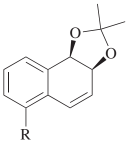
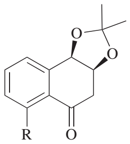
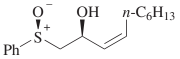
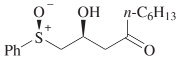
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	PdCl$_2$ (10 mol %), CuCl (1.1 eq), DMF/H$_2$O (9:1), O$_2$, 50°, 6 h	 (60)	354
	PdCl$_2$ (10 mol %), CuCl (1.1 eq), DMF/H$_2$O (9:1), O$_2$, 60°, 20 h	 (60)	354
	PdCl$_2$ (10 mol %), CuCl (1.1 eq), DMF/H$_2$O (9:1), O$_2$, 50°, 24 h	 R H (42) MeO (48)	355
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O, O$_2$, 65°, 12 h	 (78)	98

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

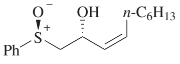
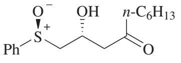
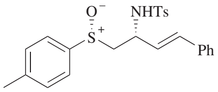
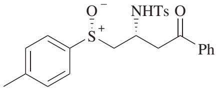
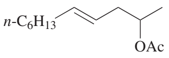
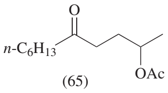
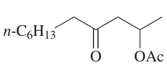
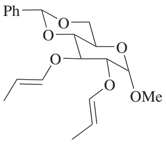
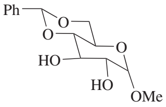
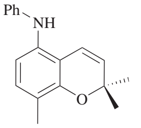
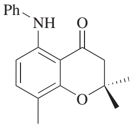
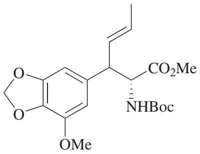
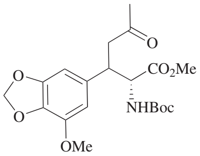
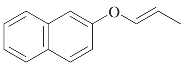
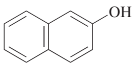
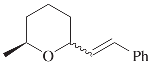
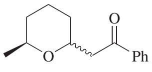
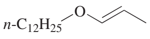
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O, O$_2$, 65°, 12 h	 (80)	98
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O, O$_2$, 65°, 12 h	 (85)	98
C_{11}			
	PdCl$_2$ (10 mol %), CuCl (1 eq), DMF/H$_2$O (7:1), O$_2$, 50°	 (65) +  (7)	100
C_{12}			
	PdCl$_2$ (*x*), CuCl (*y*), DMF/H$_2$O (10:1), O$_2$ (bubbled)	 *x* *y* 1 eq 1 eq (75) 20 mol % 20 mol % (75)	 292 82
	Pd(OAc)$_2$ (10 mol %), Cu(OAc)$_2$ (2.5 eq), AcOH/H$_2$O (10:1), 90°, 5 h	 (57)	356
	Pd(OAc)$_2$ (30 mol %), BQ (1.0 eq), HClO$_4$ (20 mol %), MeCN/H$_2$O (7:1), rt, 6 h	 (82)	357
C_{13}			
	PdCl$_2$ (20 mol %), CuCl (20 mol %), DMF/H$_2$O (10:1), O$_2$ (bubbled)	 (89)	82
C_{14}			
	PdCl$_2$ (50 mol %), CuCl (3 eq), DMF/H$_2$O (1:1), O$_2$, 50°, 72 h	 (35–44)	347
C_{15}			
	PdCl$_2$ (10 mol %), CuCl (10 mol %), DMF/H$_2$O (10:1), O$_2$ (bubbled)	n-C$_{12}$H$_{25}$OH (90)	82

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

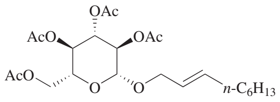
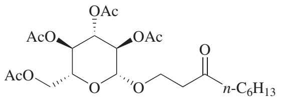
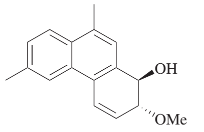
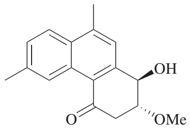
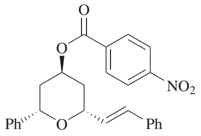
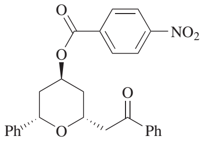
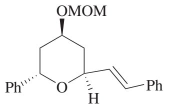
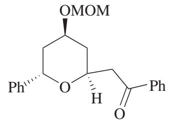
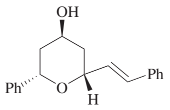
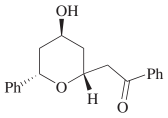
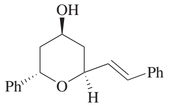
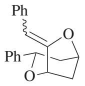
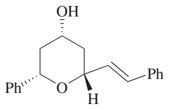
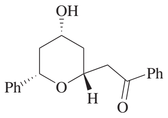
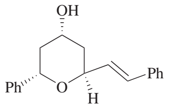
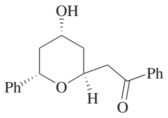
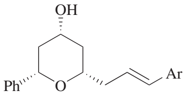
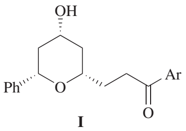
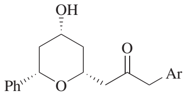
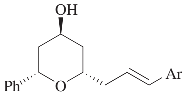
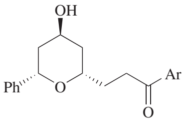
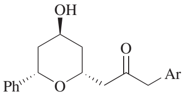
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{15}			
	$PdCl_2$ (3 eq), DMF/H_2O (6:1), 45°, 24 h	 (97)	358
C_{16}			
	$PdCl_2$ (10 mol %), CuCl (1.1 eq), DMF/H_2O (9:1), O_2, 50°, 6 h	 (70)	354
C_{19}			
	$PdCl_2$ (0.5 eq), CuCl (3 eq), DMF/H_2O (1:7), O_2, 50–55°, 3 d	 (89)	359
	$PdCl_2$ (50 mol %), CuCl (1.5 eq), DMF/H_2O (1:1), O_2, 50°, 3 d	 (55)	360
C_{19}			
	$PdCl_2$ (50 mol %), CuCl (1.5 eq), DMF/H_2O (1:1), O_2, 70° (microwave), 4 h	 (56)	360
	$PdCl_2$ (50 mol %), CuCl (1.5 eq), DMF/H_2O (1:1), O_2, 50°, 5 h	 (82)	360
	$PdCl_2$ (50 mol %), CuCl (1.5 eq), DMF/H_2O (1:1), O_2, 50°, 3 d	 (63)	360
	$PdCl_2$ (50 mol %), CuCl (1.5 eq), DMF/H_2O (1:1), O_2, 50°, 3 d	 (57)	360

TABLE 2B. WACKER OXIDATION OF INTERNAL ALKENES WITH PROXIMAL HETEROATOMS (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{20-21}			
	$PdCl_2$ (50 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2, 55°, 3 d	 **I** +  **II**	261

Ar	I	II
Ph	(24)	(18)
4-FC_6H_4	(26)	(21)
3-$CF_3C_6H_4$	(14)	(—)
4-$CF_3C_6H_4$	(16)	(17)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (50 mol %), CuCl (1 eq), DMF/H_2O (5:1), O_2, 55°, 3 d	 **I** +  **II**	261

Ar	I	II
Ph	(26)	(24)
4-FC_6H_4	(17)	(—)
3-$CF_3C_6H_4$	(9)	(22)
4-$CF_3C_6H_4$	(10)	(18)

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[a] The yield was determined by GC.

TABLE 3A. WACKER OXIDATION WITH EXOGENOUS NUCLEOPHILES RESULTING IN ACETALS

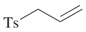
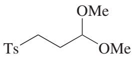
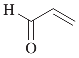
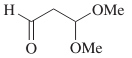
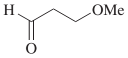
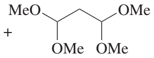
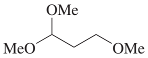
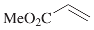
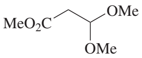
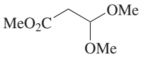
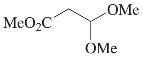
Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3				
	MeOH	$PdCl_2$ (50 mol %), $CuCl_2$ (3 eq), TMU (3 eq), EOA (40 mol %)	 (—)	362
	MeOH	$PdCl_2$, PS-BQ, O_2, sc-CO_2	 (20) +  (4) +  (47) +  (13)	363
	MeOH	$Pd(OAc)_2$ (8 wt %), NPMoV (3.2 mg/mmol), $MeSO_3H$ (3 mg/mmol), O_2, 50°, 8 h	 (95)	364
	MeOH (3.5 eq)	$PdCl_2$ (3 mol %), PS-BQ (40 mol %), O_2 (0.5 MPa), sc-CO_2 (14.5 MPa), 50°, 6 h	 (97)	365
	MeOH	$PdCl_2$ (2.5 mol %), CuCl (1 eq), DME, O_2, 50°, 48 h	 (97)	366

TABLE 3A. WACKER OXIDATION WITH EXOGENOUS NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

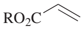
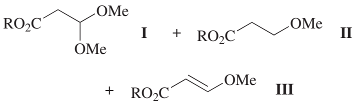
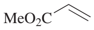
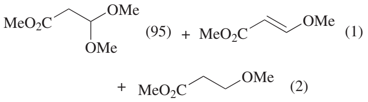
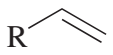
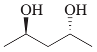
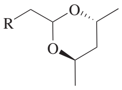
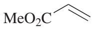
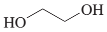
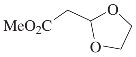
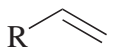
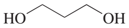
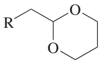
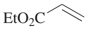
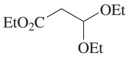
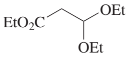
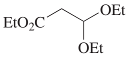
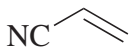
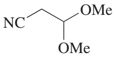
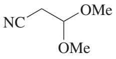
Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3				
	MeOH	$PdCl_2$ (3 mol %), PS-BQ (40 mol %), O_2 (0.5 MPa), sc-CO_2 (*x* MPa), 50°	 R / *x* / Time (h) / **I** / **II** / **III** Me / 9.5 / 12 / (96) / (0.5) / (3.1) Et / 9.5 / 12 / (85) / (0) / (9) *n*-Bu / 14.5 / 6 / (78) / (0) / (1)	363
	MeOH	$PdCl_2$ (3 mol %), $CuCl_2$ (0.8 eq), O_2 (1 MPa), sc-CO_2 (12 MPa), 40°		367
	 (1 eq)	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, O_2, 50°, 20 h	 R MeO_2C (79) NC– (45)	102
	 (1 eq)	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, O_2, 50°, 20 h	 (72)	102
	 (2 eq)	$Pd(MeCN)_2Cl_2$ (10 mol %), $BiCl_3$/LiCl (1:1, 20 mol %), Na_2HPO_4, DME, O_2, 65°, 48 h	 R MeO_2C (67) NC– (15)	101
	EtOH	[$Pd(OAc)_2$ (8 wt %), NPMoV/C (13 wt %)] (25 mg/mmol), $MeSO_3H$ (3 mg/mmol), O_2, 50°, 20 h	 (83)	364
	EtOH	Pd/C (10 wt %, 17 mg/mmol), NPMoV (2 mg/mmol), $MeSO_3H$ (2 mg), O_2, 50°, 12 h	 (95)	364
	EtOH	$Pd(OAc)_2$ (8 wt %, 25 mg/mmol), NPMoV (3 mg/mmol), $MeSO_3H$ (3 mg), O_2, 50°, 20 h	 (96)	364
	MeOH	$PdCl_2$ (3 mol %), PS-BQ (40 mol %), O_2, sc-CO_2 (8.5 MPa), 50°, 12 h	 (79)	363
	MeOH	$Pd(OAc)_2$ (8 wt %), NPMoV (22 mg/mmol), $MeSO_3H$ (10 mg/mmol), O_2, 60°, 20 h	 (96)	364

TABLE 3A. WACKER OXIDATION WITH EXOGENOUS NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

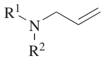
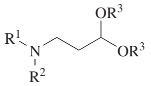
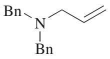
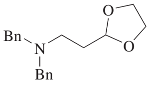
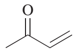
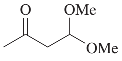
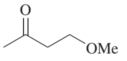
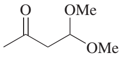
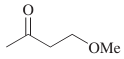
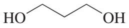
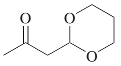
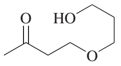
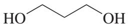
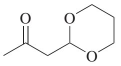
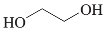
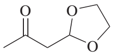
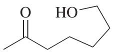
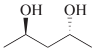
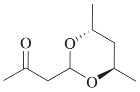
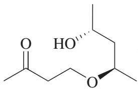
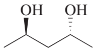
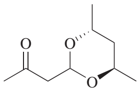
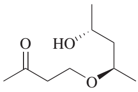
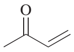
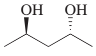
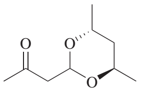
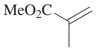
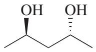
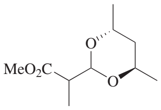
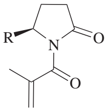
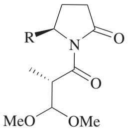
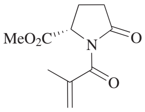
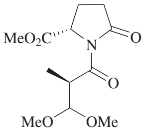
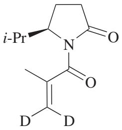
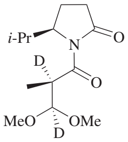
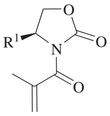
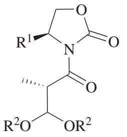
Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3				
	R^3OH	Li_2PdCl_4 (10 mol %), $CuCl_2$ (3 eq), 50°	 R^1 / R^2 / R^3 / Time (h) Me / Ph(Me)CH / Me / 8 / (76) Et / Et / Et / 70 / (85) Bn / Bn / Me / 10 / (81) Bn / Bn / Et / 20 / (81) Bn / Ph(Me)CH / Me / 10 / (82)	104
	$(CH_2OH)_2$/THF 1:5	Li_2PdCl_4 (10 mol %), $CuCl_2$ (3 eq), 50°, 70 h	 (74)	104
C_4				
	MeOH	$PdCl_2$ (3 mol %), PS-BQ (40 mol %), O_2 (0.5 MPa), sc-CO_2 (7.5 MPa), 50°, 12 h	 (77) +  (13)	363
	MeOH	$PdCl_2$ (10 mol %), CuCl (60 mol %), O_2 (0.5 MPa), sc-CO_2, 50°, 12 h	 (87) +  (13)	368
	 1 eq	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, O_2, 50°, 20 h	 (45) +  (~5)	102
	 2 eq	$Pd(MeCN)_2Cl_2$ (10 mol %), additive (20 mol %), Na_2HPO_4, DME, O_2, 65°, 24 h	 Additive $BiCl_3$/LiCl (1:1) (68) CuCl (69)	101
	 1 eq	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, O_2, 50°, 20 h	 (33) +  (~5)	102
	 1 eq	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, O_2, 50°, 20 h	 (66) +  (12)	102
	 1 eq	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_2 (10 mol %), DME, 50°, 20 h	 (69) +  (0)	102

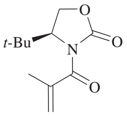
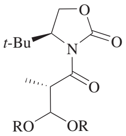
TABLE 3A. WACKER OXIDATION WITH EXOGENOUS NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C_4				
	 1 eq	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, 50°, 20 h	 (57)	181
	 1 eq	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, O_2, 50°, 20 h	 (25) dr 3:2	102
	MeOH	$PdCl_2$ (10 mol %), CuCl (1.0 eq), O_2		103

R	Solvent	Temp	Time (h)		dr
Me	DME	rt	96	(61)	61.5:38.5
t-Bu	CH_2Cl_2	rt	80	(89)	97.5:2.5
Ph	DME	50°	24	(92)	85.5:14.5
Ph	CH_2Cl_2	rt	96	(88)	90:10
Bn	DME	rt	96	(30)	65:35

Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
	MeOH	$PdCl_2$ (10 mol %), CuCl (1.0 eq), DME, O_2, rt	 (—) dr 7:3	103
	MeOH	$PdCl_2$ (10 mol %), CuCl (1.0 eq), DME, O_2, rt	 (82) dr 75:25	103
	R^2OH	$PdCl_2$ (10 mol %), CuCl (1.0 eq), DME, O_2, rt		103

R^1	R^2		dr
i-Pr	Me	(27)	85:15
i-Pr	Et	(55)	84:16
i-Pr	*n*-Pr	(24)	85.5:14.5
i-Pr	*i*-Pr	(22)	84:16
t-Bu	Me	(48)	98:2
t-Bu	Et	(56)	98:2
t-Bu	*n*-Pr	(45)	99.5:0.5
t-Bu	*i*-Pr	(39)	>99:1

Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
	ROH (*x* eq)	$PdCl_2$ (10 mol %), CuCl (1.0 eq), DME, O_2		103

R	*x*	Temp	Time (h)		dr
Me	10	50°	24	(72)	71.5:28.5
Me	25	rt	96	(66)	80.5:19.5
Me	50	rt	19	(54)	82:18
Et	10	50°	24	(76)	71.5:28.5
n-Pr	10	50°	24	(75)	74:26

TABLE 3A. WACKER OXIDATION WITH EXOGENOUS NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

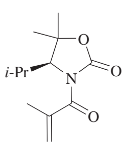
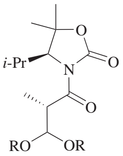
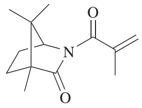
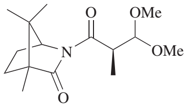
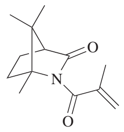
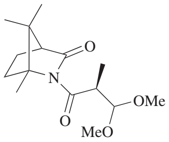
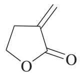
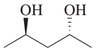
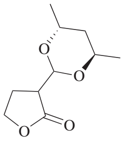
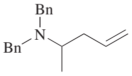
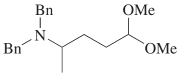
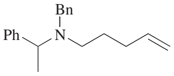
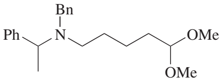
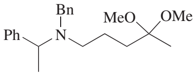
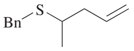
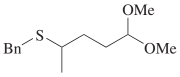
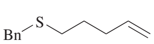
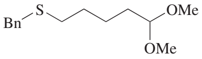
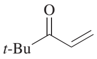
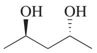
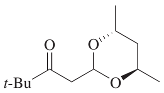
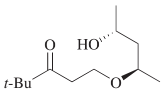
Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C_4				
	ROH	$PdCl_2$ (10 mol %), CuCl (1.0 eq), DME, O_2, rt	 R (yield) dr Me (82) 85:15 Et (72) 92.5:7.5 *n*-Pr (60) 93.5:6.5 *i*-Pr (32) 93.5:6.5	103
	MeOH	$PdCl_2$ (10 mol %), CuCl (1.0 eq), CH_2Cl_2, O_2, rt, 80 h	 (78) dr 84:16	103
	MeOH	$PdCl_2$ (10 mol %), CuCl (1.0 eq), CH_2Cl_2, O_2, rt, 80 h	 (40) dr 75:25	103
C_5				
	 1 eq	$PdCl_2$ (10 mol %), CuCl (1 eq), DME, O_2, 50°, 20 h	 (61) dr 52:48	102
	MeOH	Li_2PdCl_4 (10 mol %), $CuCl_2$ (3 eq), 50°, 72 h	 (69)	104
	MeOH	Li_2PdCl_4 (10 mol %), $CuCl_2$ (3 eq), 50°, 72 h	 (45) +  (48)	104
	MeOH	Li_2PdCl_4 (20 mol %), $CuCl_2$ (3 eq), 50°, 60 h	 (55)	104
	MeOH	Li_2PdCl_4 (20 mol %), $CuCl_2$ (3 eq), 50°, 60 h	 (55)	104
C_7				
	 1 eq	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 20 h	 (64) +  (0)	102

TABLE 3A. WACKER OXIDATION WITH EXOGENOUS NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

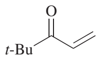
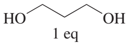
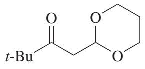
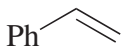
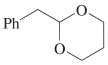
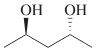
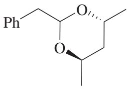
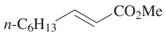
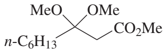
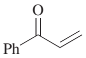
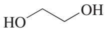
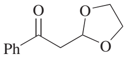
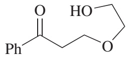
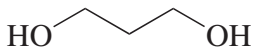
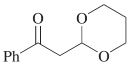
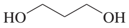
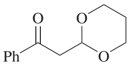
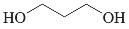
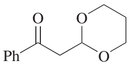
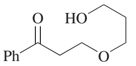
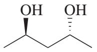
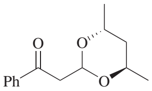
Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C$_7$				
	 1 eq	PdCl$_2$ (10 mol %), CuCl (1 eq), DME, O$_2$, 50°, 20 h	 (52)	102
C$_8$				
	 2 eq	Pd(MeCN)$_2$Cl$_2$ (10 mol %), additive, O$_2$, DME, 65°, 48 h	 Additive BiCl$_3$/LiCl (1:1, 20 mol %), Na$_2$HPO$_4$ (35) CuCl (20 mol %) (80)	101
	 1 eq	PdCl$_2$ (10 mol %), CuCl (1 eq), DME, O$_2$, 50°, 20 h	 (79)	102
C$_9$				
	MeOH	PdCl$_2$ (10 mol %), CuCl (3 eq), CuCl$_2$ (3 eq), O$_2$, 14 d	 (20)	105
	 1 eq	PdCl$_2$ (10 mol %), CuCl (*x*), additive, DME, O$_2$, 50°, 20 h	 **I** +  **II** *x* / Additive / **I** / **II** 1 eq / none / (20) / (10) 10 mol % / Na$_2$HPO$_4$ (10 mol %) / (55) / (0)	102
	 2 eq	Pd(MeCN)$_2$Cl$_2$ (10 mol %), additive (20 mol %), Na$_2$HPO$_4$ (20 mol %), DME, O$_2$, 65°	 Additive / Time (h) BiCl$_3$/LiCl (1:1) / 24 / (85) CuCl / 48 / (71)	101
		PdCl$_2$ (10 mol %), CuCl (1 eq), DME, O$_2$, 50°, 20 h	 (59)	181
	 1 eq	PdCl$_2$ (10 mol %), CuCl (*x*), additive, DME, O$_2$, 50°, 20 h	 **I** +  **II** *x* / Additive / **I** / **II** 1 eq / none / (42) / (14) 10 mol % / Na$_2$HPO$_4$ (10 mol %) / (82) / (0)	102
		PdCl$_2$ (10 mol %), CuCl (1 eq), DME, O$_2$, 50°, 20 h	 (86)	181

TABLE 3A. WACKER OXIDATION WITH EXOGENOUS NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

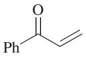
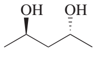
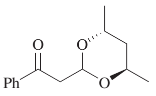
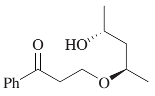
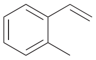
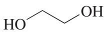
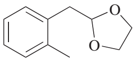
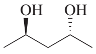
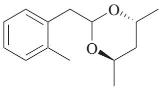
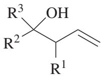
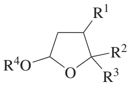
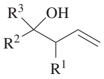
Alkene	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9				
	 1 eq	$PdCl_2$ (10 mol %), CuCl (*x*), additive, DME, O_2, 50°, 20 h	 **I** +  **II** *x* / Additive / **I** / **II** 1 eq / none / (41) / (33) 10 mol % / Na_2HPO_4 (10 mol %) / (75) / (0)	102
	 1 eq	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 20 h	 (77)	102
	 1 eq	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 20 h	 (84)	102

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{4–16}$			
	$Pd(MeCH)_2Cl(NO_2)$ (5 mol %), $CuCl_2$ (20 mol %), R^4OH, O_2, 30°	 **I** +  **II**	369

R^1	R^2	R^3	R^4	Time (h)	**I**	**II**
H	H	H	*i*-Pr	3	(—)	(70)
H	H	H	*t*-Bu	16	(30)	(0)
H	Me	Me	*i*-Pr	2	(50)	(0)
H	Me	Me	*t*-Bu	2	(80)	(0)
H	Me	Et	*i*-Pr	100	(55)	(0)
H	Me	Et	*t*-Bu	40	(70)	(0)
H	Ph	Ph	*i*-Pr	16	(70)	(0)
H	Ph	Ph	*t*-Bu	4	(32)	(0)
Me	Me	Me	*i*-Pr	1	(60)	(0)
Me	Me	Me	*t*-Bu	2	(70)	(0)

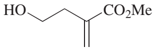
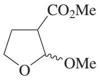
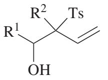
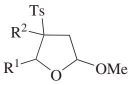
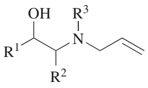
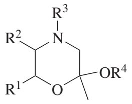
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_5			
	$Pd(MeCN)_2Cl_2$ (10 mol %), CuCl (20 mol %), MeOH (3 eq), Na_2HPO_4 (15 mol %), DME, O_2, 50°, 1 h	 (52) dr 70:30	370

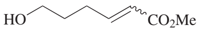
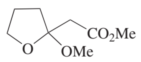
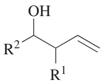
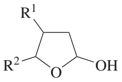
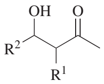
TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{5-13}			
	$PdCl_2$ (50 mol %), $CuCl_2$ (3 eq), TMU (5 eq), EOA (40 mol %), MeOH, reflux		362

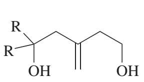
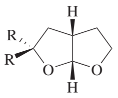
dr	R^1	R^2	Time (h)		dr
—	H	Bn	10	(23)	53:47
56:44	Me	H	5	(69)	62(2):38(2)
51:49	*i*-Bu	H	5	(81)	37:33:20:10
64:36	Ph	H	5	(69)	37:22:21:20
55:45	$BnCH_2$	H	5	(95)	44:32:15:9
57:43	*n*-C_9H_{19}	H	5	(79)	45:32:20(2)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{5-12}			
	Li_2PdCl_4 (10 mol %), $CuCl_2$ (3 eq), rt		106

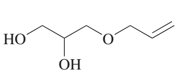
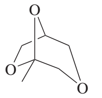
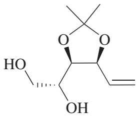
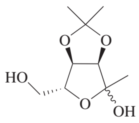
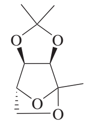
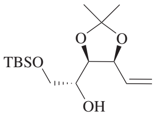
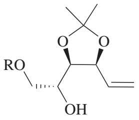
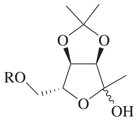
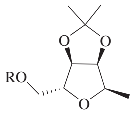
R^1	R^2	R^3	R^4	Time (h)	Solvent		de	
H	H	(*S*) Ph(Me)CH	Me	36	MeOH	(76)	<1	—
Me	H	(*S*) Ph(Me)CH	Me	36	MeOH	(83)	76	(2*R*,6*S*,*S*)
Me	H	(*R*) Ph(Me)CH	Me	36	MeOH	(92)	71	(2*R*,6*S*,*R*)
Me	H	Bn	Me	36	MeOH	(96)	91	(2*R*,6*S*)
Me	H	(*S*) Ph(Me)CH	H	24	THF/H_2O (1:10)	(84)	87	(2*R*,6*S*,*S*)
Me	H	Bn	H	24	THF/H_2O (1:10)	(78)	91	(2*R*,6*S*)
Ph	Me	(5*S*,6*R*) Me	H	48	THF/H_2O (1:10)	(74)	>99	(2*S*,5*S*,6*R*)
Ph	Me	(2*S*,5*R*) Me	Me	48	MeOH	(73)	>99	(2*R*,5*S*,6*R*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	$PdCl_2$ (10 mol %), CuCl (3 eq), $CuCl_2$ (3 eq), MeOH, O_2, 22 h	 (62)	105
C_{6-17}			
	$PdCl_2$ (10 mol %), BQ (3 eq), DMF/H_2O (50:1)	 **I** +  **II**	300

R^1	R^2	Temp	Time (h)	**I**	**II**
BnO	PhO_2CCH_2	rt	8	(81)	(—)
BnO	PhO_2CCH_2	rt	18	(87)	(—)
Me	*n*-C_6H_{13}	rt	3	(43)	(10)
MeO_2C	*n*-C_6H_{13}	40°	2	(62)	(—)
$MeO_2C(CH_2)_7$	H	rt	6	(58)	(—)
Ts	(*E*)-$CH_3CH{=}CH$	rt	80	(50)	(10)
Ts	*n*-C_6H_{13}	40°	12	(82)	(—)
$MeO_2C(CH_2)_7$	*n*-C_5H_{11}	60	6	(74)	(—)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{6-8}			
	$PdCl_2$ (5 mol %), $CuCl_2$ (0.5 eq), H_2O_2 (10 eq), 70°, 24 h		371

R	Solvent	
H	MeOH	(20)
EtO_2C	EtOH	(53)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	$PdCl_2$ (5 mol %), $CuCl_2$ (24 mol %), DME, air, 65°, 40 h	 (21)	372
	$PdCl_2$ (10 mol %), CuCl (1 eq), $MeCN/H_2O$ (1:7), O_2 (bubbled), rt, 0.5–2 h	 **I** (—) +  **II** (—) **I/II** = 8:1	373
	$PdCl_2$ (10 mol %), CuCl (1 eq), $MeCN/H_2O$ (7:1), O_2 (bubbled), rt, 0.5–2 h	(0)	373
	$PdCl_2$ (10 mol %), CuCl (1 eq), $MeCN/H_2O$ (7:1), O_2 (bubbled), rt, 0.5–2 h	 **I** +  **II** R / **I + II** / **I/II** Bn / 75–87 / 8:1 Bz / 75–87 / 7:1	373

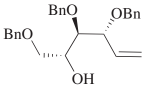
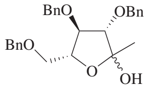
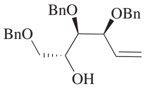
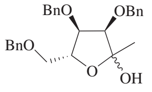
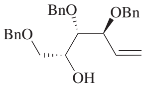
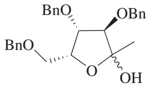
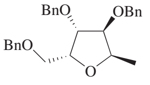
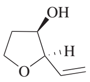
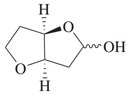
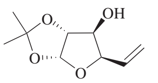
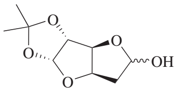
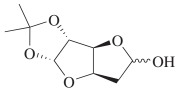
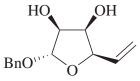
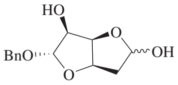
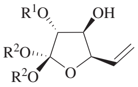
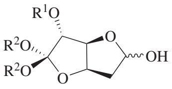
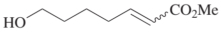
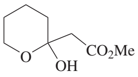
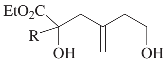
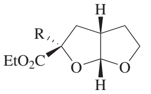
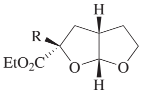
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (10 mol %), CuCl (1 eq), $MeCN/H_2O$ (7:1), O_2 (bubbled), rt, 0.5–2 h	 (75–87)	373
	$PdCl_2$ (10 mol %), CuCl (1 eq), $MeCN/H_2O$ (7:1), O_2 (bubbled), rt, 0.5–2 h	 (75–87)	373
	$PdCl_2$ (10 mol %), CuCl (1 eq), $MeCN/H_2O$ (7:1), O_2 (bubbled), rt, 0.5–2 h	 **I** +  **II** **I** + **II** (75–87), **I/II** = 3:1	373
	$PdCl_2$ (5 mol %), CuCl (1 eq), $MeCN/H_2O$ (4:1), air (bubbled), rt, 8 h	 (82)	374
	$PdCl_2$ (20 mol %), CuCl (1.5 eq), aq DMF, air (bubbled), rt, 4 h	 (83)	375
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2	 (83)	270

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	$PdCl_2$ (20 mol %), CuCl (1 eq), DMF/H_2O (7:1), O_2	 (81)	270
	$PdCl_2$ (20 mol %), CuCl (1 eq), solvent/H_2O (7:1), O_2	 R^1 | R^2 | Solvent H | Bn | MeCN | (77) TBS | Me | DMF | (81) CH_2=C(Br)CH_2 | Me | DMF | (63)	270
C_7			
	$PdCl_2$ (10 mol %), CuCl (3 eq), $CuCl_2$ (3 eq), THF/H_2O, O_2	 (31)	105
C_{7-8}			
	$PdCl_2$ (5 mol %), $CuCl_2$ (0.5 eq), H_2O_2 (10 eq), EtOH, 70°, 24 h	 **I** +  **II** R | **I** | **II** H | (49) | (15) Me | (21) | (32) CF_3 | (15) | (30)	371

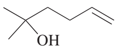
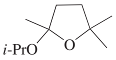
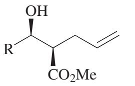
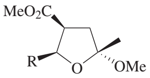
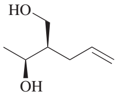
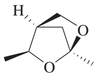
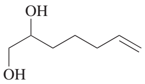
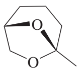
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_7			
	$Pd(MeCN)_2Cl(NO_2)$ (5 mol %), $CuCl_2$ (20 mol %), *i*-PrOH, 1 h	 (40)	369
C_{7-9}			
	$Pd(MeCN)_2Cl_2$ (10 mol %), CuCl (20 mol %), MeOH (3 eq), Na_2HPO_4 (15 mol %), Et_2O, O_2, 50°, 1 h	 R | | dr Me | (71) | 94:6 *n*-Pr | (80) | 90.5:9.5	370
C_7			
	$Pd(MeCN)_2Cl_2$ (5 mol %), CuCl (5 mol %), MeOH (3 eq), Et_2O, O_2, 30°, 1 h	 (63)	370
	$PdCl_2$ (5 mol %), $CuCl_2$ (24 mol %), DME, air, 65°, 40 h	 (30)	372

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

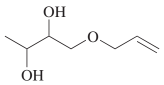
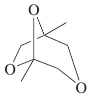
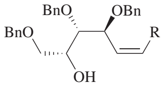
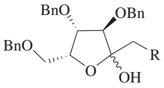
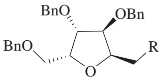
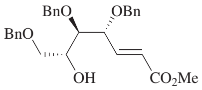
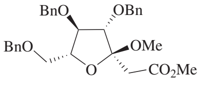
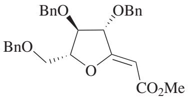
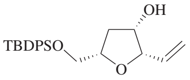
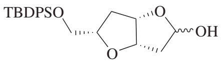
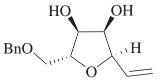
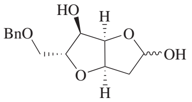
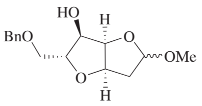
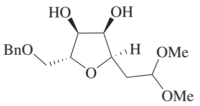
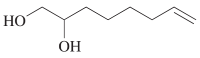
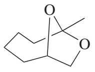
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_7			
	$PdCl_2$ (5 mol %), $CuCl_2$ (24 mol %), DME, air, 65°, 40 h	 (20) *endo*/*exo* = 5:1	372
$C_{7–8}$			
	$PdCl_2$ (10 mol %), CuCl (1 eq), $MeCN/H_2O$ (7:1), O_2 (bubbled), rt, 0.5–2 h	 **I** +  **II** R **I + II** **I/II** Me 75–87 3.5:1 Et 75–87 3.5:1	373
C_7			
	$PdCl_2$ (10 mol %), CuCl (3 eq), $CuCl_2$ (3 eq), MeOH, O_2, 50°, 8 h	 (43) +  (17)	105
	$PdCl_2$ (19 mol %), CuCl (1 eq), DMF/H_2O (4:1), O_2, rt	 (69)	376
	$PdCl_2$ (20 mol %), CuCl (1 eq), $MeCN/H_2O$ (10:1), O_2 (bubbled), rt, 2 h	 (83)	377
	$PdCl_2$ (19 mol %), CuCl (1 eq), MeOH, O_2 (bubbled), rt, 6 h	 (48) +  (36)	377
C_8			
	$PdCl_2$, $CuCl_2$, DME	 (58)	378

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

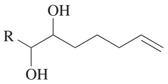
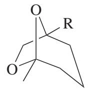
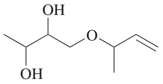
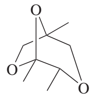
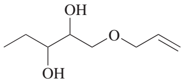
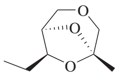
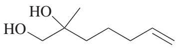
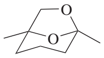
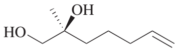
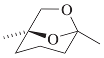
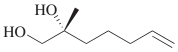
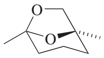
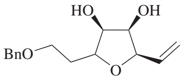
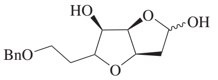
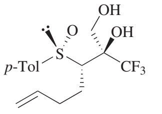
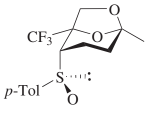
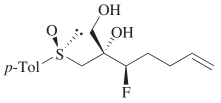
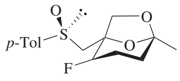
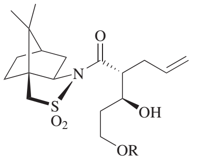
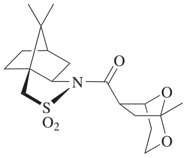
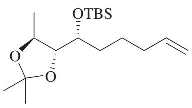
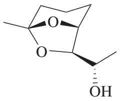
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{8–9}$			
	$PdCl_2$ (5 mol %), $CuCl_2$ (24 mol %), DME, air, 65°, 24 h	 R Me (49) Et (45)	372
C_8			
	$PdCl_2$ (5 mol %), $CuCl_2$ (24 mol %), DME, air, 65°, 40 h	 (19) mixture of isomers	372
	$PdCl_2$ (5 mol %), $CuCl_2$ (24 mol %), DME, air, 65°, 40 h	 (40)	372
	$PdCl_2$, $CuCl_2$, DME	 (50)	379
	$PdCl_2$ (10 mol %), CuCl (1 eq), triglyme, O_2, 50°	 (76)	380
	$PdCl_2$ (10 mol %), CuCl (1 eq), triglyme, O_2, 50°	 (—)	380
	$PdCl_2$ (2 mol %), CuCl (1 eq), DMF/H_2O (4:1), O_2 (bubbled), rt, 24 h	 (84)	381
	$PdCl_2$ (18 mol %), $CuCl_2$ (1 eq), DME, air (bubbling)	 (72)	107
	$PdCl_2$ (0.84 eq), $CuCl_2$ (1.5 eq), DME, air (bubbling)	 (80)	107
	$PdCl_2$ (5 mol %), $CuCl_2$, DME, O_2, 65°	 R H (60) TBS (60)	382
C_9			
	$PdCl_2$ (20 mol %), CuCl (13 eq), DMF/H_2O (4:1), O_2, rt, 6 h	 (74)	108

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

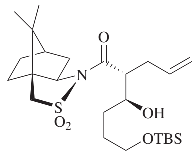
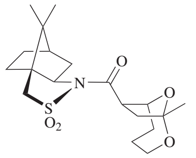
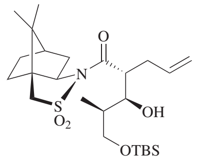
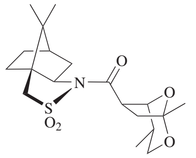
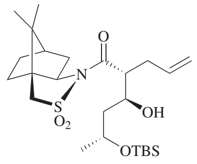
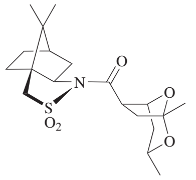
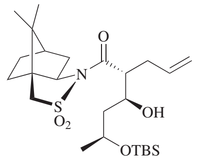
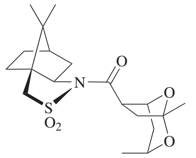
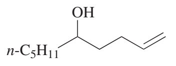
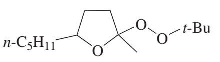
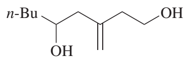
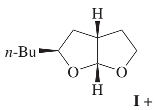
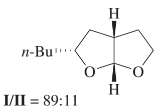
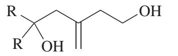
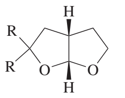
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	PdCl$_2$ (5 mol %), CuCl$_2$, DME, O$_2$, 65°	 (91)	382
	PdCl$_2$ (5 mol %), CuCl$_2$, DME, O$_2$, 65°	 (60)	382
	PdCl$_2$ (5 mol %), CuCl$_2$, DME, O$_2$, 65°	 (65)	382
	PdCl$_2$ (5 mol %), CuCl$_2$, DME, O$_2$, 65°	 (50)	382
C_{10}			
	Pd(Quinox)Cl$_2$ (3 mol %), AgSbF$_6$ (7.5 mol %), aq TBHP (12 eq), CH$_2$Cl$_2$, 0° to rt	 (81)	86
	PdCl$_2$ (5 mol %), CuCl$_2$ (50 mol %), H$_2$O$_2$ (10 eq), MeOH, 70°, 24 h	 **I** +  **II** **I** + **II** (31), **I**/**II** = 89:11	383
C_{10-18}			
	PdCl$_2$ (5 mol %), CuCl$_2$ (50 mol %), H$_2$O$_2$ (10 eq), MeOH, 70°, 24 h	 R Et (58) Ph (31)	383

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

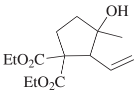
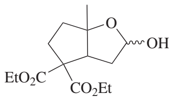
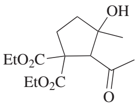
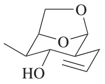
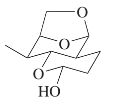
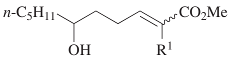
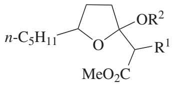
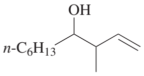
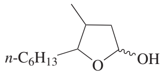
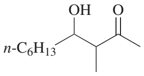
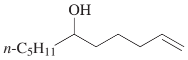
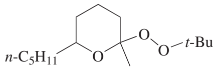
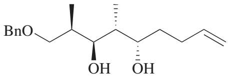
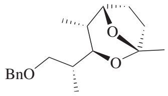
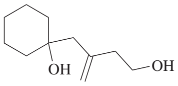
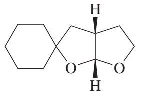
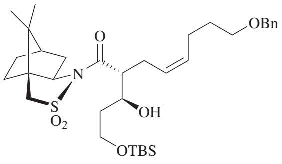
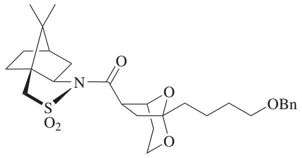
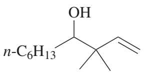
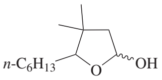
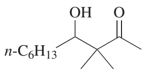
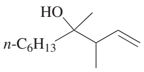
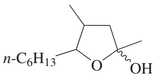
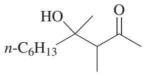
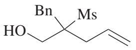
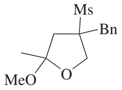
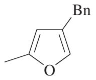
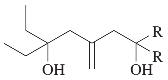
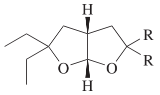
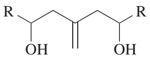
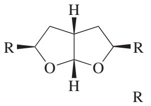
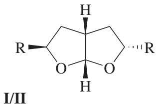
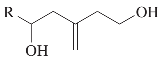
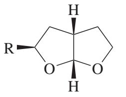
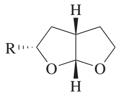
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
	$PdCl_2$ (10 mol %), BQ (3 eq), DMF (2% H_2O), rt, 10 h	 (61) +  (21)	300
	$PdCl_2$, $CuCl_2$, DMF/H_2O, O_2, rt	 (62)	384
C_{11-12}			
	$PdCl_2$ (10 mol %), CuCl (3 eq), $CuCl_2$ (3 eq), O_2	 R^1 R^2 Solvent Time (h) H H THF/H_2O — (87) H Me MeOH 4 (87) Me Me MeOH 76 (54)	105
C_{11}			
	$PdCl_2$ (10 mol %), CuCl, DMF/H_2O (50:1), O_2, 40°, 8 h	 (64) +  (—)	300
	Pd(Quinox)Cl_2 (3 mol %), $AgSbF_6$ (7.5 mol %), aq TBHP (12 eq), CH_2Cl_2, 0° to rt	 (83)	86
	$PdCl_2$ (20 mol %), $CuCl_2$ (20 mol %), THF, O_2, 0°, 4 d	 (88)	385
	$PdCl_2$ (5 mol %), $CuCl_2$ (50 mol %), H_2O_2 (10 eq), MeOH, 70°, 24 h	 (42)	383
	$PdCl_2$ (5 mol %), $CuCl_2$, DME, O_2, 65°	 (39)	382

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{12}			
	$PdCl_2$ (10 mol %), BQ (3 eq), DMF/H_2O (50:1), rt, 26 h	 (62) +  (6)	300
	$PdCl_2$ (10 mol %), BQ (3 eq), DMF/H_2O (50:1), 40°, 3 h	 (61) +  (—)	300
	$PdCl_2$ (50 mol %), $CuCl_2$ (3 eq), TMU (5 eq), EOA (40 mol %), MeOH, rt, 45 min	 (81) +  (7)	362
$C_{12–14}$			
	$PdCl_2$ (5 mol %), $CuCl_2$ (50 mol %), MeOH, H_2O_2 (5 eq), 70°, 8 h	 R Me (55) Et (94)	386
	$PdCl_2$ (5 mol %), $CuCl_2$ (50 mol %), H_2O_2 (5 eq), MeOH, 70°, 8 h	 **I** +  **II**	386

R	I + II	I/II
i-Pr	(86)	1:1
t-Bu	(86)	94:6

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{12}			
	$PdCl_2$ (5 mol %), $CuCl_2$ (*x*), H_2O_2 (10 eq), MeOH, 70°	 **I** +  **II**	

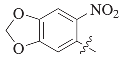
R	*x*	Time (h)	**I**	**II**	**I + II**	**I/II**	
c-C_6H_{11}	50 mol %	24	(—)	(—)	(30)	93:7	383
Ph	50 mol %	24	(—)	(—)	(35)	85:15	383
2,3,4,5,6-F_5C_6	0.5 eq	48	(49)	(11)	(—)	—	371
	0.5 eq	48	(42)	(6)	(—)	—	371

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

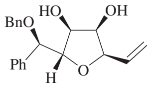
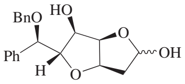
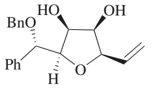
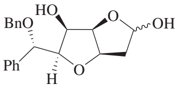
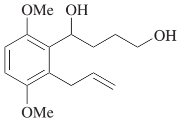
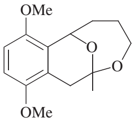
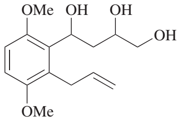
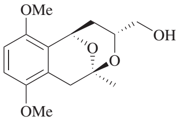
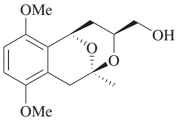
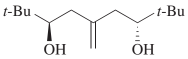
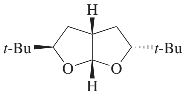
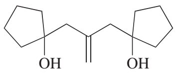
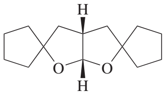
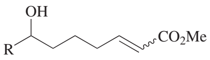
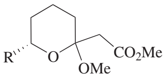
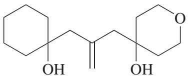
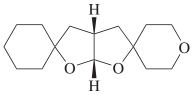
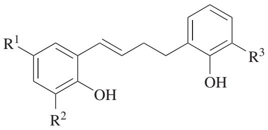
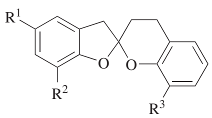
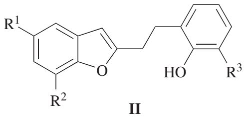
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{13}			
	$PdCl_2$ (19 mol %), CuCl (1 eq), DMF/H_2O (4:1), O_2, rt, 4 h	 (81)	387
	$PdCl_2$ (19 mol %), CuCl (1 eq), DMF/H_2O (4:1), O_2, rt, 4 h	 (83)	388
	$PdCl_2$ (10 mol %), $CuCl_2$ (1.0 eq), DMF/H_2O (1:1), O_2, 70°, 2 h	 (72)	211
	$PdCl_2$ (10 mol %), $CuCl_2$ (1.0 eq), DMF/H_2O (1:1), O_2, 70°, 2 h	 +  **I** **I** + **II** (67), **I/II** (2.3:1) **II**	211
C_{14}			
	$PdCl_2$ (5 mol %), $CuCl_2$ (50 mol %), MeOH, H_2O_2 (5 eq), 70°, 8 h	 (78)	386
	$PdCl_2$ (5 mol %), $CuCl_2$ (50 mol %), MeOH, H_2O_2 (5 eq), 70°, 8 h	 (92)	386
	$PdCl_2$ (10 mol %), CuCl (3 eq), LiCl (*x* eq), $CuCl_2$ (3 eq), MeOH, O_2, 50°	 R | *x* | Time (h) | *n*-C_7H_{15} | 6 | 48 | (79) *n*-C_7H_{15} | 0 | 24 | (72) Bn | 6 | 44 | (61)	105
C_{15}			
	$PdCl_2$ (5 mol %), $CuCl_2$ (50 mol %), MeOH, H_2O_2 (5 eq), 70°, 8 h	 (71)	386

TABLE 3B. WACKER OXIDATION WITH INTRAMOLECULAR NUCLEOPHILES RESULTING IN ACETALS (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{16–22}$			
	$PdCl_2$ (10 mol %), $CuCl_2$ (20 mol %), MeOH, O_2, 60°	 **I** +  **II**	389

R^1	R^2	R^3	Time (h)	**I**	**II**
H	H	H	10	(65)	(28)
H	MeO	H	8	(71)	(22)
H	H	MeO	13	(—)	(47)
Cl	H	H	16	(45)	(42)
Me	H	H	10	(63)	(27)
EtO_2C	H	H	22	(36)	(28)
t-Bu	H	H	11	(60)	(25)
Ph	H	H	14	(50)	(32)

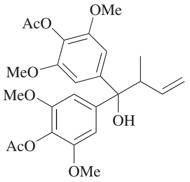
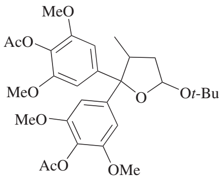
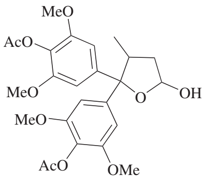
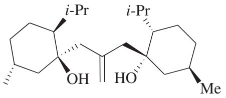
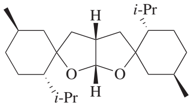
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{17}			
	$Pd(CH_3CN)_2Cl(NO_2)$, $CuCl_2$, O_2, *t*-BuOH, rt, 6 h	 **I** +  **II** **I** + **II** (77), **I/II** = 1:1	390
C_{24}			
	$PdCl_2$ (10 mol %), $CuCl_2$ (1 eq), MeOH, H_2O_2 , 70°, 24 h	 (55)	386

TABLE 3C. INTERMOLECULAR AZA–WACKER OXIDATION

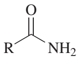
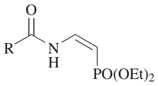
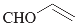
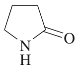
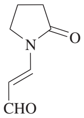
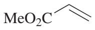
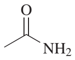
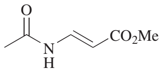
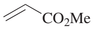
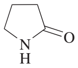
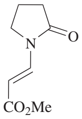
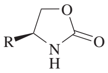
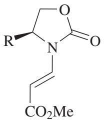
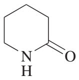
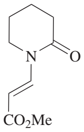
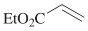
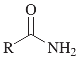
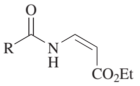
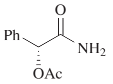
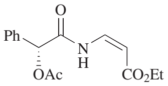
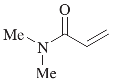
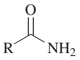
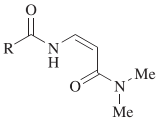
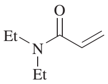
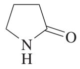
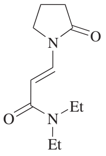
Alkene	Amine	Conditions	Product(s) and Yield(s) (%)	Refs.
C_2				
 3 eq		Pd(PhCN)$_2$Cl$_2$ (5 mol %), CuCl (10 mol %), TEMDP (10 mol %), chlorobenzene, O$_2$ (1 atm), 70°, 48 h	 R CH$_2$=C(Me) (73) *t*-Bu (77) Ph (59)	109
C_3				
	 1 eq	Pd(MeCN)$_2$Cl$_2$ (5 mol %), HMPA (5 mol %), DME, O$_2$ (1 atm), 60°, 24 h	 (67)	391
	 1 eq	Pd(MeCN)$_2$Cl$_2$ (5 mol %), CuCl (5 mol %), DME, O$_2$ (1 atm), 60°, 71 h	 (65), (*E*)/(*Z*) = 61:39	391
	 1 eq	Pd(MeCN)$_2$Cl$_2$ (5 mol %), additive (5 mol %), CuCl (5 mol %), DME, O$_2$ (1 atm), 60°, 24 h	 Additive none (85) HMPA (93)	391
	 1 eq	Pd(MeCN)$_2$Cl$_2$ (5 mol %), CuCl (5 mol %), DME, O$_2$ (1 atm), 60°	 R Time (h) H 28 (84) *i*-Pr 24 (85)	391
	 1 eq	Pd(MeCN)$_2$Cl$_2$ (5 mol %), additive (5 mol %), CuCl (5 mol %), DME, O$_2$ (1 atm), 60°	 Additive Time (h) none 27 (75) HMPA 44 (66)	391

TABLE 3C. INTERMOLECULAR AZA–WACKER OXIDATION (*Continued*)

Alkene	Amine	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3				
 3 eq	 1 eq	$Pd(PhCN)_2Cl_2$ (*x* mol %), CuCl (*y* mol %), TEMDP (*y* mol %), chlorobenzene, O_2 (1 atm), 70°, 48 h	 R, *x*, *y* EtO, 5, 10, (48) Me, 10, 20, (82) $Cl(CH_2)_2$, 10, 20, (75) CH_2=C(Me), 5, 10, (78) *t*-Bu, 10, 20, (85) Ph, 5, 10, (70) 4-BrC_6H_4, 5, 10, (54) 4-$TBSOC_6H_4CH_2$, 10, 20, (81) PhCH=CH, 5, 10, (76)	109
	 1 eq	$Pd(PhCN)_2Cl_2$ (10 mol %), CuCl (20 mol %), TEMDP (20 mol %), chlorobenzene, O_2 (1 atm), 70°, 48 h	 (53)	109
 3 eq	 1 eq	$Pd(PhCN)_2Cl_2$ (*x* mol %), CuCl (*y* mol %), TEMDP (*y* mol %), chlorobenzene, O_2 (1 atm), 70°, 48 h	 R, *x*, *y* Me, 10, 20, (80) $Cl(CH_2)_2$, 10, 20, (66) CH_2=C(Me), 5, 10, (82) *t*-Bu, 5, 10, (69) Ph, 5, 10, (71) 4-BrC_6H_4, 5, 10, (76) Bn, 5, 10, (59) 4-$TBSOC_6H_4CH_2$, 10, 20, (71) PhCH=CH, 5, 10, (83)	109
	 1 eq	$Pd(MeCN)_2Cl_2$ (5 mol %), HMPA (5 mol %), CuCl (5 mol %), DME, O_2 (1 atm), 60°, 24 h	 (60)	391

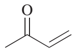
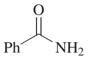
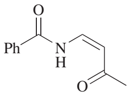
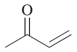
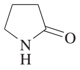
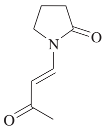
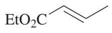
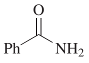
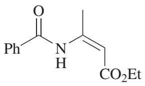
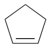
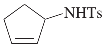
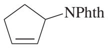
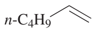
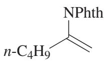
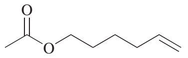
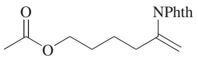
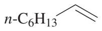
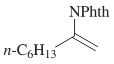
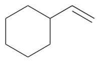
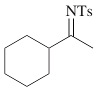
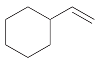
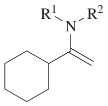
Alkene	Amine	Conditions	Product(s) and Yield(s) (%)	Refs.
C_4				
 3 eq	 1 eq	$Pd(PhCN)_2Cl_2$ (5 mol %), CuCl (10 mol %), TEMDP (10 mol %), chlorobenzene, O_2 (1 atm), 70°, 48 h	 (59)	109
	 1 eq	$Pd(MeCN)_2Cl_2$ (5 mol %), HMPA (5 mol %), CuCl (5 mol %), DME, O_2 (1 atm), 60°, 4 h	 (80)	391
 3 eq	 1 eq	$Pd(PhCN)_2Cl_2$ (5 mol %), CuCl (10 mol %), TEMDP (10 mol %), chlorobenzene, O_2 (1 atm), 70°, 48 h	 (14)	109
C_5				
 6 eq	$TsNH_2$ 1 eq, 0.75 M in PhCN	$Pd(OAc)_2$ (5 mol %), O_2 (3.5 atm, sealed vessel), 60°, 48 h	 **I** + other isomers **II** **I** + **II** (64), **I/II** = 100:12	110
	PhthNH 1 eq, 0.75 M in PhCN	$Pd(OAc)_2$ (5 mol %), O_2 (3.5 atm, sealed vessel), 60°, 24 h	 **I** + other isomers **II** **I** + **II** (80), **I/II** = 100:6	110
C_6				
 6 eq	PhthNH 1 eq, 0.75 M in PhCN	$Pd(OAc)_2$ (5 mol %), O_2 (3.5 atm, sealed vessel), 60°, 24 h	 **I** + other isomers **II** **I** + **II** (90), **I/II** =100:17	110
 12 eq	PhthNH 1 eq, 0.75 M in PhCN	$Pd(OAc)_2$ (5 mol %), O_2 (1 atm), 60°, 24 h	 (86)	110
C_8				
 6 eq	PhthNH 1 eq, 0.75 M in PhCN	$Pd(OAc)_2$ (5 mol %), O_2 (1 atm), 60°, 24 h	 **I** + other isomers **II** **I** + **II** (87), **I/II** =100:18	110
 6 eq	$TsNH_2$ 1 eq, 0.75 M in PhCN	$Pd(OAc)_2$ (5 mol %), O_2 (1 atm), 60°, 24 h	 (63)	110
 12 eq	R^1R^2NH 1 eq, 0.75 M in PhCN	$Pd(OAc)_2$ (5 mol %), O_2 (1 atm), 60°, 24 h	 R^1 R^2 —Phth— (92) Me Ts (59)	110

TABLE 3C. INTERMOLECULAR AZA–WACKER OXIDATION (*Continued*)

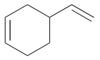
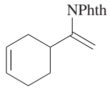
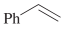
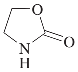
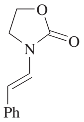
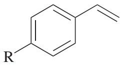
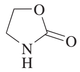
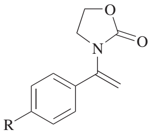
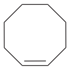
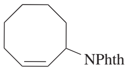
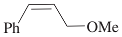
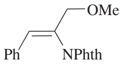
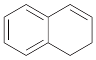
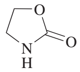
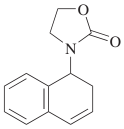
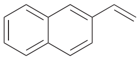
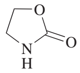
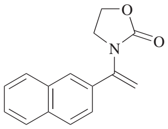
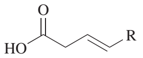
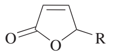
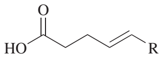
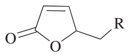
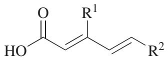
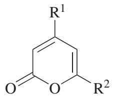
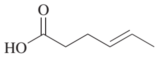
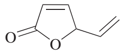
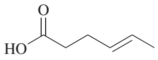
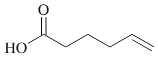
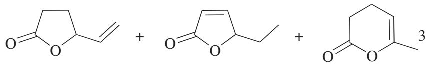
Alkene	Amine	Conditions	Product(s) and Yield(s) (%)	Refs.
C_8				
 6 eq	PhthNH 1 eq, 0.75 M in PhCN	Pd(OAc)$_2$ (5 mol %), O$_2$ (1 atm), 60°, 24 h	 (56)	110
	 1 eq	Pd(MeCN)$_2$Cl$_2$ (5 mol %), CuCl (5 mol %), DME, O$_2$ (1 atm), 60°, 88 h	 (40)	391
$C_{8–9}$				
 3 mmol	 0.5 mmol	Pd(MeCN)$_2$Cl$_2$ (0.025 mmol), CuCl$_2$ (0.025 mmol), Et$_3$N (0.05 mmol), O$_2$ (1 atm), DME, 60°, 24 h	 R H (99) Cl (70) F (77) CF$_3$ (39) Me (73)	392
C_8				
 6 eq	PhthNH 1 eq, 0.75 M in PhCN	Pd(OAc)$_2$ (5 mol %), O$_2$ (3.5 atm, sealed vessel), 60°, 24 h	 **I** + other isomers **II** **I** + **II** (60), **I**/**II** =75:28	110
C_9				
	PhthNH 1 eq	Pd(OAc)$_2$ (10 mol %), DCE, O$_2$ (1 atm), 60°, 20 h	 (20)	393
C_{10}				
 2 mmol	 0.5 mmol	Pd(MeCN)$_2$Cl$_2$ (0.025 mmol), CuCl$_2$ (0.025 mmol), Et$_3$N (0.05 mmol), O$_2$ (1 atm), DME, 60°, 24 h	 (72)	392
C_{12}				
 2 mmol	 0.5 mmol	Pd(MeCN)$_2$Cl$_2$ (0.025 mmol), CuCl$_2$ (0.025 mmol), Et$_3$N (0.05 mmol), O$_2$ (1 atm), DME, 60°, 24 h	 (98)	392

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{4-5}			
	$LiPdCl_4$ (1 eq), Na_2CO_3, H_2O, rt, 24 h	 R H (38) Me (32)	394
C_{5-6}			
	$LiPdCl_4$ (1 eq), Na_2CO_3, H_2O, rt, 24 h	 R H (38) Me (30)	394
C_{5-17}			
	Li_2PdCl_4 (1 eq), Na_2CO_3 (0.5 eq), H_2O, reflux, 4 h	 R^1 R^2 H H (72) H Me (75) H Ph (68) Me Me (65) Me Ph (65) Ph Ph (68)	395
C_6			
	$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), rt, 48 h	 (81)	396
	$Pd(MeCN)_2Cl_2$ (1.1–1.5 eq), Na_2CO_3, rt	 **I** + **II**	397

Solvent	Time (h)	**I**	**II**
DMSO	24	(100)	(—)
THF	5	(10)	(60)
MeCN	3	(30)	(30)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd source (1.1–1.5 eq), base, rt	 **I** + **II** + **III**	397

Pd Source	Base	Solvent	Time (h)	**I**	**II**	**III**
$Pd(OAc)_2$	NaOAc	THF	7	(—)	(—)	(75)
$Pd(MeCN)_2Cl_2$	NaOAc	MeCN	4–6	(10)	(—)	(90)
$Pd(MeCN)_2Cl_2$	Na_2CO_3	DMSO	28–46	(70)	(—)	(30)
$Pd(MeCN)_2Cl_2$	Na_2CO_3	MeCN	27–46	(15)	(15)	(70)
$Pd(MeCN)_2Cl_2$	Na_2CO_3	DMF	46	(25)	(10)	(65)
$Pd(MeCN)_2Cl_2$	Na_2CO_3	acetone	46	(10)	(60)	(—)
$Pd(MeCN)_2Cl_2$	Na_2CO_3	toluene	8	(30)	(20)	(—)
$Pd(MeCN)_2Cl_2$	Na_2CO_3	THF	8–28	(10)	(60)	(—)
$Pd(MeCN)_2Cl_2$	*t*-BuOK	THF	6	(20)	(—)	(80)
$Pd(MeCN)_2Cl_2$	*t*-BuOK	MeCN	6	(10)	(—)	(90)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

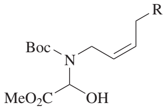
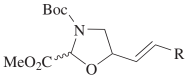
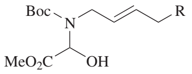
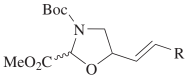
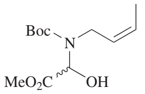
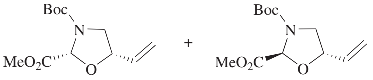
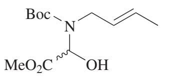
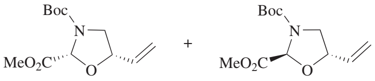
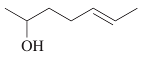
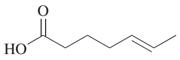
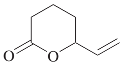
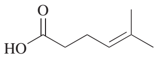
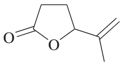
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{6-8}			
	$Pd(OAc)_2$ (0.1 eq), $Cu(OAc)_2$ (3 eq), DMSO, 70°	 R — Time (h) — — dr H — 2 — (76) — 3:1 Et — 10 — (80) — 3:1	398
	$Pd(OAc)_2$ (0.1 eq), $Cu(OAc)_2$ (3 eq), DMSO, 70°	 R — Time (h) — — dr H — 5 — (64) — 1:1 Et — 24 — (56) — 1:1	398
C_6			
	$Pd(OAc)_2$ (5 mol %), DMSO, O_2, 65–75°, 2 h	 **I** **I** + **II** (80), **I**/**II** = 24:76 **II**	399
	$Pd(OAc)_2$ (10 mol %), DMSO, O_2, 65–75°, 8 h	 **I** **I** + **II** (63), **I**/**II** = 50:50 **II**	399
C_7			
	$Pd(OAc)_2$ (10 mol %), $Cu(OAc)_2$•H_2O (1 eq), MeOH/H_2O (12:1), O_2, rt, 24 h	 **I** **I** + **II** (23), **I**/**II** = 75:25 **II**	400
	$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), 80°, 48 h	 (68)	396
	$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), rt, 168 h	 (82)	396

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

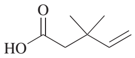
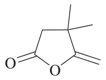
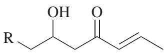
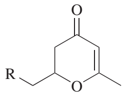
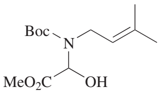
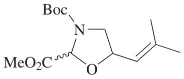
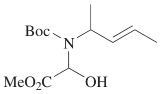
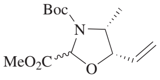
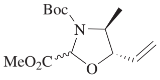
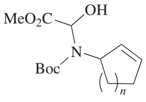
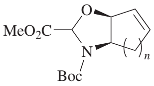
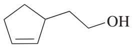
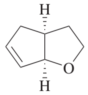
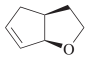
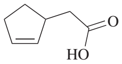
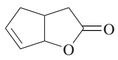
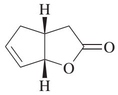
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_7			
	PdCl$_2$, CuCl$_2$, DMF/H$_2$O, O$_2$, rt to 60°	 (56)	401
C_{7-8}			
	PdCl$_2$ (10 mol %), CuCl (10 mol %), Na$_2$HPO$_4$ (10 mol %), DME, O$_2$, 50°, 20 h	 R Time (h) BnO 20 (75) Me 10 (52)	402
C_7			
	Pd(OAc)$_2$ (0.1 eq), Cu(OAc)$_2$ (3 eq), DMSO, 70°, 24 h	 (0)	398
 dr 1:1	Pd(OAc)$_2$ (0.1 eq), Cu(OAc)$_2$ (3 eq), DMSO, 70°, 7 h	 (32) dr 3:2 +  (46) dr 3:2	398
C_{7-9}			
 dr 1:1	Pd(OAc)$_2$ (0.1 eq), Cu(OAc)$_2$ (3 eq), DMSO, 70°	 n Time (h) dr 1 1 (85) 1:1 2 5 (70) 1:1 3 5 (49) 3:1	398
C_7			
	Pd(OAc)$_2$ (5 mol %), DMSO, O$_2$, rt, 24 h	 (90)	403
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na$_2$CO$_3$ (2 eq), 3 Å MS, toluene, O$_2$ (1 atm), 80°, 7.5 h	 (69) + olefin isomer (7)	45
	PdCl$_2$ (0.5 mol %), NaOAc (10 mol %), DMA, O$_2$ (6 atm), 80°, 4 h	 (80)	49
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O$_2$ (1 atm), rt, 24 h	 (86)	396

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

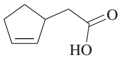
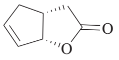
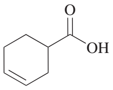
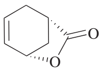
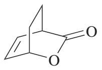
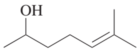
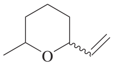
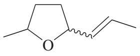
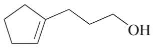
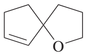
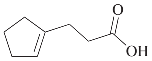
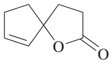
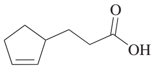
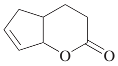
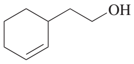
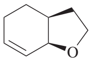
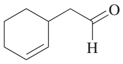
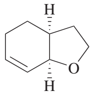
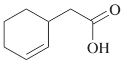
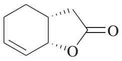
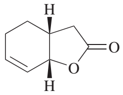
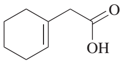
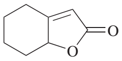
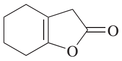
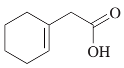
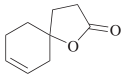
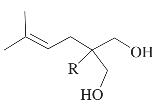
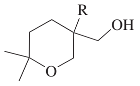
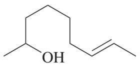
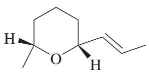
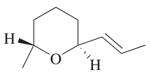
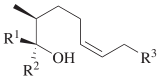
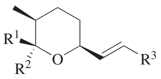
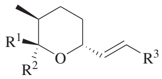
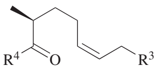
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_7			
	Pd(TFA)$_2$ (10 mol %), py (40 mol %), Na_2CO_3 (2 eq), 3 Å MS, toluene, O_2 (1 atm), 80°, 48 h	 (77)	45
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), 80°, 36 h	 **I** +  **II** **I** + **II** (56), **I/II** = 3:1	396
C_8			
	Pd(OAc)$_2$ (10 mol %), Cu(OAc)$_2$•H_2O (1 eq), MeOH/H_2O (12:1), O_2, rt, 24 h	 (10) +  (10)	400
	Pd(TFA)$_2$ (10 mol %), py (40 mol %), Na_2CO_3 (2 eq), 3 Å MS, toluene, O_2 (1 atm), 80°, 10 h	 (93)	404
	Pd(TFA)$_2$ (10 mol %), py (40 mol %), 3 Å MS, toluene, O_2 (1 atm), 80°, 48 h	 (62)	404
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), 80°, 24 h	 (87)	396
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na_2CO_3 (2 eq), 3 Å MS, toluene, O_2 (1 atm), 80°, 20 h	 +  + olefin isomer **III** **I** **II** **I** + **II** + **III** (—), **I/II/III** = 5:1:2.3	45
	Pd(OAc)$_2$ (5 mol %), DMSO, O_2, rt, 24 h	 (96)	400
	Pd(TFA)$_2$ (10 mol %), py (40 mol %), Na_2CO_3 (2 eq), 3 Å MS, toluene, O_2 (1 atm), 80°, 48 h	 (86) + olefin isomer (6)	45
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), rt, 24 h	 (90)	396
	$LiPdCl_4$ (1 eq), Na_2CO_3, H_2O, rt, 24 h	 (28) +  (10)	394

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_8			
	$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), 80°, 24 h	 (91)	396
$C_{9–15}$			
	$Pd(TFA)_2$ (15 mol %), **17** (18 mol %), BQ (4 eq), CH_2Cl_2, rt		405

R	Time (h)		er
Me	21	(70)	85.0:15.0
Et	15	(86)	85.0:15.0
Bn	15	(81)	81.5:18.5

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	$Pd(OAc)_2$ (1 eq), DMSO, Ar, rt, 14–18 h	 (90) +  (5)	406
$C_{9–14}$			
	$Pd(OAc)_2$ (1.1 eq), DMSO, Ar, rt, 24 h	 **I** +  **II** +  **III**	406

R^1	R^2	R^3	R^4	I	II	III
H	H	Me	H	(2)	(98)	(<1)
Me	H	H	Me	(56)	(34)	(10)
H	Me	Me	Me	(3)	(94)	(3)
t-$BuCH_2$	H	Me	*t*-$BuCH_2$	(48)	(28)	(15)
H	*t*-$BuCH_2$	Me	*t*-$BuCH_2$	(22)	(63)	(10)

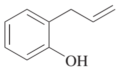
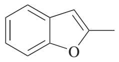
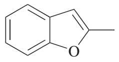
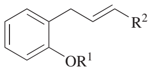
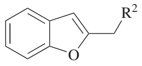
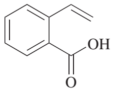
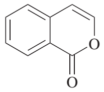
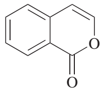
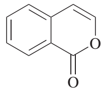
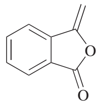
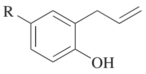
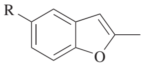
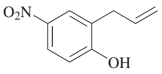
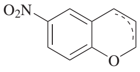
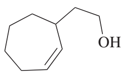
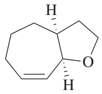
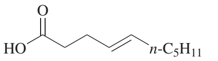
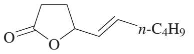
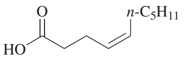
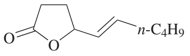
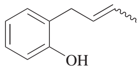
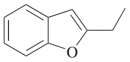
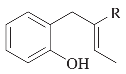
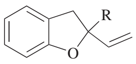
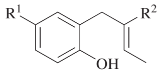
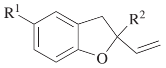
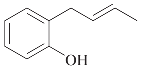
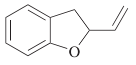
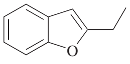
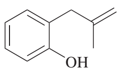
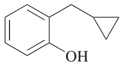
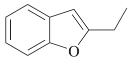
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_9			
	$Pd(MeCN)_2Cl(NO_2)$ (5 mol %), $CuCl_2$ (20 mol %), *t*-BuOH, 2.5 h	 (60)	369
	$PdCl_2$ (0.5 mol %), NaOAc (10 mol %), DMA, O_2 (6 atm), 80°, 4 h	 (95)	49

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{9-15}			
	Pd(PhCN)$_2$Cl$_2$ (1 eq), benzene, reflux, 3 h	 R^1 R^2 H H (31) H Ph (53) Na H (31) Na Ph (53)	407 407 408 408
C_9			
	LiPdCl$_4$ (1 eq), Na$_2$CO$_3$, H$_2$O/dioxane, rt, 24 h	 (46)	394
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O$_2$ (1 atm), rt, 48 h	 (90)	396
	PdCl$_2$, Na$_2$CO$_3$, THF, 3 h	 (62) +  (21)	409
C_{9-10}			
	PdCl$_2$ (2 mol %), Cu(OAc)$_2$•H$_2$O (3 eq), LiCl (0.3 eq), DMF, air, rt	 R Time (h) Br 0.5 (83) MeO 5 (90) AcHN 4 (92) Me 10 (95)	182
C_9			
	PdCl$_2$ (2 mol %), Cu(OAc)$_2$•H$_2$O (3 eq), LiCl (0.3 eq), DMF, air, 100°, 1.5 h	 (50)	182
	Pd(OAc)$_2$ (5 mol %), DMSO, O$_2$, rt, 24 h	 (91)	403
C_{10}			
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O$_2$ (1 atm), rt, 48 h	 (78)	396
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O$_2$ (1 atm), rt, 72 h	 (81)	396
	Pd(PhCN)$_2$Cl$_2$ (1 eq), benzene, reflux, 3 h	 (26)	407
C_{10-11}			
	Pd(TFA)$_2$ (5 mol %), **13** (6 mol %), DMAP, Na$_2$CO$_3$, 4 Å MS, toluene, O$_2$, 80°, 12 h	 R H (89) Me (92)	410

<table>
<tr><th>Alkene</th><th>Conditions</th><th>Product(s) and Yield(s) (%)</th><th>Refs.</th></tr>
<tr><td colspan="4"><i>Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the bold numbers.</i></td></tr>
<tr><td colspan="4">$C_{10–11}$</td></tr>
<tr><td></td><td>$Pd(TFA)_2$ (5 mol %),
py (20 mol %), Na_2CO_3 (2 eq),
3 Å MS, toluene, O_2 (1 atm), 80°</td><td><table><tr><th>R^1</th><th>R^2</th><th>Time (h)</th><th></th></tr><tr><td>H</td><td>H</td><td>3</td><td>(74)</td></tr><tr><td>Br</td><td>Me</td><td>24</td><td>(33)</td></tr><tr><td>H</td><td>Me</td><td>0.33</td><td>(95)</td></tr></table></td><td>45</td></tr>
<tr><td colspan="4">C_{10}</td></tr>
<tr><td></td><td>$Pd(OAc)_2$ (10 mol %),
$Cu(OAc)_2•H_2O$ (1 eq),
(–)-β-pinene (10 mol %),
$MeOH/H_2O$ (19:1), O_2 (1 atm), 35°</td><td> + 
(55) er 56.0:44.0 (7)</td><td>411</td></tr>
<tr><td></td><td>$Pd(TFA)_2$ (5 mol %),
py (20 mol %), Na_2CO_3 (2 eq),
3 Å MS, toluene, O_2 (1 atm), 80°, 14 h</td><td>(—)</td><td>45</td></tr>
<tr><td></td><td>$PdCl_2$ (10 mol %), $CuCl_2$ (2 eq),
dioxane, 100°, 24 h</td><td> (61)</td><td>112</td></tr>
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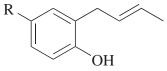
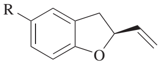
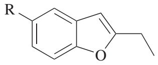
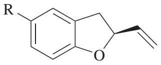
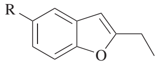
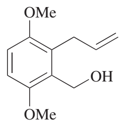
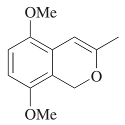
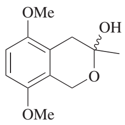
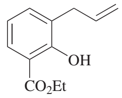
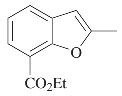
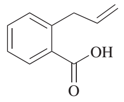
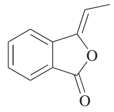
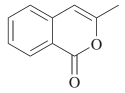
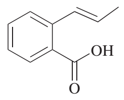
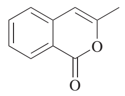
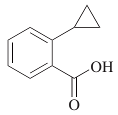
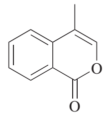
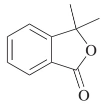
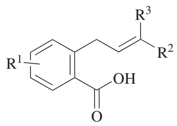
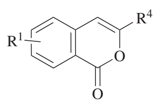
<table>
<tr><td colspan="4">$C_{10–11}$</td></tr>
<tr><td></td><td>(+)-[(3,2,10-η^3-pinene)$Pd(OAc)]_2$
(10 mol %), $Cu(OAc)_2$ (0.1 eq),
MeOH, O_2 (1 atm), 35°</td><td> + 
I II<table><tr><th>R</th><th>Time (h)</th><th>I</th><th>I er</th><th>II</th></tr><tr><td>H</td><td>4.5</td><td>(64)</td><td>59.0:41.0</td><td>(13)</td></tr><tr><td>Cl</td><td>29</td><td>(65)</td><td>53.0:47.0</td><td>(7)</td></tr><tr><td>MeO</td><td>12</td><td>(37)</td><td>63.0:37.0</td><td>(8)</td></tr><tr><td>Me</td><td>11</td><td>(63)</td><td>60.5:39.5</td><td>(13)</td></tr></table></td><td>412</td></tr>
<tr><td></td><td>(+)-[(3,2,10-η^3-pinene)$Pd(OAc)]_2$
(10 mol %), TBHP (1.2 eq),
MeOH, 35°</td><td> + 
I II<table><tr><th>R</th><th>Time (h)</th><th>I</th><th>I er</th><th>II</th></tr><tr><td>H</td><td>20</td><td>(43)</td><td>58.5:41.5</td><td>(9)</td></tr><tr><td>Cl</td><td>39</td><td>(47)</td><td>52.25:47.75</td><td>(7)</td></tr><tr><td>MeO</td><td>41</td><td>(16)</td><td>61.0:39.0</td><td>(3)</td></tr><tr><td>Me</td><td>22</td><td>(28)</td><td>59.0:41.0</td><td>(6)</td></tr></table></td><td>412</td></tr>
</table>

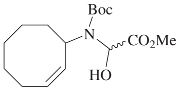
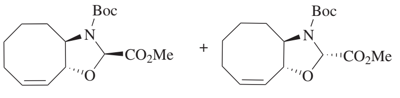
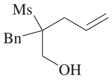
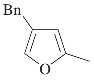
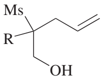
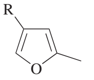
TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{10}			
	$PdCl_2$ (10 mol %), $CuCl_2$ (1.0 eq), DMF/H_2O (1:1), O_2 (bubbling), 2 h	 (50) +  (29)	413
	$PdCl_2$ (2 mol %), $Cu(OAc)_2$•H_2O (3 eq), LiCl (0.3 eq), DMF, air, 100°, 6 h	 (73)	182
	$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), 80°, 72 h	 (71)	396
	$PdCl_2$ (2 mol %), $Cu(OAc)_2$•H_2O (3 eq), $KHCO_3$ (1 eq), DMF, air, 100°, 2.5 h	 (63)	182

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O_2 (1 atm), 80°, 48 h	 (78)	396
	$PdCl_2$ (10 mol %), $CuCl_2$ (2 eq), dioxane, 80°, 12 h	 **I** +  **II** **I** + **II** (76), **I**/**II** = 86:14	112
C_{10-12}			
	$PdCl_2$, Na_2CO_3, THF		409

R^1	R^2	R^3	R^4	Time (h)	
H	H	H	Me	3	(86)
H	Me	H	Et	3	(86)
H	Me	Me	*i*–Pr	4	(96)
4-Cl	H	H	Me	4	(63)
4-Cl	Me	H	Et	4	(54)
5-MeO	H	H	Me	3	(65)

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{10}			
 dr 33:67	$Pd(OAc)_2$ (2 mol %), DMSO, O_2, 65–75°, 2 h	 **I** **I** + **II** (70), **I/II** = 33:67 **II**	399
C_{11-13}			
	1. $PdCl_2$ (10 mol %), $CuCl_2$ (2 eq), TMU (2 eq), EOA (40 mol %), MeOH, rt, 2.5 h 2. PTSA, toluene, reflux	 (73)	362
	1. $PdCl_2$ (50 mol %), $CuCl_2$ (3 eq), TMU (5 eq), EOA (40 mol %), MeOH, rt, 1 h 2. PTSA, toluene, reflux	 R — Time (h) n-C_6H_{13} 0.67 (75) Bn 1.2 (71) $Ph(CH_2)_2$ 1 (90)	362

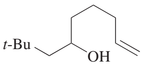
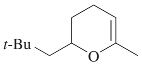
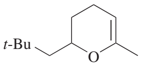
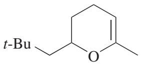
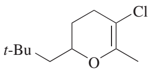
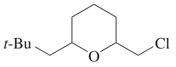
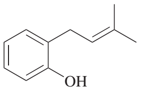
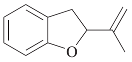
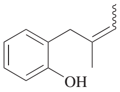
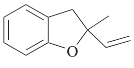
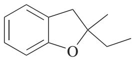
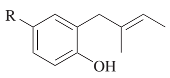
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{11}			
	$Pd(OAc)_2$ (1 eq), MeCN, Ar	 (90)	406
	$PdCl_2$ (0.2 eq), $CuCl_2$ (3 eq), MeOH, Ar	 (60)	406
	$PdCl_2$ (0.2 eq), $CuCl_2$ (3 eq), MeCN, Ar	 (5) +  (50) +  (29)	406
	$Pd(TFA)_2$ (5 mol %), **13** (6 mol %), DMAP, Na_2CO_3, 4 Å MS, toluene, O_2, 80°, 12 h	 (91)	410
	$Pd(PhCN)_2Cl_2$ (1 eq), benzene, reflux, 3 h	 (41) +  (13)	407

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

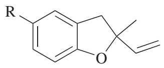
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{11}

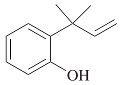


Pd(OAc)$_2$ (10 mol %), TEMPO (120 mol %), NaClO$_4$ (0.05 M), dioxane/H$_2$O (3:1), rt, divided cell, (Pt)–(Pt), 5 mA, 3.0 F/mol

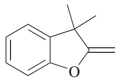


R	
H	(86)
Cl	(51)
Br	(76)
MeO	(28)

414



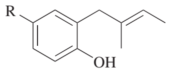
Pd(PhCN)$_2$Cl$_2$ (1 eq), benzene, reflux, 3 h



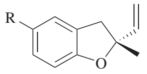
(40)

407

C_{11-15}

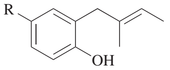


Pd(**6**)(TFA)$_2$ (10 mol %), **6** (1 eq), Ca(OH)$_2$ (2 eq), 3 Å MS, toluene, O$_2$ (1 atm)

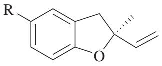


R	Temp (°)	Time (h)		er	Refs.
H	80	36	(87)	90.5:9.5	404
MeO	80	24	(64)	94.0:6.0	45
MeO	55	60	(57)[a]	95.0:5.0	404, 45
Me	80	36	(47)	93.0:7.0	45
AcO	80	24	(60)	60.0:40.0	45
t-Bu	80	36	(47)	91.5:8.5	45

C_{11-17}



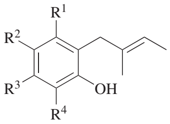
Pd(TFA)$_2$ (10 mol %), **19** (10 mol %), BQ (4 eq), acetone, 20°, 72 h



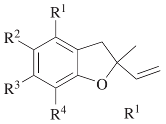
R		er
F	(89)	95.0:5.0
Ph	(87)	95.0:5.0

415

C_{11}

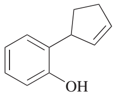


Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na$_2$CO$_3$ (2 eq), 3 Å MS, toluene, O$_2$ (1 atm), 80°

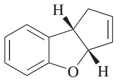


R^1	R^2	R^3	R^4	Time	
H	MeO	H	H	15 min	(89)
H	AcO	H	H	25 h	(93)
H	MeO	H	MeO	40 min	(80)
MeO	MeO	MeO	H	10 min	(86)

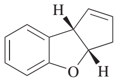
45



Pd(OAc)$_2$ (10 mol %), Cu(OAc)$_2$•H$_2$O (1 eq), (–)-β-pinene (10 mol %), MeOH/H$_2$O (19:1), O$_2$ (1 atm), 35°



I +



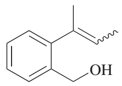
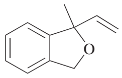
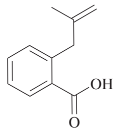
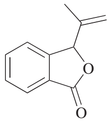
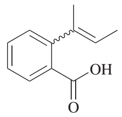
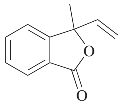
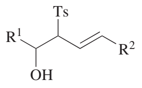
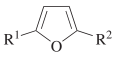
II

I + **II** (16), **I**/**II** = 93:7

411

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{11}			
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na$_2$CO$_3$ (2 eq), 3 Å MS, toluene, O$_2$ (1 atm), 80°, 3 h	 (87)	45
	PdCl$_2$, Na$_2$CO$_3$, THF, 5 h	 (31)	409
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), 3 Å MS, toluene, O$_2$ (1 atm), 80°, 8 h	 (90)	404
$C_{12–13}$			
	1. PdCl$_2$ (50 mol %), CuCl$_2$ (3 eq), TMU (5 eq), EOA (40 mol %), EtOH, time 1 2. PTSA, toluene, reflux, time 2		362

R^1	R^2	Temp	Time 1	Time 2 (h)	
Ph(CH$_2$)$_2$	H	reflux	1 h	3.5	(81)
Ph(CH$_2$)$_2$	Me	rt	3 d	0.33	(78)
n-C$_9$H$_{19}$	H	reflux	1 h	3	(71)

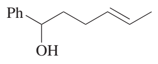
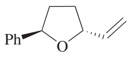
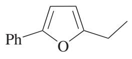
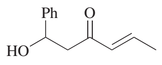
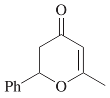
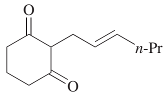
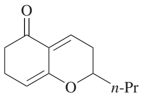
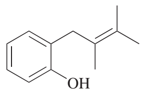
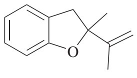
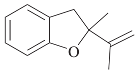
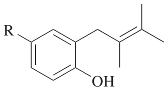
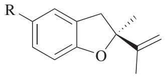
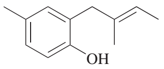
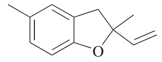
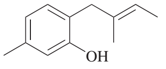
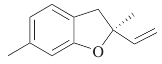
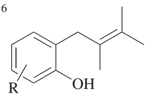
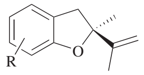
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{12}			
	Pd(OAc)$_2$ (10 mol %), Cu(OAc)$_2$•H$_2$O (1 eq), MeOH/H$_2$O (12:1), O$_2$, rt, 24 h	 (40) +  (10)	400
	PdCl$_2$ (10 mol %), CuCl (10 mol %), Na$_2$HPO$_4$ (10 mol %), DME, O$_2$, 50°, 8 h	 (86)	402
	Pd(TFA)$_2$ (10 mol %), **17** (12 mol %), BQ (2 eq), diglyme, rt, 12 h	 (68) er 76.0:24.0	114
	Pd(TFA)$_2$ (5 mol %), **13** (6 mol %), DMAP, Na$_2$CO$_3$, 4 Å MS, toluene, O$_2$, 80°, 12 h	 (96)	410
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na$_2$CO$_3$ (2 eq), 3 Å MS, toluene, O$_2$ (1 atm), 80°, 2 h	 (93)	45

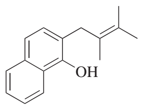
TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

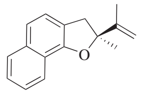
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{12}			
	Pd(TFA)$_2$/**23** (10 mol %), BQ (4 eq), MeOH, 60°, 24 h	 R (yield) er H (75) 98.0:2.0 F (82) 96.0:4.0	111
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na$_2$CO$_3$ (2 eq), 3 Å MS, toluene, O$_2$ (1 atm), 80°, 20 min	 (99)	404
	Pd(TFA)$_2$ (10 mol %), **19** (10 mol %), BQ (4 eq), acetone, 20°, 72 h	 (60) er 96.0:4.0	415
$C_{12–16}$			
	Pd(TFA)$_2$ (10 mol %), ligand (10 mol %), BQ (4 eq), MeOH, 60°, 24 h		

Ligand	R		er	Refs.
19	H	(86)	98.0:2.0	113
19	4-F	(79)	99.0:1.0	113
19	4-MeO	(81)	99.0:1.0	113
19	6-MeO	(54)	97.5:2.5	113
19	4-Me	(84)	99.0:1.0	113
19	5-Me	(63)	97.0:3.0	113
19	6-Me	(69)	99.5:0.5	113
19	4-Ph	(65)	98.5:1.5	113
19	1-naphthol*	(67)	98.5:1.5	113
20	H	(82)	92.5:7.5	416
20	4-F	(80)	93.0:7.0	416
20	4-MeO	(73)	93.0:7.0	416
20	6-MeO	(55)	92.5:7.5	416
20	4-Me	(74)	94.0:6.0	416
20	5-Me	(81)	94.5:5.5	416
20	6-Me	(41)	95.5:4.5	416
20	4-Ph	(62)	93.5:6.5	416
20	1-naphthol*	(53)	96.5:3.5	416
21	H	(92)	97.0:3.0	417
21	4-F	(65)	97.0:3.0	417
21	4-MeO	(80)	95.0:5.0	417
21	6-MeO	(79)	99.0:1.0	417
21	4-Me	(92)	95.0:5.0	417
21	5-Me	(83)	96.5:3.5	417
21	6-Me	(74)	99.0:1.0	417
21	4-Ph	(73)	95.5:4.5	417
21	1-naphthol*	(75)	96.0:4.0	417

* Substrate alkene and resluting product are:



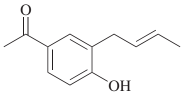
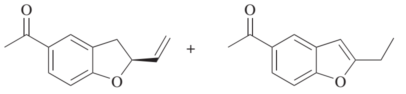
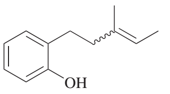
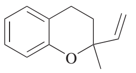
and



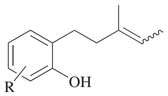
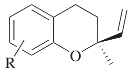
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{12}

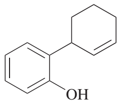
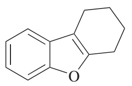
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	(+)-[(3,2,10-η^3-pinene)Pd(OAc)]$_2$ (10 mol %), Cu(OAc)$_2$ (0.1 eq), MeOH, O$_2$ (1 atm), 35°, 11 h	 (71) er 50.5:49.5 + (3)	412
 dr 3.6:1	Pd(TFA)$_2$ (5 mol %), py (20 mol %), 3 Å MS, toluene, O$_2$ (1 atm), 80°, 1.25 h	 (85)	404

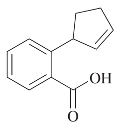
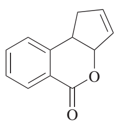
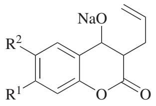
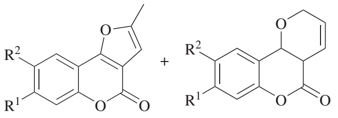
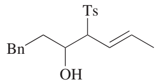
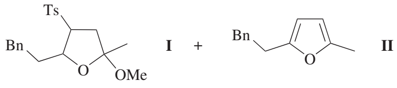
$C_{12–18}$

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(TFA)$_2$ (20 mol %), **19** (20 mol %), BQ (4 eq), MeOH, 60°, 24 h		418

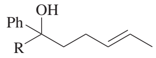
R	(*Z*)/(*E*)	Yield	er
H	1.8:1	(69)	93.5:6.5
H	(*E*) only	(68)	96.0:4.0
H	(*Z*) only	(70)	92.0:8.0
4-Cl	1.9:1	(65)	93.5:6.5
4-MeO	4.7:1	(68)	80.5:19.5
4-Me	3.3:1	(80)	87.5:12.5
5-Me	4.4:1	(73)	90.0:10.0
6-Me	3.1:1	(72)	92.5:7.5
4-*i*-Pr	2.3:1	(75)	92.0:8.0
4-Ph	1.7:1	(75)	85.0:15.0

C_{12}

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(PhCN)$_2$Cl$_2$ (1 eq), benzene, reflux, 3 h	 (40)	407

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{12}			
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO (0.05 M), O$_2$ (1 atm), rt, 72 h	 (82)	396
$C_{12–13}$			
	Pd(PhCN)$_2$Cl$_2$ (1 eq), benzene, rt, 0.5 h; then, reflux, 2 h	 (40–45) + (42–50) R^1 R^2 H H H Me H Cl H Br Cl H	419
C_{13}			
 dr 58:42	PdCl$_2$ (50 mol %), CuCl$_2$ (3 eq), TMU (5 eq), EOA (40 mol %), MeOH		362

Temp	Time	I	I dr	II
reflux	20 min	(17)	49:28:14:9	(47)
rt	overnight	(17)	49:28:14:9	(20)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{13–14}$			
	Pd(OAc)$_2$ (10 mol %), Cu(OAc)$_2$•H$_2$O (1 eq), MeOH/H$_2$O (12:1), O$_2$, rt, 24 h		400

R	I + II	I/II
Me	(52)	41:59
Et	(36)	41:59

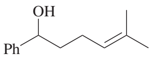
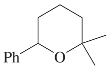
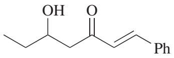
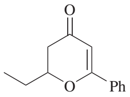
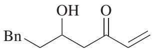
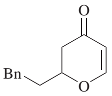
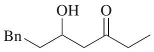
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{13}			
	Pd(OAc)$_2$ (10 mol %), Cu(OAc)$_2$•H$_2$O (1 eq), MeOH/H$_2$O (12:1), O$_2$, rt, 24 h	 (45)	400
	PdCl$_2$ (10 mol %), CuCl (10 mol %), Na$_2$HPO$_4$ (10 mol %), DME, O$_2$, 50°, 8 d	 (43)	402
	PdCl$_2$ (10 mol %), CuCl (10 mol %), Na$_2$HPO$_4$ (10 mol %), DME, O$_2$, 50°, 20 h	 (48) +  (12)	402

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

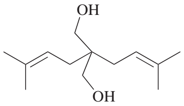
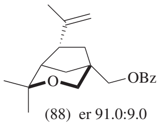
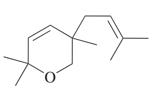
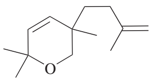
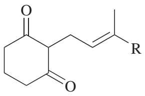
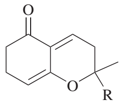
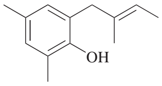
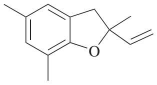
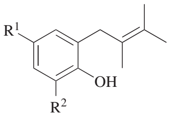
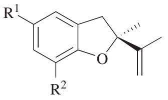
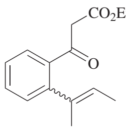
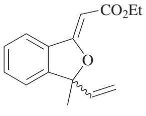
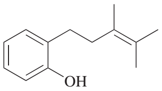
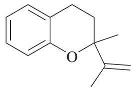
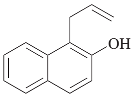
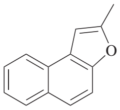
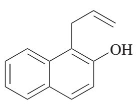
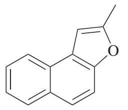
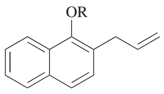
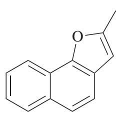
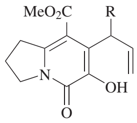
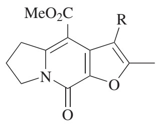
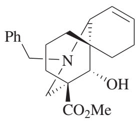
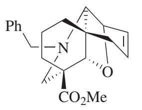
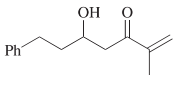
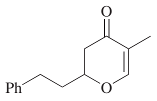
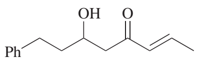
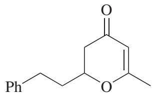
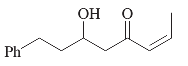
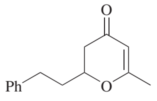
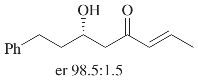
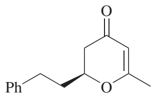
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{13}			
	Pd(TFA)$_2$/**17** (10 mol %), BQ (4 eq), CH_2Cl_2/MeOH (1:1), 0°, 24 h	 (88) er 91.0:9.0 +  (3) er 68.0:32.0 +  (8) er 78.5:21.5	405
$C_{13–16}$			
	Pd(TFA)$_2$ (10 mol %), **17** (12 mol %), BQ (2 eq), diglyme, rt, 12 h	 R | | er *i*-Pr | (53) | 83.5:16.5 *n*-Bu | (60) | 75.5:24.5 Ph | (38) | 82.5:17.5	114
C_{13}			
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na_2CO_3 (2 eq), 3 Å MS, toluene, O_2 (1 atm), 80°, 0.33 h	 (85)	45
	Pd(TFA)$_2$/**23** (10 mol %), BQ (4 eq), MeOH, 60°, 24 h	 R^1 | R^2 | | er Me | H | (86) | 97.0:3.0 H | Me | (71) | 97.0:3.0	111
	Pd(TFA)$_2$ (10 mol %), py (40 mol %), LiOAc (2 eq), 3 Å MS, toluene, O_2 (1 atm), 80°, 48 h	 (63), (*E*)/(*Z*) = 3:1	404
	Pd(TFA)$_2$/**22** (25 mol %), BQ (4 eq), MeOH, 60°, 24 h	 (61) er 98.5:1.5	111
	Pd(PhCN)$_2Cl_2$ (1 eq), benzene, reflux, 3 h	 (42)	408

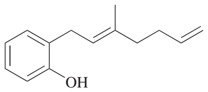
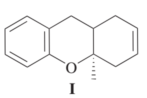
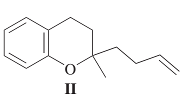
TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

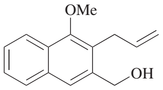
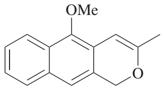
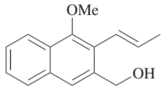
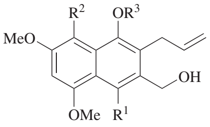
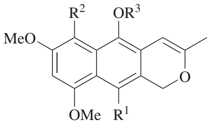
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{13}			
	$PdCl_2$ (2 mol %), $Cu(OAc)_2$•H_2O (3 eq), LiCl (0.3 eq), DMF, air, rt, 10 h	 (85)	182
	$Pd(PhCN)_2Cl_2$ (1 eq), benzene, reflux, 3 h	 R H (22) Na (22)	 407 408
$C_{12–13}$			
	$PdCl_2$, $CuCl_2$, DMF/H_2O, O_2	 R H (97) Me (95)	420
C_{13}			
	$Pd(OAc)_2$, DMSO, O_2, 5°, 18 h	 (95)	421
C_{14}			
	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 20 h	 (0)	402
	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 4 h	 (79)	402
	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 4 h	 (59)	402
 er 98.5:1.5	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 10 h	 (61) er > 98.5:1.5	402

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

C_{14}

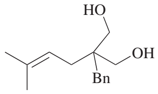
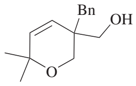
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	PtI_2(**5**) (10 mol %), Ph_2NH (20 mol %), additive (2.1 eq), $MeNO_2$, rt, dark	 **I** +  **II**	422

Additive	I	er	II
Ph_3COMe	(67)	68.0:32.0	(33)
$PhCH(OMe)_2$	(35)	67.5:32.5	(3)
$4\text{-}MeOC_6H_4CH(OMe)_2$	(7)	69.0:31.0	(0.4)
PhCHO	(48)	69.0:31.0	(20)
$CH_2(OMe)_2$	(50)	68.5:31.5	(4)

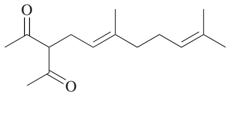
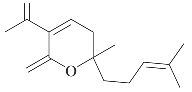
	$Pd(MeCN)_2Cl_2$ (0.3 eq), CH_2Cl_2, rt	 (60) +  (13)	423
	$PdCl_2$ (10 mol %), $CuCl_2$ (1 eq), DMF/H_2O (1:1), O_2, rt, 24 h		424

R^1	R^2	R^3	
H	H	TBS	(52)
MeO	H	Me	(63)
MeO	MeO	Me	(49)
H	MeO	Me	(64)

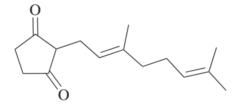
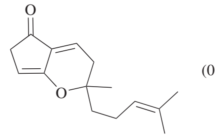
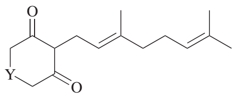
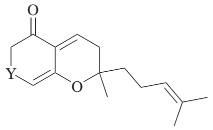
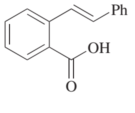
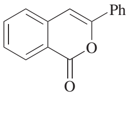
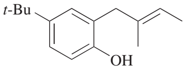
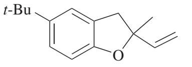
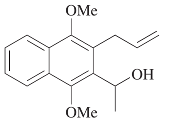
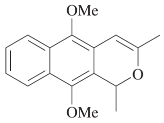
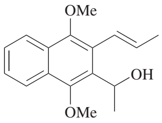
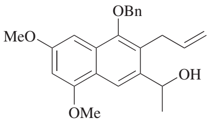
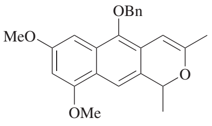
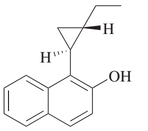
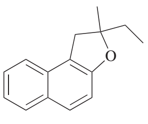
C_{15}

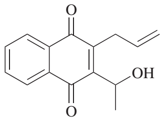
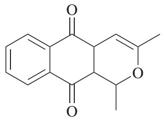
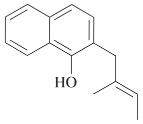
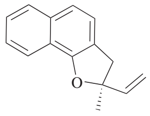
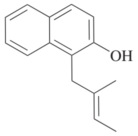
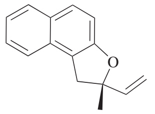
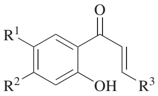
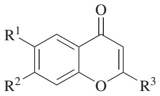
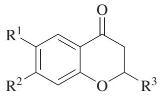
	$Pd(TFA)_2$ (10 mol %), ligand (12 mol %), BQ (4 eq), CH_2Cl_2		425

Ligand	Temp	Time (h)		er
18a	rt	39	(62)	74.0:26.0
18b	rt	31	(48)	78.0:22.0
18c	rt	31	(42)	85.5:14.5
18d	rt	38.5	(56)	83.5:16.5
18e	rt	31	(41)	81.5:18.5
18f	rt	31	(44)	84.0:16.0
18g	rt	34	(55)	77.5:22.5
18h	15°	48	(54)	81.5:18.5
18i	15°	48	(72)	83.0:17.0
18j	15°	48	(69)	91.0:9.0
18k	15°	48	(73)	85.0:15.0
18l	15°	48	(65)	87.0:13.0
18m	15°	48	(61)	89.0:11.0

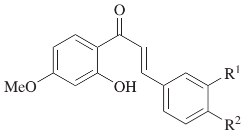
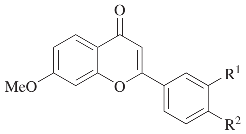
	$Pd(TFA)_2$ (10 mol %), **17** (12 mol %), BQ (2 eq), diglyme, rt, 12 h	 (0)	114

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{15}			
	Pd(TFA)$_2$ (10 mol %), **19** (12 mol %), BQ (2 eq), diglyme, rt, 12 h	 (0)	114
$C_{15–18}$			
	Pd(TFA)$_2$ (10 mol %), **17** (12 mol %), BQ (2 eq), diglyme, rt, 12 h	 Y er CH_2 (80) 90.5:9.5 MeCH (58) 92.0:8.0 Me_2C (70) 89.0:11.0 O (—) —	114
C_{15}			
	LiPdCl$_4$ (1 eq), Na$_2$CO$_3$, H$_2$O/dioxane, rt, 24 h	 (42)	394
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na$_2$CO$_3$ (2 eq), 3 Å MS, toluene, O$_2$ (1 atm), 80°, 25 min	 (90)	45
	Pd(MeCN)$_2$Cl$_2$ (0.3 eq), CH$_2$Cl$_2$, rt	 (47) +  (20)	423
	PdCl$_2$ (10 mol %), CuCl$_2$•H$_2$O (1 eq), DMF/H$_2$O (2:1), O$_2$, rt, 3 h	 (92)	426
	Pd(MeCN)$_2$Cl$_2$ (30 mol %), CuCl$_2$ (2 eq), dioxane, 100°, 24 h	 (64)	112

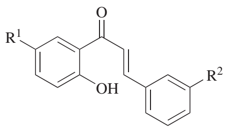
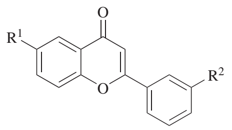
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*			
C_{15}			
	$Pd(MeCN)_2Cl_2$ (0.15 eq), CH_2Cl_2, rt	 (60)	423
	$Pd(TFA)_2$ (10 mol %), **19** (10 mol %), BQ (4 eq), acetone, 20°, 72 h	 (88) er 77.0:23.0	415
	$Pd(TFA)_2$ (10 mol %), **19** (10 mol %), BQ (4 eq), acetone, 20°, 72 h	 (92) er 85.5:14.5	415
	Li_2PdCl_4 (1 eq), MeCN, rt, 24 h	 **I** +  **II**	427

R^1	R^2	R^3	**I**	**II**
H	H	Ph	(75)	(6)
HO	H	Ph	(83)	(7)
H	MeO	Ph	(78)	(7)
H	H	$4\text{-}MeOC_6H_4$	(83)	(7)
H	MeO	$4\text{-}MeOC_6H_4$	(72)	(8)
MeO	H	$4\text{-}MeOC_6H_4$	(82)	(6)
H	H	$3,4\text{-}OCH_2OC_6H_3$	(78)	(9)

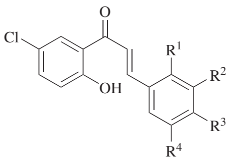
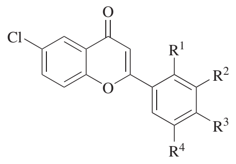
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$Na_2PdCl_4 \cdot 3H_2O$ (10 mol %), NaOAc, *t*-BuOH/H_2O (1:1), TBHP (6 eq), AcOH, 70°		428

R^1	R^2	Time (h)	
H	F	3	(81)
O_2N	H	3.5	(77)
H	MeO	2.5	(82)
MeO	H	3.5	(81)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{15} 	Na_2PdCl_4•$3H_2O$ (10 mol %), NaOAc, *t*–BuOH/H_2O (1:1), TBHP (6 eq), AcOH, 70°		428

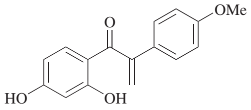
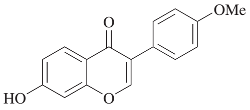
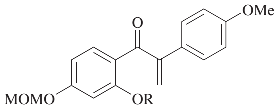
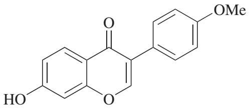
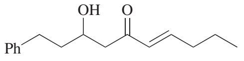
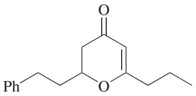
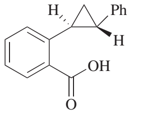
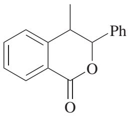
R^1	R^2	Time (h)	
F	O_2N	3.5	(89)
Cl	O_2N	4	(85)
Br	Cl	2.5	(83)
Cl	Br	4.5	(84)
Br	Br	2.5	(87)
O_2N	O_2N	4	(76)
Br	O_2N	3	(87)

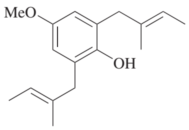
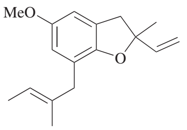
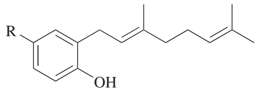
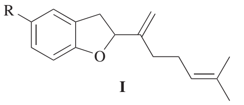
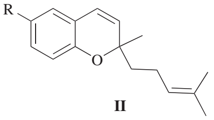
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{15–19}$ 	Na_2PdCl_4•$3H_2O$ (10 mol %), NaOAc, *t*–BuOH/H_2O (1:1), TBHP (6 eq), AcOH, 70°		428

R^1	R^2	R^3	R^4	Time (h)	
H	MeO	H	MeO	4.5	(84)
H	HO	H	H	2.5	(84)
H	MeO	H	H	2.5	(89)
H	H	*t*-Bu	H	3	(97)
H	H	HO	H	4	(79)
H	H	H	H	3	(88)
MeO	H	H	MeO	3	(92)
H	H	MeO	H	4	(90)
H	CF_3	H	H	3.5	(74)
H	H	Me_2N	H	5	(81)
H	H	F	H	2.5	(72)
H	H	CF_3	H	5	(78)
H	H	NC–	H	3.5	(71)

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

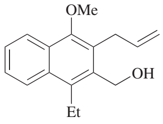
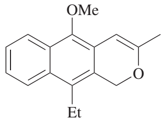
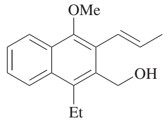
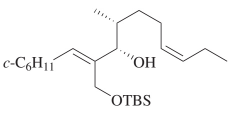
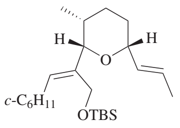
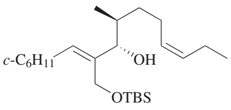
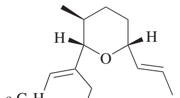
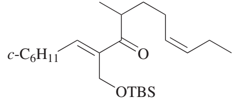
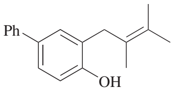
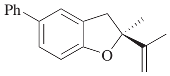
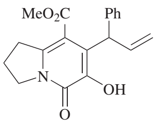
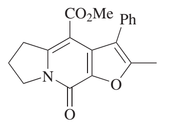
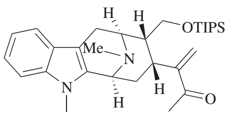
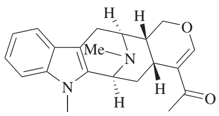
Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{15}			
	Na_2PdCl_4, TBHP, NaOAc, *t*-BuOH, AcOH, 80°, 18 h	 (52–58)	429
	Na_2PdCl_4, TBHP, NaOAc, *t*-BuOH, AcOH, 80°, 18 h; then, HCl (10 %)	 R H (52–58) MOM (52–58)	429
C_{16}			
	$PdCl_2$ (10 mol %), CuCl (10 mol %), Na_2HPO_4 (10 mol %), DME, O_2, 50°, 20 h	 (76)	402
	$PdCl_2$ (10 mol %), $CuCl_2$ (2 eq), dioxane, 80°, 12 h	 (50)	112

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(TFA)$_2$ (5 mol %), py (20 mol %), Na_2CO_3 (2 eq), 3 Å MS, toluene, O_2 (1 atm), 80°, 2 h	 (93)	45
	Pd(TFA)$_2$ (10 mol %), **17** (11 mol %), BQ (4 eq), DCE (0.3 M), 60°, 24 h, dark	 **I** +  **II**	430

R	**I**	**II**	**I/II**	**II** er
BnO	(45)	(24)	1:1.6	67.0:34.0
MeO	(42)	(19)	1:1.5	74.0:26.0
TBSO	(26)	(15)	1:1.4	74.5:25.5
MOMO	(61)	(33)	1:2.1	68.5:31.5
PivO	(57)	(35)	1:2.2	76.0:24.0
BzO	(46)	(37)	1:4.1	72.0:28.0
BocO	(68)	(52)	1:3.0	73.5:26.5
TsO	(41)	(30)	1:4.1	71.0:29.0
Br	(63)	(46)	1:4.7	77.5:22.5

TABLE 4A. WACKER CYCLIZATION WITH OXYGEN NUCLEOPHILES (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{16}			
	$Pd(MeCN)_2Cl_2$ (0.3 eq), CH_2Cl_2, rt	 (50) +  (21)	423
C_{18}			
	$Pd(OAc)_2$ (1.1 eq), DMSO, Ar, rt, 24 h	 (48)	406
	$Pd(OAc)_2$ (1.1 eq), DMSO, Ar, rt, 24 h	 (72) +  (8)	406
	$Pd(TFA)_2$/**23** (10 mol %), BQ (4 eq), MeOH, 60°, 24 h	 (62) er 95.0:5.0	111
	$PdCl_2$, $CuCl_2$, DMF/H_2O, O_2	 (80)	426
C_{19}			
	Na_2PdCl_4 (40 mol %), TBHP (1.1 eq), AcOH/H_2O/*t*-BuOH (1:3:3), 80°	 (60)	431

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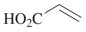
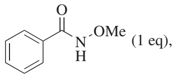
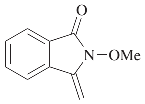
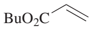
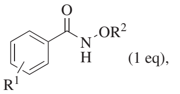
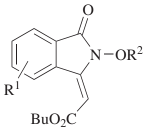
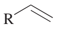
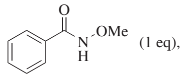
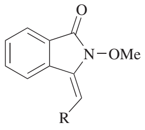
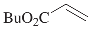
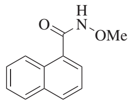
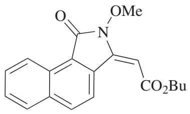
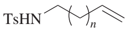
[a] A dimeric byproduct was also obtained.

TABLE 4B. AZA-WACKER CYCLIZATION

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3			
 2 eq	 (1 eq), $Pd(OAc)_2$ (5 mol %), BQ (20 mol %), AcOH, O_2 (1 atm), 110°	 (22)	146
 2 eq	 (1 eq), $Pd(OAc)_2$ (5 mol %), BQ (20 mol %), AcOH, O_2 (1 atm), 110°	 R^1 — R^2 H — *i*-Pr — (46) H — Bn — (45) 2-MeO — MeO — (18) 3-MeO — MeO — (85) 4-O_2N — MeO — (30) 3,4-$(MeO)_2$ — MeO — (75) 2-Me — MeO — (67) 3-Me — MeO — (96) 4-Me — MeO — (83) 3,4-Me_2 — MeO — (71)	146

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{3-8}			
 2 eq	 (1 eq), $Pd(OAc)_2$ (5 mol %), BQ (20 mol %), AcOH, O_2 (1 atm), 110°	 R MeO_2C (73) BuO_2C (95) *t*-BuO_2C (13) H_2NCO (65) Me_2NCO (87) *i*-PrHNCO (63) Ph (50) PhO_2S (67)	146
C_3			
 2 eq	 (1 eq), $Pd(OAc)_2$ (5 mol %), BQ (20 mol %), AcOH, O_2 (1 atm), 110°	 (70)	146
C_{4-6}			
	$Pd(MeCN)_2Cl_2$ (1–10 mol %), Na_2CO_3, LiCl, BQ, THF, reflux	*n* 1 (0) 3 (0)	116

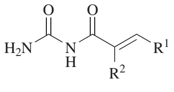
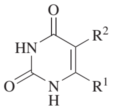
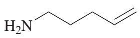
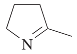
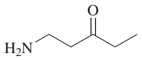
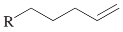
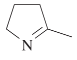
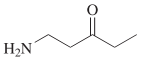
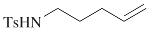
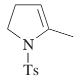
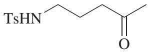
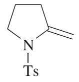
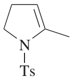
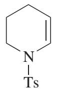
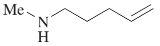
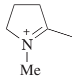
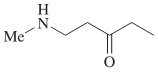
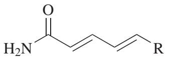
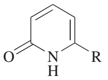
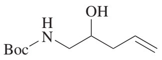
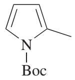
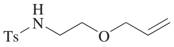
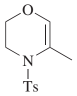
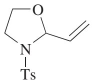
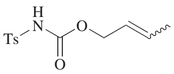
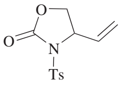
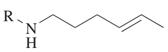
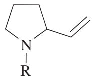
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
$C_{4–10}$			
	Li_2PdCl_4 (1 eq), Na_2CO_3 (2 eq), 60°	 R^1 R^2 H H (42) H Me (53) Me H (46) Ph H (40)	432
C_5			
	$PdCl_2$ (5 mol %), $CuCl_2$ (10 mol %), NaCl (1 eq), HCl (2 eq), H_2O, O_2, 60°, 6.5 h	 (75) +  (15)	149
	$PdCl_2$ (1 mol %), $CuCl_2$ (2 mol %), NaCl (20 mol %), HCl (40 mol %), H_2O, O_2, 60°, 30 h	 **I** +  **II** R **I** **II** ClH_3N (70) (—) MsH_3N (70) (—)	149
	$Pd(MeCN)_2Cl_2$ (1–10 mol %), Na_2CO_3, LiCl, BQ, THF, reflux	 (42) +  (—)	116
	$Pd(OAc)_2$ (5 mol %), py (10 mol %), xylenes, O_2 (1 atm), 80°, 1.5 h	 **I** +  **II** **I** + **II** (81), **I**/**II** = 7:3	433
	$Pd(MeCN)_2Cl_2$ (1 eq), Et_3N, THF	 (—)	116
	$PdCl_2$ (5 mol %), $CuCl_2$ (10 mol %), NaCl (1 eq), HCl (2 eq), H_2O, O_2, 60°, 3.5 h	 (80) +  (—)	149
$C_{5–11}$			
	Li_2PdCl_4 (1 eq), Et_3N (2 eq), MeCN, rt	 R H (62) Me (60) Ph (65)	434
C_5			
	$Pd(PhCN)_2$ (10 mol %), $Cu(OTf)_2$ (1 eq), EtOH, 30°, 24 h	 (86)	435
	$Pd(DMSO)_2(TFA)_2$ (5 mol %), DMSO (10 mol %), toluene, 3 Å MS, O_2 (60 psi), 60°, 24 h	 (60) +  (9)	436
	$Pd(OAc)_2$ (1 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 12 h	 (83)	263
C_6			
	$Pd(OAc)_2$ (5 mol %), py (10 mol %), xylenes, O_2 (1 atm), 80°	 R Time (h) Ns 8 (87) Ts 2 (87) Cbz 48 (76)	433

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

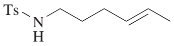
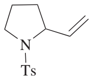
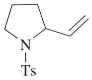
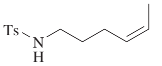
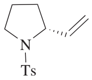
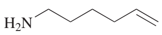
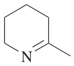
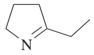
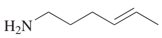
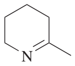
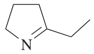
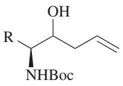
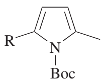
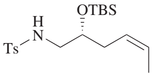
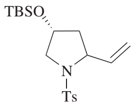
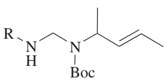
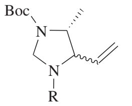
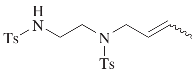
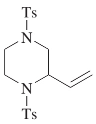
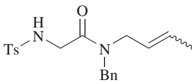
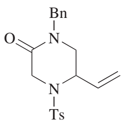
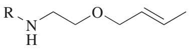
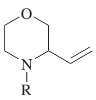
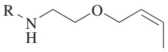
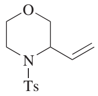
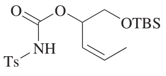
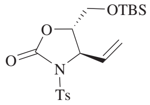
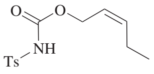
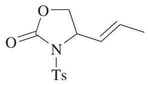
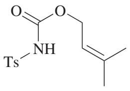
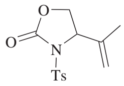
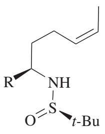
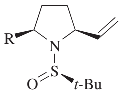
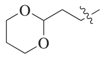
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C$_6$			
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO, O$_2$ (1 atm), rt, 72 h	 (93)	437
	16 (5 mol %), toluene, benzoic acid, O$_2$, 60°, 3 d	 (55)	44
	Pd(TFA)$_2$ (5 mol %), **11** (7.5 mol %), 3 Å MS, toluene, O$_2$ (1 atm), rt, 24 h	 (68) er 99.0:1.0	117
	PdCl$_2$ (5 mol %), CuCl$_2$ (10 mol %), NaCl (1 eq), HCl (2 eq), H$_2$O, O$_2$, 60°, 3 h	 (50) +  (25)	149
	PdCl$_2$ (5 mol %), CuCl$_2$ (10 mol %), NaCl (1 eq), HCl (2 eq), H$_2$O, O$_2$, 60°, 3 h	 (47) +  (24)	149
C$_{6–8}$			
	Pd(PhCN)$_2$ (10 mol %), Cu(OTf)$_2$ (1 eq), EtOH, 30°, 24 h	 R Me (89) *i*-Pr (87) MeS(CH$_2$)$_2$ (85)	435
C$_6$			
	Pd(TFA)$_2$ (5 mol %), ligand (7.5 mol %), 3 Å MS, toluene, O$_2$ (1 atm), rt, 24 h	 Ligand dr **11** (92) >20:1 **12** (97) >20:1	117
	Pd(OAc)$_2$, DMSO (0.2 M), O$_2$, 65–70°	 R Time (h) dr Ts 4 (66) 35:65 CHO 2 (90) 35:65 MeO$_2$C 4 (50) 47:53	438
 (*E*)/(*Z*) = 6:1	Pd(DMSO)$_2$(TFA)$_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O$_2$ (60 psi), 60°, 24 h	 (71)	436
 (*E*)/(*Z*) = 2:1	Pd(DMSO)$_2$(TFA)$_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O$_2$ (60 psi), 60°, 24 h	 (92)	436
	Pd(DMSO)$_2$(TFA)$_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O$_2$ (60 psi), 60°, 24 h	 R Ts (76) 2-Ns (86)	436

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

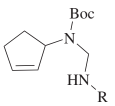
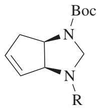
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_6			
	Pd(DMSO)$_2$(TFA)$_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O$_2$ (60 psi), 60°, 24 h	 (86)	436
	Pd(OAc)$_2$ (5 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 48 h	 (78) dr >20:1	263
	Pd(OAc)$_2$ (1 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 12 h	 (81)	263
	Pd(OAc)$_2$ (10 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 12 h	 (40)	263

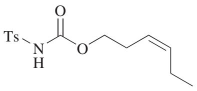
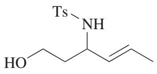
$C_{6–12}$

Alkene	Conditions	Product(s) and Yield(s) (%)	R	Temp (°)		dr	Refs.
	Pd(TFA)$_2$ (10 mol %), LiOAc, 3 Å MS, DMSO, O$_2$, 24 h		H	50	(68)	7:1	439
			Me	50	(98)	>20:1	
			i-Pr	50	(64)	>20:1	
			allyl	70	(70)	15:1	
			Ph	50	(68)	>20:1	
			4-ClC$_6$H$_4$	50	(71)	>20:1	
			(MeO)$_2$PO	50	(54)	>20:1	
			MeO$_2$CCH$_2$	50	(80)	>20:1	
				50	(67)	>20:1	

C_6

Alkene	Conditions	Product(s) and Yield(s) (%)	R	Time (h)		Refs.
	Pd(OAc)$_2$, DMSO (0.2 M), O$_2$, 65–70°		CHO	2	(86)	438
			H$_2$NCO	4	(68)	
			MeCO	4	(70)	
			MeO$_2$C	4	(83)	
			BnO$_2$C	4	(84)	
			Ts	1	(71)	

C_7

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(OAc)$_2$ (10 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 48 h	 (46)	263

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

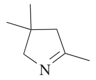
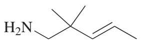
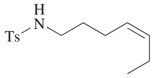
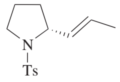
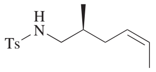
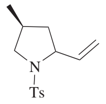
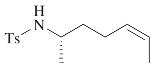
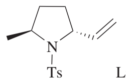
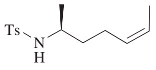
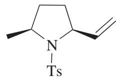
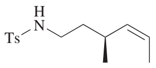
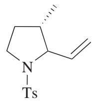
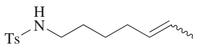
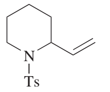
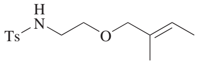
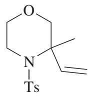
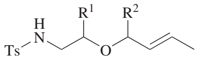
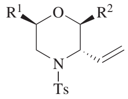
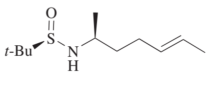
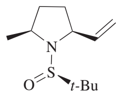
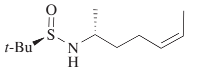
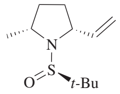
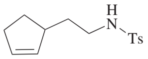
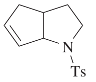
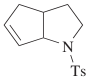
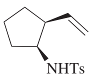
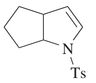
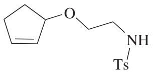
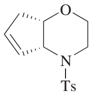
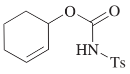
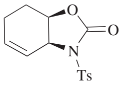
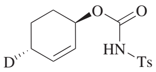
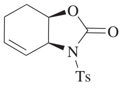
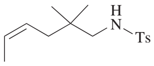
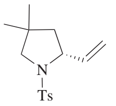
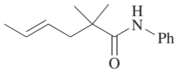
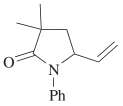
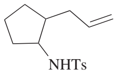
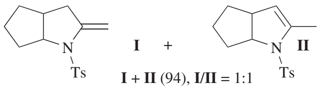
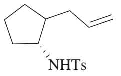
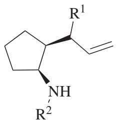
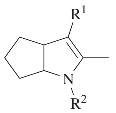
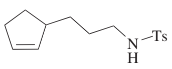
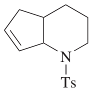
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_7			
	$PdCl_2$ (5 mol %), $CuCl_2$ (10 mol %), NaCl (1 eq), HCl (2 eq), H_2O, O_2, 60°, 3.5 h	 (40) +  (—)	149
	$Pd(TFA)_2$ (5 mol %), **11** (7.5 mol %), 3 Å MS, toluene, O_2 (1 atm), rt, 24 h	 (62) er 98.5:1.5	117
	$Pd(TFA)_2$ (5 mol %), ligand (7.5 mol %), 3 Å MS, toluene, O_2 (1 atm), rt, 24 h	 Ligand — dr **11** (90) >20:1 **12** (87) 1:17	117
	$Pd(TFA)_2$ (5 mol %), ligand (7.5 mol %), 3 Å MS, toluene, O_2 (1 atm), rt, 24 h	 **I** + alkene isomers **II** Ligand — **I** — **I** dr — **II** **11** (88) >1:20 (0) **12** (23) 7:1 (64)	117
	$Pd(TFA)_2$ (10 mol %), LiOAc, 3 Å MS, DMSO, O_2, 50°, 24 h	 (83) dr 6:1	439
	$Pd(TFA)_2$ (5 mol %), ligand (7.5 mol %), 3 Å MS, toluene, O_2 (1 atm), rt, 24 h	 Ligand — dr **11** (77) >20:1 **12** (92) >20:1	117
 (*E*)/(*Z*) = 2:1	$Pd(DMSO)_2(TFA)_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O_2 (60 psi), 60°, 24 h	 (92)	436
	$Pd(DMSO)_2(TFA)_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O_2 (60 psi), 60°, 24 h	 (73)	436
C_{7-12}			
	$Pd(DMSO)_2(TFA)_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O_2 (60 psi), 60°, 24 h	 R^1 — R^2 — — dr H Me (72) 6:1 H *i*-Pr (59) >10:1 Ph H (50) 7:1	436
C_7			
	$Pd(TFA)_2$ (10 mol %), LiOAc, 3 Å MS, DMSO, O_2, 50°, 24 h	 (41) dr 7:1	436
	$Pd(TFA)_2$ (10 mol %), LiOAc, 3 Å MS, DMSO, O_2, 50°, 24 h	 (78) dr >20:1	436

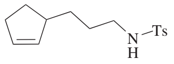
TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*			
C_7			
	Pd(OAc)$_2$ (5 mol %), py (10 mol %), xylenes, O$_2$ (1 atm), 80°, 2 h	 (91)	433
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO, O$_2$ (1 atm), rt, 72 h	 (86)	437
	16 (5 mol %), toluene, benzoic acid, O$_2$, 60°, 6 d	 **I** + **II** (65), **I/II** = 85:15	44
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	 (57)	116
	Pd(DMSO)$_2$(TFA)$_2$ (5 mol %), DMSO (10 mol %), 3 Å MS, toluene, O$_2$ (60 psi), 60°, 24 h	 (66)	436
	Pd(OAc)$_2$ (10 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 48 h	 (81) dr >25:1	263
	Pd(OAc)$_2$ (10 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 48 h	 (81)	263
C_8			
	Pd(TFA)$_2$ (5 mol %), **11** (7.5 mol %), 3 Å MS, toluene, O$_2$ (1 atm), rt, 24 h	 (58) er 96.0:4.0	117
	Pd(OAc)$_2$ (10 mol %), py (20 mol %), toluene, O$_2$, 60°, 48 h	 (16)	440
	Pd(OAc)$_2$ (5 mol %), py (10 mol %), xylenes, O$_2$ (1 atm), 80°, 1.5 h	 **I** + **II** (94), **I/II** = 1:1	433
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	(0)	116
$C_{8–9}$			
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	 R^1 R^2 H Ms (63) H Ts (85) H BnO$_2$S (76) Me Ts (82)	116
C_8			
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO, O$_2$ (1 atm), 80°, 96 h	 (82)	437

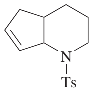
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_8

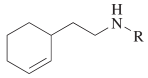


$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO, O_2 (1 atm), 80°, 96 h

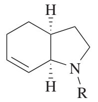


(82)

437

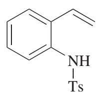


$Pd(OAc)_2$ (10 mol %), DMSO, O_2, 55°, 24 h

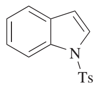


R	
Ts	(93)
BnO_2C	(95)

403



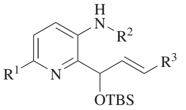
$Pd(OAc)_2$ (5 mol %), NaOAc (*x* eq), DMSO, O_2 (1 atm)



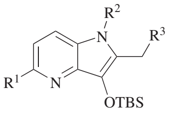
x	Temp (°)	Time (h)	
2	100	48	(38)
0	80	72	(48)

437

C_{8-14}

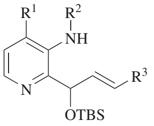


$Pd(MeCN)_2Cl_2$ (20 mol %), BQ (1.5 eq), K_2CO_3 (3 eq), LiCl (10 eq), THF

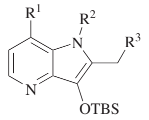


441

R^1	R^2	R^3	Temp	Time (h)	
MeO	Me	H	rt	1.75	(100)
MeO	Me	Me	75°	3.5	(51)
MeO	allyl	Me	75°	3.5	(83)
Cl	Me	Ph	rt	48	(54)



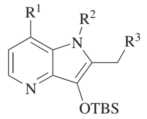
$Pd(MeCN)_2Cl_2$ (1.5 eq), Et_3N (8 eq), THF, rt



R^1	R^2	R^3	
H	Me	H	(93)
H	Me	Me	(55)
H	Me	Ph	(76)
H	allyl	H	(54)
MeO	$4\text{-}BrC_6H_4CH_2$	H	(0)

442

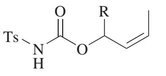
$Pd(MeCN)_2Cl_2$ (10–20 mol %), BQ (1.5 eq), K_2CO_3 (3 eq), LiCl (*x* eq), THF



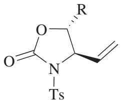
442

R^1	R^2	R^3	*x*	Temp	
H	Me	H	0	rt	(93)
H	Me	Me	10	85°	(55)
H	Me	Ph	10	rt	(76)
H	allyl	H	10	rt	(54)
MeO	$4\text{-}BrC_6H_4CH_2$	H	0	rt	(0)

C_{9-10}



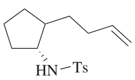
$Pd(OAc)_2$ (5 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 48 h



R		dr
t-Bu	(79)	>20:1
Et_2CH	(83)	>20:1

263

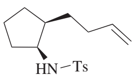
C_9



$Pd(MeCN)_2Cl_2$ (1–10 mol %), Na_2CO_3, LiCl, BQ, THF, reflux

(0)

116



$Pd(MeCN)_2Cl_2$ (1–10 mol %), Na_2CO_3, LiCl, BQ, THF, reflux

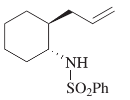
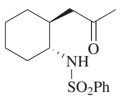
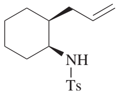
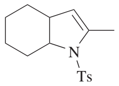
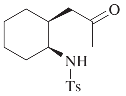
(0)

116

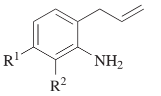
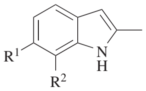
TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_9

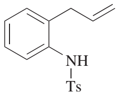
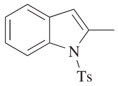
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	 (>99)	116
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	 (48) +  (—)	116

$C_{9–10}$

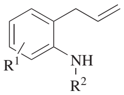
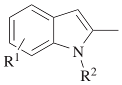
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(MeCN)$_2$Cl$_2$, Et$_3$N, THF		443

R^1	R^2	
H	H	(84)
H	MeO	(81)
Me	H	(76)
EtO$_2$C	H	(74)

C_9

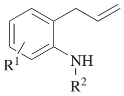
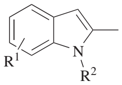
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(OAc)$_2$ (5 mol %), py (10 mol %), xylenes, O$_2$ (1 atm), 80°, 16 h	 (60)	433

$C_{9–10}$

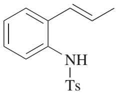
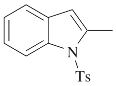
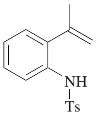
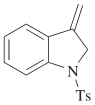
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	1. Pd(MeCN)$_2$Cl$_2$ (1 eq), THF, rt 2. Et$_3$N		444

R^1	R^2	
H	H	(85)
5-Me	H	(82)
5-MeO$_2$C	H	(74)
6-MeO	H	(82)
H	Me	(69)
H	Ac	(27)
5,6-(MeO)$_2$	H	(46)
5-MeO	H	(17)

C_9

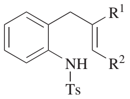
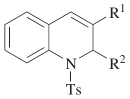
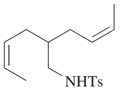
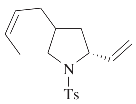
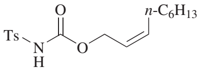
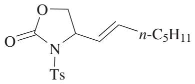
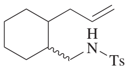
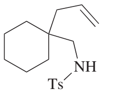
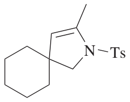
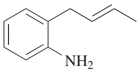
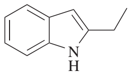
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	1. Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), CuCl$_2$ or BQ, THF, reflux 2. Et$_3$N		444

R^1	R^2	Temp	
H	H	reflux	(86)
H	Me	reflux	(89)
H	Ac	reflux	(71)
5,6-(MeO)$_2$	H	rt	(48)
5-MeO	H	rt	(32)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(OAc)$_2$ (5 mol %), NaOAc (x eq), DMSO, O$_2$ (1 atm), 40°, 24 h		437
	Pd(OAc)$_2$ (5 mol %), NaOAc (2 eq), DMSO, O$_2$ (1 atm), rt, 72 h	 (58)	437

x	
2	(44)
0	(7)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{9-15}			
	Pd(OAc)$_2$ (5 mol %), NaOAc (*x* eq), DMSO, O$_2$ (1 atm)	 R^1 R^2 *x* Temp (°) Time (h) H H 2 80 72 (86) Me H 2 100 72 (40) Me H 0 40 24 (trace) H Ph 2 80 18 (62)	437
C_{10}			
	Pd(TFA)$_2$ (5 mol %), **11** (7.5 mol %), 3 Å MS, toluene, O$_2$ (1 atm), rt, 24 h	 (86) er 96.5:3.5, dr 1.1:1 minor diastereomer er 97.5:2.5	117
	Pd(OAc)$_2$ (1 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 12 h	 (95)	263
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	(0)	116
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	 (78)	116
	1. Pd(MeCN)$_2$Cl$_2$ (1 eq), THF, 0° 2. Et$_3$N	 (10)	444

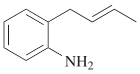
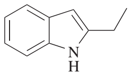
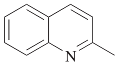
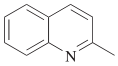
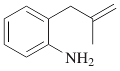
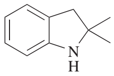
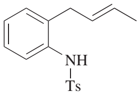
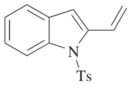
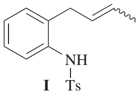
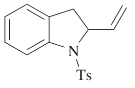
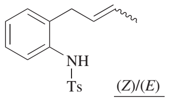
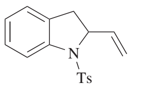
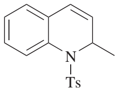
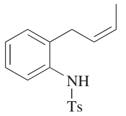
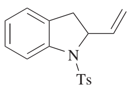
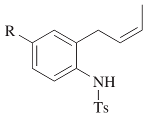
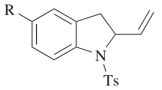
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	1. Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), LiCl (10 eq), CuCl$_2$ or BQ, THF, reflux 2. Et$_3$N	 (79)	444
	1. Pd(MeCN)$_2$Cl$_2$ (1 eq), THF 2. Et$_3$N	 (38)	444
	1. Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), CuCl$_2$ or BQ, THF, reflux 2. Et$_3$N	 (58)	444
	1. Pd(MeCN)$_2$Cl$_2$ (1 eq), THF 2. Et$_3$N	 (31)	444
	Pd(OAc)$_2$ (5 mol %), py (10 mol %), xylenes, O$_2$ (1 atm), 80°, 1.5 h	 (91)	433
 **I**	Pd(OAc)$_2$ (5 mol %), DMSO, O$_2$ (1 atm), rt, 72 h	 (*Z*)/(*E*) **I** 83:17 (86) 14:86 (88)	437

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}			
 (*Z*)/(*E*) 83:17 14:86	$Pd(OAc)_2$ (5 mol %), NaOAc (2 eq), DMSO, O_2 (1 atm), rt, 72 h	 **I** +  **II** **I + II** **I/II** (88) 95:5 (91) 83:17	437
	Catalyst (5 mol %), additive, toluene, O_2 (1 atm), 80°, 18 h	 Catalyst Additive er **15a** — (90) 52.5:47.5 **15a** BzOH (20 mol %) (91) 52.0:48.0 **15a** Na_2CO_3 (2 eq) (90) 53.0:47.0 **15b** — (82) 52.5:47.5 **15b** BzOH (20 mol %) (85) 52.0:48.0 **15b** Na_2CO_3 (2 eq) (83) 50.0:50.0	445
	**16** (5 mol %), toluene, AcOH, O_2, 80°, 4 h	 R H (86) Cl (79)	44

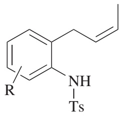
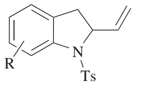
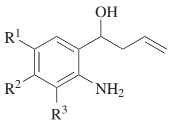
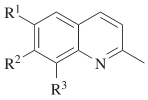
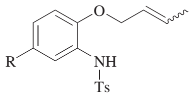
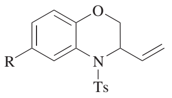
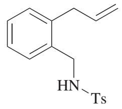
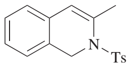
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{10–11}$			
	$Pd(OAc)_2$ (10 mol %), **9** (20 mol %), toluene, O_2, 0°, 5 d	 R er H (90) 84.5:15.5 4-Cl (90) 84.0:16.0 6-Cl (4) 32.5:67.5 4-MeO (75) 87.0:13.0 4-Me (94) 84.5:15.5 6-Me (37) 46.0:54.0	118
C_{10}			
	$Pd(OAc)_2$ (10 mol %), 1,10-phenanthroline (0.2 mol %), MeOH, air, 36 h	 R^1 R^2 R^3 Temp H H H rt (87) Cl H H rt (90) H H HO 40° (53) MeO MeO H rt (76)	115
 (*E*)/(*Z*) = 6:1	$Pd(DMSO)_2(TFA)_2$ (*x* mol %), DMSO (10 mol %), 3 Å MS, toluene, O_2 (*y*), 60°	 R *x* *y* Time (h) H 5 60 psi 24 (96) MeO 5 60 psi 24 (96) MeO 15 9% in 800 psi N_2 28 (100)	436

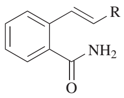
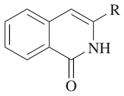
TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{10}

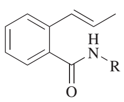
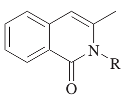
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(MeCN)$_2$Cl$_2$ (1–10 mol %), Na$_2$CO$_3$, LiCl, BQ, THF, reflux	 (84)	116

$C_{10–16}$

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Li$_2$PdCl$_4$ (1 eq), Et$_3$N (2 eq), MeCN, 60°		446

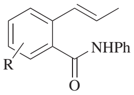
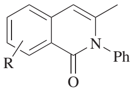
R	
NC–	(45)
Ph	(62)
PhCO	(37)
4-MeC$_6$H$_4$	(52)

C_{10}

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(MeCN)$_2$Cl$_2$ (10 mol %), CuCl$_2$ (10 mol %), Et$_3$N (20 mol %), MeOH, O$_2$, 60°		440

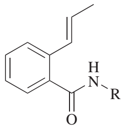
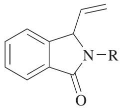
R	Time (h)	
n-Bu	18	(87)
4-ClC$_6$H$_4$	15	(95)
Bn	15	(84)
4-MeC$_6$H$_4$	15	(91)
2,4-Me$_2$C$_6$H$_3$	15	(57)
3,4-Me$_2$C$_6$H$_3$	15	(85)

$C_{10–11}$

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(MeCN)$_2$Cl$_2$ (10 mol %), CuCl$_2$ (10 mol %), Et$_3$N (20 mol %), MeOH, O$_2$, 60°		440

R	Time (h)	
H	15	(98)
4-Cl	15	(49)
5-Cl	48	(37)
4-MeO	15	(99)
3-Me	15	(86)
4-Me	15	(88)
5-Me	15	(99)

C_{10}

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	Pd(OAc)$_2$ (x mol %), phenanthroline (y mol %), MeOH, O$_2$, 60°		440

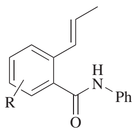
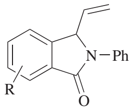
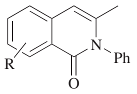
R	x	y	Time (h)	
n-Bu	20	40	48	(41)
4-ClC$_6$H$_4$	10	20	12	(87)
4-MeC$_6$H$_4$	10	20	12	(65)
Bn	10	20	12	(22)
2,4-Me$_2$C$_6$H$_3$	10	20	12	(61)
3,4-Me$_2$C$_6$H$_3$	10	20	12	(62)

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

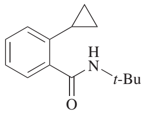
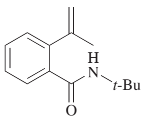
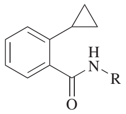
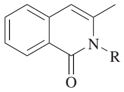
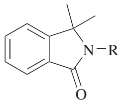
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{10-11}

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$Pd(OAc)_2$ (10 mol %), phenanthroline (20 mol %), MeOH, O_2, 60°	 **I** +  **II**	440

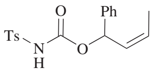
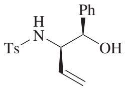
R	Time (h)	I	II
H	12	(85)	(—)
4-Cl	12	(58)	(—)
4-Cl	48	(77)	(19)
5-Cl	48	(40)	(8)
4-MeO	12	(80)	(—)
3-Me	12	(76)	(—)
4-Me	12	(77)	(—)
5-Me	12	(97)	(—)

C_{10}

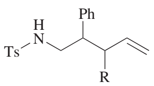
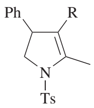
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$PdCl_2$ (10 mol %), $CuCl_2$ (2 eq), dioxane, 80°, 12 h	 (43)	112
	$Pd(MeCN)_2Cl_2$ (10 mol %), BQ (1 eq), dioxane, 80°, 12 h	 **I** +  **II**	

R	I + II	I/II	Refs.
n-Bu	(75)	87:13	112
Ph	(68)	83:17	115
Bn	(50)	88:12	112
$4-ClC_6H_4(CH_2)_2$	(51)	84:16	112
Ts	(60)	75:25	112

C_{11}

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$Pd(OAc)_2$ (5 mol %), BQ (1.5 eq), AcOH (7 eq), NaOAc (0.5 eq), THF/DMSO (9:1), 50°, 48 h	 (61) dr >20:1	263

C_{11-12}

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
	$Pd(MeCN)_2Cl_2$ (1–10 mol %), Na_2CO_3, LiCl, BQ, THF, reflux		116

R	
H	(60)
Me	(92)

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

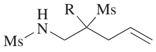
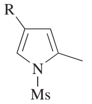
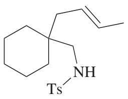
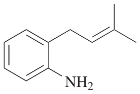
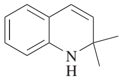
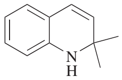
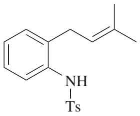
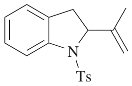
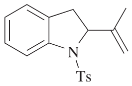
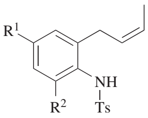
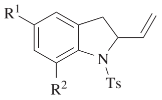
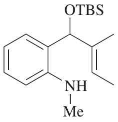
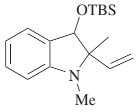
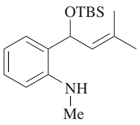
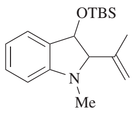
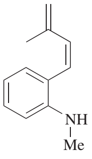
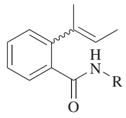
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{11-13}			
	$PdCl_2$ (50 mol %), $CuCl_2$ (3 eq), TMU (5 eq), EOA (40 mol %), MeOH, reflux, 1.5 h	 R n-C_6H_{13} (67) Bn (84) $Ph(CH_2)_2$ (65)	362
C_{11}			
	$Pd(MeCN)_2Cl_2$ (1–10 mol %), Na_2CO_3, LiCl, BQ, THF, reflux	(0)	116
	1. $Pd(MeCN)_2Cl_2$ (1 eq), THF 2. Et_3N	 (52)	444
	1. $Pd(MeCN)_2Cl_2$ (1–10 mol %), $CuCl_2$ or BQ, THF, reflux 2. Et_3N	 (54)	444
	$Pd(OAc)_2$ (5 mol %), DMSO, O_2 (1 atm), 80°, 72 h	 (62)	437
	16 (5 mol %), toluene, AcOH, O_2, 80°, 6 d	 (56)	44
	**16** (5 mol %), toluene, benzoic acid, O_2, 80°, 8 h	 R^1 R^2 Me H (72) H Me (75)	44
	$Pd(MeCN)_2Cl_2$, BQ, K_2CO_3, LiCl (10 eq), THF, 85°	 (89)	442
	$Pd(MeCN)_2Cl_2$ (1.5 eq), Et_3N (8 eq), THF, 140°	 (9) +  (30)	442

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

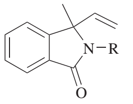
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

C_{11}



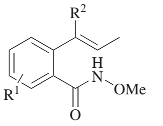
Pd(TFA)$_2$ (5 mol %), py (20 mol %), 3 Å MS, toluene, O$_2$ (1 atm), 80°



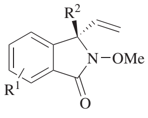
R	Time (h)	
Ts	8	(88)
BnO	4	(82)

404

C_{11-18}



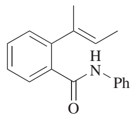
Pd(TFA)$_2$ (5 mol %), **10** (7.5 mol %), 4 Å MS, MeCN, O$_2$, 60°



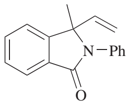
R^1	R^2	Time (h)		er
H	Me	9	(99)	98.0:2.0
H	Et	9	(99)	97.0:3.0
H	*n*-Pr	9	(99)	96.0:4.0
H	BnCH$_2$	9	(99)	96.0:4.0
H	*c*-C$_5$H$_9$	9	(99)	95.5:4.5
4-Cl	Me	18	(99)	98.0:2.0
4-F	Me	12	(99)	98.5:1.5
4-MeO	Me	18	(90)	95.5:4.5
5-MeO	Me	18	(92)	95.5:4.5
6-MeO	Me	36	(71)	94.0:6.0

447

C_{11}

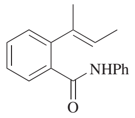


Pd(OAc)$_2$ (10 mol %), phenanthroline (20 mol %), MeOH, O$_2$, 60°, 12 h

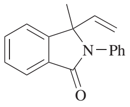


(99)

440

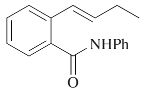


Pd(MeCN)$_2$Cl$_2$ (10 mol %), CuCl$_2$ (10 mol %), Et$_3$N (20 mol %), MeOH, O$_2$, 60°, 15 h

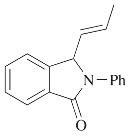


(27)

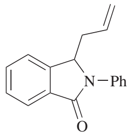
440



Pd(OAc)$_2$ (10 mol %), phenanthroline (20 mol %), MeOH, O$_2$, 60°, 12 h



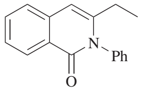
(41) +



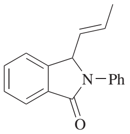
(35)

440

Pd(MeCN)$_2$Cl$_2$ (10 mol %), CuCl$_2$ (10 mol %), Et$_3$N (20 mol %), MeOH, O$_2$, 60°, 15 h



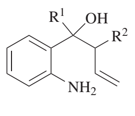
(52) +



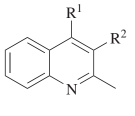
(5)

440

C_{11-17}



Pd(OAc)$_2$ (10 mol %), 1,10-phenanthroline (0.2 mol %), MeOH, air, 36 h



R^1	R^2	Temp	
H	Me	rt	(86)
Me	H	rt	(84)
Me	Me	rt	(83)
Ph	H	40°	(78)
Ph	Me	40°	(75)

115

Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the ***bold*** *numbers.*

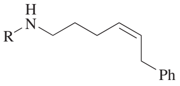
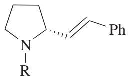
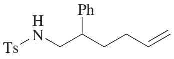
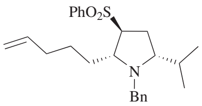
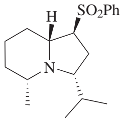
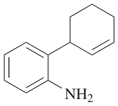
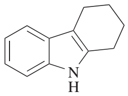
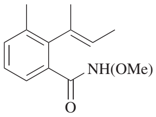
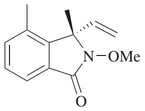
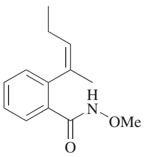
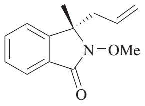
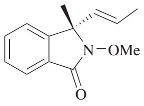
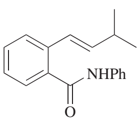
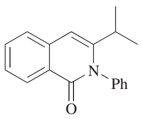
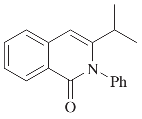
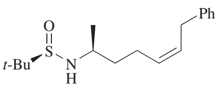
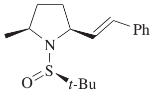
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{12}			
	$Pd(TFA)_2$ (5 mol %), **11** (7.5 mol %), 3 Å MS, toluene, O_2 (1 atm), rt, 24 h	 R — er Ns (52) 88.0:12.0 Ts (98) 96.5:3.5 Me_2NSO_2 (95) 96.0:4.0	117
	$Pd(MeCN)_2Cl_2$ (1–10 mol %), Na_2CO_3, LiCl, BQ, THF, reflux	(0)	116
	$PdCl_2$ (cat), CuCl (1 eq), DMF/H_2O, O_2	 (18)	448
	1. $Pd(MeCN)_2Cl_2$ (1 eq), THF 2. Et_3N	 (46)	444
$C_{12–14}$			
	$Pd(TFA)_2$ (5 mol %), **10** (7.5 mol %), 4 Å MS, MeCN, O_2, 60°, 18 h	 (97) er 78.5:21.5	447
C_{12}			
	$Pd(TFA)_2$ (5 mol %), **10** (7.5 mol %), 4 Å MS, MeCN, O_2, 60°, 9 h	 +  (66) er 99.5:0.5 (33) er 98.0:2.0	447
	$Pd(OAc)_2$ (10 mol %), phenanthroline (20 mol %), MeOH, O_2, 60°, 96 h	 (40)	440
	$Pd(MeCN)_2Cl_2$ (10 mol %), $CuCl_2$ (10 mol %), Et_3N (20 mol %), MeOH, O_2, 60°, 48 h	 (9)	440
C_{13}			
	$Pd(TFA)_2$ (10 mol %), LiOAc, 3 Å MS, DMSO, O_2, 50°, 24 h	 (85) dr >20:1	439

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*

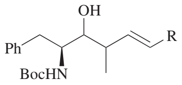
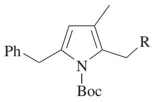
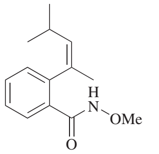
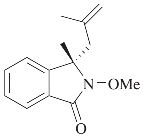
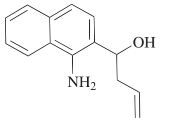
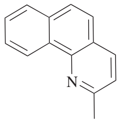
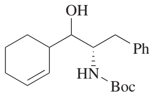
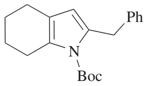
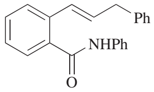
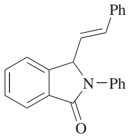
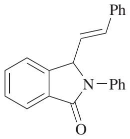
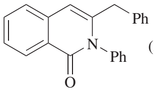
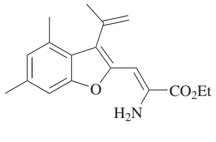
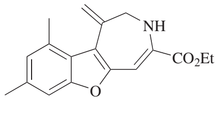
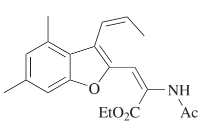
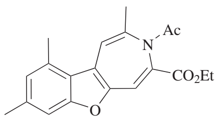
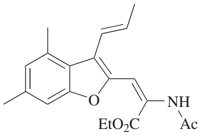
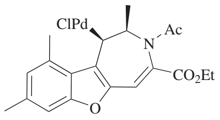
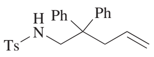
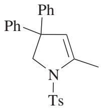
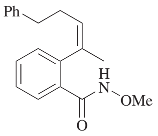
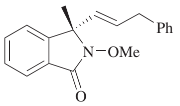
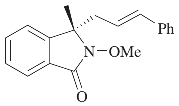
Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
$C_{13–14}$			
	Pd(PhCN)$_2$ (10 mol %), Cu(OTf)$_2$ (1 eq), EtOH, 30°, 24 h	 R H (76) Me (26)	435
C_{13}			
	Pd(TFA)$_2$ (5 mol %), **10** (7.5 mol %), 4 Å MS, MeCN, O$_2$, 60°, 9 h	 (95) er 97.0:3.0	435
C_{14}			
	Pd(OAc)$_2$ (10 mol %), 1,10-phenanthroline (0.2 mol %), MeOH, air, 40°, 36 h	 (60)	115
C_{15}			
	Pd(PhCN)$_2$ (10 mol %), Cu(OTf)$_2$ (1 eq), EtOH, 30°, 24 h	 (70)	435
C_{16}			
	Pd(OAc)$_2$ (10 mol %), phenanthroline (20 mol %), MeOH, O$_2$, 60°, 12 h	 (80)	440
	Pd(MeCN)$_2$Cl$_2$ (10 mol %), CuCl$_2$ (10 mol %), Et$_3$N (20 mol %), MeOH, O$_2$, 60°, 48 h	 (44) +  (32)	440
	Pd(MeCN)$_2$Cl$_2$ (1.1 eq), Na$_2$CO$_3$ (1.1 eq), MeCN	 (67)	116

TABLE 4B. AZA-WACKER CYCLIZATION (*Continued*)

Alkene	Conditions	Product(s) and Yield(s) (%)	Refs.
*Please refer to Chart 1 preceding the tables for ligand and catalyst structures corresponding to the **bold** numbers.*			
C_{16}			
	$Pd(PhCN)_2Cl_2$ (1.1 eq), Na_2CO_3, MeCN, 40°, 43 h	 (65)	449
	$Pd(PhCN)_2Cl_2$ (1.1 eq), Na_2CO_3, MeCN, 40°, 43 h	 (—)	449
C_{17}			
	**16** (5 mol %), toluene, benzoic acid, O_2, 60°, 24 h	 (70)	44
C_{18}			
	$Pd(TFA)_2$ (5 mol %), **10** (7.5 mol %), 4 Å MS, MeCN, O_2, 60°, 9 h	 (74) er 98.0:2.0 +  (25) er 99.0:1.0	447

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