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Pd(II)-Catalyzed cyclogeneration of carbocations: subsequent rearrangement and trapping under oxidative conditions

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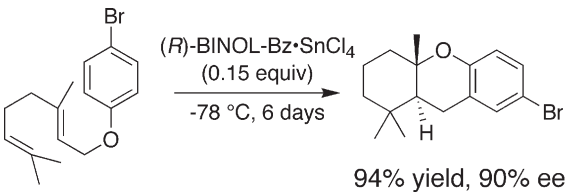
Dedicated to Professor Robert H. Grubbs in recognition of his receipt of the 2003 Tetrahedron Prize

Abstract—A catalytic oxidative polycyclization reaction initiated by the carbocyclization of 1,5-dienes with Pd(II) is reported. Trapping of a putative carbocation with suitable functional groups (phenols, alkenes, alcohols, sulfonamide), or rearrangement protocols (Pinacol) yields poly-cyclic products in good yields and in excellent diastereoselectivities. Turnover of the intermediate Pd–C bond is via β-H elimination.

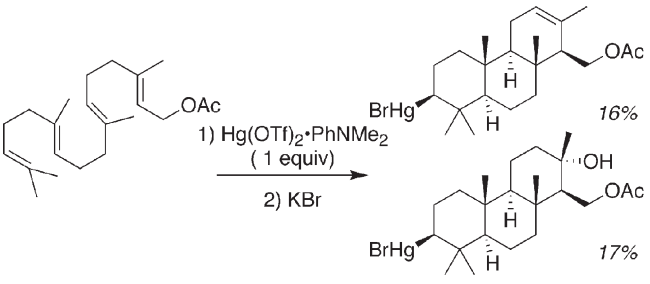
1. Introduction

Carbocations are key intermediates in the biosynthesis of the terpenoid natural products. These reactive intermediates are normally generated by alkene or epoxide protonation, or pyrophosphate elimination followed by trapping or rearrangement under careful enzymatic guidance.[1] Because enantioselective proton delivery is considerably more difficult to control in non-enzymatic situations, their application to synthesis is significantly less developed.[2] Notable exceptions, however, are Yamamoto's chiral Brønsted Lewis Acid (BLA) catalysts,[3] which can deliver H^+ with a preference for one enantioface of a polyene reactant and, thereby, initiate enantioselective cation-olefin polycyclization reactions, in analogy to steroid biosynthesis (e.g., Eq. 1).



(1)

The analogy between proton reactivity and electrophiles like Hg(II) and Br^+ has stimulated the development of methods for activating alkenes towards the addition of carbon and hetero-nucleophiles alike.[2] Similar to H^+, electrophiles like Hg(II) prefer to coordinate and activate electron rich alkenes and are thus able to initiate steroid-like cation-olefin cascades of polyprenoids, for example, Eq. 2.[4] The resulting C–Hg bond is stable and amenable to numerous derivitization protocols.[5,6]



(2)

Another electrophilic species that has shown significant utility in the activation of alkenes towards hetero-nucleophiles is Pd(II).[7] However, few applications of Pd(II) utilize carbon-based nucleophiles,[8] though several recent publications are demonstrating that this limitation is being solved, especially for enolic nucleophiles.[9–11] Like the Hg(II)-initiated cascade in Eq. 2, the addition of alkene nucleophiles to Pd(II)-alkene intermediates would be a valuable reaction as the carbocyclic products would contain Pd–C bonds that could be derivitized in situ so that the metal could be used in catalytic quantities (Hg(II) is a stoichiometric reagent).[6] The first evidence that Pd(II) could catalytically[12] generate cations by the action of an alkene nucleophile on an activated alkene was realized by Overman in the Pd(II)-catalyzed Cope-rearrangement reactions (Eq. 3),[13] wherein a cyclic cation was proposed as an intermediate in the rearrangement.[13b] Grob-type fragmentation consumed the cation and led to the diene product; one

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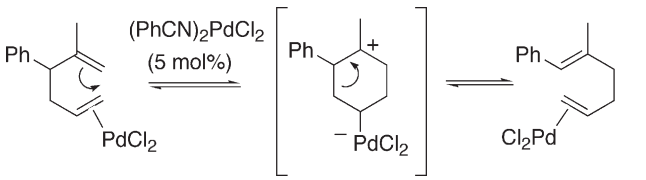
type of diene did provide a cyclic product.[14] More recent studies have shown that carbocycles can be routinely maintained if the carbon nucleophile is an enol,[9,10] or an indole.[11] Two recent intermolecular C–C bond forming reactions that reasonably propose cationic intermediates have been reported by Vitagliano using pincer-ligated Pt-dications[15] and by Wiedenhoefer with $PtCl_2$.[16]

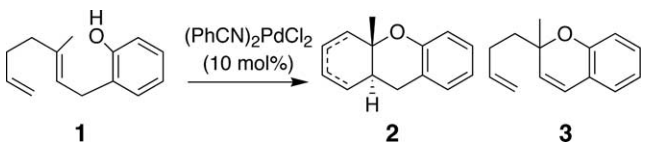


(3)

2. Results and discussion

We recently initiated a program to investigate methods for trapping the putative cation generated by the Pd(II)-mediated cycloisomerization of 1,5-dienes.[17] To this end, we examined catalysts for the bicyclization of dienylphenol **1**, which was designed to trap the cation with the heteroatom, followed by proton loss. Since Pd(II) has a strong preference for the less substituted alkenes, the terminal alkene was expected to be the point of initiation. In the case of weakly ligated Pd(II) sources, rapid β-hydride elimination of the Pd–C bond was expected, and several reoxidation (Pd(0) to Pd(II)) procedures were investigated.[7a]

As shown in Eq. 4, mono- and bicyclic products were obtained when $PdCl_2(PhCN)_2$ (10 mol%) was reacted with **1** at RT in the presence of 4 equiv. of benzoquinone (BQ). The monocyclic product (**3**) is presumably the result of a Wacker-type cyclization and is well precedented.[18] The desired product (**2**) was formed as a mixture of alkene isomers, and exclusively with a *trans* ring junction. Proof of the ring stereochemistry was obtained by comparison to the known hydrogenation product (**4**).[17,19]



(4)

Attempts to utilize $CuCl_2$ (Table 1, entry 2) or O_2 (entry 3) as the stoichiometric oxidant were less successful and products incorporating Cl (presumably Cl^- trapping of the cation) or low conversions were obtained, respectively. The optimum procedure utilized CH_3CN at elevated temperatures and provided the bicycle in 85% yield, free of the Wacker product (entry 5). In contrast to $PdCl_2$, catalytic $Pd(OAc)_2$ provided none of **2**, and only the Wacker product **3** in 95% yield (entry 6).[20]

The optimized protocol was applied to a variety of poly-enyl compounds with traps for the putative cation; the resulting alkene containing products were hydrogenated (H_2, Pd/C) and analyzed. As shown in Table 2 (entry 2), cascade cyclizations were possible from trienylphenol (**5**) to provide tricyclic products in excellent yields (89%), again as a mixture of three alkene isomers (70:17:13). Hydrogenation and NMR analysis showed the product (**6**) to have a *trans–trans* ring junction with diaxial methyl groups.[17] When primary alcohols were utilized as the terminal trapping agent both dienyl (**7**, entry 3) and trienyl (**9**, entry 4) alcohols provided the desired bi-[21] and tricyclic hydrofurans.[22] The bicyclic product (**8**) was obtained as a single isomer after hydrogenation, while the tricycle was a mixture of two (91:9). The major diastereomer (**10a**) was unambiguously assigned to be dinor-ambrox, a compound whose scent has been described as having 'a strong earthy odor reminiscent of a freshly plowed field'.[22] The minor diastereomer (**10b**) was not conclusively identified, but literature data (^{1}H NMR) was consistent with the C-9 epimer. A sulfonamide (**11**) is also an efficient trap of the cation and annulated pyrrolidine products (**12a**, **12b**) were obtained, again with good stereocontrol of the ring junction (94:6, entry 5).[23] Stimulated by the ring-expanding/contracting pinacol rearrangement reactions reported by Overman,[24] we also examined the 1,5-dienyl carbinol (**13**) in entry 6. As expected, the putative tertiary carbocation undergoes a rearrangement to provide a bicyclic ketone as a mixture of two diastereomers, each a 1:1 mixture of alkene isomers. Hydrogenation provided the saturated products as an 85:15 mixture of *cis* (**14a**) and *trans* (**14b**) ring junctions.[25] The preference for *cis*-selective migration has been noted in several bicyclic Pinacol rearrangement reactions.[24,26]

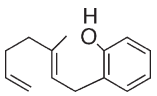
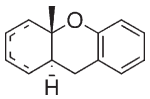
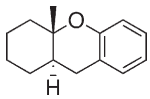
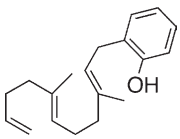
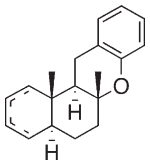
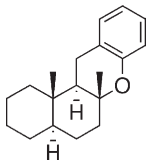
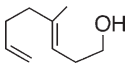
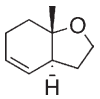
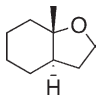
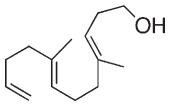
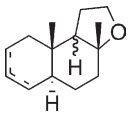
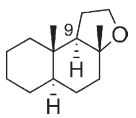
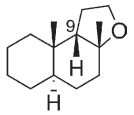
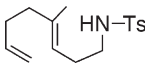
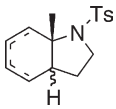
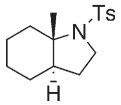
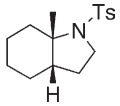
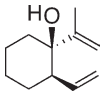
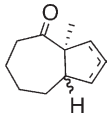
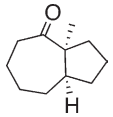
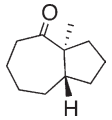
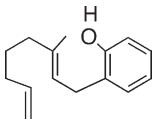
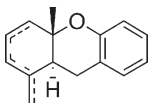
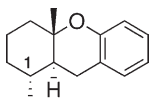
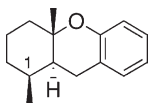
In contrast to the smooth high yielding reactions of 1,5-dienyl compounds, the 1,6-dienyl substrate (**15**) in entry 7 was more capricious. Multiple alkene products were obtained and hydrogenation provided a 68:32 mixture of two identifiable diastereomers (**16a**, **16b**), both of which

Table 1. Optimization of $PdCl_2$-catalyzd oxidative cyclization reactions

Entry	Catalyst (10 mol%)	Oxidant (equiv.)	Solvent	Temp, time	Conversion[a] (%, **2**+**3**)	Ratio[a] **2**:**3**
1	$(PhCN)_2PdCl_2$	BQ (4.0)	CH_2Cl_2	RT, 40 h	39	74:26
2	$(PhCN)_2PdCl_2$	$CuCl_2$ (2.5)	DCE	RT, 20 h	59[b]	72:28
3	$(PhCN)_2PdCl_2$	O_2 (1 atm)	THF	60 °C, 40 h	16	75:25
4	$(PhCN)_2PdCl_2$	BQ (4.0)	THF	60 °C, 40 h	75	90:10
5	$(PhCN)_2PdCl_2$	BQ (4.0)	CH_3CN	80 °C, 15 h	85	>99:1
6	$Pd(OAc)_2$	BQ (4.0)	THF	60 °C, 24 h	95	>1:99

[a] Determined by GC.
[b] 20% of a Cl containing compound (GC-MS) was observed as a byproduct.

Table 2. $PdCl_2$-catalyzed oxidative cyclization reactions[a]

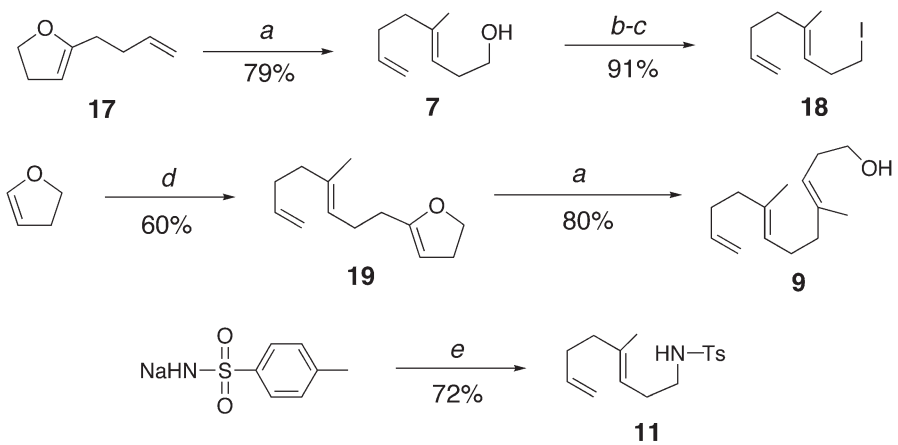
Entry	Substrate	Reaction time (h)	Alkene product (yield,[b] alkene ratio[c])	Hydrogenated product (yield,[b] dr[d])	
1	 **1**	15	 (83%, 68:19:13)	 (98%, >99:1)	**4**
2	 **5**	48	 (89%, 70:17:13)	 (98%, >99:1)	**6**
3	 **7**	15	 (80%, >99:1)	 (98%,[e] >99:1)	**8**
4	 **9**	20	 (80%, 84:8:5:3)	 **10a** (98%, 91:9)	 **10b**
5	 **11**	40	 (75%, 80:12:8)	 **12a** (98%, 94:6)[f]	 **12b**
6	 **13**	17	 (85%, 43:43:7:7)	 **14a** (98%, 85:15)	 **14b**
7	 **15**	60	 (75%, 14:27:17:15)	 **16a** (98%,[g] 68:32)	 **16b**

[a] Reaction conditions are as described in Table 1 entry 5.
[b] Yield after chromatographic purification.
[c] Determined by GC.
[d] Determined by GC and ^1H NMR.
[e] Hydrogenation was carried out in Et_2O.
[f] The major is assigned the *trans* configuration by analogy.
[g] Includes 20% of unknown isomers

contained *trans* ring junctions but were epimeric at C-1.[27] The major C-1 diastereomer was equatorial, but the natural selectivity of the C–C bond-forming step is not clear since β-H elimination compromises this stereocenter. This compound was contaminated with 20% of several unidentified structural isomers (GC-MS).

3. Conclusions

Based on the precedence established by Overman in the $PdCl_2$-catalyzed Cope-rearrangement we report herein a $PdCl_2$-catalyzed cyclization reaction that is consistent with a mechanism involving the cyclo-generation of cyclic



Scheme 1. Synthetic procedure for substrates **7**, **9**, and **11**.

3°-cations from 1,5- and 1,6-dienes.†[28] When provided with suitable traps for the cation, various poly-cyclization products are formed that are each consistent with an intermediate carbocation. Turnover is achieved by β-hydride elimination to yield cycloalkene products, usually as a mixture of alkene isomers. The resulting Pd(0) is reoxidized under standard benzoquinone oxidation conditions to the reactive Pd(II)-form. Future directions for this work will include developing traps (e.g., CO/MeOH) for the intermediate alkyl, more efficient reoxidation procedures, and asymmetric variants.

4. Experimental

4.1. General

Pd(II)-catalyzed cyclization reactions were performed under a dinitrogen atmosphere using standard Schlenk techniques. NMR spectra were recorded on a Bruker Avance400 spectrometer; chemical shifts are given in ppm and are referenced to residual solvent peaks. Gas chromatography was performed on an HP 6890 gas chromatography equipped with an HP-5 column. GC-MS analysis was performed on an Agilent 5973. High resolution mass spectrum was performed by the Mass Spectrometry Service Laboratory at the University of Minnesota. Synthesis of **1**, **5**, and **15** were performed as previously described,[17] as was **13**.[29] Synthesis of **7**, **9**, and **11** were performed by modification of existing literature procedures[30,31] (Scheme 1). The cyclization products **4**, **6**, and **16** were previously reported,[17] as were **8**,[21] **10**,[22] and **14**.[25] All new compounds were determined to be >95% pure by GC and ^{1}H NMR spectroscopy.

† The bicyclization reactions in entries 1, 3, 5 and 7 can also be explained by an initiating oxypalladation of the alkene proximal to the heteroatom,[28] followed by a 6-*endo* coordination insertion/β-hydride elimination. The all *trans* ring junctions in the tricyclic products are not consistent with a propagating 6-*endo* cyclization, since this leads to a *cis* A-ring junction. The terminally trisubstituted compound *ortho*-geranylphenol does not react under the standard reaction conditions. A more thorough mechanistic analysis will be published in due course.

4.2. Substrate synthesis

4.2.1. 1,5-Dienyl alcohol (7).[30] A solution of methylmagnesium bomide in ether (21 mL, 60 mmol) was added to a stirred suspension of bis(triphenylphosphine)nickel dichloride (650 mg, 1.0 mmol) in dry toluene (45 mL) under dry nitrogen. The resulting red solution was stirred at room temperature for 20 min, and a solution of 5-(3-butenyl)-2,3-dihyrofuran (**17**) (2.5 g, 20 mmol) in toluene (30 mL) was then added. The mixture was heated to 80 °C for 1.5 h, cooled to room temperature, and poured into a saturated ammonium chloride solution (60 mL) with vigorous stirring. The mixture was stirred until decolorized and the organic material was extracted with ether. The combined extracts were dried ($MgSO_4$) and evaporated to leave a yellow oil. The crude mixture was purified by column chromatography on silica gel (Hexene–EtOAc=2:1) to give the product (**7**) as a colorless oil (2.2 g, 79%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.76 (m, 1H), 5.11 (t, J=6.0 Hz, 1H), 4.96 (dd, J=17.2, 1.6 Hz, 1H), 4.92 (dd, J=10.0, 1.2 Hz, 1H), 3.59 (q, J=6.4 Hz, 2H), 2.27 (q, J=6.8 Hz, 2H), 2.09–2.16 (m, 4H), 1.57 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.9, 138.6, 120.7, 114.9, 62.7, 39.5, 32.5, 31.8, 16.5; HRMS (CI) [M+H]/z Calcd 141.1279, found 141.1279.

4.2.2. 1,5,9-Trienyl alcohol (9).[30] 1,5,9-Trienyl alcohol (**9**) was prepared in 80% yield from **19** as described for **7**. ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.77 (m, 1H), 5.09 (dd, J=8.0, 7.6 Hz, 2H), 4.98 (dd, J=16.8, 2.0 Hz, 1H), 4.91 (dd, J=10.0, 1.2 Hz, 1H), 3.59 (t, J=6.4 Hz, 2H), 2.26 (q, J=6.4 Hz, 2H), 2.02–2.16 (m, 8H), 1.65 (s, 3H), 1.58 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.2, 139.1, 135.1, 124.6, 120.3, 114.6, 62.8, 40.1, 39.4, 32.7, 31.8, 26.8, 16.5, 16.3; HRMS (CI) [M+NH_4]/z Calcd 226.2171, found 226.2178.

4.2.3. 1,5-Dienyl sulfonamide (11). A mixture of 8-iodo-5-methyl-1,5-octadiene (**18**) (0.38 g, 1.54 mmol) and tosylamide monosodium salt[31] (0.3 g, 1.54 mmol) in DMF (5.0 mL) were stirred at 80 °C for 5 h. The reaction mixture was cooled to room temperature and ether was added. The resulting solution was washed with brine, dried over $MgSO_4$, and evaporated under vacuum. The crude mixture

was purified by column chromatography on silica gel (Hexene–EtOAc=4:1) to give the product (**11**) as a colorless oil (0.32 g, 72%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, J=8.0 Hz, 2H), 7.27 (d, J=8.0 Hz, 2H), 5.71 (m, 1H), 4.89–4.99 (m, 3H), 4.61 (t, J=6.0 Hz, 1H), 2.91 (q, J=6.4 Hz, 2H), 2.39 (s, 3H), 1.98–2.15 (m, 6H), 1.51 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.2, 138.5, 138.4, 137.1, 129.6, 127.0, 120.0, 114.6, 42.8, 38.9, 32.0, 27.9, 21.4, 16.0; HRMS (CI) [M+H]/z Calcd 294.1528, found 294.1532.

4.3. General procedure for catalytic cyclization

To a solution of $(PhCN)_2PdCl_2$ (7.1 mg, 18.5 μmol), and benzoquinone (80 mg, 0.74 mmol) in CH_3CN (3.0 mL) was added trienylphenol (**5**) (50 mg, 0.185 mmol). The resulting solution was stirred at 80 °C for 48 h. The reaction mixture was cooled to room temperature, filtered through a plug of silica gel, and eluted with ether. The filtrate was concentrated under vacuum and chromatographed (hexane–EtOAc=9:1) to give a mixture of alkene products (44 mg, 89%, 70:17:13). The colorless oil was taken up in MeOH (2.0 mL), and Pd/C (5 mol%) was added. The resulting slurry was stirred under hydrogen atmosphere (1 atm) at room temperature for 5 h. The reaction mixture was filtered through a plug of Celite, and washed with ether. The filtrate was concentrated under vacuum to give tricyclic product (**6**) as a colorless oil (44 mg, 98%).[17]

4.3.1. *Trans*-fused bicyclic furan (8). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.80 (m, 2H), 1.58–1.86 (m, 7H), 1.35–1.41 (m, 4H), 0.92 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 80.9, 64.7, 47.9, 38.7, 28.9, 26.7, 26.5, 23.7, 17.1; HRMS (CI) [M+H]/z Calcd 141.1279, found 141.1280.

4.3.2. *Trans*-fused bicyclic pyrrolidine (12a). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, J=8.0 Hz, 2H), 7.24 (d, J=8.0 Hz, 2H), 3.43 (td, J=9.2, 1.2 Hz, 1H), 3.27 (t, J=9.2 Hz, 1H), 2.39 (s, 3H), 1.78 (m, 1H), 1.49–1.71 (m, 4H), 1.47 (dd, J=12.8, 4.4 Hz, 1H), 1.15–1.38 (m, 5H), 1.04 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.5, 139.1, 129.7, 127.5, 66.5, 49.8, 46.5, 38.4, 30.1, 26.9, 25.8, 22.6, 21.8, 17.3; HRMS (CI) [M+H]/z Calcd 294.1528, found 294.1533.

4.3.3. Wacker product (3). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.07 (t, J=7.6 Hz, 1H), 6.94 (d, J=7.2 Hz, 1H), 6.80 (t, J=7.2 Hz, 1H), 6.73 (d, J=8.0 Hz, 1H), 6.34 (d, J=10.0 Hz, 1H), 5.80 (m, 1H), 5.53 (d, J=10.0 Hz, 1H), 4.99 (d, J=17.2 Hz, 1H), 4.91 (d, J=8.8 Hz, 1H), 2.11–2.70 (m, 2H), 1.69–1.84 (m, 2H), 1.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.1, 138.5, 129.3, 129.0, 126.3, 122.9, 120.9, 120.5, 116.0, 114.3, 40.5, 28.3, 26.6, 25.2; HRMS (ESI) [M+Na]/z Calcd 223.1094, found 223.1091.

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References and notes

1. Richards, J. H.; Hendrickson, J. B. *The Biosynthesis of Steroids, Terpenes, and Acetogenins*. W.A. Benjamin Inc: New York, 1964; pp 240–288.
2. Bartlett, P. A. *Asymmetric Synthesis*, Morrison, J. D., Ed.; Academic: New York, 1984; Vol. 3, pp 341–409.
3. (a) Ishihara, K.; Ishibashi, H.; Yamamoto, H. *J. Am. Chem. Soc.* **2002**, *124*, 3647–3655. (b) Nakamura, S.; Ishihara, K.; Yamamoto, H. *J. Am. Chem. Soc.* **2000**, *122*, 8131–8140.
4. Nishizawa, M.; Takenaka, H.; Hayashi, Y. *J. Org. Chem.* **1986**, *51*, 806–813.
5. Larock, R. C. *Organomercury Compounds in Organic Synthesis*. Springer: Berlin, 1985; pp 155–229.
6. Several recent developments in Hg(II) chemistry include (a) enantioselective L*Hg(II) reagents and (b) an enyne carbocyclization that is catalytic in Hg(OTf)2; (a) Kang, S. H.; Kim, M. *J. Am. Chem. Soc.* **2003**, *125*, 4684–4685. (b) Nishizawa, M.; Yadav, V. K.; Skwarczynski, M.; Imagawa, T. H.; Sugihara, T. *Org. Lett.* **2003**, *5*, 1609–1611.
7. (a) Hegedus, L. S. *Transition Metals in the Synthesis of Complex Organic Molecules*. University Science Books: Mill Valley, CA, 1994; pp 199–236. (b) Hegedus, L. S. *Comprehensive Organic Synthesis*, Trost, B. M., Ed.; Pergamon, 1991; Vol. 4, pp 551–569.
8. Hegedus, L. S. *Comprehensive Organic Synthesis*, Trost, B. M., Ed.; Pergamon, 1991; Vol. 4, pp 571–583.
9. (a) Qian, H.; Widenhoefer, R. A. *J. Am. Chem. Soc.* **2003**, *125*, 2056–2057. (b) Wang, X.; Pei, T.; Han, X.; Widenhoefer, R. A. *Org. Lett.* **2003**, *5*, 2699–2701. (c) Widenhoefer, R. A. *Acc. Chem. Res.* **2002**, *35*, 905–913. (d) Pei, T.; Widenhoefer, R. A. *J. Am. Chem. Soc.* **2001**, *123*, 11290–11291. (e) Yang, D.; Li, J.-H.; Gao, Q.; Yan, Y.-L. *Org. Lett.* **2003**, *5*, 2869–2871.
10. Toyota, M.; Rudyanto, M.; Ihara, M. *J. Org. Chem.* **2002**, *76*, 3374–3386.
11. Ferreira, E. M.; Stoltz, B. M. *J. Am. Chem. Soc.* **2003**, *125*, 9578–9579.
12. For early examples of stoichiometric Pd(II) reactivity see: (a) Trebellas, J. C.; Olechowski, J. R.; Jonassen, H. B. *J. Organomet. Chem.* **1966**, *6*, 412–420. (b) Heimbach, P.; Molin, M. *J. Organomet. Chem.* **1973**, *49*, 477–482. (c) Heimbach, P.; Molin, M. *J. Organomet. Chem.* **1973**, *49*, 483–494. (d) Brown, E. D.; Sam, T. W.; Sutherland, J. K.; Torre, A. *J. Chem. Soc., Perkin Trans. 1* **1975**, 2326–2332. (e) Hegedus, L. S.; Williams, R. E.; McGuire, M. A.; Hayashi, T. *J. Am. Chem. Soc.* **1980**, *102*, 4973–4979.
13. (a) Overman, L. E.; Knoll, F. M. *J. Am. Chem. Soc.* **1980**, *102*, 865–867. (b) Overman, L. E.; Jacobsen, E. J. *J. Am. Chem. Soc.* **1982**, *104*, 7225–7231. (c) Overman, L. E.; Renaldo, A. F. *J. Am. Chem. Soc.* **1990**, *112*, 3945–3949.
14. Overman, L. E.; Renaldo, A. F. *Tetrahedron Lett.* **1983**, *24*, 235–238.
15. Hahn, C.; Cucciolito, M. E.; Vitagliano, A. *J. Am. Chem. Soc.* **2002**, *124*, 9038–9039.
16. Wiang, W.; Widenhoefer, R. A. *Chem. Commun.* **2004**, 660–661.
17. For examples of non-oxidative Pd(II)- and Pt(II)-mediated cation-olefin reactions with pincer-ligated metal complexes, see: Koh, J. H.; Gagné, M. R. *Angew. Chem., Int. Ed.* **2004**, in press.
18. For a recent example of an asymmetric variant using BQ see:

Uozumi, Y.; Kyota, H.; Kato, K.; Ogasawara, M.; Hayashi, T. *J. Org. Chem.* **1999**, *64*, 1620–1625.
19. Palucki, M.; Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 10333–10334.
20. Chloride-containing Pd(II)-catalyzed Wacker cyclizations are known to proceed by *exo* addition of nucleophile, while non-chloride containing catalyst can proceed by *endo* addition mechanisms, see Hayashi, T.; Yamasaki, K.; Mimura, M.; Uozumi, Y. *J. Am. Chem. Soc.* **2004**, *126*, 3036–3037.
21. The *cis*-fused bicyclic furan is known, see: Nishizawa, M.; Iwamoto, Y.; Takao, H.; Imagawa, H.; Sugihara, T. *Org. Lett.* **2002**, *2*, 1685–1687.
22. Dinorambrox and 9-epi-dinorambrox, see: Ohloff, G.; Giersch, W.; Pickenhagen, W.; Furrer, A.; Frei, B. *Helv. Chim. Acta* **1985**, *68*, 2002–2029.
23. We assign the *trans* configuration for entry 5 by analogy.
24. (a) Overman, L. E.; Wolfe, J. P. *J. Org. Chem.* **2002**, *67*, 6421–6429. (b) Overman, L. E. *Acc. Chem. Res.* **1992**, *25*, 352–359.
25. (a) House, H. O.; Gaa, C. P.; VanDerveer, D. *J. Org. Chem.* **1983**, *48*, 1661–1670. (b) House, H. O.; Nomura, S. G.; VanDerveer, D.; Wissinger, E. J. *J. Org. Chem.* **1986**, *51*, 2408–2416.
26. For examples of *cis* selective pinacol rearrangements, see (a) Trost, B. M.; Neilsen, J. B.; Hoogsteen, K. *J. Am. Chem. Soc.* **1992**, *114*, 5432–5434. (b) Hirst, G. C.; Howard, P. N.; Overman, L. E. *J. Am. Chem. Soc.* **1989**, *111*, 1514–1515. (c) Herrinton, P. M.; Hopkins, M. H.; Mishra, P.; Brown, M. J.; Overman, L. E. *J. Org. Chem.* **1987**, *52*, 3711–3712.
27. The stereochemistry of the major diastereomer was unambiguously determined by X-ray methods, see Ref. 17 for additional characterization on both stereoisomers.
28. For references related to the alternative oxypalladation-initiated mechanism, see: (a) Hayashi, T.; Yamasaki, K.; Mimura, M.; Uozumi, Y. *J. Am. Chem. Soc.* **2004**, *126*, 3036–3037. (b) Hosokawa, T.; Murahashi, S.-I. *Acc. Chem. Res.* **1990**, *23*, 49–54. (c) Balsells, D.; Maseras, F.; Keay, B. A.; Ziegler, T. *Organometallics* **2004**, *23*, 2784–2796. (d) Weider, P. R.; Hegedus, L. S.; Asada, H.; D'Andreq, S. V. *J. Org. Chem.* **1985**, *50*, 4276–4281.
29. Holt, D. A. *Tetrahedron Lett.* **1981**, *22*, 2243–2246.
30. Kocienski, P.; Wadman, S.; Cooper, K. *J. Org. Chem.* **1989**, *54*, 1215–1217.
31. Bottino, F.; Grazia, M. D.; Finocchiaro, P.; Fronczek, R. R.; Mamo, A.; Pappalardo, S. *J. Org. Chem.* **1988**, *53*, 3521–3529.