Synthesis of α-Necrodol: Unexpected Formation of a Cyclopropene

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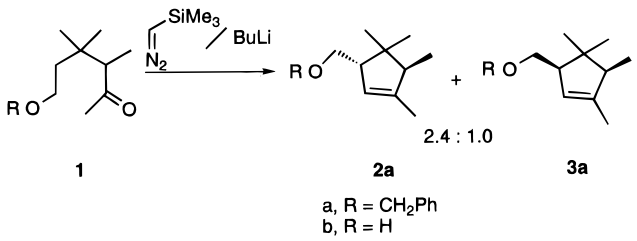
Significant 1,3-induction in intramolecular alkylidene C−H insertion is reported. Thus, exposure of ketone **I** to the lithium salt of (trimethylsilyl)diazomethane provides a 2.4:1.0 ratio of **IIa** and **IIIa**, which are deprotected to α-necrodol **IIb** and the epimeric **IIIb**. The 1,3-insertion product cyclopropene **IV** was also formed.

Introduction

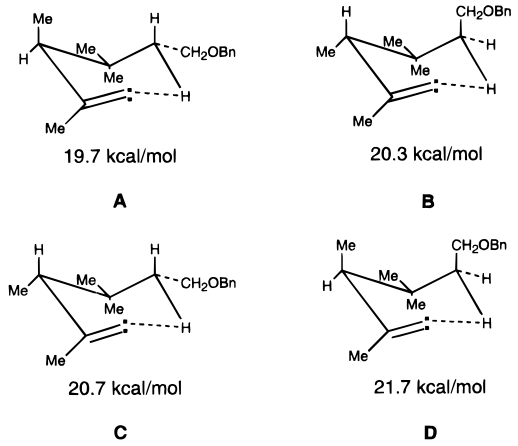
The intramolecular alkylidene carbene insertion has recently been developed as a method for constructing cyclopentenes.[1] However, the diastereoselectivity of methylene insertion is still a issue that must be resolved. In our earlier paper,[1k] the diastereoselectivity of 1,2-induction, in which the target methylene was *adjacent* to the established chiral center, was studied. We now report significant *1,3-induction* of relative configuration on methylene insertion. This has allowed the diastereoselective synthesis of α-necrodol **2b**, a monoterpene alcohol isolated from the defensive spray of the red-lined carrion beetle.[2]



α-Necrodol (**2b**) was first synthesized[3] by Meinwald and co-workers in 1990. In that initial synthesis, the cyclopentene skeleton of **2b** was derived over several steps from camphoric anhydride. No subsequent synthetic work has been reported.[4]

Computational Analysis. The key questions in the synthesis were whether the alkylidene carbene would insert into a methylene group that was deactivated[5] by a β-oxygen and, if the insertion were successful, whether the desired *trans* cyclopentene would be a major product. Our analysis of the transition states for this cyclization is outlined below.

Relative Transition State Energies:



As we have recently reported,[1s,6,7] the transition state for the alkylidene insertion can be approximated by establishing a "weak" bond (meaningful in Mechanics)[7] between the carbene carbon and the target H-atom. Following this analysis, transition states A and B would lead to the *trans* diastereomer, while transition states C

[⊗] Abstract published in *Advance ACS Abstracts,* March 1, 1997.

(1) For references to cyclopentene construction by intramolecular C−H insertion by an alkylidene carbene, see: (a) Karpf, M.; Dreiding, A. S. *Helv. Chim. Acta* **1979**, *62*, 825. (b) Gilbert, J. C.; Giamalva, D. H.; Weerasooriya, U. *J. Org. Chem.* **1983**, *48*, 5251. (c) Gibert, J. C.; Giamalva, D. H.; Baze, M. E. *J. Org. Chem.* **1985**, *50*, 2557. (d) Ochiai, M.; Kunishima, M.; Nagao, Y.; Fuji, K.; Shiro, M.; Fujita, E. *J. Am. Chem. Soc.* **1986**, *108*, 8281. (e) Gilbert, J. C.; Giamalva, D. H. *J. Org. Chem.* **1992**, *57*, 4185. (f) Ochiai, M.; Uemura, K.; Masaki, Y. *J. Am. Chem. Soc.* **1993**, *115*, 2528. (g) Schildknegt, K.; Bohnstedt, A. C.; Feldman, K. S.; Sambandam, A. *J. Am. Chem. Soc.* **1994**, *116*, 93. (h) Kunishima, M.; Hioki, K.; Tani, S.; Kato, A. *Tetrahedron Lett.* **1994**, *35*, 7253. (i) Williamson, B. L.; Tykwinski, R. R.; Stang, P. J. *J. Am. Chem. Soc.* **1994**, *116*, 93. (j) Kim, S.; Cho, C. M. *Tetrahedron Lett.* **1994**, *35*, 8405. (k) Taber, D. F.; Meagley, R. P. *Tetrahedron Lett.* **1994**, *35*, 7909. (l) Taber, D. F.; Walter, R.; Meagley, R. P. *J. Org. Chem.* **1994**, *59*, 6014. (m) Taber, D. F.; Sahli, A.; Yu, H.; Meagley, R. P. *J. Org. Chem.* **1995**, *60*, 6571. (n) Ohira, S.; Okai, K.; Moritani, T. *J. Chem. Soc., Chem. Commun.* **1995**, *36*, 1537. (o) Ohira, S.; Noda, I.; Mizobata, T.; Yamato, M. *Tetrahedron Lett.* **1995**, *36*, 3375. (p) Ohira, S.; Sawamoto, T.; Ymato, M. *Tetrahedron Lett.* **1995**, *36*, 1537. (q) Ohira, S.; Yamasaki, K.; Nozaki, H.; Yamato, M.; Nakayama, M. *Tetrhadron Lett* **1995**, *36*, 8843. (r) Taber, D. F.; Christos, T. E.; Hodge, C. N. *J. Org. Chem.* **1996**, *61*, 2081. (s) Taber, D. F.; Meagley, R. P.; Doren, D. J. *J. Org. Chem.* **1996**, *61*, 5723.

(2) (a) Eisner, T.; Meinwald, J. *Psyche* **1982**, *89* , 357. (b) Eisner, T.; Deyrup, M.; Jacobs, R.; Meinwald, J. *J. Chem. Ecol.* **1986**, *12*, 1407. (c) Meinwald, J. *Ann. N. Y. Acad. Sci.* **1986**, *471*, 197. (d) Roach, B.; Eisner, T.; Meinwald, J. *J. Org. Chem.* **1990**, *55*, 4047.

(3) Jacobs, R. T.; Feutrill, G. I.; Meinwald, J. *J. Org. Chem.* **1990**, *55*, 4051.

(4) For the references to the syntheses of β-necrodol and *epi*-β-necrodol, see: (a) Oppolzer, W.; Schneider, P. *Helv. Chim. Acta* **1986**, *69*, 1817. (b) Trost, B. M.; Braslau, R. *Tetrahedron Lett.* **1988**, *29*, 1231. (c) Schulte-Elte, K. H.; Pamingle, H. *Helv. Chim. Acta* **1989**, *72*, 1158.

(5) Stork, G.; Nakatani, K. *Tetrahedron Lett.* **1988**, *29*, 2283.

(6) For an RHF approximation of the insertion transition state, see our Web site at "http://valhalla.chem.udel.edu/alkylidene.html". The lead graphic in this document depicts the calculated orbital overlap in the C-H insertion transition state. The RHF approximation is also available electronically (see the Supporting Information).

(7) (a) Molecular mechanics calculations were carried out using the program Mechanics, implemented on a Tektronix CAChe workstation interfaced with a Silicon Graphics Indigo workstation. This code is based on the MM2 molecular mechanics code of Allinger, with extensions provided by the CAChe group. Full documentation is available from Oxford Molecular, Beaverton, OR. (c) For a detailed analysis of the electronic structure of alkylidenes (vinylidenes) and of the rearrangement to the corresponding alkyne, see: Gallo, M. M.; Hamilton, T. P.; Schaefer, H. F., III. *J. Am. Chem. Soc.* **1990**, *112*, 8714.

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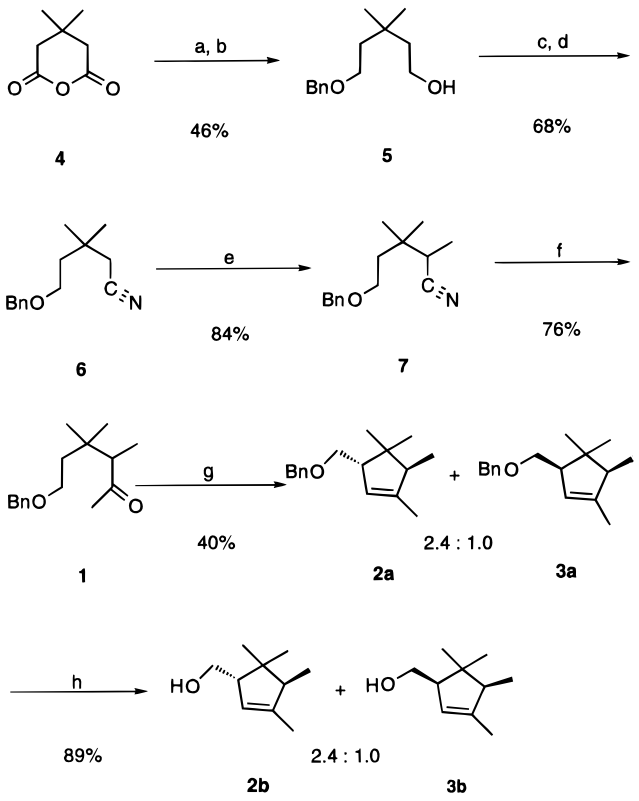
Scheme 1[a]



[a] Key: (a) $LiAlH_4$, THF; (b) benzyl bromide, NaH, THF; (c) Swern; (d) 1,2-epoxy-3-phenoxypropane, *N*,*N*-dimethylhydrazine, 2-propanol; (e) LDA, MeI, THF; (f) MeMgBr, CuBr (cat.), THF; (g) (trimethylsilyl)diazomethane, BuLi, DME; (h) Na/NH_3, THF.

and D would lead to the *cis* diastereomer. The relative energies after minimization of these transition-state models were compared. The results indicate that the transition state A leading to the *trans* product is more stable than the nearest competitor that would lead to the 1,3-*cis* product by (a modest) 1.0 kcal/mol.

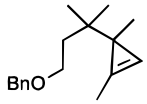
In both transition state A and transition state B, one of the substituents is pseudoaxial on the intermediate "cyclohexene". It is striking that both of these transition states are predicted to be more stable than C, in which both substituents are pseudoequatorial. The key to this difference is in the gauche interactions of these substituents with the *gem*-dimethyl groups between them. In C, the gauche interactions are maximized.

Preparation of ketone 1. Starting with commercially available 3,3-dimethylglutaric anhydride **4** (Scheme 1), reduction by $LiAlH_4$ followed by monobenzylation led to the primary alcohol **5**. After Swern oxidation,[8] the aldehyde was converted to the nitrile **6** using the method developed by Ikeda and co-workers.[9,10] Alkylation of **6**[11] proceeded smoothly to provide the monomethylated nitrile **7** as the only product.

Converting the nitrile **7** to ketone **1** was not successful using MeLi addition. When MeMgBr was used instead of MeLi, the ketone was formed in acceptable yield but only with a large excess of the reagent and a long reflux time. This addition was more efficient in the presence of a catalytic amount of copper(I) bromide.[12]

Synthesis of α-necrodol. Ketone **1** was converted to the transient alkylidene carbene following our modifications[1k,l] of the Ohira protocol. Thus, treatment of the DME solution of (trimethylsilyl)diazomethane with *n*-butyllithium in hexane at −60 °C resulted in a slurry of [(trimethylsilyl)diazomethyl]lithium that was allowed to warm until just homogeneous. This solution was chilled again to −40 °C before addition of ketone **1**. Under these conditions, insertion proceeded to give the *trans*-cyclopentene **2a**:*cis*-cyclopentene **3a** in a 2.4:1.0 ratio, in 41% total yield. Deprotection then gave α-necrodol **2b** and the *cis* diastereomer **3b** in the same 2.4:1.0 ratio.[13] By TLC, ^{13}C NMR, ^1H NMR, IR, and mass spectra, the synthetic material was identical to that originally reported.

Cyclopropene Formation. The yield from the cyclization of ketone **1** was unusually low. In fact, we isolated another product from the cyclization in 41% yield. This was determined to be the unexpected cyclopropene **8**.[14] At least two factors may accelerate 1,3-insertion in this case. On the one hand, insertion into a methine CH is more facile than insertion into a methylene CH.[1b,c] Further, the target CH for 1,5-insertion in this case is deactivated by a β-oxygen.[5]



8

Jones[13a] has reported a similarly substituted cyclopropene with ^{13}C chemical shifts for the alkene CH at δ 110.2 and for the quaternary alkene carbon at δ 130.2.[15] Our usual ^{13}C pulse sequence puts methylene and quaternary carbons "up" and methine and methyl carbons "down". However, the signal at δ 110.0 for **8** was "up". HETCOR analysis established that this signal correlated with the ^1H alkene signal at δ 6.51. This anomaly is due to the CH coupling constant, an unusually high 218 Hz.[16]

Conclusion

Although it is certainly not yet a rigorously quantitative analysis, it is encouraging that our computational approach to understanding the transition state for intramolecular alkylidene CH insertion was successful in predicting the preference for a *trans* product from the cyclization of ketone **1**. The observation of competing 1,3-insertion may open a new route to cyclopropenes.

Experimental Section[17]

3,3-Dimethyl-5-phenylmethoxy-1-pentanol (5). To a flask containing $LiAlH_4$ (1.1 g, 30.2 mmol) in THF (100 mL) at 0 °C was added dropwise over 20 min 3,3-dimethylglutaric

(8) Manusco, A. J.; Huang, S. L.; Swern, D. J. *J. Org. Chem.* **1978**, *43*, 2480.

(9) Ikeda, I.; Machii, Y.; Okahara, M. *Synthesis* **1978**, 301.

(10) Almost any monosubstituted epoxide should work in this procedure. The original authors used ethylene oxide and propylene oxide.

(11) Edstrom, E.; Livinghouse, T. *J. Chem. Soc., Chem. Commun.* **1986**, 279.

(12) Weiberth, F. J.; Hall, S. S. *J. Org. Chem.* **1987**, *52*, 3901.

(13) The ratio of products from the cyclization was determined by integration of the ^1H NMR spectrum of the crude product mixture.

(14) For leading references to cyclopropene construction, see: (a) Likhotvorik, I. R.; Brown, D. W.; Jones, M. *J. Am. Chem. Soc.* **1994**, *116*, 6175. (b) Boese, R.; Blaser, D.; Billups, W. E.; Haley, M. M.; Luo, W.; Arney, B. E. *J. Org. Chem.* **1995**, *59*, 8125. (c) Baldwin, J. E.; Villarica, K. A. *J. Org. Chem.* **1995**, *60*, 186. (d) Kurek-Tyrlik, A.; Minksztym, K.; Wicha, J. *J. Am. Chem. Soc.* **1995**, *117*, 1849.

(15) As the arene carbons dominated the ^{13}C spectrum in this area, we were unable to confirm this signal for **8**.

(16) We have found that the ^{13}C signals of terminal alkynes also are "up". Again, the C−H coupling constant in this case is large, 230 Hz.

(17) For general experimental procedures, see: Taber, D. F.; Houze, J. B. *J. Org. Chem.* **1994**, *59*, 4004.

anhydride (3.6 g, 25.2 mmol) in 20 mL of THF. The mixture was warmed to rt overnight, and then was carefully quenched with 1 mL of water. The mixture was stirred for 10 min, 10% aqueous NaOH (1 mL) was added dropwise over 10 min, the mixture was stirred for another 10 min, and then 2 mL of water was added. After filtration with EtOAc (3 × 20 mL), the combined filtrate was dried (K_2CO_3) and concentrated to give 2.9 g of diol.

To a cold solution (0 °C) of diol (2.9 g, 22.0 mmol) in 70 mL of THF was added NaH (1.1 g, 24.2 mmol, 60% in mineral oil). After the reaction subsided, benzyl bromide (4.5 g, 26.4 mmol) was added. The mixture was stirred overnight and then was quenched with water (20 mL) and extracted with CH_2Cl_2 (2 × 20 mL). The combined organic extract was dried (Na_2SO_4) and concentrated. The residue was chromatographed to give the alcohol **5** (2.6 g, 11.7 mmol, 46% yield from anhydride) as a clear yellow oil: TLC R_f (20% EtOAc/petroleum ether) = 0.18; ^{1}H NMR δ 7.33−7.30 (m, 5H), 4.48 (s, 2H), 3.65 (t, J = 6.1 Hz, 2H), 3.53 (t, J = 7.1 Hz, 2H), 2.14 (bs, 1H), 1.61 (t, J = 6.1 Hz, 2H), 1.53 (t, J = 7.1 Hz, 2H), 0.92 (s, 6H); ^{13}C NMR δ down 128.3, 127.6, 127.5, 27.9; up 138.9, 73.0, 67.3, 59.4, 44.4, 41.1, 31.6; IR (cm^{-1}) 3393, 2956, 2930, 2869, 1453, 1366, 1101; MS (*m*/*z*) 113 (19), 108 (21), 107 (49), 91 (100); HRMS calcd for $C_{14}H_{22}O_2$ 222.1620, found 222.1624.

3,3-Dimethyl-5-(phenylmethoxy)pentanenitrile (6). DMSO (1.1 mL, 15.7 mmol) was added slowly at −78 °C to a solution of oxalyl chloride (1.3 g, 10.2 mmol) in 50 mL of CH_2Cl_2. After the reaction subsided, alcohol **5** (1.8 g, 7.9 mmol) in 10 mL of CH_2Cl_2 was added dropwise. The mixture was kept at −78 °C for 1 h, and then triethylamine (4.0 mL, 39.4 mmol) was added dropwise and the reaction mixture was warmed slowly to rt. Water (10 mL) was added, the layers were separated, and the aqueous layer was extracted with CH_2Cl_2 (2 × 10 mL). The combined organic extract was dried (Na_2SO_4) and concentrated to give the crude aldehyde.

1,2-Epoxy-3-phenoxypropane (3.0 g, 19.8 mmol) was added to a solution of *N*,*N*-dimethylhydrazine (0.57 g, 9.5 mmol) in 2-propanol (4 mL). The flask containing the mixture was closed tightly and heated to 50 °C for 3 h. The above *fresh* aldehyde in 4 mL of 2-propanol was added to this mixture at rt and then stirred at rt for an additional 3 h. 2-Propanol was evaporated *in vacuo*, and the residue was chromatographed to give 1.2 g (5.4 mmol, 68% yield from **5**) of nitrile **6** as a pale yellow oil: TLC R_f (10% EtOAc/petroleum ether) = 0.40; ^{1}H NMR δ 7.35−7.24 (m, 5H), 4.45 (s, 2H), 3.53 (t, J = 6.3 Hz, 2H), 2.28 (s, 2H), 1.67 (t, J = 6.3 Hz, 2H), 1.06 (s, 6H); ^{13}C NMR δ down 128.3, 127.5, 127.4, 27.1; up 138.1, 118.6, 73.0, 66.7, 40.3, 32.5, 30.7; IR (cm^{-1}) 2962, 2933, 2872, 2242, 1454, 1370, 1103; MS (*m*/*z*) 231 (14), 217 (16), 181 (30), 167 (24), 131 (19), 119 (34), 111(12); HRMS calcd for $C_{14}H_{19}NO$ 217.1467, found 217.1469. Anal. Calcd for $C_{14}H_{19}NO$: C, 77.38; H, 8.81. Found: C, 77.30; H, 9.06.

3,3-Dimethyl-2-methyl-5-(phenylmethoxy)pentanenitrile (7). *n*-BuLi (14.6 mL of 1.25 M in hexane, 18.2 mmol) was added dropwise at −78 °C to diisopropylamine (2.1 g, 20.6 mmol) in THF (20 mL). After the mixture was stirred at −78 °C for 15 min, nitrile **6** (2.5 g, 11.4 mmol) in 2 mL of THF was added quickly. The solution was stirred for another 7 min at −78 °C, and then MeI (2.6 g, 18.2 mmol) was added dropwise. The mixture was stirred at −78 °C for 1 h and then stirred at rt for another hour. The mixture was poured into ice-cold 10% aqueous HCl (20 mL), and then water (20 mL) and EtOAc (20 mL) were added. The layers were separated, and the aqueous layer was extracted with EtOAc (3 × 20 mL). The combined organic extract was dried (Na_2SO_4) and concentrated, and the residue was chromatographed to give the methylated nitrile **7** (2.2 g, 9.5 mmol, 84% yield) as a pale yellow oil: TLC R_f (10% EtOAc/petroleum ether) = 0.40; ^{1}H NMR δ 7.28−7.17 (m, 5H), 4.39 (s, 2H), 3.45 (t, J = 6.7 Hz, 2H), 2.51 (q, J = 7.2, 1H), 1.60 (dt, J = 2.4 Hz, J = 6.7 Hz, 2H), 1.13 (d, J = 7.2 Hz, 3H), 0.97 (s, 3H), 0.94 (s, 3H); ^{13}C NMR δ down 128.3, 127.5, 127.4, 36.1, 25.0, 24.2, 12.9; up 138.2, 122.1, 73.0, 66.6, 38.7, 34.6; IR (cm^{-1}) 2966, 2361, 2237, 1454, 1368, 1104; MS (*m*/*z*) 231 (10), 110 (14), 107 (35); HRMS calcd for $C_{15}H_{21}NO$ 231.1623, found 231.1619.

4,4-Dimethyl-3-methyl-6-(phenylmethoxy)-2-hexanone (1). To a stirred solution of nitrile **7** (413 mg, 1.79 mmol) and MeMgBr (0.66 mL of 3.0 M in ether, 2.0 mmol) in 5 mL of THF was added CuBr (5 mg, 0.03 mmol), and the mixture was refluxed at 80 °C under nitrogen for 24 h. The mixture was cooled to ambient temperature, and then 5 mL of water was cautiously added, followed by 5 mL of 15% aqueous HCl. This mixture was maintained at 100 °C for 3 h. After the mixture was cooled to rt, 10 mL of EtOAc was added, the layers were separated, and the aqueous layer was extracted twice more with 10 mL portions of EtOAc. The combined organic extract was dried (Na_2SO_4) and concentrated. The black residue was chromatographed to afford ketone **1** (337 mg, 1.36 mmol, 76% yield from **7**) as a colorless oil: TLC R_f (10% EtOAc/petroleum ether) = 0.40; ^{1}H NMR δ 7.35−7.30 (m, 5H), 4.48 (s, 2H), 3.53 (t, J = 6.5 Hz, 2H), 2.54 (q, J = 7.1 Hz, 1H), 2.12 (s, 3H), 1.73−1.62 (m, 2H), 1.02 (d, J = 7.1 Hz, 3H), 0.98 (s, 3H), 0.95 (s, 3H); ^{13}C NMR δ down 128.3, 127.6, 127.5, 54.4, 32.0, 25.0, 24.7, 12.1; up 213.2, 138.5, 73.0, 67.1, 39.5, 34.9; IR (cm^{-1}) 2967, 2877, 2366, 1710, 1457, 1364, 1102; MS (*m*/*z*) 157 (6), 142 (6), 141 (18), 125 (9); HRMS calcd for $C_{16}H_{24}O_2$ 248.1776, found 248.1775.

3-[(Phenylmethoxy)methyl]-1,4,4,5-tetramethylcyclopentene (2a and 3a). Under nitrogen, *n*-BuLi (0.55 mL of 2.1 M in hexane, 1.15 mmol) was added dropwise at −60 °C to (trimethylsilyl)diazomethane (0.57 mL, 2.0 M in hexane, 1.15 mmol) in DME (1.5 mL). After 5 min at −60 °C, the dry ice bath was removed, and the mixture was allowed to warm until it turned homogeneous. The mixture was then cooled to −40 °C, and ketone **1** (141 mg, 0.57 mmol) in 1 mL of DME was added dropwise over 5 min. The solution was stirred at −30 to −40 °C for another 45 min and then warmed to −10 °C over 2 h. The mixture was quenched with 5 mL of saturated aqueous NH_4Cl at −10 °C, the layers were then separated, and the aqueous layer was extracted with EtOAc (3 × 5 mL). The combined organic extract was dried (Na_2SO_4) and concentrated, and the residue was chromatographed to give the cyclopentenes **2a** and **3a** and cyclopropene **8** (61 mg, 0.25 mmol, 83% yield) in a 2.4:1.0:3.4 ratio, followed by 66 mg of ketone **1**.

2a was separated from cyclopropene **8** by preparative TLC as a pale yellow oil: R_f (2% EtOAc/petroleum ether) = 0.72; ^{1}H NMR δ 7.27−7.17 (m, 5H), 5.17−5.14 (m, 1H), 4.42 (s, 2H), 3.43−3.34 (m, 2H), 2.48−2.40 (m, 1H), 2.04−2.01 (m, 1H), 1.57 (s, 3H), 0.89 (s, 3H), 0.85 (s, 3H), 0.78 (d, J = 7.2 Hz, 3H); ^{13}C NMR δ down 128.3, 127.5, 127.3, 124.2, 53.4, 52.8, 24.5, 24.0, 15.3, 12.6; up 144.5, 138.2, 73.1, 71.1, 43.0.

3a was separated from cyclopropene **8** by preparative TLC as a pale yellow oil: R_f (2% EtOAc/petroleum ether) = 0.72; ^{1}H NMR δ 7.27−7.17 (m, 5H), 5.17−5.14 (m, 1H), 4.41 (s, 2H), 3.32−3.23 (m, 2H), 2.48−2.40 (m, 1H), 2.04−2.01 (m, 1H), 1.50 (s, 3H), 1.01 (s, 3H), 0.78 (d, J = 7.2 Hz, 3H), 0.66 (s, 3H); ^{13}C NMR δ down 128.3, 127.5, 127.3, 124.3, 54.6, 52.9, 29.3, 17.7, 15.3, 13.0; up 144.5, 138.2, 73.1, 71.9, 43.0.

2a + 3a: IR (cm^{-1}) 2961, 2869, 1454, 1362, 1112, 1028; MS (*m*/*z*) 153 (20), 136 (55), 135 (11), 124 (14), 123 (100), 121 (25); HRMS calcd for $C_{17}H_{24}O$ 244.1827, found 244.1819.

8 was separated from cyclopentenes **2a** and **3a** by preparative TLC as a clear oil: R_f (2% EtOAc/petroleum ether) = 0.67; ^{1}H NMR δ 7.25−7.12 (m, 5H), 6.51 (s, 1H), 4.39 (s, 2H), 3.42 (t, J = 7.9 Hz, 2H), 1.90 (s, 3H), 1.55 (dt, J = 2.4, 7.9 Hz, 2H), 0.90 (s, 3H), 0.63 (s, 3H), 0.61 (s, 3H); ^{13}C NMR δ down 128.3, 127.6, 127.4, 27.3, 27.0, 21.0, 11.1; up 138.7, 110.0 (see text), 72.9, 68.2, 40.1, 37.2, 28.8; IR (cm^{-1}) 2959, 2866, 1765, 1454, 1363, 1101, 1028; MS (*m*/*z*) 153 (15), 123 (18), 135 (11), 110 (14), 109 (31); HRMS calcd for $C_{17}H_{24}O$ 244.1827, found 244.1838.

3-(Hydroxymethyl)-1,4,4,5-tetramethylcyclopentene (2b and 3b). To 25 mL of liquid ammonia at −78 °C was added sodium metal (30 mg, 1.3 mmol) in small pieces. Cyclopentene **2a** and **3a** (70 mg, 0.29 mmol) in 5 mL of THF was added to the above dark blue solution. The mixture was stirred at −78 °C for 15 min, and then solid NH_4Cl (50 mg) was added to quench the reaction. The mixture was warmed to rt over 1 h and then was diluted with 10 mL of water and 10 mL of EtOAc. The phases were separated, and the aqueous layer was

extracted with EtOAc (3 × 5 mL). The combined organic extract was dried (Na_2SO_4) and concentrated. The residue was chromatographed to give cyclopentenes **2b** and **3b** (40 mg, 0.26 mmol, 89% yield from **2a** and **3a**) in a 2.4:1.0 ratio as a pale yellow oil: TLC R_f (15% EtOAc/petroleum ether) = 0.45.

2b: ^{1}H NMR δ 5.22−5.21 (m, 1H), 3.65−3.44 (m, 2H), 2.36−2.24 (m, 1H), 2.18−2.07 (m, 1H), 1.65 (d, J = 1.3 Hz, 3H), 0.98 (s, 3H), 0.89 (s, 3H), 0.84 (d, J = 7.5 Hz, 3H); ^{13}C NMR δ down 123.1, 56.4, 52.2, 24.9, 23.6, 15.2, 11.9; up 145.7, 63.1, 43.0.

3b: ^{1}H NMR δ 5.22−5.21 (m, 1H), 3.65−3.44 (m, 2H), 2.36−2.24 (m, 1H), 2.18−2.07 (m, 1H), 1.65 (d, J = 1.3 Hz, 3H), 1.04 (s, 3H), 0.86 (d, J = 7.5 Hz, 3H), 0.79 (s, 3H). ^{13}C NMR δ down 123.2, 57.6, 53.1, 30.5, 18.3, 15.2, 13.6; up 145.2, 63.7, 43.1.

2b + **3b**: IR (cm^{-1}) 3384, 2961, 2870, 1459, 1364, 1260, 1018; MS (*m*/*z*) 154 (11), 139 (16), 123 (100), 121 (22), 119 (17); HRMS calcd for $C_{17}H_{24}O$ 154.1358, found 154.1380.

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Supporting Information Available: ^{1}H and ^{13}C spectra for all new compounds (14 pages). An RHF approximation of the insertion transition state is also available electronically. This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for information.

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