Synthesis of Linear and Angular Triquinane Skeletons by *O*-Stannyl Ketyl-Promoted Fragmentation−Cyclization Reactions of α-Keto Cyclopropanes

Eric J. Enholm* and Zhaozhong J. Jia

Department of Chemistry, University of Florida, Gainesville, Florida 32611

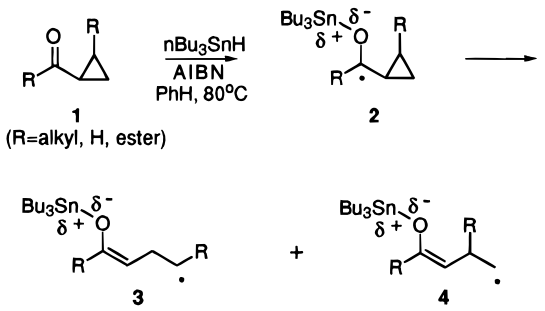
Received August 27, 1996[⊗]

Several investigations of rigid α-keto cyclopropane cleavage by *O*-stannyl ketyls are summarized herein. Tricyclo[3.3.0.0^{2,8}]octan-3-one ring systems were treated with nBu_3SnH, which produced different ring-cleavage products depending on the location and type of substituent present. An examination of both radical-stabilizing substituents and stereoelectronic factors was initiated to understand what factors bias bond cleavage in a configurationally restricted α-ketocyclopropane via *O*-stannyl ketyls. A preference for cleavage of the cyclopropane bond with the best orbital overlap with the ketyl radical sp^2-orbital even in the presence of radical stabilizing groups is indicated by these results. An *O*-stannyl ketyl ring scission−cyclization resulted in the novel synthesis of either a linear or an angular triquinane skeleton depending on the length and location an alkene tether on the tricyclo[3.3.0.0^{2,8}]octan-3-one precursor.

Introduction

Tributyltin hydride (nBu_3SnH) reacts with a variety of precursor functional groups to generate carbon-centered radicals.[1,2] A much less studied *O*-stannyl ketyl radical is formed from the chemically neutral reaction of nBu_3SnH and a ketone or aldehyde.[3,4] The electron-rich radical character of this radical anion species should promote bond scissions and rearrangement reactions. However, the participation of an *O*-stannyl ketyl in subsequent radical rearrangements is generally not well-understood and has been the subject of only a few sparse reports.[2]

Scheme 1



An interesting application of an *O*-stannyl ketyl is to promote the opening of a strained ring, a reaction demonstrated in a seminal mechanistic study over 15 years ago, shown in Scheme 1.[2,5] *O*-Stannyl ketyl **2** can cleave the cyclopropane leading to either **3** or **4**. An α-radical scission of a cyclopropane bearing a radical-stabilizing function, such as an ester attached to the ring, generally cleaves to favor stabilization of the radical center, leading to **3**. It is also important to note that a stereoelectronic requirement (vide infra) in correct orbital overlap is concurrently essential as well. Interestingly, except for the early *mechanistic* studies on simple substrates, the modern *synthetic* potential of α-keto cyclopropane scission by *O*-stannyl ketyls still remains completely unexplored.[2]

The unique strained structure of tricyclo[3.3.0.0^{2,8}]-octan-3-one (**5**), containing a rigid fused α-keto cyclopropane component, is an interesting template for the study of the tin ketyl-promoted opening of cyclopropane rings (Figure 1). Rotation about the C_3-C_2 bond is not possible in this tricycle, which should lead to preferred cleavage of a single bond in the cyclopropane.

Cleavage of the α-keto cyclopropane in **5** bearing appropriate alkene appendages at C_1 or C_7 can also lead to new synthetic sequences that allow for the synthesis of linear- and angular-fused triquinane skeletons.

[⊗] Abstract published in *Advance ACS Abstracts,* December 15, 1996.

(1) (a) Giese, B. *Radicals in Organic Synthesis: Formation of Carbon-Carbon Bonds*; Pergamon Press: New York, 1986. (b) Neumann, W. P. *Synthesis* **1987**, 665. (c) Curran, D. P. *Synthesis* **1988**, 417, 489. (d) Jasperse, C. P.; Curran, D. P.; Ferig, T. L. *Chem. Rev.* **1991**, *91*, 1237. (e) Motherwell, W. B.; Crich, D. *Free Radical Chain Reactions in Organic Synthesis*; Academic Press: New York, 1992. (f) Curran, D. P. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: New York, 1992; Vol. 4.

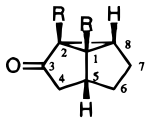
(2) Pereyre, M.; Quintard, J. -P.; Rahm, A. *Tin in Organic Synthesis*; Butterworths: Boston, 1987.

(3) (a) Enholm, E. J.; Prasad, G. *Tetrahedron Lett.* **1989**, 4939. (b) Enholm, E. J.; Kinter, K. S. *J. Am. Chem. Soc.* **1991**, *113*, 7784. (c) Enholm, E. J.; Burroff, J. A. *Tetrahedron Lett.* **1992**, 1835. (d) Enholm, E. J.; Xie, Y. *J. Org. Chem.* **1995**, *60*, 1112. (e) Enholm, E. J.; Kinter, K. S. *J. Org. Chem.* **1995**, *60*, 4850. (f) Enholm, E. J.; Whitley, P. E. *Tetrahedron Lett.* **1996**, 559. (g) Enholm, E. J.; Jia, Z. J. *Tetrahedron Lett.* **1996**, 1177. (h) Enholm, E. J.; Jia, Z. J. *Tetrahedron Lett.* **1995**, 6819. (i) Enholm, E. J.; Whitley, P. E. *Tetrahedron Lett.* **1995**, 9157. (j) Enholm, E. J.; Jia, Z. J. *J. Chem. Soc., Chem. Commun.* **1996**, 1567. (k) Enholm, E. J.; Whitley, P. E.; Xie, Y. *J. Org. Chem.* **1996**, *61*, 5384.

(4) (a) Rawal, V.; Krishnamurthy, V.; Fabre, A. *Tetrahedron Lett.* **1993**, 2899. (b) Hagesawa, E.; Ishiyama, K.; Horaguchi, T.; Shimizu, T. *J. Chem. Soc., Chem. Commun.* **1990**, 550. (c) Hagesawa, E.; Ishiyama, K.; Horaguchi, T.; Shimizu, T. *Tetrahedron Lett.* **1991**, 2029. (d) Hagesawa, E.; Ishiyama, K.; Kato, T.; Horaguchi, T.; Shimizu, T. *J. Org. Chem.* **1992**, *57*, 5352. (e) Bowman, W. R.; Brown, D. S.; Burns, C. A.; Marples, B. A.; Zaidi, N. A. *Tetrahedron* **1992**, *48*, 6883. (f) Degueil-Castaing, M.; Rahm, A.; Dahan, N. *J. Org. Chem.* **1986**, *51*, 1672. (g) Neumann, W. P.; Hillgartner, H.; Baines, K. M.; Dicke, R.; Vorspohl, K.; Kobs, U.; Nussbeutel, U. *Tetrahedron* **1989**, *45*, 951. (h) Yoo, S.; Yi, K.; Lee, S.-H.; Jeong, K. *Chem. Lett.* **1990**, 575. (i) Lee, E.; Tae, J. S.; Chong, Y. H.; Park, Y. C.; Yun, M.; Kim, S. *Tetrahedron Lett.* **1994**, 129. (j) Sugawara, T.; Otter, B. A.; Ueda, T. *Tetrahedron Lett.* **1988**, 75. (k) Beckwith, A. L. J.; Roberts, D. H. *J. Am. Chem. Soc.* **1986**, 5983. (l) Hays, D. H; Fu. G. C. *J. Am. Chem. Soc.* **1995**, *117*, 7283. (m) Hays, D. H; Fu. G. C. *J. Org. Chem.* **1996**, *62*, 4. (n) Rawal, V. H.; Dufour, C.; Iwasa, S. *Tetrahedron Lett.* **1993**, 2899. (o) Newcomb, M. *Tetrahedron* **1993**, *49*, 1151. (p) Castellino, A. J.; Bruice, T. C. *J. Am. Chem. Soc.* **1988**, *110*, 7512. (q) Harling, J. D.; Motherwell, W. B. *J. Chem. Soc. Chem. Comm.* **1988**, 1380. (r) Rawal, V. H.; Dufour, C. *J. Am. Chem. Soc.* **1994**, *116*, 2613.

(5) Pereyre, M.; Godet, J. Y. *Tetrahedron Lett.* **1970**, 3653.

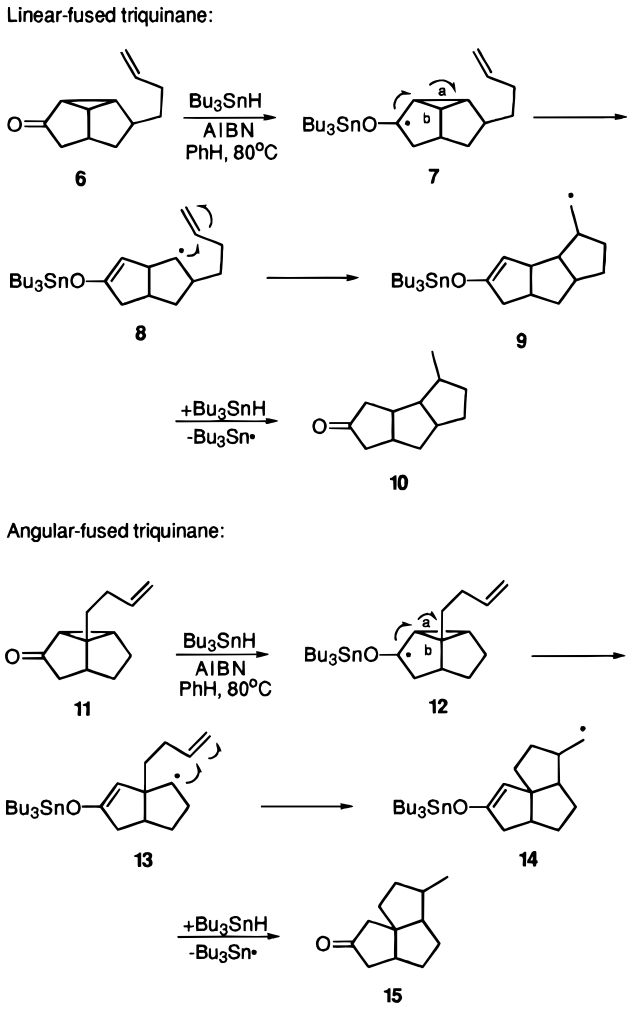
S0022-3263(96)01655-6 CCC: $14.00



5
(R=alkyl, H, ester)

Figure 1.

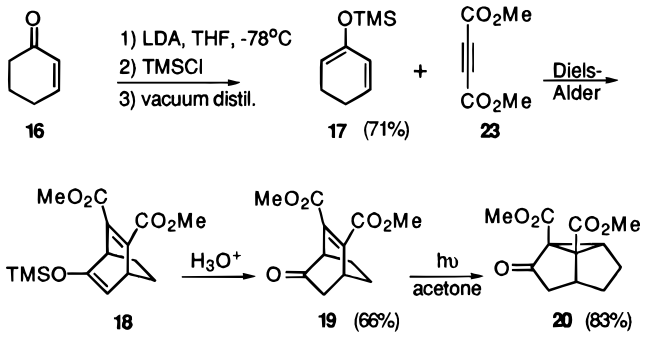
Scheme 2



Triquinanes rank among the most important natural carbon frameworks.[6] These carbon skeletons possess three five-membered rings that share one or two carbon−carbon bonds. Natural products from a variety of biological sources demonstrate that these compounds bear a wide range of functionality. These interesting structures have also been the target of many synthetic efforts.[6,7]

As shown in Scheme 2, if bond "a" is cleaved in the ring-opening process of **7** or **12**, the capture of the generated radicals by suitably tethered olefins will afford linear triquinane **10** or angular triquinane framework **15**, respectively. Thus, an investigation of the *O*-stannyl ketyl-promoted cyclopropane scission in tricyclooctanone systems **6** and **11** will hopefully lead to a powerful new approach to the synthesis of either skeleton. It is worth noting that because diquinanes **6** and **11** differ only in the location of the alkene tether, each might arise from a similar methodology. This paper will examine the regiochemical control of the cyclopropane bond scission in **5** and related molecules. The effects of both radical-stabilizing substituents and stereoelectronic factors in configurationally restricted α-keto cyclopropanes will be considered. The application of those studies to the triquinane synthetic protocol in Scheme 2 will also be discussed. To begin the study of these reactions, a general method to prepare the rigid tricyclic ketones common to both skeletons was first examined.

Scheme 3



Configurationally Restricted α-Keto Cyclopropanes. The construction of tricyclo[3.3.0.0^{2,8}]octan-3-one skeletons has been achieved by different routes, including metal carbene insertion reactions.[8a] Although not previously used in tin hydride reactions, they have been used in the synthesis of various natural products.[8] We decided to use an oxadi-π-methane (ODPM) rearrangement to construct this strained tricycle as shown in Scheme 3.[8,10,11] Thus, trimethylsilyl chloride was used to trap out the lithium enolate of cyclohexenone **16** in 71% yield.[12] The Diels−Alder reaction of **17** with dimethylacetylene dicarboxylate (DMAD) was carried out in refluxing benzene at 80 °C. The desired cycloadduct **19** was isolated in 51% yield after acidic workup.[9] The photochemical ODPM rearrangement of **19** with a 450 W Hanovia lamp indeed afforded the desired tricyclic product **20** using acetone as a triplet sensitizer.[13]

O-Stannyl ketyl **25**, generated from the diester-functionalized tricyclic ketone **20**, can cleave the cyclopropane ring to afford **27a** by "a" cleavage or **27b** by "b" cleavage (Scheme 4).[14] We initially thought that the ester (R_2 = CO_2R) in **20** might enhance "b" cleavage by intermediate

(6) For reviews, see: Paquette, L. A.; Doherty, A. M. In Polyquinane Chemistry. In *Reactivity and Structure Concepts in Organic Chemistry*; Springer-Verlag: New York, 1987; Vol. 26. (b) Hudlicky, T.; Rulin, F.; Lovelace, T. C.; Reed, J. W. In *Studies in Natural Products Chemistry*; Atta-ur-Rahman, Ed.; Elsevier: Amsterdam, 1989; Vol. 3, pp 3−72.

(7) (a) Curran, D. P.; Rakiewicz, D. M. *J. Am. Chem. Soc.* **1985**, *107*, 1448. (b) Curran, D. P.; Chen, M. H. *Tetrahedron Lett.* **1985**, 4991. (c) Curran, D. P.; Kuo, S. -C. *J. Am. Chem. Soc.* **1986**, *108*, 1106. (d) Curran, D. P.; Ferig, T. L.; Elliott, R. L. *J. Am. Chem. Soc.* **1988**, *110*, 5064. (e) Curran, D. P.; Jasperse, C. P. *J. Am. Chem. Soc.* **1990**, *112*, 5601.

(8) (a) Demuth, M. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: New York, 1992; Chapter 2.6. (b) Demuth, M.; Raghavan, P. R.; Carter, C.; Nakano, K.; Schaffner, K. *Helv. Chim. Acta* **1980**, *63*, 2434. (c) Demuth, M.; Chandrasekhar, S.; Nakano, K.; Raghavan, P. R.; Schaffner, K. *Helv. Chim. Acta* **1980**, *63*, 2440. (d) Demuth, M.; Schaffner, K. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 820.

(9) Rubottom, G. M.; Krueger, D. S. *Tetrahedron Lett.* **1977**, 611.

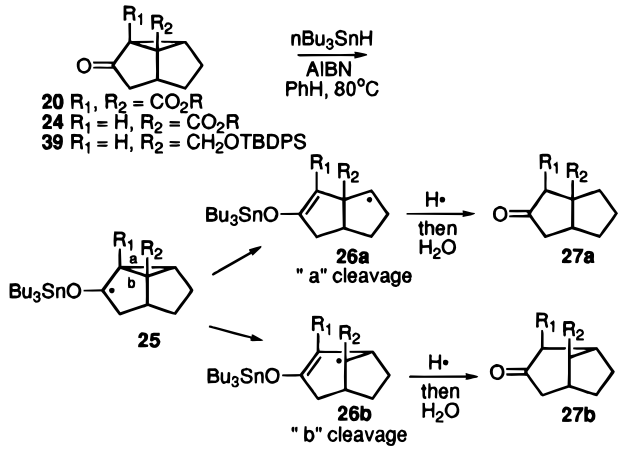
(10) For general reviews of oxadi-π-methane rearrangement, see: (a) Hixon, S. S.; Mariano, P. S.; Zimmerman, H. E. *Chem. Rev.* **1973**, *73*, 531. (b) Dauben, W. G.; Lodder, G.; Ipaktschi, J. *Top. Curr. Chem.* **1975**, *54*, 73.

(11) Houk, K. N. *Chem. Rev.* **1976**, *76*, 1.

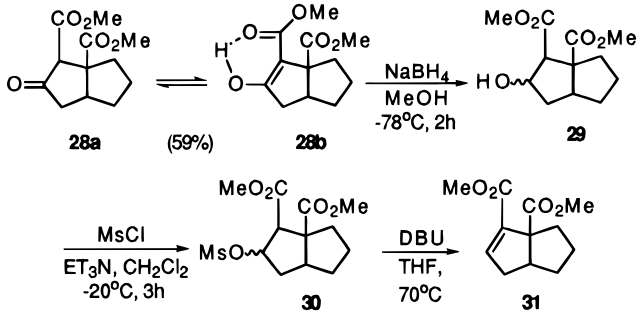
(12) Rubottom, G. M.; Grube, J. M. *J. Org. Chem.* **1977**, *42*, 1051.

(13) (a) Givens, R. S.; Oettle, W. F.; Coffin, R. L.; Carlson, R. G. *J. Am. Chem. Soc.* **1971**, *93*, 3957. (b) Givens, R. S.; Oettle, W. F. *J. Am. Chem. Soc.* **1971**, *93*, 3963.

Scheme 4



Scheme 5



radical stabilization.[1,15] Surprisingly, only the product of "a" bond cleavage was observed in 59% isolated yield. Spectroscopic evidence was not conclusive because the diester product was complicated by an equilibrium mixture with its tautomer, as shown in Scheme 5.[16] In order to clearly confirm the structure, we removed the carbonyl at C_3 using the three-step sequence shown in Scheme 5, affording bicyclo[3.3.0]octene **31** as the sole isolable product. Compound **31**, confirmed by its ^{13}C NMR and the attached proton test (APT), offered clear evidence that **28a** was the product of "a" bond cleavage.[17,18]

A second example, using the monoester **24**, gave exclusively the symmetrical molecule **32** in 88% yield under almost identical conditions with nBu_3SnH in refluxing benzene. This reaction was clearly different from above because it resulted in bond "b" cleavage. Symmetry simplified the structure and NMR spectra of **32**, which was additionally confirmed by forming its (2,4-dinitrophenyl)hydrazone derivative **33** (Scheme 6). In this case, it first appeared that stabilization of the intermediate radical predominated and bond "b" won out.

Although radical scissions of cyclopropanes bearing radical-stabilizing functions, such as an ester or phenyl

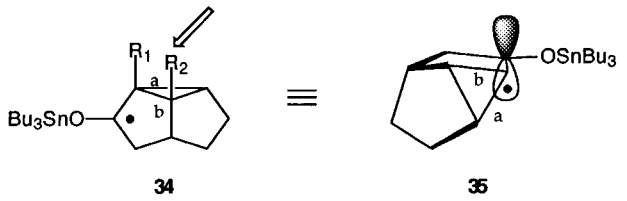
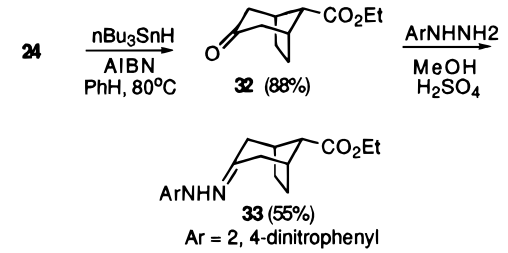
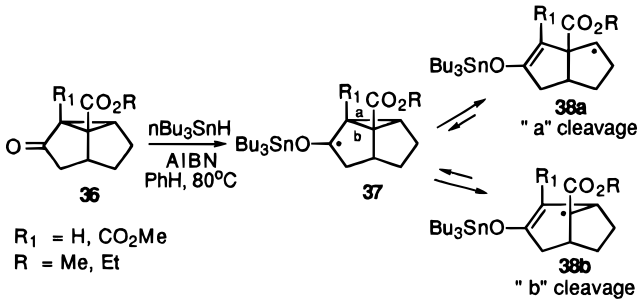


Figure 2.

Scheme 6



Scheme 7



group, usually favor stabilization of the radical center, both **20** and **24** have ester functions capable of stabilization. Each differs, however, only by the presence of an additional ester ($R_1 = CO_2Me$) in **20** that is not located properly for radical stabilization. To explain the two contrasting results from very similar structures, we propose that stereoelectronic effects initially favor the cleavage of bond "a" in both **20** and **24**. The cyclopropane "a" σ-bond has better orbital overlap with the sp^2-like orbital of the adjacent ketyl as seen in structures **34** and **35** (Figure 2).[1,15,19] Bond "b," conversely, is almost orthogonal to the sp^2-like orbital of the ketyl radical.

Another observation is that both processes involve cyclopropylmethyl-type radicals and potentially can involve a reversible ring-closure process; however, bond cleavage is highly favored because of the release of ring strain energy, as shown in Scheme 7.[20,21] If $R_1 = H$ in **36** (as in the case of **24**), reclosure could become more facile because no substituent is present and the center is less hindered. At this point, cleavage of bond "b" likely occurs, leading to the resonance-stabilized radical intermediate **38b** in which the reverse reaction is possible, but less likely.

If $R_1 = CO_2Me$, the ester sterically blocks or slows the radical in **38a** toward reclosure to **37**. Similar rate-retarding effects by blocking 5-hexenyl radical cyclizations at the internal position (C_5) of the alkene are well-

(14) Examples of the Li−NH_3 opening: (a) Monti, S. A.; Bucheck, D. J.; Shepard, J. C. *J. Org. Chem.* **1969**, *34*, 3080. (b) Yates, P.; Stevens, K. E. *Tetrahedron* **1981**, *37*, 4401. (c) Dauben, W. G.; Deviny, E. J. *J. Org. Chem.* **1966**, *31*, 3794.

(15) Deslongchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon Press: Oxford, 1983.

(16) The IR spectrum of **28a/28b** showed a broad peak at 3427 cm^{-1} indicating the presence of an enolized β-keto ester group. Its ^1H NMR spectrum was complex but included a singlet at 10.55 ppm for an enolic proton. Its ^{13}C NMR had signals at 119.0 and 103.9 ppm, attributed to an enolic olefin.

(17) The attached proton test (APT) for structure of **31** featured two CH_3 units, four CH_2 units, two CH units, and four quaternary carbons, ruling out the product of "b" bond cleavage (**27b**, R_1, $R_2 = CO_2Me$).

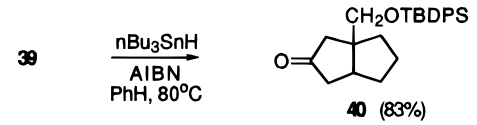
(18) Hashimoto, S.; Shinoda, T.; Shimada, Y.; Honda, T.; Ikegami, S. *Tetrahedron Lett.* **1987**, 637.

(19) (a) Beckwith, A. L. J. *Tetrahedron* **1981**, *37*, 3073. (b) Beckwith, A. L. J.; Easton, C. J.; Serelis, A. K. *J. Chem. Soc., Chem. Commun.* **1980**, 482.

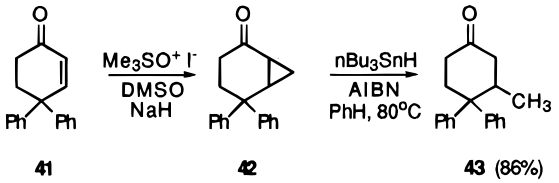
(20) For an example of a reversible cyclopropylmethyl radical, see: Giese, B.; Jay, K. *Chem. Ber.* **1977**, *110*, 1364.

(21) (a) Beckwith, A. L. J.; Moad, G. *J. Chem. Soc., Perkin Trans. 2* **1980**, 1473. (b) Mariano, P. S.; Bay, E. *J. Org. Chem.* **1980**, *45*, 1763.

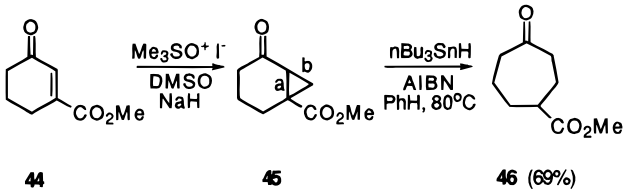
Scheme 8



Scheme 9



Scheme 10



established[1] but are not well-understood for 3-butenyl radical cyclizations. It is also noteworthy that if R_1 = CO_2Me (as in the case of **20**) the reverse reaction of reclosure (**38a** → **37**) prevents conjugation of the ester with the olefin, which is also energetically less favorable.

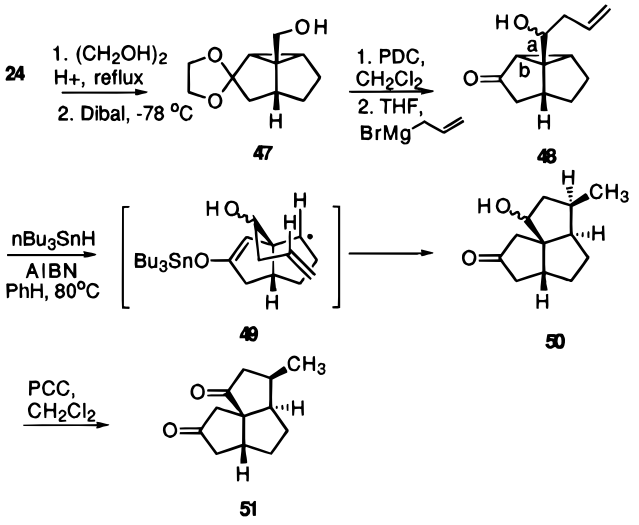
To lend support to the above argument we planned an investigation of the *O*-stannyl ketyl-promoted cyclopropane opening in the tricyclic template **39**, which lacks the radical-stabilizing ester function altogether.

Treatment with nBu_3SnH and AIBN afforded **40**, the sole product of "a" bond cleavage, in 83% yield (Scheme 8). This result is consistent with the reversible ring opening−reclosure process discussed above; however, now the $CH_2OTBDPS$ substituent cannot stabilize the radical by delocalization. The ring opening is now controlled by stereoelectronic effects alone.

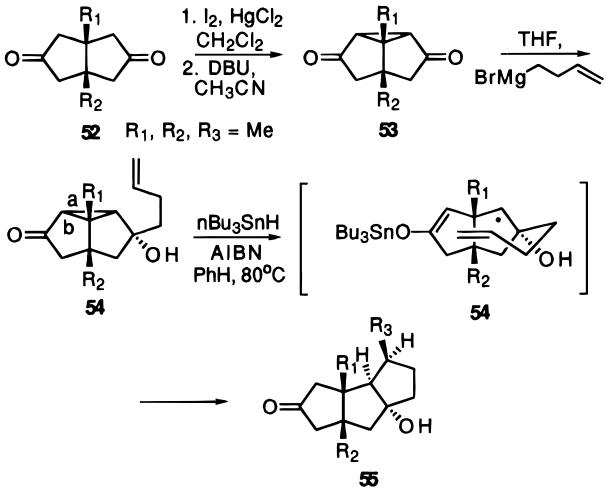
Two other examples that differ from the structures above, but contain rigid α-keto cyclopropanes, also readily cleave with *O*-stannyl ketyls. Schemes 9 and 10 show their preparation and the results from the radical scission. Although ring-opened products **43** and **46** in these reactions have been explained by traditional radical stability arguments in the past, suitable orbital overlap with the radical and reversibility should now be considered a viable pathway in the formation of **46** from **45**. Orbital overlap of the sp^2-like ketyl radical formed from **45** is clearly superior for the cleavage of bond "b" rather than orthogonal bond "a." These results contrast direct radical cleavage of bond "a" due to radical stability and suggest that stereoelectronic factors perhaps play a much greater role.

Application to the Synthesis of Triquinanes. Now that cleavage of the cyclopropane can be reliably predicted, a route to an angular triquinane skeleton was next studied. The successful implementation of the novel tandem scission−cyclization approach postulated in Scheme 2 could now be tested in a real system by the synthetic approach shown in Scheme 11. Protection of the ketone carbonyl in **24** (97%), followed by dibal reduction (90%), readily afforded **47**. Oxidation with PDC smoothly gave an aldehyde (67%) in which an allyl unit was next added with allylmagnesium bromide. The ketal protecting group was removed in the standard

Scheme 11



Scheme 12



acidic workup (85%) for the Grignard reaction, producing two diastereomers of **48** (*ca.* 1.3:1) by GC analysis that were not separable by column chromatography. Treatment of the mixture with nBu_3SnH furnished the angular triquinane **50** in 94% yield. Cleavage of the "a" bond was the only pathway followed by the reaction.

Excellent stereochemical control was realized in the 5-*exo*-*trig* radical cyclization where the endo:exo stereoselectivity for the methyl was found to be >57:1. A Beckwith chairlike intermediate **49** readily explains the stereochemistry of the *endo*-methyl in **50**.[22] Diketone **51** was obtained by direct oxidation with PCC, providing a single diastereomer of triquinane diketone **51** in 78% yield. The *endo*-methyl stereochemistry in **51** and its precursor **50** was readily established from Whitesell's ^{13}C NMR studies of closely related fused-cyclopentanes.[23] The entire synthetic sequence here is very efficient, producing triquinane **50** in 46% overall yield from **24**.

A model linear triquinane was also constructed using a related methodology, as shown in Scheme 12. A cyclopropane ring would be first installed in commercial diquinane **52** using a two-step method of monoiodination,

(22) (a) Beckwith, A. L. J. *Tetrahedron* **1981**, *37*, 3073. (b) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron* **1985**, *41*, 3925.

(23) (a) Whitesell, J. K.; Matthews, R. S. *J. Org. Chem.* **1977**, *42*, 3878. See also: (b) Hudlicky, T.; Koszyk, F. J.; Kutchan, T. M.; Sheth, J. P. *J. Org. Chem.* **1980**, *45*, 5020.

followed by treatment with DBU.[24] The labile iodide intermediate was not characterized but was directly used in the next step after workup. The dehydrohalogenation constructed the symmetrical tricyclodione **53** in a 52% overall yield. Next, reaction with the Grignard reagent of 4-bromo-1-butene gave **54** as the sole stereoisomer, which was isolated in 64% yield. Stereoselective addition of the Grignard reagent to the most accessible face of the carbonyl in **53** was important for later elaboration to the normal cis,anti,cis configuration of the linear triquinane skeleton.

Cleavage of the "a" bond by treatment with nBu_3SnH afforded linear triquinane **55** in 83% yield as the only isolable product. Compared to the angular triquinane, only modest stereochemical control was realized in this 5-*exo*-*trig* radical cyclization where the endo:exo stereoselectivity ratio, determined by capillary GC, was *ca.* 4:1. As in the angular triquinane, a Beckwith chairlike intermediate **54** readily explained the stereochemistry of the *endo*-methyl in **55**.[22] The *endo*-methyl was also established by comparison with previous ^{13}C NMR studies of closely related fused-cyclopentanes.[23] The *endo*-methyl in **55** was observed at 14 ppm by ^{13}C NMR, which is in good agreement with Whitesell's reported average value of 15 ppm for an *endo*-methyl rather than 20 ppm for an *exo*-methyl substituent.

Conclusion

Collectively, these examples show that the *O*-stannyl ketyl-promoted α-ketocyclopropane opening is predominantly controlled by stereoelectronic effects in rigid ring systems. A preference for cleavage of the cyclopropane bond with the best orbital overlap with the ketyl radical sp^2-orbital even in the presence of radical-stabilizing groups is indicated by these results. If the ring-scission is reversible, ester substituents can eventually lead to bond scissions that favor stabilization of the radical by resonance delocalization. The cleavage reaction was applied to the synthesis of angular and linear triquinane carbon skeletons by a novel tandem scission−cyclization approach.

Experimental Section

General Methods. Melting points were determined on a capillary melting point apparatus and are uncorrected. All reactions were run under an inert atmosphere of argon using flame- or heat-dried apparatus. All reactions were monitored by thin-layer chromatography (TLC) and judged complete when starting material was no longer visible in the reaction mixture. All yields reported refer to isolated material judged to be homogeneous by thin-layer chromatography and NMR spectroscopy. Temperatures above and below ambient temperature refer to bath temperatures unless otherwise stated. Solvents and anhydrous liquid reagents were dried according to established procedures by distillation under nitrogen from an appropriate drying agent: ether, benzene, and THF from benzophenone ketyl; CH_2Cl_2 from CaH_2. Other solvents were used "as received" from the manufacturer.

Analytical TLC was performed using precoated silica gel plates (0.25 mm) with phosphomolybdic acid in ethanol as an indicator. Column chromatography was performed using Kieselgel silica gel 60 (230−400 mesh) by standard flash chromatographic techniques. Product ratios were determined on a capillary gas chromatograph using a fused silica capillary column (30 m; film thickness 0.25 μm), unless otherwise noted.

2-[(Trimethylsilyl)oxy]-1,3-cyclohexadiene (17). This compound was prepared by the method of Rubottom and coworkers.[12]

2,3-Bis(methoxycarbonyl)bicyclo[2.2.2]oct-3-en-5-one (19). Diene **17** (10.7 g, 59.2 mmol) and dimethyl acetylenedicarboxylate (10.1 g, 71.1 mmol) were refluxed in benzene (200 mL) at 80 °C overnight. After benzene was rotovaped, to the residue was added ether (200 mL) and 6 M HCl (20 mL). After the mixture was stirred for 8 h, the ether phase was separated. The aqueous layer was extracted with ether and ethyl acetate. The organic layers were combined, dried, and rotovaped. Chromatographic purification of the residue afforded **19** (9.3 g, 61%) as a yellow thick oil: R_f (1:2 hexane/ether) 0.30. IR (KBr) 2954, 1723, 1636; ^1H NMR δ 3.72 (s, 3H), 3.70 (s, 3H), 3.63 (t, 1H), 3.43 (m, 1H), 1.68−1.88 (m, 4H); ^{13}C NMR δ 208.6, 166.0, 164.7, 143.4, 134.6, 52.4, 49.6, 38.8, 34.9, 24.0, 22.7. Anal. Calcd for $C_{12}H_{14}O_5$: C, 60.50; H, 5.92. Found: C, 60.37; H, 6.08.

1,2-Bis(methoxycarbonyl)tricyclo[3.3.0.0^{2,8}]octan-3-one (20). Octenone **19** (180 mg, 0.76 mmol) was dissolved in acetone (9.6 mL) in a Pyrex tube. The solution was degassed with dry nitrogen stream for 30 min and then stirred under direct irradiation of a 450 W Hanovia lamp for 24 h. The reaction mixture was rotovaped and chromatographed to give **20** (150 mg, 83%) as a clear thick oil: R_f (1:2 hexane/ether) 0.37; IR (KBr) 2955, 1720 (broad),1637 (weak); ^1H NMR δ 3.75 (s, 3H), 3.72 (s, 3H), 3.46 (m, 1H), 3.14 (d, 1H), 2.74 (m, 1H), 2.25 (m, 2H), 1.96 (d, 1H), 1.65 (m, 2H); ^{13}C NMR δ 207.0 (s) 169.5 (s), 165.2 (s), 57.3 (s), 56.1 (s), 52.7 (q), 52.3 (q), 47.5 (t), 41.8 (d), 39.8 (t), 38.6 (d), 24.7 (t). Anal. Calcd for $C_{12}H_{11}O_5$: C, 60.50; H, 5.92. Found: C, 60.43, H, 6.08.

1-(Ethoxycarbonyl)tricyclo[3.3.0.0^{2,8}]octan-3-one (24). Diene **17** (15.0 g, 88.2 mmol), ethyl propiolate (13.0 g, 132 mmol), and a few BHT crystals (*ca.* 20 mgs) were heated in benzene (44 mL) at 75 °C for 7 days. Then the reaction mixture was rotovaped to remove benzene and acidified by 1 M HCl. After being stirred overnight, the aqueous mixture was extracted with chloroform. The chloroform phase was dried, rotovaped, and chromatographed to give 2-(ethoxycarbonyl)bicyclo[2.2.2]oct-2-en-5-one (15.1 g, 88%) as a colorless oil: R_f (ether) 0.67; ^1H NMR δ 7.20 (d, 1H), 4.24 (q, 2H), 3.62 (m, 1H), 3.35 (m, 1H), 2.07 (m, 2H), 1.84−1.56 (m, 4H), 1.33 (t, 3H); ^{13}C NMR δ 210.5, 164.0, 140.0, 138.0, 60.6, 49.6, 39.5, 31.9, 24.1, 22.5, 14.1. Anal. Calcd for $C_{11}H_{14}O_3$: C, 68.02; H, 7.27. Found: C, 67.83; H, 7.40.

The Diels−Alder adduct (316 mg, 1.61 mmol) was next dissolved in acetone (20 mL) in a Pyrex tube. The solution was degassed with a dry nitrogen stream for 30 min and stirred under irradiation of a 450 W Hanovia lamp for 24 h. The reaction mixture then was rotovaped and chromatographed to produce **24** as a colorless oil (265 mg, 84%): R_f (ether) 0.67; IR (KBr) 2957, 1724, 1624 (weak); ^1H NMR δ 4.17 (q, 2H), 3.42 (m, 1H), 2.71−2.58 (m, 3H), 2.23 (m, 2H), 1.83 (d, 1H), 1.65 (m, 2H), 1.27 (t, 3H); ^{13}C NMR δ 211.7 (s), 171.3 (s), 60.7 (t), 49.8 (s), 47.6 (d), 46.9 (t), 40.6 (t), 38.9 (d), 37.8 (d), 24.6 (t), 14.1 (q). Anal. Calcd for $C_{11}H_{14}O_3$: C, 68.02; H, 7.27. Found: C, 67.88; H, 7.36.

1,2-Bis(methoxycarbonyl)bicyclo[3.3.0]octan-3-one (28a/b). To a solution of tricyclic octanone **20** (450 mg, 1.89 mmol) in benzene (20 mL) were added tributyltin hydride (1.38 g, 4.74 mmol) and AIBN (100 mg, 0.61 mmol). The mixture was degassed with an argon stream for 15 min and refluxed at 80 °C for 3 h. The reaction mixture was rotovaped and chromatographed to yield **28a/b** (270 mg, 59%) as a clear thick oil: R_f (1/2 hexane/ether) 0.48; IR (KBr) 3427 (broad), 1729, 1664, 1626 (weak), 1286; ^1H NMR δ 10.55 (s, 0.8H), 3.78 (s, 3.0H), 3.70 (s, 3.0H), 2.93 (m, 1.1 H), 2.65 (m, 1.0H), 2.39 (m, 1.0 H), 2.26 (d, J = 18.3 Hz, 1.1H), 1.50−2.10 (m, 7.6H), 1.40 (m, 1.0H), 1.26 (m, 0.5H), 0.90 (m, 0.5H); ^{13}C NMR δ 177.0 (s), 176.3 (s), 119.6 (s), 119.0 (s), 103.9 (s), 68.2 (s), 61.7 (s), 52.1 (q), 51.2 (q), 44.4 (d), 38.9 (t), 35.6 (t), 35.2 (t), 26.0 (t), 25.1 (d), 23.4 (d). Anal. Calcd for $C_{12}H_{16}O_5$: C, 59.99; H, 6.71. Found: C, 59.87; H, 6.82.

(24) (a) Barluenga, J; Martinez-Gallo, J. M.; Najera, C.; Yus, M. *Synthesis* **1986**, 678. (b) Gleiter, R.; Jahne, G.; Muller, G.; Nixdorf, M.; Irngartinger, H. *Helv. Chim Acta* **1986**, *63*, 71.

1,2-Bis(methoxycarbonyl)bicyclo[3.3.0]oct-2-ene (31). Octanone **28a/b** (220 mg, 0.92 mmol) was dissolved in methanol (3 mL). At −78 °C, to the solution was added sodium borohydride (140 mg, 3.67 mmol). After the mixture was stirred for 3 h at −78 °C, the reduction reaction was quenched with water and multiply extracted with ethyl acetate. The organic layer was rotovaped to afford **29** (200 mg, 90%) as an oil, R_f (ether) 0.31. The crude **29** (200 mg, 0.83 mmol) was dissolved in CH_2Cl_2 (2 mL) with triethylamine (417 mg, 4.13 mmol). At −20 °C, to the mixture was added mesyl chloride (188 mg, 1.65 mmol, in 2 mL of CH_2Cl_2) dropwise. After being stirred for 1 h, the reaction mixture was allowed to warm to room temperature and stirred for 2 h. The mixture was rotovaped to afford crude solid mesylate **30**. To the mesylate were added DBU (628 mg, 4.13 mmol) and THF (3 mL). This mixture was refluxed overnight. The reaction was quenched with water and extracted with ether. The ether layer was dried, rotovaped, and chromatographed to produce **31** (35 mg, 20%) as a clear oil: R_f (1:1 hexane/ether) 0.45; ^{1}H NMR δ 6.82 (d, 1H), 3.74 (s, 3H), 3.65 (s, 3H), 2.83 (m, 1H), 2.24 (m, 1H), 2.12 (m, 1H), 1.94 (m, 2H), 1.75 (m, 2H), 1.68(m, 1H), 1.38 (m, 1H); ^{13}C NMR δ 176.6 (s), 164.6 (s), 144.8 (d), 137.6 (s), 65.7 (s), 52.2 (q), 51.5 (q), 49.4 (d), 39.7 (t), 35.6 (t), 35.4 (t), 26.1 (t). Anal. Calcd for $C_{12}H_{16}O_4$: C, 64.27; H, 7.19. Found: C, 64.12; H, 7.31.

8-(Ethoxycarbonyl)bicyclo[3.2.1]octan-3-one (32). A mixture of tricyclic ketone **24** (112 mg, 0.571 mmol), tributyltin hydride (384 mL, 1.43 mmol), and AIBN (30 mg, 0.171 mmol) in benzene (5.7 mL) was degassed with argon for 15 min and refluxed at 80 °C for 5 h. The reaction mixture was rotovaped and chromatographed to afford **32** (106 mg, 94%) as a colorless oil: R_f (1:2 hexane/ether) 0.53; IR (KBr) 2956, 1709, 1642; ^{1}H NMR δ 4.22 (q, J = 7 Hz, 2H), 2.82−2.76 (m, 5H), 2.24 (d, J = 15 Hz, 2H), 1.89 (d, J = 9 Hz, 2H), 1.73−1.55 (m, 2H), 1.30 (t, J = 7 Hz, 3H); ^{13}C NMR δ 211.6 (s), 172.5 (s), 60.5 (t), 49.6 (d), 46.2 (2C, t), 36.6 (2C, d), 29.1 (2C, t), 14.3 (q). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.18; H, 8.34.

(2,4-Dinitrophenyl)hydrazone (33). In a dry flask was dissolved (2,4-dinitrophenyl)hydrazine (125 mg, 0.631 mmol) in methanol (4 mL) with concd H_2SO_4 (0.2 mL) and the mixture warmed by a water bath. In another dry flask the bicyclic ketone **32** (100 mg, 0.510 mmol) was dissolved in methanol (5 mL). To this ketone solution was added dropwise the clear orange solution of (dinitrophenyl)hydrazine. An orange precipitate formed immediately. After the solution was chilled in an ice bath, the precipitate was collected by vacuum filtration. This dark orange crude product was multiply recrystallized with ethanol−water. The clean product was obtained as golden flakes (105 mg, 55%): mp 106−107.5 °C; ^{1}H NMR δ 11.14 (s, 1H), 9.10 (s, 1H), 8.28 (d, 1H), 7.95 (d, 1H), 4.22 (q, 2H), 2.84 (m, 1H), 2.78 (m, 4H), 2.53 (m, 2H), 1.90 (m, 2H), 1.64 (m, 1H), 1.47 (m, 1H), 1.31 (t, 3H); ^{13}C NMR δ 196.1 (s), 172.3 (s), 158.1 (s), 145.1 (s), 139.6 (s), 129.8 (d), 123.4 (d), 116.3 (d), 60.4 (t), 49.8 (d), 38.3 (t), 36.1 (d), 35.4 (d), 31.8 (t), 29.6 (t), 28.3 (t), 14.3 (q). Anal. Calcd for $C_{17}H_{20}O_6N_4$: C, 54.25; H, 5.36; N, 14.89. Found: C, 54.15; H, 5.37; N, 14.93.

1-[(*tert*-Butyldiphenylsiloxy)methyl]tricyclo[3.3.0.0^{2,8}]-octan-3-one (39). In a flask the tricyclic ketoester **24** (560 mg, 2.86 mmol) was dissovled in CH_2Cl_2 (7.2 mL) and chilled at −78 °C. To this flask was added Dibal (1.0 M solution in hexane, 14.3 mL, 14.3 mmol) dropwise with a syringe. The mixture was stirred at −78 °C for 2 h and then warmed to room temperature. When the reaction was complete, it was quenched with methanol at −78 °C. To this mixture was added sodium potassium tartrate (aqueous saturated), and the resulting mixture was stirred overnight to clear up the aqueous layer. The mixture was then extracted with ethyl acetate. The acetate phase was dried and rotovaped to afford a diol (440 mg, 99%), R_f (ethyl acetate) 0.28. Without further purification this diol (420 mg, 2.73 mmol) was dissolved in pyridine (5.4 mL). At 0 °C, to this solution was added *tert*-butyldiphenylsilyl chloride (851 mL, 3.27 mmol). The mixture was stirred for 10 h and quenched with water. The mixture then was rotovaped and pumped to remove pyridine, and the residue was chromatographed to give 1-[(*tert*-butyldiphenylsiloxy)-methyl]tricyclo[3.3.0.0^{2,8}]octan-3-ol (393 mg, 37%) as a clear thick oil: R_f (1:2 hexane/ether) 0.53; ^{1}H NMR δ 7.71−7.65 (m, 4H), 7.39−7.32 (m, 6H), 4.78 (m, 1H), 3.78 (m, 2H), 2.64 (m, 1H), 2.51 (m, 1H), 2.31−1.79 (m, 4H), 1.57−1.45 (m, 1H), 1.38 (m, 1H), 1.27 (m, 1H), 1.06 (s, 9H); ^{13}C NMR δ 135.5 (d), 134.0 (s), 129.5 (d), 127.5 (d), 76.1 (d) and 73.0 (d), 65.9 (t) and 65.8 (t), 50.5 (s) and 49.2 (s), 46.7 (t), 45.1 (d) and 43.7 (d), 39.8 (t) and 39.7 (t), 38.6 (d) and 38.2 (d), 32.1 (d) and 29.1 (d), 26.9 (q) and 26.8 (q), 24.9 (t) and 23.6 (t), 19.2 (s); HRMS for $C_{25}H_{32}O_2Si$ calcd 392.2172, found 392.2053.

Pyridinium chlorochromate (PCC) (420 mg, 1.94 mmol) was finely ground with Kieselgel silica gel 60 (420 mg, 1 wt equiv), and the light orange powder was suspended in CH_2Cl_2 (4 mL). The tricyclic alcohol (320 mg, 0.816 mmol) was dissolved in CH_2Cl_2 (2 mL) and added to the PCC suspension. After 2 h, the reaction mixture was filtered through a Celite bed. The brown cake was washed with copious amounts of ether. The filtrate was rotovaped and chromatographed to yield **39** (222 mg, 70%, overall 26%) as a clear thick oil: R_f (1:1 hexane/ether) 0.46; ^{1}H NMR δ 7.67−7.63 (m, 4H), 7.42−7.37 (m, 6H), 3.92 (m, 2H), 2.87 (dd, 1H), 2.58 (dd, 1H), 2.07 (m, 2H), 1.86 (m, 1H), 1.75 (d, 1H), 1.63−1.51 (m, 2H), 1.27 (m, 1H), 1.06 (s, 9H); ^{13}C NMR δ 214.8 (s), 135.4 (d), 133.5 (s), 129.7 (d), 127.6 (d), 64.3 (t), 51.9 (s), 47.2 (t), 43.2 (d), 39.9 (t), 39.5 (d), 34.4 (d), 26.8 (q), 25.3 (t), 19.2 (s); HRMS for $C_{25}H_{30}O_2Si$ M + H calcd 391.2093, found 391.2040. Anal. Calcd for $C_{25}H_{30}O_2Si$: C, 76.88; H, 7.74. Found: C, 76.73; H, 7.84.

1-[(*tert*-Butyldiphenylsiloxy)methyl]bicyclo[3.3.0]octan-3-one (40). To a solution of the tricyclic ketone **39** (120 mg, 0.308 mmol) in benzene (3.1 mL) was added tributyltin hydride (250 mL, 0.923 mmol) and AIBN (50 mg, 0.308 mmol). The mixture was degassed with argon for 15 min and refluxed at 80 °C for 4 h. The reaction mixture was rotovaped and chromatographed to give **40** (89 mg, 83%) as a clear oil along with unreacted starting ketone **39** (13 mg): R_f (1:1 hexane/ether) 0.54; ^{1}H NMR δ 7.66−7.63 (m, 4H), 7.43−7.38 (m, 6H), 3.52 (m, 2H), 2.64 (m, 1H), 2.59−2.52 (m, 2H), 2.11 (m, 2H), 1.95 (m, 1H), 1.75−1.49 (m, 4H), 1.39 (m, 1H), 1.05 (s, 9H); ^{13}C NMR δ 219.6 (s), 135.6 (d), 135.6 (d), 133.4 (s), 133.3 (s), 129.7 (d), 129.7 (d), 127.7 (d), 70.4 (t), 52.5 (s), 48.2 (t), 45.4 (t), 42.7 (d), 36.3 (t), 34.1 (t), 26.9 (q), 24.8 (t), 19.3 (s); HRMS for $C_{25}H_{32}O_2Si$ M + H calcd 393.2250, found 393.2201. Anal. Calcd for $C_{25}H_{32}O_2Si$: C, 76.48; H, 8.22. Found: C, 76.32; H, 8.30.

5,5-Diphenylbicyclo[4.1.0]heptan-2-one (42).[25] Sodium hydride (60% in oil, 39 mg, 0.968 mmol) was placed in a three-necked flask, washed with *n*-pentane, and pumped to dryness. Trimethyloxosulfonium iodide (213 mg, 0.968 mmol) was added. DMSO (2 mL) was dripped to the solid mixture through an addition funnel. After hydrogen evolution, a milky solution turned clear and was stirred for 15 min. 4,4-Diphenyl-2-cyclohexen-1-one (200 mg, 0.806 mmol) was added, and the mixture was stirred overnight. The reaction was quenched with water and extracted with ether. The ether layer was dried, rotovaped, and chromatographed to give **42** as a white solid (171 mg, 81%): R_f (ether) 0.65; IR (KBr) 1681; ^{1}H NMR δ 7.38−7.17 (m, 10H), 2.55−2.42 (m, 1H), 2.33−2.11 (m, 4H), 1.89−1.76 (m, 1H), 1.41−1.35 (m, 1H), 1.21−1.13 (m, 1H); ^{13}C NMR δ 207.3 (s), 148.3 (s), 146.3 (s), 128.3 (d), 128.2 (d), 127.7 (d), 126.7 (d), 126.4 (d), 126.2 (d), 44.5 (s), 33.5 (t), 28.5 (d), 27.9 (t), 27.6 (d), 10.0 (t); HRMS for $C_{19}H_{18}O$ M + H calcd 263.1436, found 263.1441.

3-Methyl-4,4-diphenylcyclohexanone (43). The mixture of **42** (84 mg, 0.321 mmol), tributyltin hydride (173 mL, 0.642 mmol), and AIBN (53 mg, 0.321 mmol) in benzene (3.2 mL) was degassed by argon stream for 15 min. The mixture was refluxed at 80 °C for 2.5 h. After being quenched with ethanol, the reaction mixture was rotovaped and chromatographed to give **43** as a white solid (73 mg, 86%): R_f (ether) 0.71; ^{1}H NMR δ 7.55−7.08 (m, 10H), 3.37−3.32 (m, 1H), 2.98−2.86 (m, 2H), 2.70 (m, 1H), 2.41−2.38 (m, 1H), 2.36−2.25 (m, 2H), 0.81 (d, J = 7 Hz, 3H); ^{13}C NMR δ 210.9 (s), 146.8 (s), 145.0 (s), 128.9 (d), 128.3 (d), 126.8 (d), 126.5 (d), 126.2 (d), 125.7 (d), 48.2 (s),

(25) Corey, E. J.; Chaykovsky, M. *J. Am. Chem. Soc.* **1965**, *87*, 1353.

45.7 (t), 38.4 (t), 37.7 (d), 29.6 (t), 16.7 (q); HRMS for $C_{19}H_{20}O$ M + H calcd 265.1592, found 265.1598. Anal. Calcd for $C_{19}H_{20}O$: C, 86.31; H, 7.63. Found: C, 86.27; H, 7.85.

6-(Methoxycarbonyl)bicyclo[4.1.0]heptan-2-one (45). This compound was identical to that prepared by Cossy and co-workers.[25,26]

4-(Methoxycarbonyl)cycloheptanone (46). This compound was identical to that prepared by Cossy and co-workers.[25,26]

1-(Hydroxymethyl)tricyclo[3.3.0.0^{2,8}]octan-3-one Ethylene Ketal (47). The mixture of **24** (2000 mg, 10.3 mmol), anhydrous ethylene glycol (1.72 mL, 30.9 mmol), PPTS (170 mg, catalyst), and benzene (20 mL) was refluxed overnight in a 100 mL flask fitted with a Dean−Stark tube. After 12 h the reaction mixture was poured into cold water and extracted with ether. The ether phase was dried, rotovaped, and chromatographed to yield 1-(ethoxycarbonyl)tricyclo[3.3.0.0^{2,8}]-octan-3-one ethylene ketal (2203 mg, 90%) as a colorless oil, and a small amount of unreacted **24** (148 mg) was recovered: R_f (1:1 ether/hexane) 0.44; IR (KBr) 1720; ^{1}H NMR δ 4.11 (q, J = 7 Hz, 2H), 4.00−3.85 (m, 4H), 3.18−3.13 (m, 1H), 2.53−2.45 (m, 1H), 2.33−1.95 (m, 5H), 1.63 (d, J = 14 Hz, 1H), 1.60−1.54 (m, 1H), 1.24 (t, J = 7 Hz, 3H); ^{13}C NMR δ 173.1 (s), 117.5 (s), 64.7 (t), 63.8 (t), 60.2 (t), 48.2 (t), 48.2 (s), 45.0 (d), 40.6 (d), 40.4 (t), 37.7 (d), 23.6 (t), 14.1 (q). Anal. Calcd for $C_{13}H_{18}O_4$: C, 65.53; H, 7.61. Found: C, 65.38; H, 7.68.

This compound (3210 mg, 13.5 mmol) was dissolved in CH_2Cl_2 (25 mL) and chilled to −78 °C. To this solution was added Dibal (1.0 M in hexane, 28.3 mL, 28.3 mmol) dropwise via a syringe. After 1 h the reaction was quenched with ethanol, warmed, and diluted with a large amount of ethyl acetate. The aqueous solution of Rochelle's salt was added, and the mixture was vigorously stirred to clear up the aqueous phase. The mixture was separated, and the aqueous layer was extracted with ethyl acetate. The organic phase was dried, rotovaped, and chromatographed to give **47** as a colorless oil (2.53 g, 96%): R_f (ether) 0.36; IR (KBr) 3406; ^{1}H NMR δ 4.01−3.66 (m, 6H), 3.34−3.30 (m, 1H), 2.71−2.67 (m, 1H), 2.18−1.88 (m, 3H), 1.59 (d, J = 14 Hz, 1H), 1.57−1.47 (m, 3H); ^{13}C NMR δ 119.0 (s), 64.6 (t), 64.5 (t), 63.4 (t), 49.0 (s), 48.5 (t), 42.7 (d), 40.0 (t), 38.6 (d), 30.0 (d), 23.9 (t); HRMS for $C_{11}H_{16}O_3$ M + H calcd 197.1178, found 197.1226.

1-(1-Hydroxy-3-butenyl)tricyclo[3.3.0.0^{2,8}]octan-3-one (48). The alcohol **47** (2050 mg, 10.5 mmol) was dissolved in CH_2Cl_2 (20 mL). To the stirred solution were added Celite (4.0 g) and PDC (7866 mg, 21.0 mmol). The reaction was stirred overnight. The mixture was diluted with a large amount of ether and vigorously stirred for 20 min. Then the ether solution was decanted, and a new portion of ether was added to the residue. This process was repeated five times. The decanted ether solution was combined, rotovaped, and chromatographed to give 1-formyltricyclo[3.3.0.0^{2,8}]octan-3-one ethylene ketal as an oil (1368 mg, 67%): R_f (2:1 ether/hexane) 0.45; ^{1}H NMR δ 9.09 (s, 1H), 4.03−3.85 (m, 4H), 3.25−3.20 (m, 1H), 2.50−2.23 (m, 4H), 2.13−1.99 (m, 2H), 1.69 (d, J = 15 Hz, 1H), 1.66−1.59 (m, 1H); ^{13}C NMR δ 198.0 (d), 116.9 (s), 64.8 (t), 63.9 (t), 59.6 (s), 48.3 (t), 45.3 (d), 40.5 (t), 37.9 (d), 37.6 (d), 23.3 (t); HRMS for $C_{11}H_{14}O_3$ calcd 194.0943, found 194.0958. The aldehyde (480 mg, 2.47 mmol) was dissolved in THF (12 mL) and chilled to −78 °C. To the solution was added dropwise allylmagnesium bromide (1.0 M in ether, 9.9 mL, 9.9 mmol) via a syringe. After 1 h the dry ice bath was removed. After being stirred for another hour the reaction was quenched with ethanol and acidified with 3 M HCl. After being stirred for 30 min, the mixture was extracted with ethyl acetate. The acetate phase was dried, rotovaped, and chromatographed to give **48** as an oil (403 mg, 85%). The GC ratio of the two diastereomers of was found to be 1.3:1: R_f (ether) 0.50; IR (KBr) 3419, 1709; ^{1}H NMR δ 5.93−5.78 (m, 1H), 5.20−5.10 (m, 2H), 3.84−3.70 (m, 1H), 3.00−2.93 (m, 1H), 2.82 (s, broad, 1H), 2.64−2.52 (m, 1H), 2.45−2.25 (m, 2H), 2.16−2.00 (m, 4H), 1.80−1.74 (1H; 1.77, d, J = 18 Hz, 0.43H; 1.76, d, J = 18 Hz, 0.57H), 1.69−1.53 (m, 2H); ^{13}C NMR δ 215.5 (s), 134.5 (d), 117.8 (t), 71.2 (d), 55.2 (s), 47.3 (t), 43.2 (d), 40.2 (t), 40.0 (t), 38.3 (d), 34.3 (d), 25.1 (t) for the major diastereomer and δ 215.3 (s), 134.3 (d), 117.9 (t), 70.9 (d), 54.8 (s), 47.1 (t), 42.7 (d), 40.0 (t), 39.8 (t), 38.2 (d), 34.6 (d), 25.1 (t) for the minor diastereomer; HRMS for $C_{12}H_{16}O_2$ M + H calcd 193.1229, found 193.1226.

11-Hydroxy-9-methyltricyclo[6.3.0.0^{1,5}]undecan-3-one (50). Ketone **48** (120 mg, 0.625 mmol) was dissolved in benzene (6.2 mL). To the solution were added tributyltin hydride (336 mL, 1.25 mmol) and AIBN (102 mg, 0.625 mmol). The mixture was degassed with argon for 15 min and refluxed overnight. After 14 h ethanol was added to quench the reaction. The mixture was rotovaped and chromatographed to yield the cyclization product **50** as an oil (113 mg, 94%). The GC ratio of the major (9-*endo*-methyl) and the minor (9-*exo*-methyl) cyclization products was 57:1. The GC ratio of the two C11 diastereomers of the 9-*endo*-methyl products was still 1.3:1. The major and minor cyclization products had the same R_f, and they were not separable from each other: R_f (ether) 0.56; IR (KBr) 3432, 1727; ^{1}H NMR δ 3.98−3.82 (m, 1H), 3.02−2.90 (m, 1H), 2.73−2.40 (m, 3H), 2.27−2.00 (m, 3H), 1.96−1.20 (m, 6H), 0.97−0.92 (3H: 0.96, d, J = 7 Hz; 0.93, d, J = 7 Hz); ^{13}C NMR δ 221.2 (s), 81.2 (d), 59.6 (s), 55.2 (d), 51.3 (t), 44.0 (t), 41.8 (d), 40.2 (t), 34.0 (t), 31.0 (d), 27.9 (t), 14.5 (q) for the major C11 diastereomer and δ 220.7 (s), 77.3 (d), 63.0 (s), 54.9 (d), 46.7 (d), 44.9 (t), 43.1 (t), 41.9 (t), 34.0 (t), 33.2 (d), 27.0 (t), 14.6 (q) for the minor C_{11} diastereomer; HRMS for $C_{12}H_{18}O_2$ M + H calcd 195.1385, found 195.1383.

11-Oxo-9-methyltricyclo[6.3.0.0^{1,5}]undecan-3-one (51). The triquinane alcohol **50** (31 mg, 0.16 mmol) was dissolved in CH_2Cl_2 (0.5 mL). PCC (70 mg, 0.32 mmol) and silica gel (70 mg) were finely ground and added to the CH_2Cl_2 solution. After the solution was stirred for 1 h, a large amount of ether was added and the dark brown suspension was filtered through a Celite bed. The bed was thoroughly rinsed with ether. The ether phase then was rotovaped and chromatographed to give the oxidation product **51** as an oil (24 mg, 78%): R_f (2:1 ether/hexane) 0.47; IR (KBr) 1728; ^{1}H NMR δ 2.70−2.66 (m, 1H), 2.64−2.58 (m, 2H), 2.46−2.04 (m, 6H), 1.93−1.83 (m, 1H), 1.56−1.45 (m, 1H), 1.39−1.21 (m, 2H), 1.14 (d, J = 6 Hz, 3H); ^{13}C NMR δ 222.1 (s), 216.5 (s), 64.4 (s), 54.4 (d), 46.6 (t), 45.6 (d), 43.8 (t), 43.0 (t), 34.8 (t), 30.1 (d), 26.9 (t), 16.2 (q); HRMS for $C_{12}H_{16}O_2$ calcd 192.1150, found 192.1159.

1,5-Dimethyltricyclo[3.3.0.0^{2,8}]octane-3,7-dione (53).[24] To the stirred solution of **52** (1000 mg, 6.02 mmol) and $HgCl_2$ (820 mg, 3.01 mmol) in CH_2Cl_2 (12 mL) was added iodine (1530 mg, 6.02 mmol). $HgCl_2$ was not initially soluble in CH_2Cl_2, which turned dark purple after the iodine addition. A dark orange powder was gradually formed and accumulated in amount, which was HgI_2. The reaction was stopped after 6 h, and the insoluble orange HgI_2 was removed by filtration. The CH_2Cl_2 solution was washed with 0.5 M $Na_2S_2O_3$ and saturated KI aqueous solutions, dried, and rotovaped to give a crude light brown solid (1.43 g). The solid was dissolved in MeCN (13 mL). To this stirred solution was added DBU (880 mL, 5.90 mmol, in 3 mL of MeCN) dropwise via an addition funnel. The mixture was stirred overnight and rotovaped. The residue was dissolved in $CHCl_3$ and washed with water, 1 M HCl, and saturated $NaHCO_3$. The organic solution then was dried, rotovaped, and chromatographed to give **53** (508 mg, 51%) as a white needle crystal: R_f (ether) 0.39; ^{1}H NMR δ 2.56 (d, J = 17 Hz, 2H), 2.36 (s, 2H), 2.16 (d, J = 17 Hz, 2H), 1.51 (s, 3H), 1.47 (s, 3H); ^{13}C NMR δ 208.3 (s), 56.2 (t), 47.5 (d), 41.8 (s), 22.8 (q), 13.6 (q). Anal. Calcd for $C_{10}H_{12}O_2$: C, 73.15; H, 7.37. Found: C, 72.98; H, 7.32.

7-(3-Butenyl)-1,5-dimethyl-7-hydroxytricyclo[3.3.0.0^{2,8}]-octan-3-one (54). The dione **53** (280 mg, 1.71 mmol) was dissolved in THF (5.7 mL) and chilled to −78 °C. To the stirred solution was dropwise added 3-butenylmagnesium bromide (0.5 M in THF, 4.44 mL, 2.22 mmol) through a syringe in 10 min. The reaction was quenched for 3 h with water, acidified with 1 M HCl, and extracted with ethyl acetate. The acetate phase was dried, rotovaped, and chromatographed. Unreacted starting dione (46 mg) was recovered, and **54** was isolated as a white solid (188 mg, 64%): R_f (ether) 0.55; ^{1}H NMR δ 5.82 (m, 1H), 4.95 (m, 2H), 3.42 (s, 1H), 2.40−2.08 (m, 4H), 2.00−

(26) Cossy, J.; Furet, N.; BouzBouz, S. *Tetrahedron* **1995**, *51*, 11751.

1.67 (m, 6H), 1.24 (s, 3H), 1.21 (s, 3H); ^{13}C NMR δ 214.9 (s), 138.6 (d), 114.4 (t), 80.3 (s), 58.5 (t), 54.8 (t), 50.4 (d), 49.5 (s), 46.3 (s), 45.7 (d), 42.3 (t), 28.7 (t), 23.0 (q), 14.8 (q); HRMS for $C_{14}H_{20}O_2$ M + H calcd 221.1542, found 221.1544. Anal. Calcd for $C_{14}H_{20}O_2$: C, 76.33; H, 9.15. Found: C, 76.31; H, 9.16.

Linear Triquinane (55). The tricyclic ketone **54** (34 mg, 0.155 mmol), tributyltin hydride (125 mL, 0.465 mmol), and AIBN (25 mg, 0.155 mg) were dissolved in benzene (0.6 mL). The mixture was degassed with a steady argon stream for 15 min and refluxed overnight. The reaction was quenched with ethanol and chromatographed to afford **55** as an oil (28 mg, 83%): R_f (ether) 0.68; IR 4000 (broad), 2956, 1708, 1462; ^{1}H NMR δ 2.35 (q, J = 18 Hz, 1H), 1.97−1.85 (m, 2H), 1.73−1.66 (m, 2H), 1.53−1.24 (m, 9H), 0.91−0.78 (m, 6H); ^{13}C NMR δ 214.1 (s), 81.0 (s), 58.9 (s), 55.0 (t), 50.0 (d), 46.5 (s), 46.0 (d), 43.1 (t), 29.3 (t), 27.4 (t), 23.2 (q), 15.0 (q), 13.7 (q), 8.8 (t); HRMS for $C_{14}H_{22}O_2$ calcd 222.1620, found 222.1616. Anal. Calcd for $C_{14}H_{22}O_2$: C, 75.63; H, 9.97; Found: C, 75.62; H, 9.95.

Acknowledgment. We gratefully acknowledge support from the National Science Foundation (Grant CHE-9414240) for this work.

Supporting Information Available: Spectral data for compounds **42**, **47**, **48**, **50**, and **51** (5 pages). 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 ordering information.

JO961655E