Oxy-Cope Rearrangements of Bicyclo[3.2.0]heptenones. Synthesis of Bicyclo[4.2.1]non-1(4)-en-6-ones and Bicyclo[5.2.1]dec-1(10)-en-5-ones

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Received November 12, 1999

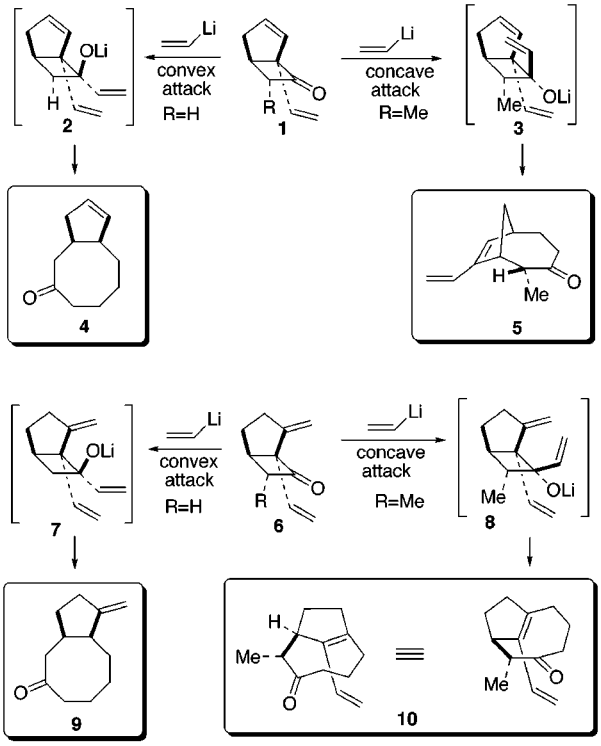
6-*exo*-Methylbicyclo[3.2.0]hepten-7-ones and their 2-alkylidene analogues are readily prepared from dialkyl squarates. These compounds undergo facial oxy-Cope ring expansions upon treatment with vinyllithium; the former leads to bicyclo[4.2.1]non-1(4)-en-6-ones and the latter to the first examples of bicyclo[5.2.1]dec-1(10)-en-5-ones, compounds having exceptionally strained bridgehead double bonds. The transformations are controlled by the 6-*exo*-methyl group in the starting material along with the substituent at position-1 (bridgehead) which force attack of the lithium reagent from the concave face of the starting material, thus allowing the cyclopentenyl or alkylidene groups to participate in the sigmatropic event.

Introduction

1-Alkenylbicyclo[3.2.0]hepten-7-ones and their 2-alkylidene analogues of general structures **1** and **6** (Scheme 1) are readily available from squaric acid and have been shown to be useful synthetic intermediates.[1,2] Previously, we reported syntheses of bicyclo[6.3.0]undecenones **4** and **9** from, respectively, **1** and **6** (R = H) upon treatment of alkenyllithium reagents.[3,4] Such oxy-Cope transformations arise via convex face attack of the alkenyllithium to give the corresponding adducts **2** and **7** and subsequent participation of the 1-alkenyl group in the sigmatropic reaction.[5] In contrast, we now report that vinyllithium attacks **1** and **6** from the concave face for those examples bearing an exo-disposed methyl group at position-6 (R = Me). This new reaction results in adducts **3** and **8**, which then proceed to, respectively, bicyclo[4.2.1]non-1(4)-en-6-ones **5** and the previously unknown highly strained bridgehead alkenes, bicyclo[5.2.1]dec-1(10)-en-5-ones **10**, via oxy-Cope reactions in which the cyclopentenyl or alkylidenyl double bonds are participants.

Specific examples of the previously reported convex face attack mode are represented by the tandem reaction sequence outlined in Scheme 2. Here, bicyclo[3.2.0]-heptenone **11** was observed to give the triquinane **13** (67%) via an initial oxy-Cope ring expansion to **12** followed by transannular ring closure upon hydrolytic desilylation during the workup procedure.[3a] Analogously, 2-alkylidenebicyclo[3.2.0]heptanone **14** provided the triquinane **16** (67%) via the intermediate **15**. It is noteworthy that the reaction can be terminated at the bicyclo[6.3.0]undecenone stage when the starting materials bear *tert*-butyldimethylsilyl (TBS) rather than trimethylsilyl (TMS) protecting groups.

Scheme 1



Results and Discussion

Reported herein are the results of a study of the oxy-Cope ring expansions of bicyclo[3.2.0]heptenones induced by 1,2-addition of vinyllithium to the carbonyl group from

(1) For a recent review of the synthesis and reactions of cyclobutenones, see: Moore, H. W.; Yerxa, B. R. *Adv. Strain Org. Chem.* **1995**, *4*, 81−162.

(2) Gayo, L. G.; Winters, M. P.; Moore, H. W. *J. Org. Chem.* **1992**, *57*, 6896.

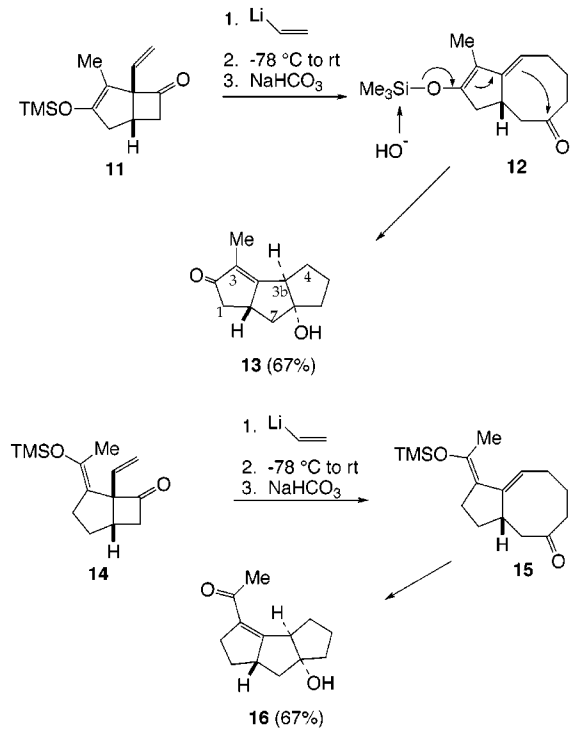
(3) For examples see the following and references therein: (a) Santora, V. S.; Moore, H. W. *J. Org. Chem.* **1996**, *61*, 7976. (b) Santora, V. S.; Moore, H. W. *J. Am. Chem. Soc.* **1995**, *117*, 8486. (c) Jung, M. E.; Rayle, H. L. *J. Org. Chem.* **1997**, *62*, 4601. (d) Enholm, E. J.; Zia, Z. Z. J. *J. Org. Chem.* **1997**, *62*, 174.

(4) For reviews of the oxy-Cope rearrangement, see: (a) Paquette, L. A. *Tetrahedron* **1997**, *53*, 13971−14020. (b) Paquette, L. A. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 609−626. (c) Lutz, R. P. *Chem. Rev.* **1984**, *84*, 6−243.

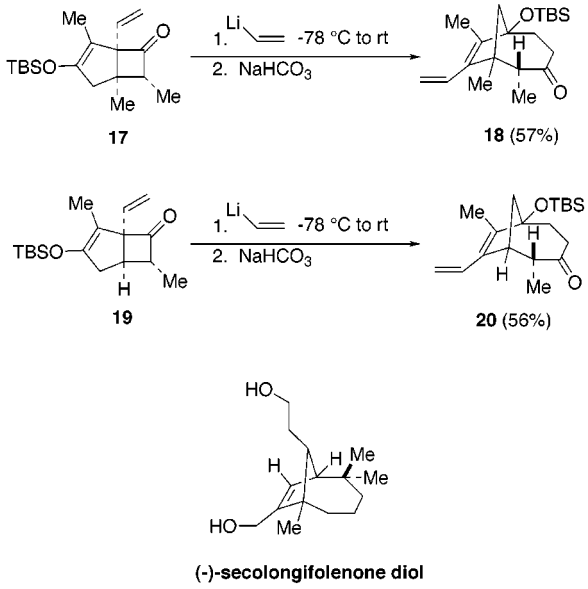
(5) (a) MacDougall, J. M.; Turnbull, P. S.; Verma, S. K.; Moore, H. W. *J. Org. Chem.* **1997**, *62*, 3792. (b) MacDougall, J. M.; Santora, V. J.; Verma, S. K.; Turnbull, P.; Hernandez, C. R.; Moore, H. W. *J. Org. Chem.* **1998**, *63*. 6905.

10.1021/jo991765w CCC: $19.00
Published on Web 05/11/2000

Scheme 2



Scheme 3

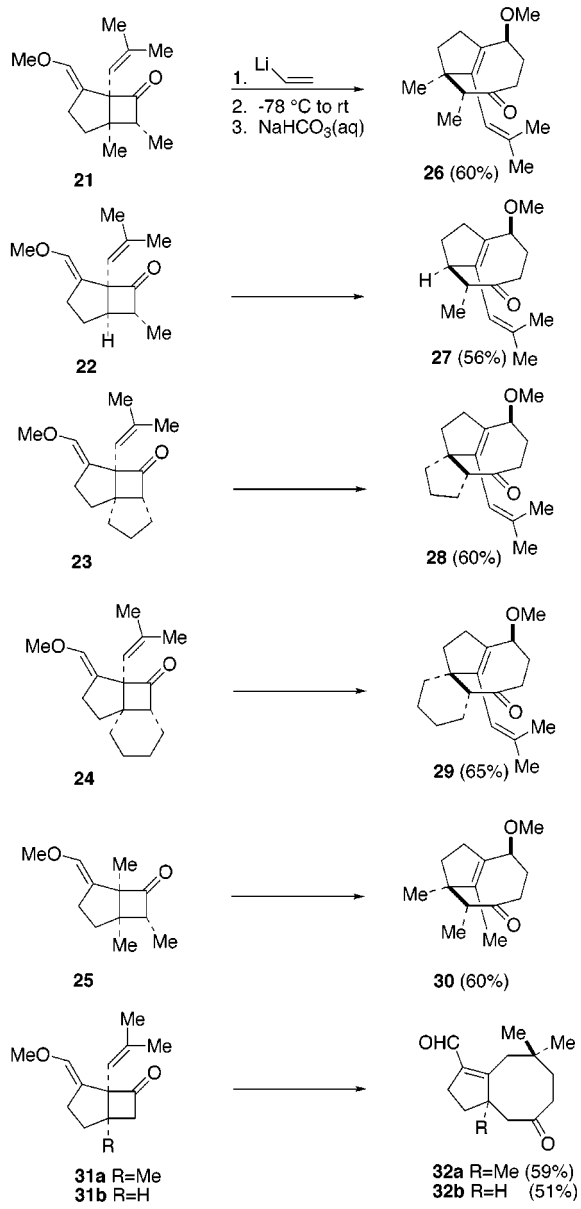


the concave face of the molecule. This modification is complrmentary to the tandem sequence described above and appears to be generally applicable if the starting materials bear an *exo*-methyl group at position-6.

For example, **17** gives the bicyclo[4.2.1]nonenone **18** as a single diastereomer in 57% isolated yield and **19** gives **20** in 56% yield (Scheme 3). This transformation is of potential importance as a possible key step in the synthesis of natural products such as secolongifolenone, an antipode of a fungal metabolite of *Helminthosporium sativum*.[6]

In a similar fashion, 6-*exo*-methyl-2-alkylidenebicyclo-[3.2.0]heptanones gave bicyclo[5.2.1]dec-1(10)-en-5-ones, members of the previously unknown class of highly strained polycyclic bridgehead alkenes.[7] Specifically, **21**−**25** gave **26**−**30**, respectively, in yields ranging from 56 to 65% (Scheme 4).

Scheme 4



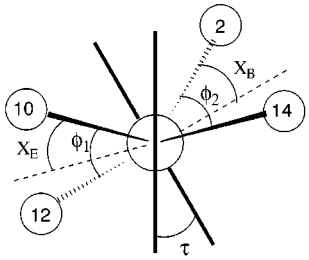
This rearrangement is of particular note since it appears to be general, and the starting materials are readily prepared in a variety of substitution patterns. In this regard, the conversion of **25** to **30** is highlighted since it shows the reaction to be applicable for examples bearing groups other than the bulky 2-methylpropenyl group at the bridgehead position. Also of mechanistic interest is the observation that treatment of **31a**,**b** under the reaction conditions gave, respectively, bicyclo[6.3.0]-undecenones **32a** (59%) and **32b** (51%), both of which must arise via the convex attack mode. Thus, as discussed above, the presence of a 6-*exo*-methyl group in the starting material is a requisite to induce the reaction sequence arising from concave attack of vinyllithium.

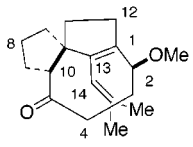
The structure assignments for **18** and **20** are based upon characteristic spectral data. Their stereochemistry

(6) Satyanarayana, N.; Nayak, U. K. *Synth. Commun.* **1985**, *15*, 331.

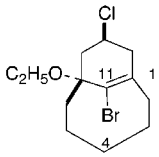
(7) For a review of strained bridgehead alkenes, see: Warner, P. M. *Chem. Rev.* **1989**, *89*, 1067.

X_E: 180->C14C13C1C10=11.0°; X_B: 180->C2C1C13C12=23.9°
ϕ_1: >C10C13C1C12=-15.7(3)°; ϕ_2: <C14C13C1C2=-28.5(4)°;
τ: 0.5[ϕ_1+ϕ_2]=-22.1(3)°; θ_1: >C10C13C1C2=140.5(2)°; θ_2:
>C14C13C1C12=175.4(2)°





28



33

Figure 1. View along the bridgehead double bond of **28**.

is assumed on the basis of mechanistic considerations. The ^{13}C NMR spectrum of **18** shows a carbonyl carbon atom absorption at δ 216 and a tertiary alkoxy carbon at δ 85. The presence of eight CH_3, four CH_2, and two CH groups was established by DEPT analysis. In addition, the ^{13}C NMR spectrum reveals the presence of two quaternary carbon atoms and two tetrasubstituted olefinic carbon atoms. The ^1H NMR spectra showed absorptions for the vinyl protons at δ 6.27 (dd, J = 17.9, 11.6 Hz), 5.31 (dd, J = 17.9, 1.8 Hz), and 5.28 (dd, J = 11.6, 1.8 Hz), together with a doublet for the methyl substituted methine group at δ 1.06 (J = 7.5 Hz). Two singlets at δ 1.76 and 1.22 account for the methyl groups attached to quaternary carbon atoms. The infrared spectrum shows carbonyl absorption at 1701 cm^{-1}. Similar data were observed for **20** (see the Experimental Section).

The structure of **28** was unambiguously established by single-crystal X-ray crystallography. This provides the foundation for the assigned structure and stereochemistry of **26**, **27**, **29**, and **30**, all of which show common characteristic spectral features.

Analysis of the X-ray data for **28** reveals it to have one of the most distorted double bonds experimentally detected. Indeed, it compares to that reported for 11-bromo-*endo*-9-chloro-7-ethoxybicyclo[5.3.1]undec-1(11)-ene (**33**, Figure 1), a compound claimed to have the most distorted double bond for which X-ray data exists.[8,9] The *trans*-cyclooctene double bonds in both **28** and **33** are in the particularly unfavorable position being directed toward the smallest one carbon bridge. Strain relief in both compounds stems more from torsion (τ_{33} = 29.3°, cf. τ_{28} = 22.1°) than from pyramidalization of the olefinic carbon atoms ($X_{m(33)}$ = 17.1°, cf. $X_{m(28)}$ = 17.5°). This is unusual since, per degree of deformation, torsion requires more energy than pyramidalization,[8,10] and thus, geometrically less restricted alkenes respond preferentially by pyramidalization. The dominance of torsional strain release

Table 1. Observed and Calculated Distortion Parameters for Bridgehead Alkenes[a]

compd	X_E	X_B	X_m	τ	Φ_1	Φ_2	θ_1	θ_2
28 (obsd)	11.1	23.9	17.5	22.1	−15.7	−28.5	140.5	174.4
28 (calcd)	10.0	19.9	14.9	21.8	−16.9	−26.6	143.6	175.8
33 (obsd)	20.8	13.4	17.1	29.3	−25.6	−33.0	133.6	167.8
33 (calcd)	16.1	20.0	18.0	24.7	−22.7	−26.7	137.3	173.4
26 (calcd)	11.1	20.0	15.5	20.9	−16.4	−25.3	143.6	174.8
27 (calcd)	11.2	20.1	15.7	21.8	−17.3	−26.2	142.6	173.9
29 (calcd)	11.0	19.9	15.4	20.2	−15.7	−24.6	144.4	175.3
30 (calcd)	16.3	20.1	18.2	18.9	−16.9	−20.9	142.0	179.2

[a] Calculations are based upon the cff91 Potential Set with Insight-Discover 93.

appears to be common to nearly all of the bridgehead alkenes described herein as evidenced by the force field calculations presented in Table 1; i.e., the τ-values are consistently of greater magnitude than the X_m values. An exception is compound **30**, where the degree of pyramidalization $X_{m(30)}$=18.2° is calculated to be nearly equivalent to the torsional strain (τ_{30}=18.9°).

It is noteworthy that even though the degree of pyramidalization is nearly the same in both **28** and **33** (X_m = 17.5 cf 17.1°), there is an inverse correlation between the individual olefinic carbon atoms. That is, the bridgehead carbon atom in **33** shows less pyramidalization (X_B = 13.4°) than that in **28** (X_B = 23.9°), while the exocyclic double bond in **33** shows more (X_E = 20.8°) than that in **28** (X_E = 11.1°). This apparent anomaly may be due to a greater interaction of the bromine in **33** with the C4-H (exo) of the pentamethylene bridge as compared to the analogous interaction of the C13-(3-methylpropenyl) with the C4-H (exo) in **28**. Thus, the former requires greater pyramidalization at C11 than the latter at C13.

Finally, it is noted that the bridgehead C=C bond length in **28**, like that in **33** as well as in other bridgehead olefins,[9] does not suffer significant elongation despite the high degree of distortion; i.e., the bond distance in **28** is 1.348(3) Å and that in **33** is 1.319(8) Å.

The requisite substituted bicycloheptenones used in this study were prepared in analogy to previously reported methods starting with dialkyl squarates.[1,2,5,11] For example, **17** and **19** stem from 3-ethenyl-4,4-dimethoxy-2-methylcyclobutenone **34**, which is easily prepared from dimethylsquarate in a "one pot" sequence of reactions, i.e., treatment of the squarate ester with vinyllithium in THF at −78 °C followed by the sequential addition of trifluroacetic anhydride and then methanol.[3a] Allylation of **34** upon treatment with, respectively, the Grignard reagents obtained from 3-chloro-2-methylpropene or allylmagnesium bromide followed by acidic workup and silylation using TBSOTf gave the cyclobutenones **35a** (68%) and **35b** (63%) (Scheme 5).[12] Thermolysis (toluene, 110 °C) of these induced their electrocyclic ring opening to the corresponding vinylketenes, which give the respective bicyclo[3.2.0]heptenones upon intramolecular [2 + 2] cycloaddition.[3] Treatment of the resulting products with LDA followed by MeI then gave **17** and **19** in 63−67% overall yield.

Syntheses of **21**[5a] and **31a**,**b** are outlined in Scheme 6. A preliminary account describing these compounds has appeared.[5a] The known cyclobutenone **36** was prepared

(8) Wijsman, G. W.; de Wolf, W. H.; Bickelhaupt, F.; Kooijman, H.; Spek, A. L. *J. Am. Chem. Soc.* **1992**, *114*, 9191.

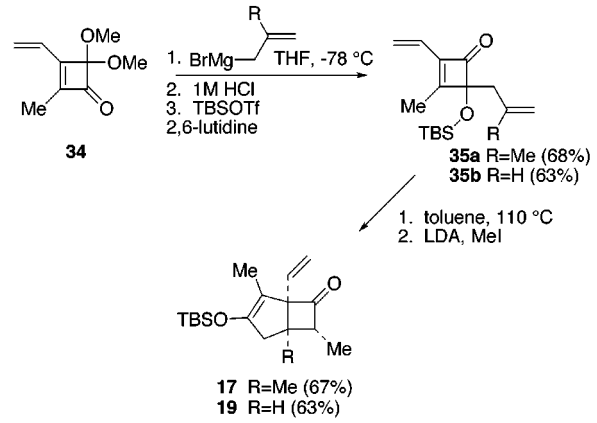
(9) For a review concerning the X-ray data of bridged alkenes, see: Lease, T. G.; Shea, K. J. *Advances in Theoretically Interesting Molecules*; JAI Press Inc.: New York, 1992; Vol. 2, pp 79−112.

(10) Ermer, O.; Lifson, S. *J. Am. Chem. Soc.* **1973**, *95*, 4121.

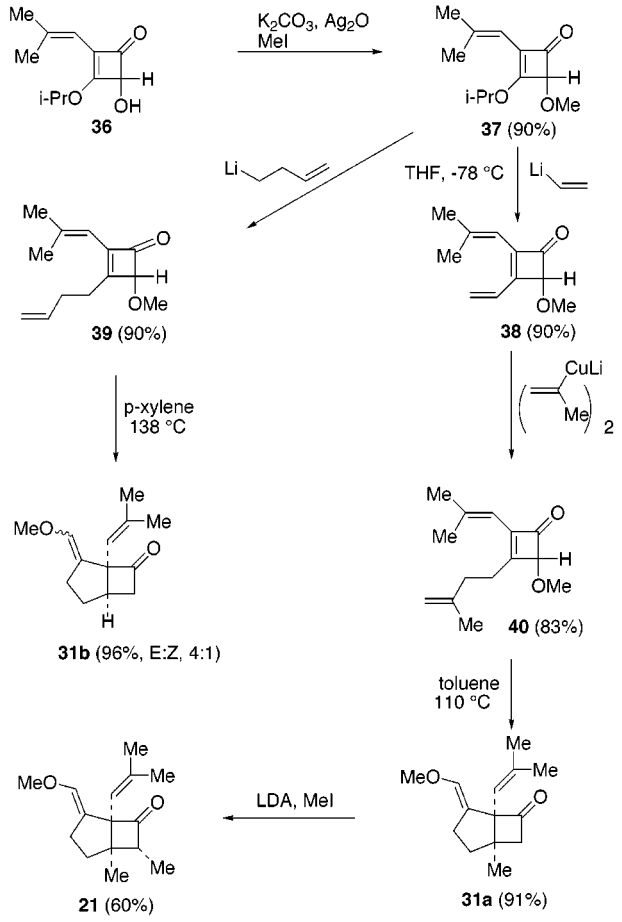
(11) Liu, H.; Tomooka, C.; Moore, H. W *Synth. Commun.* **1997**, *27*, 2177.

(12) For the preparation of TBSOTf, see: Corey, E. J. et. al. *Tetrahedron Lett.* **1981**, 3465.

Scheme 5



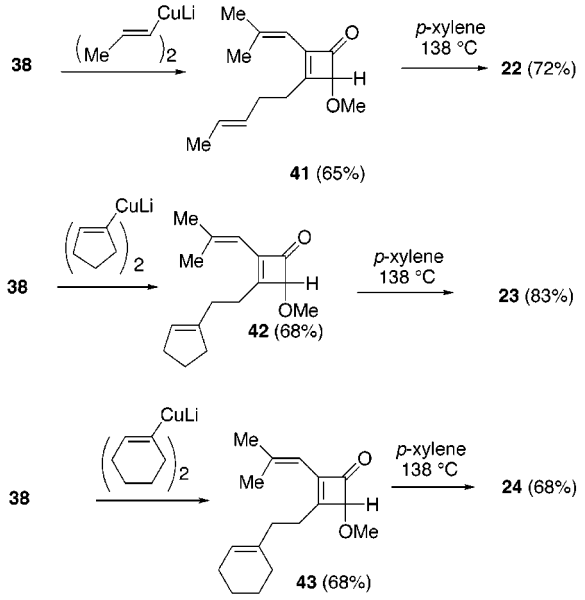
Scheme 6



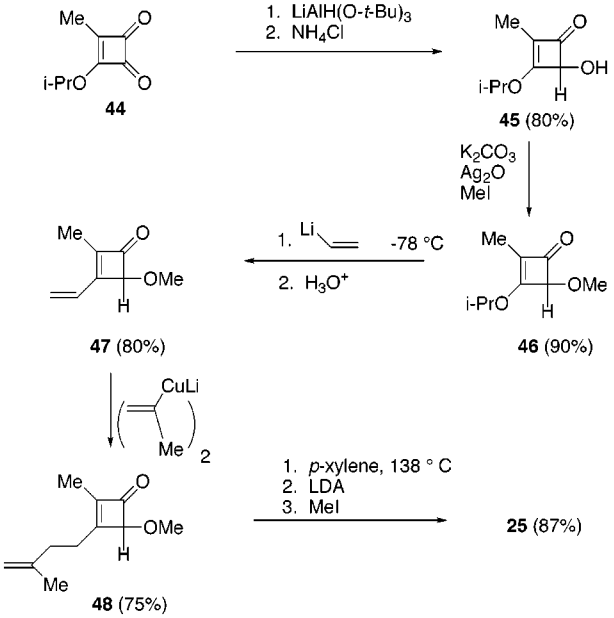
from diisopropyl squarate.[5b] O-Methylation of the free hydroxyl group gave **37**[5a] (90%), which was converted to **38** (90%) and **39** (90%) upon treatment with, respectively, vinyllithium or 4-lithio-1-butene. Cyclobutenone **38** is a key starting material for the synthesis of a number of substituted cyclobutenones since it readily undergoes 1,6-addition of cuprates.[13] For example, its treatment with lithium di-(2-propenyl)cuprate gave **40**[5a] in 83% yield. Thermolysis of **40** resulted in **31a** (91%), which then gave **21** (60%) upon methylation. In analogy, **39** gave **31b** upon thermolysis (96%).

Further demonstration of the efficient 1,6-addition of cuprates to **38** is outlined in Scheme 7. Here, treatment

Scheme 7



Scheme 8



of **38** with the corresponding diorganocuprates gave cyclobutenones **41**−**43** (65−68%), which upon thermolysis (*p*-xylene, 138 °C) gave the bicyclo[3.2.0]heptenones **22**−**24** in yields ranging from 68 to 83% (Scheme 7).

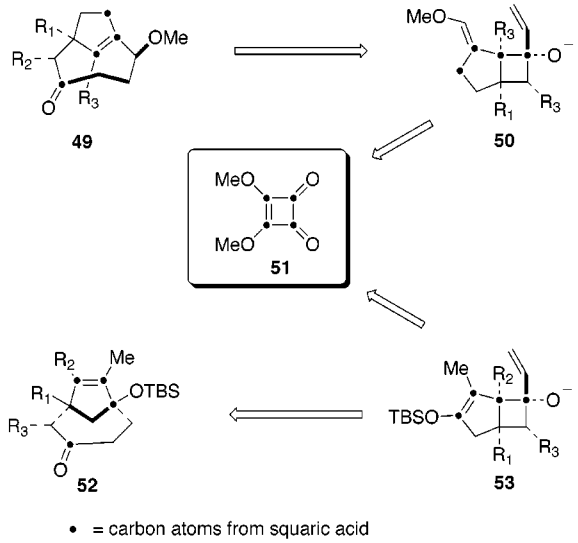
Bicycloheptanone **25** was efficiently prepared using the methods outlined above (Scheme 8). Specifically, the cyclobutenone **44** was prepared from diisopropyl squarate and then converted to **45** (80%), **46** (90%), and **47** (80%) using standard procedures. Cyclobutenone **48** was then obtained in 75% yield upon treatment with lithium di-(2-propenyl)cuprate. Thermolysis (*p*-xylene, 138 °C) followed by convex face methylation of the resulting bicyclo-[3.2.0]heptenone gave **25** in 87% yield.

Conclusion

In conclusion, we wish to note the following significant points: (1) 6-*exo*-methylbicyclo[3.2.0]heptenones and their 2-alkylidene analogues are readily available from dialkyl

(13) For related 1.6-additions of cuprates, see: Liu, H.; Tomooka, C.; Moore, H. W. *J. Org. Chem.* **1996**, *61*, 6009.

Scheme 9



squarates and are useful precursors to bicyclo[4.2.1]-nonenones and bicyclo[5.2.1]decenones, respectively; (2) the complexity of these structures and their relation to a starting dialkyl squarate is generally outlined in Scheme 9; e.g., bicyclo[5.2.1]decenone **49** and bicyclo-[4.2.1]nonenone **52** translate respectively to **50** and **53** and these to dimethyl squarate **51**; (3) finally, it is noted that the rearrangements reported here add to a growing list of polycyclic compounds (e.g., polyquinanes, bicyclo-[6.3.0]undecenones, bicyclo[4.2.1]non-1(4)-en-6-ones, and bicyclo[5.2.1]dec-1(10)-en-5-ones) that are now available from the oxy-Cope ring expansions of the squarate-derived cyclobutenones.

Experimental Section

General Information. All reactions were conducted under a positive pressure of nitrogen or argon at ambient temperature using flame-dried glassware unless otherwise indicated. Temperatures designated to be 0 or −78 °C are approximate and refer to bath temperatures. Air- and moisture-sensitive liquids were transferred via syringe at ambient temperature or via cannula at −78 °C through rubber septa. Silica gel (230−400 mesh) was used for column chromatography unless otherwise specified. Tetrahydrofuran and diethyl ether were purged with nitrogen and then passed through two 4 × 36 in. columns of anhyd neutral A-2 alumina (8 × 14 mesh). Toluene, *p*-xylene, and CH_2Cl_2 were distilled from CaH_2 immediately before use. Triethylamine and 2,6-lutidine were distilled from CaH_2 and stored over KOH pellets. *n*-Butyllithium and *tert*-butyllithium were used as solutions in hydrocarbon solvents. Methyllithium and vinyllithium[14] were used as solutions in ether and their molarities established by titration against diphenyl acetic acid in THF. Methyl iodide was filtered through a pipet of basic alumina under N_2 before use. All other solvents and reagents were used as received. ^{1}H NMR and ^{13}C NMR spectra were recorded at 500 and 125 MHz, respectively, in $CDCl_3$, unless specified otherwise. Melting points are uncorrected.

(±)-3-*tert*-Butyldimethylsiloxy-1-ethenyl-2-*endo*-5,6-trimethylbicyclo[3.2.0]hept-2-ene-7-one (17). A solution of **35a** (1.0 g, 3.42 mmol) in 40 mL of toluene was refluxed for 5 h. The solvent was removed in vacuo to give (±)-3-*tert*-butyldimethylsiloxy-1-ethenyl-2,5-dimethylbicyclo[3.2.0]hept-2-en-7-one as a yellow oil that slowly solidified. To a 0 °C THF (20 mL) solution of diisopropylamine (0.161 mL, 1.23 mmol) was added *n*-BuLi (0.98 mL, 1.23 mmol). After being stirred for 10 min, the reaction mixture was cooled to ca. −78 °C and the above product (301 mg, 1.03 mmol) in THF (1 mL) was added. The cold bath was immediately removed, and after 45 min, methyl iodide (0.083 mL, 1.33 mmol) was added. After an additional 45 min, the reaction was quenched with H_2O (5 mL). The aqueous layer was extracted with ether, and the combined organic layer was washed with brine, dried ($MgSO_4$), filtered, and concentrated. Chromatography (95% hexanes/EtOAc) gave **17** (220 mg, 70%) as a pale yellow oil: ^{1}H NMR δ 5.53 (d, J = 17.6, 10.8 Hz, 1H), 5.28 (dd, J = 17.6, 1.7 Hz, 1H), 5.22 (dd, J = 10.8, 1.7 Hz, 1H), 3.22 (q, J = 7.6 Hz, 1H), 2.50 (dd, J = 16.0, 2.4 Hz, 1H), 2.39 (dd, J = 16.0, 1.7 Hz, 1H), 1.48 (s, 3H), 1.04 (d, J = 7.6 Hz, 3H), 0.98 (s, 3H), 0.94 (s, 9H), 0.15 (s, 6H); ^{13}C NMR δ 212.6, 148.9, 132.6, 118.1, 114.3, 81.2, 60.0, 48.2, 39.3, 25.6 (3C), 18.1, 16.5, 9.8, 8.5, −3.9 (2C); IR (neat) 1768, 1670 cm^{-1}; HRMS (EI) calcd for $C_{18}H_{30}O_2Si$ (M^+) 306.2015, found 306.2014.

(±)-1-*tert*-Butyldimethylsiloxy-3-ethenyl-(*endo*)2,(*endo*)4,5-trimethylbicyclo[4.2.1]non-1(4)-2-en-6-one (18). Vinyllithium (1.22 mL, 0.915 mmol) was added to a solution of **17** (0.140 g, 0.458 mmol) in 10 mL of THF (−78 °C). After being stirred for 10 min, the reaction mixture was allowed to warm to ambient temperature. After 30 min, it was quenched with H_2O (5 mL). The aqueous layer was extracted with ether, and the combined organic layers were washed with brine (1 × 10 mL), dried over $MgSO_4$, filtered, and concentrated. Chromatography (95% hexanes/EtOAc) gave **18** (87 mg, 57%) as a colorless oil: ^{1}H NMR δ 6.27 (dd, J = 17.9, 11.6 Hz, 1H), 5.31 (dd, J = 17.9, 1.8 Hz, 1H), 5.28 (dd, J = 11.6, 1.8 Hz, 1H), 2.45 (q, J = 7.5 Hz, 1H), 2.36 (ddd, J = 6.1, 4.8, 2.0 Hz, 1H), 2.07−2.03 (m, 1H), 1.89 (dd, J = 12.3, 2.2 Hz, 1H), 1.88−1.83 (m, 1H), 1.80 (d, J = 12.3 Hz, 1H), 1.76 (s, 3H), 1.75−1.69 (m, 1H), 1.22 (s, 3H), 1.06 (d, J = 7.5 Hz, 3H), 0.862 (s, 9H), 0.068 (s, 3H), 0.039 (s, 3H); ^{13}C NMR δ 216.5, 142.5, 137.0, 132.2, 117.8, 85.4, 61.7, 55.2, 46.5, 35.8, 35.1, 26.4, 25.8 (3C), 18.1, 14.8, 10.4, −2.1, −2.5; IR (neat) 1701, 1671, 1632 cm^{-1}, HRMS (EI) calcd for $C_{20}H_{34}O_2Si$ (M^+) 334.2328, found 334.2326.

(±)-3-*tert*-Butyldimethylsiloxy-1-ethenyl-2,(*endo*)6-bicyclo[3.2.0]hept-2-en-7-one (19). In the manner analogous to the preparation of **17**, the title compound was prepared by refluxing a solution of **35b** (3.20 g, 11.5 mmol) in toluene (250 mL), which gave (±)-1-ethenyl-2-methyl-3[(trimethylsilyl)oxy]-bicyclo[3.2.0]hept-2-en-7-one (3.05 g, 95%) as a pale yellow oil. This product (0.145 g, 0.521 mmol) was treated directly with LDA, prepared from diisopropylamine (0.090 mL, 0.677 mmol) and *n*-BuLi (0.410 mL, 0.677 mmol), and methyl iodide (0.050 mL, 0.781 mmol). Workup and chromatography (90% hexanes/EtOAc) gave **19** (0.100 g, 66%) as a pale yellow oil: ^{1}H NMR δ 5.85 (dd, J = 17.5, 10.7 Hz, 1H), 5.22 (dd, J = 17.5, 1.5 Hz, 1H), 5.12 (dd, J = 10.7, 1.5 Hz, 1H), 2.96−2.91 (m, 1H), 2.88−2.82 (m, 1H), 2.30−2.26 (m, 1H), 2.09 (dd, J = 5.2, 2.1 Hz, 1H), 1.51 (t, J = 2.1 Hz, 3H), 1.19 (d, J = 7.6 Hz, 3H), 0.946 (s, 9H), 0.149 (s, 3H), 0.143 (s, 3H); ^{13}C NMR δ 211.5, 148.9, 134.9, 115.6, 112.9, 79.5, 57.6, 47.1, 39.0, 25.6 (3C), 18.1, 14.0, 9.2, −4.0 (2C); IR (neat) 1772, 1672 cm^{-1}; HRMS (CI) calcd for $C_{17}H_{29}O_2Si$ (MH^+) 293.1936, found 293.2183.

(±)-1-*tert*-Butyldimethylsiloxy-2,(*endo*)5-dimethyl-3-ethenylbicyclo[4.2.1]non-2-en-6-one (20). Following the general procedure as described for **18**, the title compound was prepared from **19** (95 mg, 0.358 mmol) and vinyllithium (0.358 mL, 0.358 mmol). Workup and chromatography (90% hexanes/EtOAc) gave **20** (58 mg, 56%) as a pale yellow oil: ^{1}H NMR δ 6.64 (dd, J = 17.6, 11.1 Hz, 1H), 5.23 (d, J = 17.6 Hz, 1H), 5.17 (d, J = 11.1 Hz, 1H), 3.10 (t, J = 7.0 Hz, 1H), 2.80 (quin, J = 7.0 Hz, 1H), 2.30 (dt, J = 11.6, 5.1 Hz, 1H), 2.24−2.19 (m, 1H), 2.16−2.12 (m, 1H), 1.85−1.80 (m, 1H), 1.77−1.68 (m, 2H), 1.72 (s, 3H), 1.05 (d, J = 7.3 Hz, 3H), 0.858 (s, 9H), 0.074 (s, 3H), 0.038 (s, 3H); ^{13}C NMR δ 216.0, 144.1, 134.7, 131.9, 115.3, 87.7, 55.1, 47.2, 40.6, 36.2, 34.0, 29.7, 25.7 (3C), 17.4, 9.2, −2.1, −2.5; IR (neat) 1701 cm^{-1}; HRMS (EI) calcd for $C_{19}H_{32}O_2Si$ (M^+) 320.2171, found 320.2179.

(±)-*endo*-6,7-Dimethyl-*exo*-2-methoxy-10-(2-methyl-1-propenyl)bicyclo[5.2.1]dec-1(10)-en-5-one (26). Vinyllithium (0.272 mL, 0.272 mmol) and **21**[5a] (55 mg, 0.248 mmol)

(14) For a preparation of vinyllithium, see: Seyfurth, D.; Wiener, M. A. *J. Am. Chem. Soc.* **1961**, *83*, 3583.

were used to prepare **26** in a manner analogous to the procedure used for the preparation of **18**. Chromatographic purification of the crude product (80% hexanes/EtOAc) gave **26** (37 mg, 60%) as a white solid: mp 73−74 °C; ^{1}H NMR δ 6.03 (s, 1H), 4.13 (dd J = 7.0, 2.3 Hz, 1H), 3.32 (s, 3H), 2.51 (t, J = 12.6 Hz, 1H), 2.44 (q, J = 7.4 Hz, 1H), 2.20−2.10 (m, 3H), 2.02−1.95 (m, 2H), 1.87 (s, 3H), 1.75 (s, 3H), 1.72−1.64 (m, 2H), 1.23 (d, J = 7.5 Hz, 3H), 1.06 (s, 3H); ^{13}C NMR δ 217.5, 144.1, 138.4, 136.8, 121.7, 80.9, 67.3, 57.3, 55.7, 35.6, 35.0, 34.7, 29.7, 26.6, 21.6, 19.9, 13.6; IR (neat) 1691, 1640 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{26}O_2$ (M^+) 262.1933, found 262.1931.

(±)-2-[2-(*E*)-(Methoxy)methylidene]-1-(2-methyl-1-propenyl)-6-*endo*-methylbicyclo[3.2.0.]heptan-7-one (22). The title compound was prepared by refluxing a solution of **41** (77 mg, 0.350 mmol) in *p*-xylene (15 mL) for 2 h. Concentration and filtration through a plug of silica (10:1 hexanes/EtOAc) gave **22** (54 mg, 72%) as a pale yellow oil: ^{1}H NMR δ 5.87 (s, 1H), 5.38 (s, 1H), 3.58 (s, 3H), 2.84−2.77 (m, 2H), 2.46 (t, J = 6.0 Hz, 1H), 2.43−2.34 (m, 1H), 2.08−2.01 (m, 1H), 1.89 (overlapping d, J = 8.1, 4.7 Hz, 1H), 1.71 (s, 3H), 1.56 (s, 3H), 1.18 (d, J = 7.5 Hz, 3H), ^{13}C NMR δ 212.8, 143.2, 135.8, 123.3, 121.2, 77.3, 59.9, 55.1, 48.8, 30.4, 26.2 (2C), 20.1, 13.7; IR (neat) 1770, 1675 cm^{-1}; HRMS (EI) calcd for $C_{14}H_{20}O_2$ (M^+) 220.1463, found 220.1468.

(±)-*exo*-2-Methoxy-*endo*-6-methyl-10-(2-methyl-1-propenyl)bicyclo[5.2.1]dec-1(10)-en-5-one (27). The title compound was prepared from **22** (35 mg, 0.182 mmol) and vinyllithium (0.200 mL, 0.200 mmol) according to the general procedure used for the synthesis of **26**. Workup and chromatography (80% hexanes/EtOAc) gave **27** (24 mg, 61%) as a pale yellow oil: ^{1}H NMR δ 6.32 (s, 1H), 4.31 (dd J = 6.9, 2.5 Hz, 1H), 3.32 (s, 3H), 2.85 (d, J = 6.3 Hz, 1H), 2.66−2.59 (m, 2H), 2.24−2.15 (m, 3H), 1.99−1.82 (m, 3H), 1.87 (s, 3H), 1.80 (s, 3H), 1.68 (dd, J = 12.4, 6.0 Hz, 1H), 1.30 (d, J = 7.5 Hz, 3H); ^{13}C NMR δ 218.3, 141.8, 138.5, 135.4, 122.1, 80.2, 62.8, 57.1, 55.6, 35.1, 34.3, 30.5, 27.0, 26.1, 20.3, 16.5; IR (neat) 1693 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{24}O_2$ (M^+) 248.1776, found 248.1769.

(±)-2-[2-(*E*)-(Methoxy)methylidene]-1-(2-methyl-1-propenyl)-*1H*-cyclobuta[1,2:1,4]dicyclopenten-4-one (23). The title compound was prepared by refluxing a solution of **42** (205 mg, 0.830 mmol) in *p*-xylene (30 mL) for 3 h. Concentration and filtration through a plug of silica (10:1 hexanes/EtOAc) gave **23** (170 mg, 83%) as a white solid: mp 70−71 °C; ^{1}H NMR δ 5.80−5.79 (m, 1H), 5.28−5.27 (m, 1H), 3.55 (s, 3H), 3.09 (d, J = 8.9 Hz, 1H), 2.80 (dd, J = 16.5, 8.4 Hz, 1H), 2.38−2.30 (m, 1H), 2.05−1.97 (m, 2H), 1.92−1.88 (m, 1H), 1.78−1.70 (m, 2H), 1.73 (d, J = 1.3 Hz, 3H), 1.60−1.52 (m, 2H), 1.48 (s, 3H), 1.37−1.30 (m, 1H), ^{13}C NMR δ 216.0, 143.2, 137.2, 120.8, 119.5, 75.5, 65.0, 59.8, 58.2, 35.5, 32.4, 29.6, 26.9, 26.6 26.1, 20.7; IR (neat) 1765, 1677 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{22}O_2$ (M^+) 246.1619, found 246.1612.

(±)-*exo*-2-Methoxy-13-(2-methyl-1-propenyl)tricyclo-[7.3.1.0^{1,10}]tridec-1(13)-en-5-one (28). The title compound was prepared from **23** (57 mg, 0.231 mmol) and vinyllithium (0.580 mL, 0.580 mmol) in analogy to the procedure used for the synthesis of **26**. Chromatography (80% hexanes/EtOAc) furnished **28** (38 mg, 60%) as a white solid: mp 73−74 °C; ^{1}H NMR δ 5.87 (s, 1H), 4.15 (t, J = 7.5 Hz, 1H), 3.31 (s, 3H), 2.74 (dd, J = 12.0, 7.5 Hz, 1H), 2.48 (dt, J = 12.0, 1.6 Hz, 1H), 2.26−2.19 (m, 3H), 2.11−2.04 (m, 1H), 2.01−1.94 (m, 1H), 1.92−1.85 (m, 4H), 1.84 (s, 3H), 1.82−1.75 (m, 3H), 1.73 (s, 3H), 1.68−1.61 (m, 1H); ^{13}C NMR δ 217.2, 144.9, 139.3, 136.6, 121.8, 80.9, 72.3, 66.5, 57.2, 35.7, 34.7, 33.5, 31.6, 30.1, 28.5, 26.5, 24.5, 19.8; IR ($CHCl_3$) 1680, 1638 cm^{-1}; HRMS (EI) calcd for $C_{18}H_{26}O_2$ (M^+) 274.1932, found 274.1931.

(±)-2-[2-(*E*)-(Methoxy)methylidene]-1-(2-methyl-1-propenyl)-1*H*-cyclopenta[1,4]cyclobuta[1,2]benzen-4-one (24). The title compound was prepared by refluxing a solution of **43** (132 mg, 0.508 mmol) in *p*-xylene (15 mL) for 3 h. Concentration and filtration through a plug of silica (10:1 hexanes/EtOAc) gave **24** (90 mg, 68%) as a white solid: mp 90−92 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.85 (t, J = 2.4 Hz, 1H), 5.42 (t, J = 1.3 Hz, 1H), 3.56 (s, 3H), 2.99 (dd, J = 8.1, 3.5 Hz, 1H), 2.80 (ddd, J = 16.1, 9.0, 1.6 Hz, 1H), 2.57−2.47 (m, 1H), 2.10 (dd, J = 12.8, 8.2 Hz, 1H), 1.96−1.90 (m, 1H), 1.80−1.72 (m, 1H), 1.74 (d, J = 1.3 Hz, 3H), 1.60−1.58 (m, 2H), 1.51 (d, J = 0.9 Hz, 3H), 1.49−1.45 (m, 3H), 1.28−1.25 (m, 2H), ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.5, 143.8, 136.3, 121.6, 121.5, 76.5, 59.8, 56.4, 48.7, 37.9, 29.1, 26.2, 26.1, 21.4, 21.3, 20.7, 20.1; IR (neat) 1745, 1672 cm^{-1}; HRMS (CI) calcd for $C_{17}H_{24}O_2$ (M^+) 260.1776, found 260.1774.

(±)-*exo*-2-Methoxy-14-(2-methyl-1-propenyl)tricyclo-[7.4.1.0^{1,10}]tetradec-1(14)-en-5-one (29). The title compound was prepared from **24** (47 mg, 0.181 mmol) and vinyllithium (0.400 mL, 0.400 mmol) in analogy to the procedure used for the synthesis of **26**. Chromatography (80% hexanes/EtOAc) gave **29** (33 mg, 65%) as a white solid: mp 83−84 °C; ^{1}H NMR δ 6.27 (s, 1H), 4.13 (dd J = 6.9, 2.5 Hz, 1H), 3.27 (s, 3H), 2.55 (dt, J = 11.5, 1.5 Hz, 1H), 2.37 (dd, J = 9.1, 4.2 Hz, 1H), 2.21−2.14 (m, 1H), 2.11−2.06 (m, 2H), 2.01−1.91 (m, 1H), 1.90−1.80 (m, 3H), 1.86 (s, 3H), 1.79−1.69 (m, 2H), 1.71 (s, 3H), 1.63−1.53 (m, 4H), 1.48−1.40 (m, 1H) 1.24−1.12 (m, 1H); ^{13}C NMR δ 217.6, 145.5, 140.8, 135.2, 123.8, 80.9, 71.1, 57.3, 55.5, 36.4, 35.7, 35.1, 33.9, 28.8, 26.2 (2C), 24.6, 22.5, 19.5; IR (neat) 1684 cm^{-1}; HRMS (EI) calcd for $C_{19}H_{28}O_2$ (M^+) 288.2089, found 288.2093.

(±)-*endo*-5,6-Dimethyl-(*E*)-2-methoxymethylidene-1-methylbicyclo[3.2.0]heptan-7-one (25). A solution of cyclobutenone **48** (410 mg, 2.28 mmol) in 100 mL of *p*-xylene was refluxed for 1 h. Removal of the solvent provided 396 mg (96%) of a pale yellow oil that was used without further purification. Methylation of this according to the procedure used in the preparation of **17** followed by chromatographic purification (90% hexanes/EtOAc) gave **25** (0.352 g, 91%) as a yellow oil: ^{1}H NMR δ 5.92−5.91 (m, 1H), 3.59 (s, 3H), 3.06 (q, J = 7.4 Hz, 1H), 2.69 (ddd, J = 17.2, 8.9, 1.2 Hz, 1H), 2.46−2.42 (m, 1H), 1.92 (overlapping d, J = 8.2 Hz, 1H), 1.65−1.61 (m, 1H), 1.04 (s, 3H), 1.02 (s, 3H), 0.991 (d, J = 7.4 Hz, 3H); ^{13}C NMR δ 212.2, 142.8, 122.3, 70.2, 59.8, 57.0, 45.4, 37.7, 25.5, 15.5, 14.3, 8.0; IR (neat) 1766, 1688, 1674 cm^{-1}; HRMS (EI) calcd for $C_{12}H_{17}O_2$ ($M - 1$) 193.1229, found 193.1223.

(±)-*endo*-6,7-Dimethyl-*exo*-2-methoxy-10-methyl-bicyclo-[5.2.1]dec-1(10)-en-5-one (30). The title compound was prepared from **25** (53 mg, 0.273 mmol) and vinyllithium (0.875 mL, 0.656 mmol) in analogy to the procedure used for the synthesis of **26**. Workup and chromatography (80% hexanes/EtOAc) gave **30** (36 mg, 60%) as an oil: ^{1}H NMR δ 4.30 (dd, J = 6.7 Hz, 1H), 3.28 (s, 3H), 2.46−2.40 (m, 2H), 2.25−2.20 (m, 1H), 2.09−2.06 (m, 1H), 2.04−1.99 (m, 2H), 2.02 (s, 3H), 1.97−1.95 (m, 1H), 1.70 (ddd, J = 12.4, 6.4, 1.4 Hz, 1H), 1.27−1.24 (m, 1H), 1.17 (d, J = 7.5 Hz, 3H), 1.14 (s, 3H); ^{13}C NMR δ 216.8, 142.4, 136.6, 79.6, 67.5, 56.9, 55.9, 35.2, 34.8, 34.3, 29.4, 20.1, 15.7, 13.8; IR (neat) 1691 cm^{-1}; HRMS (EI) calcd for $C_{14}H_{22}O_2$ (M^+) 222.1620, found 222.1620.

(±)-2-[2-(*E*)-(Methoxy)methylidene]-5-exo-methyl-1-(2-methyl-1-propenyl)bicyclo[3.2.0]heptan-7-one (31a). The title compound was prepared by refluxing a solution of **40**[5a] (550 mg, 2.50 mmol) in *p*-xylene (100 mL). Concentration and filtration through a plug of silica (10:1 hexanes/EtOAc) gave 31a (500 mg, 91%) of **31a** as a clear oil: ^{1}H NMR δ 5.83 (s, 1H), 5.24 (s, 1H), 3.57 (s, 3H), 2.89 (d, J = 18.0 Hz, 1H), 2.79 (dd, J = 16.8, 8.4 Hz, 1H), 2.64 (d, J = 18.0 Hz, 1H), 2.33−2.41 (m, 1H), 1.92 (dd, J = 12.8, 7.9 Hz, 1H), 1.77 (dd, J = 12.2, 8.5 Hz, 1H), 1.76 (s, 3H), 1.54 (s, 3H), 1.21 (s, 3H); 13C NMR δ 210.4, 143.3, 137.4, 121.0, 120.2, 77.1, 59.9, 54.7, 45.2, 38.7, 26.3, 25.8, 22.0, 21.0; IR (neat) 1771, 1675, cm^{-1}; HRMS (EI) calcd for $C_{14}H_{20}O_2$ (M^+) 220.1463, found 220.1469.

(±)-1-Formyl-3a*β*,8,8-trimethyl-cyclopentacycloocten-1-en-5-one (32a). The title compound was prepared from **31a** (70 mg, 0.300 mmol) and vinyllithium (0.490 mL, 0.490 mmol) in analogy to the procedure used for the synthesis of **26**. Workup and chromatography (90% hexanes/EtOAc) gave **32a** (44 mg, 59%) as a white solid: mp 88−89 °C; ^{1}H NMR δ 9.93 (s, 1H), 2.78 (d, J = 11.6 Hz, 1H), 2.68−2.63 (m, 2H), 2.52−2.39 (m, 3H), 2.27 (ddd J = 7.4, 4.6, 2.4 Hz, 1H), 1.95 (d, J = 14.1 Hz, 1H), 1.89−1.82 (m, 2H), 1.75−1.68 (m, 1H), 1.52 (dd, J = 8.1, 7.0 Hz, 1H), 1.14 (s, 3H), 1.08 (s, 3H), 1.02 (s, 3H); ^{13}C NMR δ 212.3, 190.1, 165.4, 139.7, 49.5, 41.5, 37.5, 35.8, 35.5, 35.2, 29.7, 29.5, 28.9, 26.9, 25.6; IR (neat) 1697, 1664,

1614 cm^{-1}; HRMS (CI) calcd for $C_{15}H_{23}O_2$ (MH^+) 235.1698, found 235.1696.

(±)-2-[2-(*E*)-(Methoxy)methylidene]-1-(2-methyl-1-propenyl)bicyclo[3.2.0.]heptan-7-one (31b). The title compound was obtained by refluxing a *p*-xylene solution (30 mL) of **39** (166 mg, 0.806 mmol). Concentration and filtration through a plug of Florisil (10:1 hexanes/EtOAc) gave the product as a colorless oil (160 mg (96%), which consisted of a 4:1 mixture of *E*/*Z* diastereomers (separable by chromatography, 20:1 hexanes/EtOAc). Irradiation of the enolic vinyl proton (*δ*, 5.85) of the major isomer resulted in a slight enhancement of the absorbance of the proton at the bridghead position (*δ*, 5.33), whereas an analogous study with the minor isomer produced no effect. On the basis of these data, the major isomer is assigned the *E*-configuration. Characteristic spectral data for this compound follow: ^{1}H NMR *δ* 5.85 (s, 1H), 5.33 (s, 1H), 3.59 (s, 3H), 3.13 (d, *J* = 9.2 Hz, 1H), 2.91 (dd, *J* = 9.1 Hz, 6.0 Hz, 1H), 2.78 (dd, *J* = 16.6 Hz, 8.6 Hz, 1H), 2.61 (dd, *J* = 5.6 Hz, 1H), 2.34 (m, 1H), 2.01 (m, 1H), 1.83 (dd, *J* = 13.2 Hz, 7.9 Hz, 1H), 1.73 (s, 3H), 1.58 (s, 3H); ^{13}C NMR *δ* 210.9, 142.8, 136.5, 122.7, 120.8, 76.9, 59.9, 48.4, 39.5, 30.8, 26.1, 25.6, 20.1; [*Z*]-*δ* 5.72 (s, 1H), 5.40 (s, 1H), 3.54 (s, 3H), 3.13 (d, *J* = 9.2 Hz, 1H), 2.46−2.51 (m, 1H), 2.35−2.42 (m, 1H), 2.17−2.27 (m, 3H), 1.97−2.05 (m, 1H), 1.75 (s, 3H), 1.61 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) *δ* 209.8, 141.9, 136.1, 121.0, 119.0, 70.2, 59.7, 55.1, 31.5, 29.5, 25.6, 20.3, 17.2; IR (neat) 1773, 1702, 1683; HRMS (EI) calcd for $C_{13}H_{18}O_2$ (M^+) 206.1307, found 206.1308.

(±)-3a*β*-8,8-Dimethyl-1-formylcyclopentacycloocten-1-en-5-one (32b). The title compound was prepared from **31b** (75 mg, 0.364 mmol) and vinyllithium (0.400 mL, 400 mmol) according to the general procedure used for the synthesis of **26**. Workup and chromatography (90% hexanes/EtOAc) gave **32b** (41 mg, 51%) as a colorless oil: ^{1}H NMR *δ* 9.94 (s, 1H), 2.73 (t, *J* = 11.6 Hz, 1H), 2.70−2.66 (m, 1H), 2.61−2.53 (m, 2H), 2.46−2.33 (m, 3H), 2.23−2.18 (m, 2H), 2.05 (d, *J* = 14.2 Hz, 1H), 1.96−1.90 (m, 1H), 1.60−1.56 (m, 1H), 1.50−1.44 (m, 1H), 1.06 (s, 3H), 1.04 (s, 3H); ^{13}C NMR *δ* 213.8, 189.6, 161.7, 141.6, 52.3, 44.4, 41.6, 37.4, 35.8, 35.4, 29.9, 29.5, 28.8, 28.6; IR (neat) 2720, 1697, 1660, 1619 cm^{-1}; HRMS (EI) calcd for $C_{14}H_{20}O_2$ (MH^+) 220.1463, found 220.1463.

2-Ethenyl-3-methyl-4-(2-methyl-2-propenyl)-4-*tert*-butyldimethylsiloxy-2-cyclobuten-1-one (35a). The Grignard reagent was formed by the dropwise addition of an ether (260 mL) solution of 3-chloro-2-methylpropene (25.9 mL, 262 mmol) to lightly sanded and cut magnesium ribbon (5.5 g, 227 mmol) over 25 min. This was then added over 20 min at −78 °C to a THF (300 mL) solution of 3-ethenyl-2-methyl-4,4-dimethoxycyclobuutenone **(34)** (1.62 g, 9.63 mmol) until the green-yellow color of the cyclobutenone had dissipated. This required 150 mL of the Grignard solution. Water (100 mL) was added and the cooling bath was removed. The mixture was extracted with ether, washed with brine, dried (Na_2SO_4), filtered, and concentrated. The resulting crude cyclobutenedione monoketal intermediate was dissolved in THF (100 mL), cooled to 0 °C and treated with 0.5 mL of 1 M HCl. After 40 min, 50 mL of saturated $NaHCO_3$ was added, and the mixture was extracted with EtOAc, washed with brine, dried (Na_2SO_4), filtered, and concentrated. Chromatography (2:1 hexanes/EtOAc) gave 2-ethenyl-4-hydroxy-3-methyl-4-(2-methyl-2-propenyl)-2-cyclobuten-1-one (1.57 g, 92%) as a white crystalline solid: mp 46−47 °C; ^{1}H NMR *δ* 6.18 (dd, *J* = 17.6, 11.1 Hz, 1H), 5.98 (d, *J* = 17.6 Hz, 1H), 5.49 (d, *J* = 11.1 Hz, 1H), 4.93 (s, 1H), 4.85 (s, 1H), 3.09 (bs, 1H), 2.59 (d, *J* = 13.8 Hz, 1H), 2.46 (d, *J* = 13.8 Hz, 1H), 2.17 (s, 3H), 1.79 (s, 3H); ^{13}C NMR *δ* 193.2, 175.1, 146.1, 140.8, 123.8, 122.9, 115.9, 92.3, 42.1, 23.1, 11.0; IR (film, cm^{-1}) 3410, 3076, 1760, 1748, 1651, 1612, 1582; HRMS (EI) calcd for $C_{11}H_{14}O_2$ (M^+) 178.0994, found 178.0992.

A CH_2Cl_2 (10 mL, 0 °C) solution of the above alcohol (0.950 g, 5.33 mmol) was treated with 2,6-lutidine (1.60 mL, 13.3 mmol) followed by TBSOTf (2.08 mL, 9.06 mmol).[12] After 30 min, 0.5 mL of concentrated HCl was added, and the reaction mixture was allowed to stand for 10 min. After neutralization with aqueous $NaHCO_3$, the aqueous layer was extracted with ether, and the combined organic layer was washed with brine and $NaHCO_3$, dried over $MgSO_4$, filtered, and concentrated. Chromatography (30:1 hexanes/EtOAc) gave **35a** (1.08 g, 69%) as a pale yellow green oil: ^{1}H NMR *δ* 6.15 (dd, *J* = 17.6, 11.1 Hz, 1H), 5.95 (dd, *J* = 17.6, 1.9 Hz, 1H), 5.46 (dd, *J* = 11.1, 1.9 Hz, 1H), 4.80 (m, 1H), 4.74 (m, 1H), 2.51(dd, *J* = 7.7 Hz, 2H), 2.15 (s, 3H), 1.71 (s, 3H), 0.85 (s, 9H), 0.10 (s, 3H), −0.05 (s, 3H); ^{13}C NMR *δ* 193.4, 176.6, 145.3, 141.3, 123.3, 123.0, 115.0, 95.2, 43.7, 25.6 (3C), 23.5, 18.1, 11.5, −3.7, −3.8; IR (neat) 1761, 1654, cm^{-1}; HRMS (EI) calcd for $C_{17}H_{28}O_2Si$ (M^+) 292.1859, found 292.1865.

2-Ethenyl-3-methyl-4-(2-propenyl)-4-*tert*-butyldimethylsiloxy-2-cyclobuten-1-one (35b). In a manner analogous to that used for the synthesis of **35a**, **34** (355 mg, 2.11 mmol) gave **35b** (2.50 g, 91%) as a pale yellow oil: ^{1}H NMR *δ* 6.13 (dd, *J* = 17.6, 11.1 Hz, 1H), 5.95 (d, *J* = 17.6, 1.9 Hz, 1H), 5.70 (m, 1H), 5.46 (dd, *J* = 11.1, 1.9 Hz, 1H), 5.02 (m, 2H), 2.49 (dd, *J* = 7.7 Hz, 2H), 2.14 (s, 3H), 0.85 (s, 9H), 0.11 (s, 3H), −0.01 (s, 3H); ^{13}C NMR *δ* 193.7, 177.1, 145.2, 133.0, 123.3, 123.0, 117.9, 94.9, 39.8, 25.6 (3C), 18.1, 11.8, −3.7 (2C); IR (neat) 1760, 1656, 1644 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{27}O_2Si$ (MH^+) 279.1702, found 279.1780.

3-Ethenyl-4-methoxy-2-(2-methyl-1-propenyl)-2-cyclobuten-1-one (38). Vinyllithium (3.93 mL, 3.93 mmol) was added to a THF (35 mL) solution of **37**[5a] (750 mg, 3.57 mmol) at −78 °C. After the green-yellow solution was stirred for 15 min, 5 M HCl (2 mL) was added, and the cold bath was removed. After 30 min, the reaction mixture was neutralized with saturated $NaHCO_3$ (10 mL). The aqueous layer was extracted with ether and the combined organic layer washed with brine, dried over $MgSO_4$, filtered, and concentrated. Chromatography (9:1 hexanes/EtOAc) furnished 566 mg (90%) of **38** as a yellow oil: ^{1}H NMR *δ* 6.83 (dd, *J* = 17.3, 10.6 Hz, 1H), 5.92 (d, *J* = 17.6 Hz, 1H), 5.76 (d, *J* = 10.6 Hz, 1H), 5.71 (s, 1H), 5.11 (s, 1H), 3.40 (s, 3H), 2.07 (s, 3H), 1.87 (s, 3H); ^{13}C NMR *δ* 190.5, 163.4, 146.9, 146.6, 126.9, 126.5, 112.3, 89.8, 55.1, 26.7, 21.7; IR (neat) 2977, 2920, 2826, 1746, 1647, 1613, cm^{-1}; HRMS (EI) calcd for $C_{11}H_{14}O_2$ (M^+) 178.0993, found 178.0994.

3-(3-Butenyl)-4-methoxy-2-(2-methyl-1-propenyl)-2-cyclobuten-1-one (39). 4-Lithio-1-butene in 125 mL of THF, prepared from *tert*-butyllithium (13.3 mL, 22.6 mmol) and 4-bromo-1-butene (1.15 mL, 11.3 mmol, was added to a THF (50 mL) solution of **37**[5a] (950 mg, 4.52 mmol) at − 78 °C. The reaction mixture was then removed from the cold bath, treated with 5 M HCl (3 mL), and allowed to warm to ambient temperature. It was quenched with $NaHCO_3$ (40 mL), and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and concentrated. Chromatography (9:1 hexanes/EtOAc) provided 832 mg (90%) of **39** as a colorless oil: ^{1}H NMR *δ* 5.87−5.79 (m, 1H), 5.58 (s, 1H), 5.08 (d, *J* = 17.0 Hz, 1H), 5.03 (d, *J* = 9.8 Hz, 1H), 4.81 (s, 1H), 3.46 (s, 3H), 2.74−2.69 (m, 1H), 2.67−2.60 (m, 1H), 2.44−2.34 (m, 2H), 2.02 (s, 3H), 1.84 (s, 3H); ^{13}C NMR *δ* 189.1, 173.3, 148.9, 145.0, 136.9, 115.8, 112.1, 91.0, 56.8, 30.2, 27.1, 26.4, 21.4; IR (neat) 1663, 1639 cm^{-1}; HRMS (EI) calcd for $C_{13}H_{18}O_2$ (M^+) 206.1307, found 206.1308.

4-Methoxy-3-[*(E)*-3-pentenyl]-2-(2-methyl-1-propenyl)-2-cyclobuten-1-one (41). Following the general procedure as described for **48**, the title compound was prepared from **38** (100 mg, 0.562 mmol) and the lithium reagent prepared from *trans*-1-bromopropene (0.174 mL, 2.02 mmol) and *tert*-butyllithium (2.38 mL, 4.04),and $CuBr{\cdot}SMe_2$ (208 mg, 1.01 mmol). Workup and chromatography (20:1 hexanes/EtOAc) furnished 80 mg (65%) **41** as a pale yellow oil: ^{1}H NMR *δ* 5.58 (s, 1H), 5.54−5.46 (m, 1H), 5.44−5.42 (m, 1H), 4.81 (s, 1H), 3.46 (s, 3H), 2.70−2.56 (m, 2H), 2.37−2.27 (m, 2H), 2.02 (s, 3H), 1.85 (s, 3H), 1.65 (d, *J* = 6.2 Hz, 3H); ^{13}C NMR *δ* 189.1, 173.8, 148.7, 144.7, 129.4, 126.4, 112.2, 91.0, 56.7, 29.1, 27.8, 26.7, 21.4, 17.8; IR (neat) 1752, 1657, cm^{-1}; HRMS (CI) calcd for $C_{14}H_{21}O_2$ (MH^+) 221.1541, found 221.1544.

4-Methoxy-3-[2-(1-cyclopentenyl)ethyl)]-2-(2-methyl-1-propenyl)-2-cyclobuten-1-one (42). In analogy to the procedure used for the synthesis of **48**, the title compound was prepared from **38** (218 mg, 1.22 mmol), 1-iodocyclopentene (0.65 mL, 5.86 mmol), *tert*-butyllithium (6.88 mL, 11.7 mmol),

and CuBr·SMe_2 (602 mg, 2.93 mmol). Workup and chromatography (20:1 hexanes/EtOAc) furnished 205 mg (68%) **42** as a pale yellow oil: ^{1}H NMR δ 5.57 (s, 1H), 5.37 (t, J = 1.7 Hz, 1H), 4.79 (s, 1H), 3.44 (s, 3H), 2.80−2.74 (m, 1H), 2.70−2.64 (m, 1H), 2.40−2.36 (m, 2H), 2.30−2.24 (m, 4H), 2.00 (s, 3H), 1.88−1.82 (m, 2H), 1.83 (s, 3H); ^{13}C NMR δ 189.1, 174.0, 148.6, 144.7, 142.9, 124.4, 112.1, 90.9, 56.7, 35.0, 32.4, 27.5, 26.4, 26.2, 23.4, 21.3; IR (neat) 1754, 1660 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{22}O_2$ (M^+) 246.1619, found 246.1625.

4-Methoxy-3-[2-(1-cyclohexenyl)ethyl)]-2-(2-methyl-1-propenyl)-2-cyclobuten-1-one (43). In analogy to the procedure used for the synthesis of **48**, the title compound was prepared from **38** (140 mg, 0.787 mmol), 1-iodocyclohexene (393 mg, 1.89 mmol), *tert*-butyllithium (2.22 mL, 3.78) and CuBr·SMe_2 (194 mg, 0.944 mmol). Workup and chromatography (20:1 hexanes/EtOAc) furnished 138 mg (68%) **43** as a pale yellow oil: ^{1}H NMR δ 5.56 (s, 1H), 5.44−5.43 (m, 1H), 4.80 (s, 1H), 3.45 (s, 3H), 2.75−2.69 (m, 1H), 2.65−2.59 (m, 1H), 2.29−2.20 (m, 2H), 2.01 (s, 3H), 1.98−1.95 (m, 4H), 1.83 (s, 3H), 1.65−1.60 (m, 2H), 1.55−1.51 (m, 2H); ^{13}C NMR δ 189.2, 174.3, 148.6, 144.6, 136.1, 122.1, 112.2, 91.0, 56.7, 34.1, 28.1, 26.4, 26.1, 25.2, 22.8, 22.3, 21.4; IR (neat) 1753, 1661 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{24}O_2$ (M^+) 260.1776, found 260.1770.

4-Hydroxy-3-isopropoxy-2-methyl-2-cyclobutene-1-one (45). Lithium tri-*tert*-butoxyaluminohydride (2.12 g, 8.34 mmol) was slowly added to a THF (100 mL) solution of 4-methyl-3-isopropoxycyclobutene-1,2-dione (**44**) (1.0 g, 6.95 mmol) at 0 °C. After being stirred for 15 min, the colorless, cloudy reaction mixture was quenched with 10% HCl (20 mL). After 10 min, the aqueous phase was extracted with ether and the combined organic layer washed with brine, dried over $MgSO_4$, filtered, and concentrated. Chromatography (50% hexanes/EtOAc) gave **45** (0.810 g, 80%) as a colorless oil: ^{1}H NMR δ 5.46 (d, J = 5.9 Hz, 1H), 5.08 (dd, J = 5.9, 1.7 Hz, 1H), 4.82 (sept, J = 6.2 Hz, 1H), 1.53 (s, 3H), 1.35 (d, 6.2 Hz, 3H), 1.30 (d, J = 6.2 Hz, 3H); ^{13}C NMR δ 192.1, 182.0, 122.1, 81.3, 77.1, 22.8, 22.3, 6.0; IR (neat) 3359, 1754, 1609; HRMS (EI) calcd for $C_8H_{13}O_3$ (MH^+) 157.0864, found 157.0862.

3-Isopropoxy-4-methoxy-2-methyl-2-cyclobuten-1-one (46). To a slurry containing **45** (0.720 g, 4.62 mmol), K_2CO_3 (6.38 g, 46.2 mmol) and Ag_2O (2.14 g, 9.24 mmol) in acetonitrile (50 mL) was added CH_3I (2.88 mL, 46.2 mmol). After stirring for 12 h at room temperature, the contents were filtered through Celite (1/2"), and concentrated. Chromatography (70% hexanes/EtOAc) gave **46** (0.708 g, 90%) as a pale yellow oil: ^{1}H NMR δ 4.74−4.73 (m, 1H,), 4.63 (sept., J = 6.2 Hz, 1H), 3.34 (s, 3H), 1.56 (s, 3H), 1.30 (d, J = 6.2 Hz, 6H); ^{13}C NMR δ 188.8, 179.3, 123.2, 88.8, 76.7, 55.8, 22.6, 22.3, 6.2; IR (neat) 1623 cm^{-1}; HRMS (EI) calcd for $C_9H_{14}O_3$ (M^+) 170.0943, found 170.0944.

3-Ethenyl-4-methoxy-2-methyl-2-cyclobuten-1-one (47). Vinyllithium (5.10 mL, 4.37 mmol) was added to a THF (40 mL) solution of **46** (675 mg, 3.97 mmol) at −78 °C. After the green-yellow solution was stirred for 15 min, HCl (5M, 2 mL) was added, and the cold bath was removed. After 30 min the reaction mixture was neutralized with saturated $NaHCO_3$ (10 mL). The aqueous layer was extracted with and combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and concentrated. Chromatography (75% hexanes/EtOAc) gave **47** (0.440 g, 80%) as a pale yellow oil: ^{1}H NMR δ 6.76 (dd, J = 17.3, 10.6 Hz, 1H), 5.90 (d, J = 17.3 Hz, 1H), 5.76 (d, J = 10.6 Hz, 1H), 5.08 (s, 1H), 3.38 (s, 3H), 1.78 (s, 3H); ^{13}C NMR δ 193.4, 168.8, 147.8, 127.0, 126.4, 90.7, 55.5, 7.8; IR (neat), 1752, 1638, 1628 cm^{-1}.

3-(2-Methyl-1-butenyl)-2-methyl-4-methoxy-2-cyclobuten-1-one (48). To a THF (20 mL) solution of 2-bromopropene (0.658 mL, 7.40 mmol) at −78 °C was added *tert*-butyllithium (8.70 mL, 14.8 mmol). After 5 min, CuBr·SMe_2 (0.760 g, 3.70 mmol) was added in a single portion resulting in an immediate color change from colorless to orange. After 5 min, the reaction mixture was warmed to 0 °C, at which point it became homogeneous. A THF (5 mL) solution of **47** (0.425 g, 3.08 mmol) was added to the cuprate solution at −78 °C. The resulting bright red-orange reaction mixture was stirred for 30 min while it was allowed to warm to ambient temperature. The contents were quenched with saturated NH_4Cl (5 mL) and diluted with H_2O (10 mL). The aqueous layer was extracted with ether and the combined organic layer washed with aqueous NH_4Cl, dried over $MgSO_4$, filtered, and concentrated. Chromatography (80% hexanes/EtOAc) gave **48** (0.413 g, 75%) as a volatile pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.77−4.75 (m, 2H), 4.69 (s, 1H), 3.42 (s, 3H), 2.77−2.69 (m, 1H), 2.67−2.59 (m, 1H), 2.38−2.25 (m, 2H), 1.74 (s, 3H),1.69 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.3, 177.7, 148.9, 143.9, 110.7, 91.7, 56.9, 33.6, 25.8, 22.2, 7.6; IR (neat) 1762, 1637 cm^{-1}; HRMS (CI) calcd for $C_{11}H_{17}O_2$ (MH^+) 181.1228, found 181.1233

Acknowledgment. The authors thank the National Institutes of Health (GM-36312) for financial support of this work and SmithKline Beecham for a generous gift of squaric acid.

Supporting Information Available: X-ray crystallographic data for (±)-*exo*-2-methoxy-13-(2-methyl-1-propenyl)-tricyclo[7.3.1.0^{1,10}]tridec-1(13)-en-5-one (**28**). This material is available free of charge via the Internet at http://pubs.acs.org.

JO991765W