Synthesis of Angular Triquinanes from 1-Alkynylbicyclo[3.2.0]hept-2-en-7-ones. A Tandem Alkoxy-Cope Ring Expansion/Transannular Ring Closure Reaction

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Addition of ethenyllithium reagents to the carbonyl group of dialkyl squarate-derived 1-alkynylbicyclo-[3.2.0]hept-2-ene-7-ones **(15)**, followed by a TBAF workup, results in a low-temperature anion-accelerated alkoxy-Cope rearrangement which proceeds by way of a strained cyclic allene intermediates **(**e.g.,**17)**. This leads to the formation of angularly fused triquinanes **(**e.g., **20)** in which each of the rings is functionally differentiated. Bicyclo[6.3.0]undecadienones (e.g., **36**) are the major products when the reactions are quenched with aqueous bicarbonate rather than TBAF. Under analogous conditions 2-alkylidene-1-alkynylbicyclo[3.2.0]heptan-7-ones also give bicyclo-[6.3.0]undecadienones by a mechanism that was established to involve a 1,5-hydrgen shift in a strained allene intermediate. The synthetic scope and mechanism of these and related transformations are discussed.

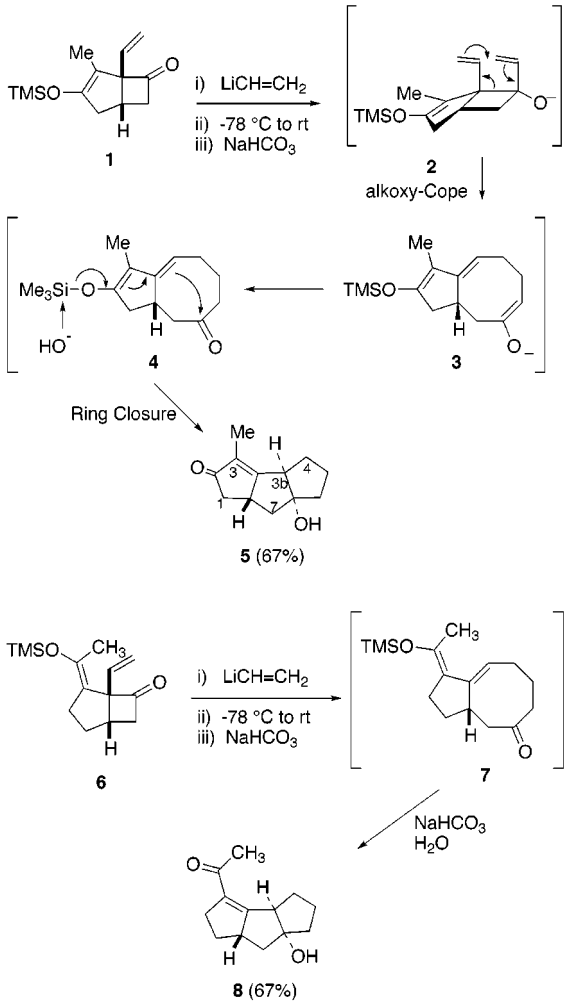
Introduction

Work previously reported from this laboratory detailed new developments in cyclobutenone-based methods for the regiospecific synthesis of complex polycyclic compounds.[1] For example, a powerful tandem alkoxy-Cope rearrangement/transannular ring closure sequence was described in which energy release of a strained ring is the key driving force of the reaction.[2] As an illustration, dialkylsquarate-derived 1-alkenylbicyclo[3.2.0]hept-2-en-7-ones can be efficiently converted to linear triquinanes upon treatment with alkenyllithium reagents, e.g., **1** gives **5** via the sequence involving intermediates **2**, **3**, and **4** (Scheme 1). In an analogous manner, the alkoxy-Cope ring expansion of bicyclo[3.2.0]heptenone **6** gives **7** which collapses to the linear triquinane **8** upon treatment with aqueous sodium bicarbonate.

In a related study bicyclo[3.2.0]heptenones bearing an exo-disposed methyl group at position-6, e.g., **9** and **12**, are attacked by vinyllithium from the concave face of the molecule (Scheme 2).[3] The resulting adducts **10** and **13** then proceed to the respective products **11** and **14** via an alkoxy-Cope ring expansion involving the incoming vinyl group and the ring-based cyclopentenyl or alkylidenyl double bonds.

We now report an extension of the above work in which 1-alkyny-3-trimethylsiloxybicyclo[3.2.0]heptenones and related 2-alkylidene analogues were treated with alkenyllithium reagents at −78 °C. In both series the alkynyl and alkenyl groups participate in an alkoxy-Cope ring expansion to give strained allene intermediates which

Scheme 1



(1) For a review concerning the synthetic applications of cyclobutenones, see: Moore, H. W.; Yerxa, B. R. *Advances in Strain in Organic Chemistry*; JAI Press: Greenwich, CT, 1995; Vol. 4.

(2) For examples, see the following and references sited therein: (a) MacDougall, J. M.; Santora, V. S.; Verma, S. K.; Turnbull, P. S., Hernandez, C. R.; Moore, H. W. *J. Org. Chem.* **1998**, *63*, 6905−6913 (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.

(3) Verma, S. K.; Nguyen, Q. H.; MacDougall, J. M.; Fleischer, E. B.; Moore, H. W. *J. Org. Chem.* **2000**, *65*, 3379.

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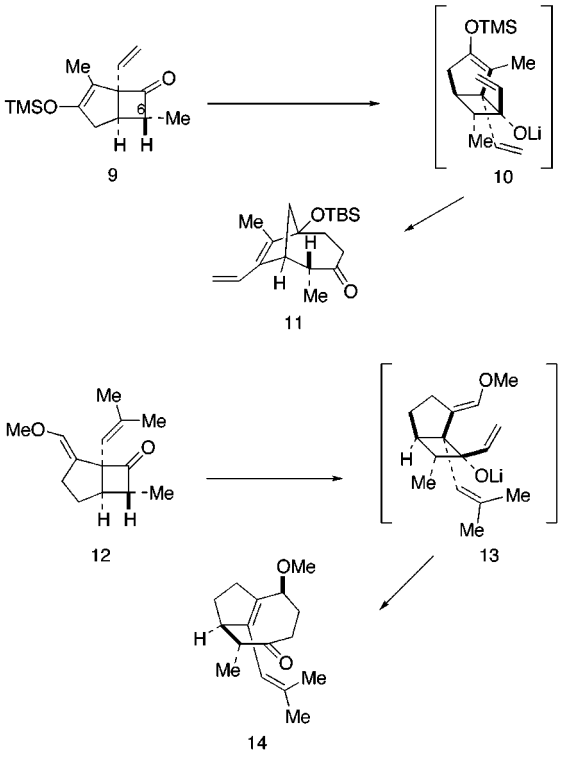
Scheme 2



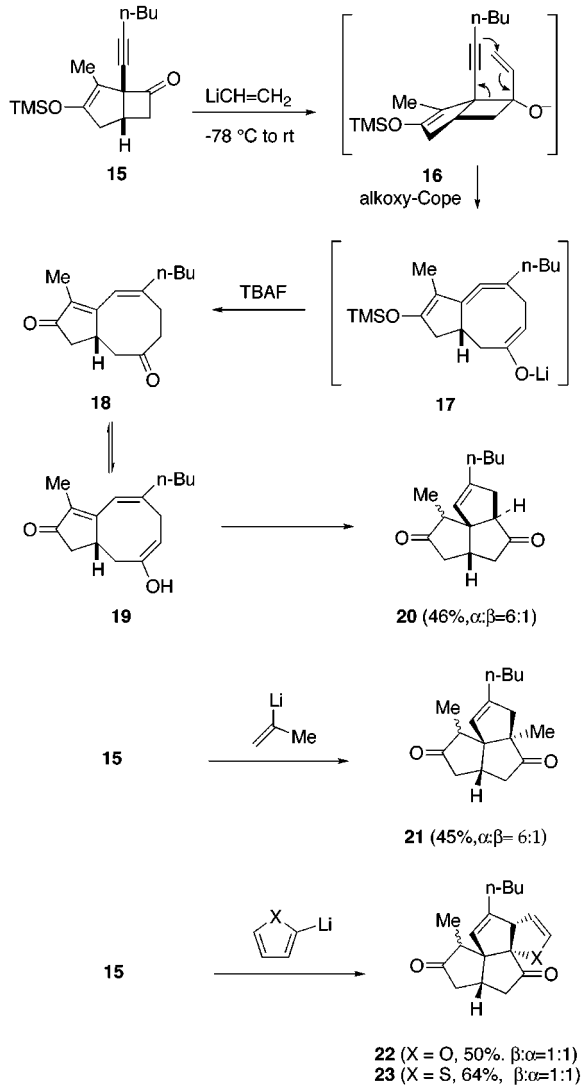
lead to products after desilylation of the trimethylsiloxy enol ether moiety upon workup with tetra-*n*-butylammonium fluoride (TBAF) or aqueous sodium bicarbonate.[4–7]

Results and Discussion

Illustrative examples of the general transformations of 1-alkenylbicyclo[3.2.0]hept-2-en-7-ones are outlined in Scheme 3. Specifically, treatment of 1-hexynyl-2-methyl-3-trimethylsiloxybicyclo[3.2.0]hept-2-en-7-one **15** (THF, −78 °C) with vinyllithium followed by a tetra-*n*-butylammonium fluoride (TBAF) quench (ambient temperature) gave the angular triquinane **20** in 46% yield as a 6:1 mixture of, respectively, α- and *β*-methyl diastereomers. This transformation is envisaged to occur via the initially formed adduct **16** which undergoes ring expansion to the strained allene **17.** Subsequent reaction of this with TBAF leads to bicyclo[6.3.0]undecadienone **18** which undergoes an intramolecular Michael addition via the enol (or enolate) **19** to provide the angular triquinane **20**.

In an analogous fashion, **15** was converted to the angular triquinane **21** (45%, α: *β* = 6:1) when 2-lithiopropene was employed. Additional examples include the

Scheme 3



conversions of **15** to, respectively, **22** (50%, 10:1 α: *β*) and **23** (64%, 1:1 α: *β*) using, respectively, 2-lithiofuran and 2-lithiothiophene. These are particularly interesting cases since they illustrate the structural complexity of the polyquinanes that are available from this reaction sequence. *In addition, to our knowledge, they represent the first examples of an alkoxy-Cope reaction in which aryl and alkynyl bonds are partners in the sigmatropic event.*[8]

A comparison study that speaks to some limitations of the above reaction sequence is outlined in Scheme 4. Specifically, when **15** was treated with (Z)-1-lithiopropene under reaction conditions analogous to the above, the expected triquinane **26** was obtained in 53% as a 10:1 (α: *β*) mixture of diastereomers. In contrast, when the reaction was carried out using (*E*)-1-lithiopropene only the bicyclo[6.3.0]undecadiendione **28** was obtained (68%). The fact that enol **27**, unlike its diastereomer **25,** does not lead to the corresponding triquinane is likely due to steric effects in the intramolecular Michael addition reaction. That is, such a transformation for **27** would result in a steric interaction between the methyl groups

(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.

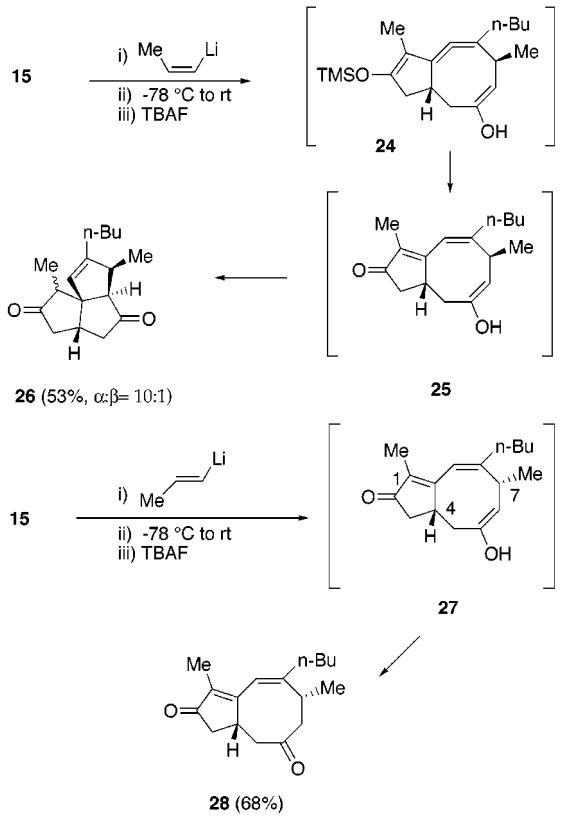
(5) For recent examples of other tandem reactions involving oxy-Cope reactions, see (a) Jacobi, P. A.; Armacost, L. M.; Brielmann, H. L.; Cann, R. O.; Kravitz, J. I.; Martinelli, M. J. *J. Org. Chem.* **1994**, *59*, 5292−5304. (b) Balakumar, A.; Janardhanam, S.; Rajagopalan, K. *J. Org. Chem.* **1993**, *58*, 5482−5486. (c) Paquette, L. A.; Shi, Y.-J. *J. Org. Chem.* **1989**, *54*, 5205−5207. (d) Jisheng, L.; Gallardo, T.; White, J. B. *J. Org. Chem.* **1990**, *55*, 5426−5428.

(6) For a review on the participation of acetylenic groups in oxy-Cope reactions, see: Viola, A.; Collins, J. J.; Fillip, N. *Tetrahedron* **1981**, *37*, 3765.

(7) For an example of this rearrangement on a similar bicyclo[3.2.0] systems, see: Gadwood, R. C.; Lett, R. M.; Wissinger, J. E. *J. Am. Chem. Soc.* **1986**, *108*, 6343.

(8) For examples of the rare occurrence of aryl groups in the alkoxy-Cope rearrangements, see: Santora, V. S.; Moore, H. W. *J. Org. Chem.* **1996**, *61*, 7976.

Scheme 4



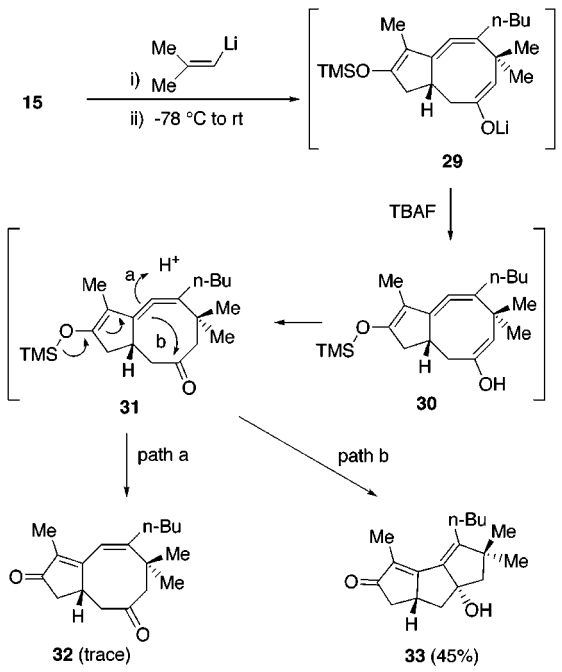
at positions-1 and -7 while the analogous interaction in **25** would be between a methyl (C-7) and a proton (C-1). Thus, the latter leads to triquinane **26** while the former terminates at undecadiendione **28**.

When 1-lithio-2-methylpropene was employed, the reaction took still another course. Surprisingly, the linear triquinane **33** (45%) was obtained along with trace amounts of the bicyclo[6.3.0]undecadiendione **32** (Scheme 5). Here, the proposed allene intermediate **31**[9] is envisaged to partition between desilylation/protonation (path a) to give **32** and desilylation/transannular aldol condensation to provide **33** (path b).

The *gem*-dimethyl group formed during the alkoxy-Cope rearrangement plays a critical role in controlling the reaction pathway. For example, the α-oriented methyl group in the enol of **32**, like that in **27** (Scheme 4), prevents angular triquinane formation via an intramolecular Michael addition. In addition, the bulky geminal substitution pattern apparently retards the rate of desilylation/protonation (path a), thus opening the intramolecular aldol condensation pathway (path b) leading to the linear triquinane **33**.

An additional mechanistic consequence stems from the assumed precursor relationship of **30/31** to **33.** That is, one can reasonably conclude that the TBAF quench of the lithium enolate site in **29** (Hofmann elimination) precedes desilylation/protonation of the silyl enol ether

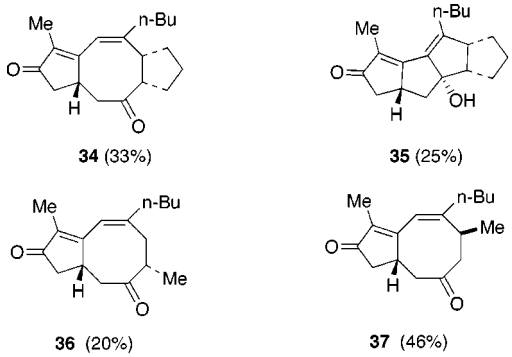
Scheme 5



linkage. This then results in **30/31,** and thus the required electrophilic cyclooctenyl carbonyl is generated prior to the desilylation/transannular aldol condensation step. If TBAF-induced desilylation/protonation of the silyl enol ether linkage in **29** preceded the enolate quench, a dienone moiety would result. Intermediates having such a structural unit, (e.g., **32**) could not function as precursors to linear triquinane under the basic condition of the reaction.

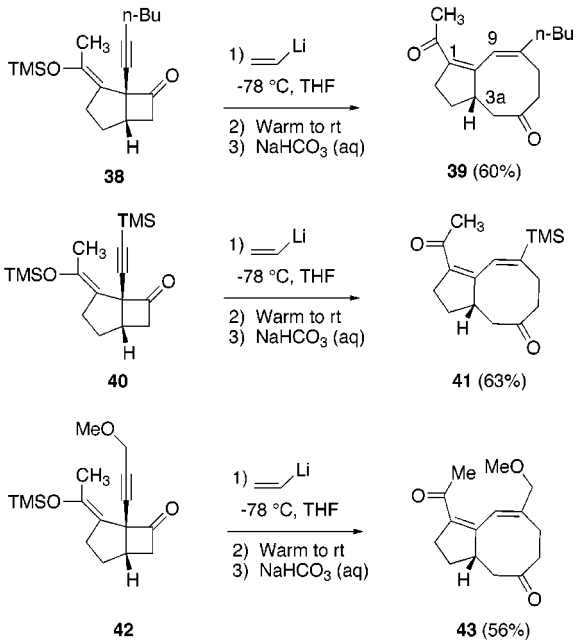
Upon the basis of the above mechanistic paradigm, the yield of **32** should increase at the expense of **33** if the reaction is worked up under aqueous (protic) conditions. That is, path a should more effectively compete with path b since the rate of desilylation/protonation should be enhanced. This was observed to be the case. Specifically, when the reaction was quenched with excess aqueous sodium bicarbonate, the yield of **32** increased from a trace to 27% and that of **33** decreased from 45% to 35%.

Under analogous conditions (aqueous bicarbonate workup), **15** was observed to react with 1-lithiocyclopentene to give **34** and the linear tetraquinane **35** in respective yields of 33% and 25%. It is again of interest to note that angular triquinane products were not observed, an expected result, since the α-disposed cyclopentyl ring in **34** (or its enol) is assumed to prevent intramolecular Michael addition.



(9) For general reviews on cumulene chemistry: (a) Johnson, R. P. *Molecular Structure and Energetics*; Liebman, J. F., Greenberg, A.; Eds.; VCH Publishers: Deerfield Beach, FL, 1986; Vol. 3, Chapter 3, p 85. (b) Pasto, D. J. *Tetrahedron* **1984**, *40*, 2805. (c) Schuster, H. F.; Coppola, G. M. *Allenes in Organic Synthesis*; Wiley: New York, 1984. (d) Landor, S. R., Ed. *The Chemistry of Allenes*; Academic Press: New York, 1982; Vols. 1−3. (d) Johnson, R. P. *Chem. Rev.* **1989**, *89*, 1111. (e) Patai, S. *The Chemistry of Ketenes, Allenes, and Related Compounds*;J. Wiley: New York, 1980, and references therein.

Scheme 6

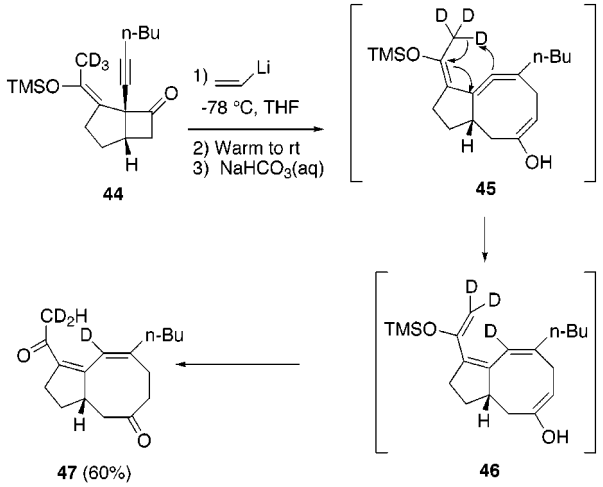


The synthetic scope of bicyclo[6.3.0]undecadiendione formation (aqueous bicarbonate workup) was further probed for the reactions of **15** with vinyllithium, 2-lithiopropene, and (*Z*)-1-lithiopropene. These examples gave, respectively, the undecadiendiones **18** (18%), **36** (20%), and **37** (46%) along with their corresponding angular triquinanes (approximately $\alpha:\beta$ = 6:1) **20** (33%), **21** (33%), and **26** (14%). As noted above (Schemes 3 and 4), when the reactions were quenched with TBAF instead of aqueous bicarbonate, the only products isolated were the triquinanes **20** (46%), **21** (45%), and **23** (53%).

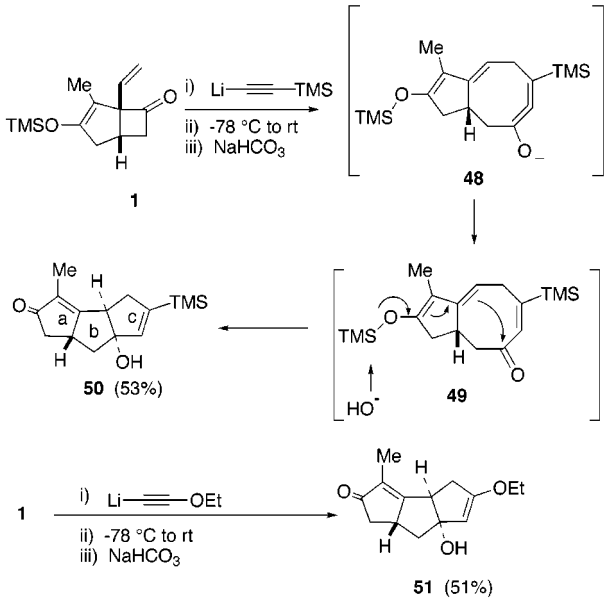
In a related study 2-alkylidene-1-alkynylbicyclo[3.2.0]-hetptan-7-ones **38**, **40**, and **42** were treated with vinyllithium followed by an aqueous sodium bicarbonate quench (Scheme 6). Here, the only products isolated were the respective bicyclo[6.3.0]undecadienones **39** (60%), **41** (63%), and **43** (56%); no linear triquinanes stemming from a transannular aldol condensation were detected. These results would be anticipated from consideration of the above mechanistic discussion, i.e., the protic workup conditions would favor undecadienone formation at the expense of linear triquinane formation since the rate of desilylation/protonation at the strained allene intermediate stage would be enhanced relative to desilylation/transannular aldol condensation. This seemingly reasonable interpretation is, however, incorrect as shown by the following study.

The formation of undecadienones and the absence of linear triquinane products are indeed due to the fact that the strained allene intermediate suffers rapid protonation. However, this arises from an intramolecular proton transfer rather than from a proton source in the aqueous workup. That is, the reaction involves an intramolecular proton transfer from the proximal methyl group on the alkylidene moiety to the strained allenic double bond leading ultimately to only undecadienone products (Scheme 7). This is based upon data obtained from a deuterium labeling experiment that allows formulation of the following specific mechanism. The strained allene intermediate **45**, resulting from the alkoxy-Cope ring expansion, undergoes a 1,5-deuterium shift to give **46**.[9]

Scheme 7



Scheme 8



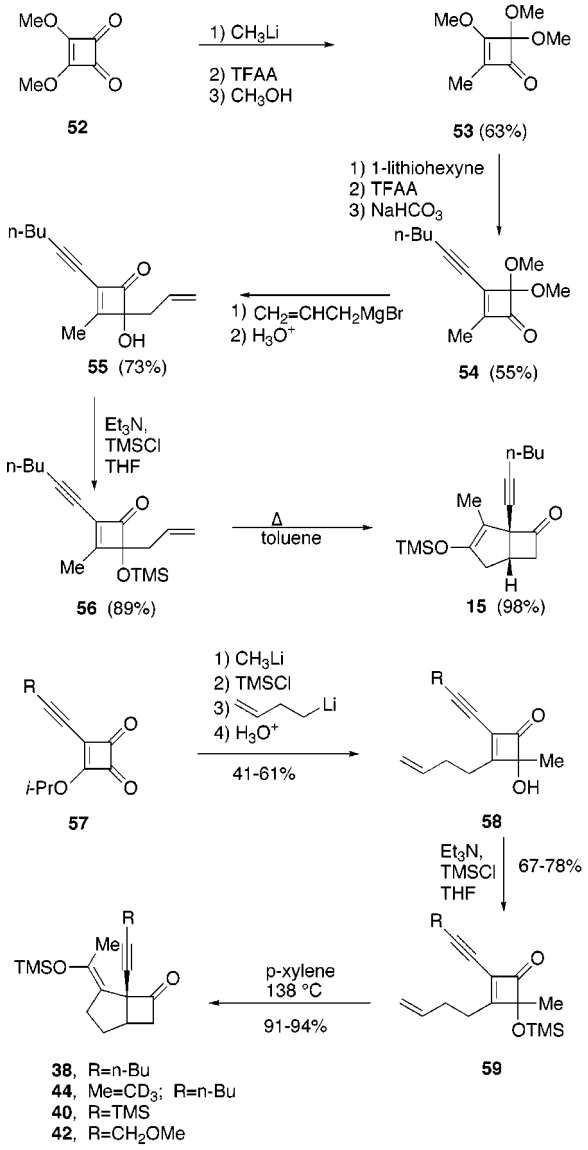
Hydrolytic desilylation of the newly formed trimethylsilyl enol ether linkage during the workup procedure then leads to the observed product **47**. The intramolecular proton-transfer mechanism was established as follows. The ^{1}H NMR spectrum of **47**, the product obtained when **44** was subjected to the above reaction conditions using a protic aqueous bicarbonate quench, revealed migration of a deuterium atom from the CD_3 group to the vinyl position in the cyclooctenone ring. This was evidenced by the fact that the vinyl proton absorption appearing at δ 6.37 in **39** is missing in **47**. Similarly, the methyl group absorption in **39** appears as a three-proton singlet at δ 2.25 and reduces to a one-proton singlet in **47**.

Finally, a limited study was accomplished in which 1-ethenyl-2-methyl-3-trimethylsiloxybicyclo[3.2.0]hept-2-en-7-one (**1**) was treated with selected alkynyllithium reagents (Scheme 8). The examples studied resulted in the formation of linear triquinanes bearing a synthetically versatile site of functionalized unsaturation in ring C. As an example, **1** and 1-lithio-2-trimethylsilylacetylene gave the linear triquinane **50** (53%) bearing a vinyl silane group in ring C. Analogously, **1** and 1-lithio-2-ethoxyacetylene gave the enol ether-substituted triquinane **51** in 51% isolated yield.

These products are envisaged to arise in analogy to the tandem reaction sequence noted earlier (Scheme 1). That is, alkoxy-Cope ring expansion of **1** would give the allenyl enolate **48**, which upon protonation results in **49**. Hydrolytic desilylation and concomitant transannular ring closure then provides the triquinane **50**.

The starting bicyclo[3.2.0]heptanone **15, 38, 40, 42**, and **44** utilized in the above studies were prepared as outlined in Schemes 9. Compound **15** arises from dimethylsquarate **52**[10] which gave the ketal **53**[11] (63%) upon treatment with methyllithium followed by trifluoroacetic anhydride (TFAA) and an anhydrous methanol quench. Subsequent addition of 1-lithiohexyne[12] followed by trifluoroacetylation of the β-hydroxy enol ether and then workup under mildly basic conditions gave the corresponding cyclobutenedione monoketal **54** in (55%). Treatment of this with allylmagnesium bromide followed by hydrolysis of the dimethyl ketal linkage provided the 4-allyl-4-hydroxycyclobutenone **55** (73%).[13] Trimethylsilylation of the 4-hydroxy group (TMSCl) gave **56**, which upon thermolysis (toluene, 110 °C) resulted in a torquoselective[14] electrocyclic ring opening to a vinyl ketene intermediate. This then undergoes an intramolecular [2 + 2] cycloaddition to the proximal allyl double bond to give bicyclo[3.2.0]heptenone **15** in nearly quantitative yield.[15] The remaining bicyclo[3.2.0]heptenones **38**, **40**, **42**, and **44** were also prepared via the above intramolecular [2 + 2] ketene/alkene cycloaddition mode. Specifically, 4-alkynyl-3-isopropoxycyclobutenedione **57** was converted to cyclobutenones **59** by a sequence of reaction involving CH_3Li (or CD_3Li) addition followed by protection (TMS) of the resulting hydroxyl group. 1,2-Addition of 4-lithio-1-butene to the carbonyl group followed by hydrolysis of the resulting β-hydroxyenol ether during the workup gave the corresponding cyclobutenones in yields in the range of 41−61%. Reprotection of the hydroxyl group gave **59** (67−78%) which were converted to the desired bicyclo[3.2.0]heptenones (91−94%) upon thermolysis at 138 °C (refluxing *p*-xylene).

Scheme 9



Structure Assignments

The structure assignments of the new compounds reported here are based upon their spectral properties as well as X-ray crystallographic data. For example, the structure of **23** (α-diastereomer) was established by single-crystal X-ray crystallography. This provides the foundation for the assigned structures of related angular polyquinanes **20**−**22** and **26**. The IR spectra of these compounds all show carbonyl stretching peaks at approximately 1735 cm^{-1}, and their ^{13}C NMR spectra reveal the presence of two carbonyl groups (approximately δ 200). In addition, comparative NOE studies support the assignments of the stereochemistry (see Experimental Section).

An X-ray crystal structure was also obtained for the bicyclo[6.3.0]undecadienone **37**; knowing this structure allowed the unambiguous assignment of the structure of its diastereomer **28**. These data, along with characteristic spectral properties provide the foundation for structure assignments of the related undecadienones **32**, **34**, **18**, and **36**. Absorptions in the range δ 207−210 in their ^{13}C NMR spectra revealed the presence of two carbonyl groups. As a representative example, the ^{13}C chemical shifts of the carbonyl carbons in **18** appear at δ 209 and 207. The DEPT 135 for this compound indicated two CH_3, seven CH_2, two CH, and the remaining carbon atoms being quaternary. The ^1H NMR spectrum shows the presence of 22 protons with the vinyl proton at C-9 appearing as a singlet at δ 6.23. The methyl group absorption appears as a doublet at δ 1.72 (J = 1.5 Hz), as a result of homoallylic coupling with the bridgehead proton at C-3a.

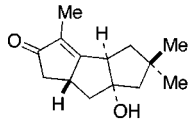
Characteristic structural data for **39** include ^1H NMR chemical shifts for the vinyl proton at δ 6.37 and the methyl ketone at δ 2.25. In addition to carbonyl absorptions in its IR spectrum centered at 1702 cm^{-1}, the two carbonyl carbon atoms appear at δ 210 and 198 in its ^{13}C NMR spectrum. Similar data were observed for **41** and **43**.

(10) For the preparation of dialkyl squarates from squaric acid, see: Lui, H.; Tamooka, C. S.; Moore, H. W. *Synth. Commun.* **1997**, *27*, 2177.

(11) Moore, H. W.; Liu, H.; Gayo, L. M.; Sullivan, R. W.; Choi, A. Y. H. *J. Org. Chem.* **1994**, *59*, 3284.

(12) Lithium reagents were prepared using standard methods. For leading references, see: (a) Wakefield, B. J. *Organolithium Methods*; Academic Press: New York, 1988. (b) Brandsma, L.; Verkruijsse, H. *Preparative Polar Organometallic Chemistry 1*; Springer-Verlag: New York, 1987.

Assignments of the structures of the linear polyquinanes **33**, **35**, **50**, and **51** are based upon their spectral properties and comparison of these to related data reported previously for similar compounds. Specifically, the polyquinanes **5**, **60**, and **61** have previously been reported, and their structures are based either directly (**5**) or indirectly upon X-ray data.[2b] Representative spectral data for **60** include the chemical shift of the methyl group at δ 1.68 (d, $J = 2$ Hz, 3H), the allylic bridgehead protons at δ 3.18 (t, $J = 9.0$ Hz, 1H) and 2.94 (bs, 1H), the carbonyl carbon at δ 210, and IR absorptions at 3427 cm^{-1} (OH) and 1703 cm^{-1} (C═O). Analogous data for **33** show the vinyl methyl group at δ 1.86 (s, 3H), a single allylic bridgehead absorption at δ 3.02 (bs, 1H), the carbonyl carbon at δ 211, and IR absorptions at 3430 cm^1 (OH) and 1667 cm^{-1} (C═O). Similarly, the tetraquinane **61** shows absorptions for its vinyl methyl group at δ 1.65 (s, 3H), the allylic bridgehead protons at δ 3.05 (dd, $J =$ 9.0, 2.5 Hz, 1H) and δ 2.97 (m, 1H), the carbonyl carbon at δ 210, and IR absorptions at 3425 cm^1 (OH) and 1695 cm^{-1} (C═O). Analogous data for **35** are δ 1.84, (d, $J =$ 2.3 Hz, 3H), δ 3.25 (dd, $J = 7.9$ Hz, 1H), δ, 3.07 (m, 1H), δ 211, 3435, and 1672 cm^{-1}.



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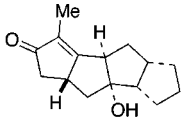

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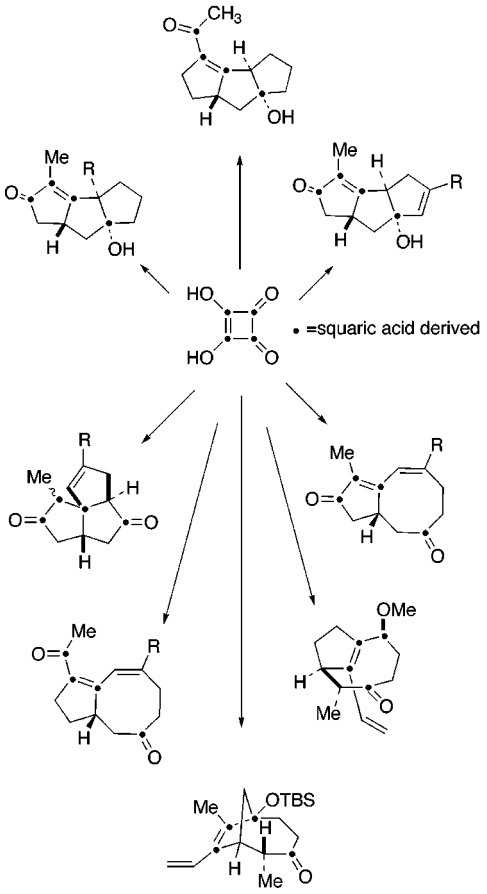
Conclusion

Important points arising from this study include the following: (1) a general synthesis of angularly fused triquinanes in which each of the rings is functionally differentiated is now available from squarate-derived 1-alkynylbicyclo[3.2.0]hept-2-en-7-ones upon treatment with alkenyllithium reagents followed by a TBAF quench;[16] (2) in contrast, linear triquinanes result when 1-ethenyllbicyclo[3.2.0]hept-2-en-7-ones are treated with alkynyllithium reagents: (3) a modification of the angular triquinane synthesis allows the preparation of bicyclo-[6.3.0]undecadiendiones upon treatment of 1-alkynylbicyclo[3.2.0]hept-2-en-7-ones with alkenyllithium reagents followed by aqueous bicarbonate rather than TBAF;[17] (4) a related study employing 2-alkylidene-1-alkynylbicyclo-[3.2.0]heptan-7-ones results in the formation of complementary bicyclo[6.3.0]undecadiendiones; (5) the mechanism of these transformations involves alkoxy-Cope ring expansions to strained allene intermediates which proceed to the observed products as a function of the substitution patterns of the starting materials and the workup conditions employed.

Scheme 10



Finally, the transformations outlined here add to a growing list of polycyclic ring systems available from squaric acid. These include the examples generally outlined in Scheme 10 where the highlighted carbon atoms stem from squaric acid and the remaining structure units come primarily from readily available organometallic reagents.

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 °C 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 (chromatography) unless otherwise specified. Tetrahydrofuran and diethyl ether (ether) were purged with nitrogen and then passed through two 4 × 36 in. columns of anhyd neutral A-2 alumina (8 × 14 mesh. Toluene and *p*-xylene were distilled from CaH_2 immediately before use. Triethylamine was distilled from CaH_2 and stored over KOH pellets. *n*-Butyllithium and *tert*-butyllithium were used as solutions in hydrocarbon solvents. Methyllithium and vinyllithium were used as solutions in ether. Methyl iodide was filtered through a pipet of basic alumina under N_2 before use. All other solvents and reagents were used as received. ^1H NMR and ^{13}C NMR spectra were recorded at 500 and 125 MHz, respectively, in $CDCl_3$ unless specified otherwise. Melting points are uncorrected.

(13) This is an excellent procedure for the regiospecific preparation of substituted cyclobutenones. For more details, see: Gayo, L.; Winters, M. P.; Moore, H. W. *J. Org. Chem*. **1992**, *57*, 6896.

(14) For references to the torquoselective ring opening of cyclobutenes and cyclobutenones, see: (a) Kirmse, W.; Rondan, N. G.; Houk, K. N. *J. Am. Chem. Soc*. **1984**, *108*, 7989. (b) Niwayama, S.; Kallel, E. A.; Houk, K. N. *J. Org. Chem*. **1996**, *61*, 2517.

(15) (a) Moore, H. W.; Xu, S. L.; *J. Org. Chem*. **1989**, *54*, 6018. (b) Moore, H. W.; Xia, H.; Xu, S. L. *J. Org. Chem*. **1991**, *56*, 6094. (c) For reviews on intramolecular ketene cycloadditions, see: Snider, B. *Chemtracts* **1991**, 403. Snider, B. *Chem. Rev*. **1988**, *88*, 793.

(16) For a reviews of the synthesis of polyquinanes, see: (a) Mehta, G.; Srikrishna, A. *Chem. Rev*. **1997**, *97*, 671. (b) Paquette, L. A.; Doherty. A. M. *Polyquinane Chemistry In Reactivity and Structure Concepts in Organic Chemistry*; Springer-Verlag: New York, 1987; Vol. 26. (c) Trost, B. M.; *Chem. Soc. Rev*. **1982**, *11*, 141−170. (d) Paquette, L. A. *Top. Curr. Chem*. **1979**, *79*, 43−152. (e) 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.

(17) For selected other methods of constructing the bicyclo[6.3.0]-undecane ring system, see: (a) Wender, P. A.; Nuss, J. M.; Smith, D. B.; SuarezSobrino, A. *J. Org. Chem*. **1997**, *62*, 4908. (b) Snapper, M. L.; Tallarico, J. A.; Randall, M. L. *J. Am. Chem. Soc*. **1997**, *119*, 1478.

General Method for the Tandem alkoxy-Cope/Intramolecular Aldol Condensation Sequence. (±)-1α,3,-3a*β*,4,5aα,6,8,8a*β*-Heptahydro-7-*n*-butyl-1-methyl-1*H*-cyclopenta[*c*]pentalen-7-ene-2,5-dione (20). To a −78 °C THF (5 mL) solution of **15** (100 mg, 0.345 mmol) was added vinyllithium (0.50 mL, 0.379 mmol), and after 10 min the cooling bath was removed. After 30 min, TBAF (0.41 mL, 0.41 mmol) was added, and after an additional 10 min, the dark mixture was diluted with $NaHCO_3$ and extracted with ether. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. Chromatography (3:1 hexanes/EtOAc) gave **20** (39 mg, 46%) as a colorless oil that consisted of a 6:1 α:*β* mixture of diastereomers. Data for **20**, major diastereomer (α-Me): ^{1}H NMR *δ* 5.17 (s, 1H), 2.83−2.76 (m, 2H), 2.56 (ddd, *J* = 8.6, 2.0, 1.0 Hz, 1H), 2.51−2.40 (m, 3H), 2.33−2.29 (m, 2H), 2.07 (t, *J* = 7.1 Hz, 2H), 1.77 (q, *J* = 7.2 Hz, 1H), 1.45−1.38 (m, 2H), 1.25 (sextet, *J* = 7.6 Hz, 2H), 0.97 (d, *J* = 7.0 Hz, 3H), 0.88 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR *δ* 221.8, 217.5, 147.9, 126.8, 66.7, 52.9, 50.1, 43.7, 43.6, 40.1, 37.4, 30.5, 29.8, 22.4, 13.9, 8.7; IR (film, cm^{-1}) 1735, 1719; HRMS (EI) calcd for $C_{16}H_{23}O_2$ (MH^+) 247.1698, obsd 247.1692.

(±)-1α,3,3a*β*,4,6,8,8a*β*-Hexahydro-7-*n*-butyl-1,5a-dimethyl-1*H*-cyclopenta[*c*]pentalen-7-ene-2,5-dione (21). In the manner analogous to the synthesis of **20**, compound **15** (100 mg, 0.345 mmol) was treated with 2-lithiopropene, generated from 2-bromopropene (0.037 mL, 0.414 mmol) and *tert*-butyllithium (0.487 mL, 0.828 mmol) in THF at −78 °C. Workup and chromatography (2:1 hexanes/EtOAc) gave **21** (40 mg, 45%) as a colorless oil, which consisted of a 6:1 α:*β* mixture of diastereomers. Data for **21**, major diastereomer (α-CH_3): ^{1}H NMR *δ* 5.05 (s, 1H), 2.78 (dd, *J* = 10.3, 1.6 Hz, 1H), 2.75−2.70 (m, 1H), 2.59−2.50 (m, 3H), 2.35 (d, *J* = 10.0 Hz, 1H), 2.23 (ddd, *J* = 16.5, 2.1, 1.0 Hz, 1H), 2.02 (t, *J* = 7.8 Hz, 2H), 1.91 (q, *J* = 8.0 Hz, 1H), 1.40−1.34 (m, 2H), 1.28−1.22 (m, 2H), 1.09 (d, *J* = 7.0 Hz, 3H), 1.01 (s, 3H), 0.86 (t, *J* = 7.4 Hz, 3H); ^{13}C NMR *δ* 224.6, 217.0, 147.5, 128.6, 67.4, 56.5, 53.9, 48.2, 43.2, 42.2, 37.2, 30.6, 29.7, 22.3, 18.6, 13.8, 8.3; IR (film, cm^{-1}) 1729; HRMS (EI) calcd for $C_{17}H_{24}O_2$ (M^+) 260.1776, obsd 260.1773.

(±)-1α,3,3a*β*,4,5a*β*,6*β*,8,8a*β*-Hexahydro-7-*n*-butyl-[5a,6-d]furanyl-1*β*-methyl-1*H*-cyclopenta[*c*]pentalen-7-ene-2,5-dione (22*β*), and (±)-1*β*,3,3a*β*,4,5a*β*,6*β*,8,8a*β*-Hexahydro-7-*n*-butyl-[5a,6-d]furanyl-1α-methyl-1*H*-cyclopenta-[*c*]pentalen-7-ene-2,5-dione (22α). In the manner analogous to the synthesis of **20**, compound **15** (100 mg, 0.345 mmol) was treated with 5 mL **of** 2-lithiofuran[12] (0.50 mmol, 0.10 M in THF). Workup and chromatography (2:1 hexanes/EtOAc) gave **22**α,*β* (50 mg, 50%) as a 1:1 mixture of diastereomers. Data for **22***β*: ^{1}H NMR *δ* 6.33 (t, *J* = 2.5 Hz, 1H), 5.24 (d, *J* = 1.5 Hz, 1H), 5.07 (d, *J* = 2.5 Hz, 1H), 3.86 (d, *J* = 1.7 Hz, 1H), 2.75−2.70 (m, 1H), 2.66−2.56 (m, 3H), 2.34 (dd, *J* = 17.3, 4.4 Hz, 1H), 2.13−2.04 (m, 3H), 1.49−1.43 (m, 2H), 1.30 (quintet, *J* = 7.3 Hz, 2H), 1.03 (d, *J* = 7.5 Hz, 3H), 0.90 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR *δ* 218.1, 213.9, 147.2, 145.7, 125.1, 102.1, 96.7, 66.6, 61.2, 46.2, 42.4, 42.2, 38.3, 29.5, 29.3, 22.4, 13.9, 11.6; IR (film, cm^{-1}) 1744; HRMS (CI) calcd for $C_{18}H_{22}O_3$ (M^+) 286.1569, obsd 286.1570.

Irradiation of the methyl group doublet at 1.03 ppm shows an enhancement of the vinyl proton signal at 5.24 ppm (ca. 3%). Irradiation of the same methyl group in the **22**α isomer shows no enhancement.

Data for **22**α: mp = 62−63 °C; ^{1}H NMR *δ* 6.26 (t, *J* = 2.5 Hz, 1H), 5.14 (d, *J* = 1.5 Hz, 1H), 5.00 (d, *J* = 2.5 Hz, 1H), 3.90 (d, *J* = 2.0 Hz, 1H), 2.75−2.63 (m, 3H), 2.50 (q, *J* = 7.0 Hz, 1H), 2.32 (d, *J* = 16.4 Hz, 1H), 2.18−2.09 (m, 2H), 1.78 (q, *J* = 11.7 Hz, 1H), 1.53−1.46 (m, 2H), 1.33 (quintet, *J* = 7.3 Hz, 2H), 1.03 (d, *J* = 7.0 Hz, 3H), 0.91 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR *δ* 214.8, 214.1, 147.7, 146.9, 127.6, 100.6, 95.4, 68.0, 64.1, 53.6, 41.7, 40.8, 38.4, 29.6, 29.5, 22.4, 13.9, 7.8; IR (film, cm^{-1}) 1750, 1608; HRMS (CI) calcd for $C_{18}H_{22}O_3$ (M^+) 286.1569, obsd 286.1570

(±)-1α,3,3a*β*,4,5a*β*,6*β*,8,8a*β*-Hexahydro-7-*n*-butyl-1*β*-methyl-[5a,6-*d*]thiophene-1*H*-cyclopenta[*c*]pentalen-7-ene-2,5-dione (23*β*), and (±)-1*β*,3,3a*β*,4,5a*β*,6*β*,8,8a*β*-Hexahydro-7-*n*-butyl-1α-methyl-[5a,6-d]thiophene-1*H*-cyclopenta-[*c*]pentalen-7-ene-2,5-dione (23α). In the manner analogous to the synthesis of **20**, compound **15** (100 mg, 0.345 mmol) was treated with 5 mL of 2-lithiothiophene[12] (0.14 M in THF). Workup and chromatography (2:1 hexanes/EtOAc) gave **23**α,*β* (67 mg, 64%) as 1:1 mixture of diastereomers. Data for **23***β*: ^{1}H NMR *δ* 5.93 (dd, *J* = 5.8, 2.7 Hz, 1H), 5.49 (dd, *J* = 5.8, 2.5 Hz, 1H), 5.26−5.25 (m, 1H), 4.20−4.19 (m, 1H), 2.75−2.69 (m, 1H), 2.67−2.56 (m, 3H), 2.41 (dd, *J* = 18.2, 4.4 Hz, 1H), 2.26−2.07 (m, 3H), 1.96 (dddd, *J* = 18.8, 10.2, 1.4 Hz, 1H), 1.49−1.43 (m, 1H), 1.34−1.29 (m, 1H), 1.25−1.22 (m, 1H), 1.10 (d, *J* = 7.6 Hz, 3H), 0.89 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR *δ* 218.5, 216.8, 147.0, 125.6, 123.8, 121.5, 75.3, 70.0, 68.4, 50.9, 43.4, 42.9, 38.3, 29.8, 29.6, 22.4, 13.9, 12.4; IR (film, cm^{-1}) 1742, 1738; HRMS (CI) calcd for $C_{18}H_{22}O_3$ (M^+) 302.1340, obsd 302.1335. Irradiation of the doublet methyl group absorption at 1.10 ppm shows an enhancement of the vinyl proton signal at 5.25 ppm (ca. 4%). Irradiation of the same methyl group absorption for **23**α shows no enhancement.

Data for **23**α: mp = 141−142 °C, ^{1}H NMR *δ* 5.94 (dd, *J* = 5.7, 3.0 Hz, 1H), 5.46 (dd, *J* = 5.7, 2.4 Hz, 1H), 5.17−5.16 (m, 1H), 4.21−4.20 (m, 1H), 2.78−2.70 (m, 2H), 2.56 (dd, *J* = 18.8, 6.7 Hz, 1H), 2.52−2.45 (m, 2H),, 2.24−2.11 (m, 2H), 1.81−1.73 (m, 1H), 1.52−1.44 (m, 2H), 1.36−1.27 (m, 2H), 1.12 (d, *J* = 7.0 Hz, 3H), 0.90 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR *δ* 219.2, 214.9, 147.6, 127.2, 125.5, 120.3, 72.7, 71.8, 71.6, 55.3, 42.7, 41.9, 38.7, 30.0, 29.7, 22.4, 13.9, 7.9; IR (film, cm^{-1}) 1742, 1735; HRMS (CI) calcd for $C_{18}H_{22}O_{2S}$ (M^+) 302.1340, obsd 302.1335.

(±)-1*β*,3,3a*β*,4,6α,8,8a*β*-Hexahydro-7-*n*-butyl-1α,6*β*-dimethyl-1*H*-cyclopenta[c]pentalen-7-ene-2,5-dione (26). In the manner analogous to the synthesis of **20**, compound **15** (90 mg, 0.310 mmol) was treated with *cis*-1-lithiopropene, generated from *cis*-1-bromopropene (0.050 mL, 0.620 mmol) and *tert*-butyllithium (1.25 mL, 1.25 mmol) in THF at −78 °C. Workup and chromatography (2:1 hexanes/EtOAc) gave **26** (38 mg, 53%) as a colorless oil, which consisted of a 10:1 α:*β* mixture of diastereomers. Data for **26** (α-CH_3): ^{1}H NMR *δ* 5.18 (s, 1H), 3.00−2.95 (m, 1H), 2.73−2.66 (m, 2H), 2.49−2.39 (m, 2H), 2.32−2.23 (m, 2H), 2.13−2.07 (m, 1H), 1.99−1.95 (m, 1H), 1.69 (q, *J* = 12.8 Hz, 1H), 1.49−1.31 (m, 4H), 1.02 (m, *J* = 7.5 Hz, 3H), 0.969 (d, *J* = 7.0 Hz, 3H), 0.907 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR *δ* 218.1, 217.5, 150.7, 126.3, 65.6, 53.0, 52.5, 45.4, 44.7, 42.5, 37.1, 29.6, 28.3, 22.5, 14.6, 13.9, 8.8; IR (film, cm^{-1}) 1739; HRMS (CI) calcd for $C_{17}H_{24}O_2$ (M^+) 260.1776, obsd 260.1775.

(±)-3,3a*β*,4,6,7*β*,9-Hexahydro-8-*n*-Butyl-1,7α-dimethyl-1*H*-cyclopentacyclooct-8-ene-2,5-dione (28). In the manner analogous to the synthesis of **20**, compound **15** (90 mg, 0.310 mmol) was treated with *trans*-1-lithiopropene, generated from *trans*-1-bromopropene (0.053 mL, 0.620 mmol) and *tert*-butyllithium (1.24 mL, 1.24 mmol) in THF at −78 °C. Workup and chromatography (2:1 hexanes/EtOAc) gave **28** (55 mg, 68%) as a white solid: mp, 94−95 °C, ^{1}H NMR *δ* 6.22 (s, 1H), 4.16−4.13 (m, 1H), 3.90 (sept, *J* = 6.3 Hz, 1H), 3.01 (dd, *J* = 13.0, 7.0 Hz, 1H), 2.91 (dd, *J* = 15.1, 5.5 Hz, 1H), 2.72 (dd, *J* = 18.7, 6.6 Hz, 1H), 2.33 (dt, *J* = 10.9, 1.8 Hz, 1H), 2.20−2.13 (m, 3H), 1.93 (dd, *J* = 16.8, 1.9 Hz, 1H), 1.74 (d, *J* = 1.6 Hz, 3H), 1.48−1.40 (m, 2H), 1.39−1.34 (m, 2H), 1.17 (d, *J* = 6.7 Hz, 3H), 0.930 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR *δ* 208.4, 206.6, 166.3, 154.7, 137.9, 120.1, 51.7, 42.1, 38.2, 34.1, 33.0, 30.5, 29.7, 22.8, 18.4, 13.9, 8.4; IR (film, cm^{-1}) 1692, 1621; HRMS (CI) calcd for $C_{17}H_{24}O_2$ (M^+) 260.1776, obsd 260.1787.

(±)-3,3α,4,6,9-pentahydro-8-*n*-butyl-1,7,7-trimethyl-1*H*-cyclopentacyclooct-8-ene-2,5-dione (32), (±)-1,6,6α,7,7a*β*-Pentahydro-6aα-hydroxy-4-*n*-butyl-1,5,5-trimethyl-1*H*-cyclopenta[*a*]pentalene-3b-en-2-one (33). In the manner analogous to the synthesis of **20**, a THF (10 mL) solution (−78 °C) of compound **15** (95 mg, 0.328 mmol) was treated with 1-lithio-2-methylpropene, prepared from 1-bromo-2-methylpropene (0.07 mL, 0.655 mmol) and *t*-BuLi (1.31 mL, 1.31 mmol) in THF (5 mL) at −78 °C. Workup and chromatography (2:1 hexanes/EtOAc) gave **32** (22 mg, 27%) and **33** (28 mg, 35%) as colorless oils. Data for **32**: ^{1}H NMR *δ* 5.97 (s, 1H), 3.12−3.10 (br s, 1H), 2.90 (dd, *J* = 14.4, 5.7 Hz, 1H), 2.87 (d, *J* = 15.9 Hz, 1H), 2.60 (ddd, *J* = 18.4, 6.4, 1.3 Hz, 1H), 2.54 (ddd, *J* = 14.4, 4.0, 1.5 Hz, 1H), 2.20−2.17 (m, 3H), 2.03 (s, 1H),

1.73 (d, J = 2.3 Hz, 3H), 1.59−1.47 (m, 2H), 1.45−1.36 (m, 2H), 1.11 (s, 6H), 0.942 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 209.7, 206.7, 172.4, 152.2, 138.0, 116.4, 56.3, 43.6, 40.6, 39.9, 38.9, 33.5, 33.0, 32.1, 25.3, 22.8, 14.0, 8.9; IR (film, cm^{-1}) 1703, 1662; HRMS (EI) calcd for $C_{18}H_{26}O_2$ (M^+) 274.1933, obsd 274.1938.

Data for **33**: ^{1}H NMR δ 3.04−2.99 (m, 1H), 2.70 (dd, J = 17.3, 6.6 Hz, 1H), 2.34−2.27 (m 2H), 2.19 (dd, J = 17.3, 4.4 Hz, 1H), 2.11−2.07 (m, 2H), 1.97 (s, 1H), 1.86 (s, 3H), 1.55 (dd, J = 14.2, 7.5 Hz, 1H), 1.53−1.48 (m, 2H), 1.44−1.31 (m, 3H), 1.36 (3H), 1.15 (s, 3H), 0.887 (t, J = 7.2 Hz, 3H); ^{13}C NMR δ 210.5, 169.6, 152.8, 138.5, 131.7, 91.6, 56.1, 51.8, 44.3, 44.1, 42.9, 31.6, 29.2, 28.1, 27.7, 23.3, 13.9, 10.0; IR (film, cm^{-1}) 3430, 1699, 1667; HRMS (EI) calcd for $C_{18}H_{27}O_2$ (MH^+) 275.2011, obsd 275.2005.

(±)-3,3a*β*,4,5a*β*,6,7,8,8a*β*,10-Nonahydro-9-*n*-butyl-1-methyl-1*H*-dicyclopenta[*a*,*e*]cyclooct-9-ene-2,5-dione (34) and (±)-1,4a*β*,5,6,7,7a*β*,7b,8,8a*β*-Nonahydro-7bα-hydroxy-4-*n*-butyl-1-methyl-1*H*-dicyclopenta[*a*,*e*]pentalene-3b-en-2-one (35). In the manner analogous to the synthesis of **20**, a THF (10 mL) solution (−78 °C) of compound **15** (95 mg, 0.328 mmol) was treated with 1-lithiocyclopentene, prepared from 1-iodocyclopentene (0.07 mL, 0.655 mmol) and *t*-BuLi (1.31 mL, 1.31 mmol) in THF (5 mL) at −78 °C. Workup and chromatography (2:1 hexanes/EtOAc) gave **34** (31 mg, 33%) and **35** (23 mg, 25%) as a colorless oils. Data for **34**: ^{1}H NMR δ 6.17 (s, 1H), 4.12−4.09 (m, 1H), 4.02−3.99 (m, 1H), 3.41−3.35 (m, 1H), 2.80−2.75 (m, 2H), 2.16−2.10 (m, 2H), 2.07−2.00 (m, 4H), 1.97−1.85 (m, 3H), 1.71 (s, 3H), 1.65−1.60 (m, 1H), 1.42−1.31 (m, 4H), 0.910 (t, J = 7.2 Hz, 3H); ^{13}C NMR δ 209.4, 206.7, 167.0, 154.0, 137.2, 120.6, 57.3, 51.5, 44.1, 41.5, 37.7, 35.5, 31.1, 28.6, 26.4, 24.1, 22.7, 13.9, 8.4; IR (film, cm^{-1}) 1698, 1667; HRMS (EI) calcd for $C_{19}H_{26}O_2$ (M^+) 286.1933, obsd 286.1938.

Data for **35**: ^{1}H NMR δ 3.25 (q, J = 7.9 Hz, 1H), 3.10−3.05 (m, 1H), 2.85 (dt, J = 8.7, 3.2 Hz, 1H), 2.71 (dd, J = 17.0, 6.6 Hz, 1H), 2.33−2.28 (m, 1H), 2.26−2.21 (m, 2H), 2.11 (J = 11.1, 2.8 Hz, 1H), 2.02−1.96 (m, 1H), 1.84 (d, J = 2.3 Hz, 3H), 1.80−1.76 (m, 3H), 1.62−1.57 (m, 2H), 1.50−1.44 (m, 3H), 1.32−1.25 (m, 3H), 0.876 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 210.6, 169.5, 146.9, 140.3, 131.4, 93.9, 58.4, 53.7, 44.9, 44.2, 42.6, 31.1, 30.3, 30.1, 29.6, 24.8, 22.7, 13.8, 10.0; IR (film, cm^{-1}) 3435, 1699, 1684, 1672; HRMS (EI) calcd for $C_{19}H_{26}O_2$ (M^+) 286.1933, obsd 286.1933.

(±)-1α,3,3a*β*,4,5aα,6,8,8a*β*-Heptahydro-7-*n*-butyl-1-methyl-1*H*-cyclopenta[*c*]pentalen-7-ene-2,5-dione (20) and (±)-3,3a*β*,4,6,7,9-Hexahydro-8-*n*-Butyl-1-methyl-1*H*-cyclopentacyclooct-8-ene-2,5-dione (18). To a THF (10 mL) solution (−78 °C) of compound **15** (90 mg, 0.310 mmol) was added vinyllithium (0.379 mL, 0.341 mmol), and after 10 min. the cold bath was removed. After 30 min., the contents were quenched with $NaHCO_3$ and extracted with ether. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. Chromatography (2:1 hexanes/EtOAc) gave **20** (25 mg, 33%) and **18 (**14 mg, 18%) as a colorless oils. Spectral data for **20** were identical to those of the product obtained when the reaction was quenched with TBAF. Data for **18**: ^{1}H NMR δ 6.23 (s, 1H), 3.94−3.91 (m, 1H), 3.25−3.19 (m, 1H), 2.92−2.88 (m, 1H), 2.90 (dd, J = 14.2, 5.7 Hz, 1H), 2.70 (dd, J = 18.7, 6.6 Hz, 1H), 2.62−2.55 (m, 1H), 2.33−2.28 (m, 2H), 2.27−2.23 (m, 1H), 2.22−2.17 (m, 2H), 1.72 (s, 3H), 1.48−1.45 (m, 2H), 1.37−1.32 (m, 2H), 0.95−0.92 (m, 3H); ^{13}C NMR δ 209.4, 206.9, 166.8, 150.2, 137.5, 120.8, 50.9, 42.8, 42.1, 40.0, 37.9, 29.8, 27.7, 22.4, 13.9, 8.4; IR (film, cm^{-1}) 1690, 1631; HRMS (EI) calcd for $C_{16}H_{22}O_2$ (M^+) 246.1620, obsd 246.1620.

(±)-3,3a*β*,4,6*β*,9-Hexahydro-8-*n*-Butyl-1,6α-dimethyl-1*H*-cyclopentacyclooct-8-ene-2,5-dione (36) and (±)-1α,3,-3a*β*,4,6,8,8a*β*-Hexahydro-7-*n*-butyl-1α,5a*β*-dimethyl-1*H*-cyclopenta[*c*]pentalen-7-ene-2,5-dione (21). In the manner analogous to the synthesis of **35**, compound **15** (105 mg, 0.362 mmol) was treated with 2-lithiopropene, generated from 2-bromopropene (0.062 mL, 0.724 mmol) and *tert*-butyllithium (0.771 mL, 1.45 mmol) in THF at −78 °C. Workup and chromatography (2:1 hexanes/EtOAc) gave **36** (19 mg, 20%) as a white solid, and **21** (31 mg, 33%) as a colorless oil. Data for **36**: mp, 61−62 °C, ^{1}H NMR δ 6.10 (s, 1H), 3.66−3.64 (m, 1H), 3.09−2.92 (m, 2H), 2.76−2.68 (m, 2H), 2.36 (t, J = 12.5 Hz, 1H), 2.22−2.13 (m, 3H), 2.02 (dd, J = 18.6, 1.5 Hz, 1H), 1.68 (m, 3H), 1.47−1.40 (m, 2H), 1.37−1.28 (m, 2H), 1.14 (d, J = 6.6 Hz, 3H), 0.90 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 211.6, 207.1, 167.7, 148.3, 137.7, 121.0, 48.1, 46.8, 42.1, 40.2, 38.7, 35.5, 30.0, 22.3, 16.9, 13.9, 8.4; IR (film, cm^{-1}) 1693, 1624; HRMS (CI) calcd for $C_{17}H_{24}O_2$ (M^+) 260.1776, obsd 260.1777. Spectral data for **21** were identical to those of the product obtained when the reaction was quenched with TBAF.

(±)-3,3a*β*,4,6,7α,9-Hexahydro-8-*n*-Butyl-1,7*β*-dimethyl-1*H*-cyclopentacyclooct-8-ene-2,5-dione (37) and (±)-1*β*,3,-3a*β*,4,6α,8,8a*β*-Hexahydro-7-*n*-butyl-1α,6*β*-dimethyl-1*H*-cyclopenta[*c*]pentalen-7-ene-2,5-dione (26). In the manner analogous to the synthesis of **35**, compound **15** (90 mg, 0.310 mmol) was treated with *cis*-1-lithiopropene, generated from *cis*-1-bromopropene (0.050 mL, 0.620 mmol) and *tert*-butyllithium (1.24 mL, 1.24 mmol) in THF at −78 °C. Workup and chromatography (2:1 hexanes/EtOAc) gave **37** (33 mg, 46%) as a white solid, and **26** (10 mg, 14%) as a colorless oil. Data for **37**: mp, 59−60 °C, ^{1}H NMR δ 5.80 (s, 1H), 3.17−3.12 (m, 1H), 3.07−3.04 (m, 1H), 2.71−2.65 (m, 2H), 2.55−2.51 (m, 2H), 2.34 (t, J = 12.9 Hz, 1H), 2.08−2.03 (m, 3H), 1.97 (s, 3H), 1.47−1.42 (m, 2H), 1.40−1.34 (m, 2H), 1.14 (d, J = 6.9 Hz, 3H), 0.946−0.910 (m, 3H); ^{13}C NMR δ 209.7, 207.3, 170.7, 147.5, 138.8, 120.0, 54.0, 46.5, 41.7, 40.5, 33.0, 30.5, 30.2, 22.7, 17.9, 14.0, 8.6; IR (film, cm^{-1}) 1697, 1657, 1610; HRMS (CI) calcd for $C_{17}H_{24}O_2$ (M^+) 260.1776, obsd 260.1698. Spectral data for **26** were identical to those of the product obtained when the reactions was quenched with TBAF.

(±)-2,3,3a*β*,4,6,7,9-Heptahydro-1-acetyl-8-*n*-butyl-1*H*-cyclopentacyclooct-8-ene-2,5-dione (39). In the manner analogous to the synthesis of **20**, compound **38** (100 mg, 0.329 mmol) was treated with vinyllithium (0.48 mL, 0.362 mmol). Workup and chromatography (3:1 hexanes/EtOAc) gave **39** (51 mg, 60%) as a colorless oil: ^{1}H NMR δ 6.37 (s, 1H), 3.53−3.49 (m, 1H), 2.75−2.64 (m, 3H), 2.62−2.54 (m, 4H), 2.43−2.38 (m, 1H), 2.25 (s, 3H), 2.18−2.10 (m, 3H), 1.49 (dddd, J = 8.7, 5.4, 4.3, 2.2 Hz, 1H), 1.41 (quintet, J = 7.6 Hz, 2H), 1.30 (quintet, J = 7.3 Hz, 2H), 0.90 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 210.6, 198.1, 152.9, 145.7, 138.5, 121.9, 47.7, 47.5, 43.8, 38.2, 31.5, 30.6, 29.9, 29.8, 27.4, 22.5, 13.9; IR (film, cm^{-1}) 1702, 1659; HRMS (EI) calcd for $C_{17}H_{24}O_2$ (MH^+) 260.1776, obsd 260.1776.

(±)-2,3,3a*β*,4,6,7,9-Heptahydro-1-acetyl-8-trimethylsilyl-1*H*-cyclopentacyclooct-8-ene-2,5-dione (42). In the manner analogous to the synthesis of **20**, compound **40** (100 mg, 0.313 mmol) was treated with vinyllithium (0.31 mL, 0.344 mmol). Workup and chromatography (6:1 hexanes/EtOAc) gave **41** (54 mg, 63%) as a pale oil: ^{1}H NMR δ 6.76 (s, 1H), 3.39−3.37 (m, 1H), 2.78−2.65 (m, 2H), 2.63−2.60 (m, 3H), 2.59−2.51 (m, 3H), 2.23 (s, 3H), 2.20−2.10 (m, 1H), 1.52 (dddd, J = 13.5, 8.5, 5.6, 1.4 Hz, 1H), 0.13 (s, 9H); ^{13}C NMR δ 210.6, 197.9, 153.9, 146.6, 139.6, 135.5, 47.3, 46.9, 45.3, 31.4, 30.6, 29.7, 25.5, −1.9 (3C); IR (film, cm^{-1}) 1705, 1657; HRMS (EI) calcd for $C_{16}H_{24}O_2Si$(M-1) 275.1467, obsd 275.1467.

(±)-2,3,3a*β*,4,6,7,9-Heptahydro-1-acetyl-8-methoxymethylene-1*H*-cyclopentacyclooct-8-ene-2,5-dione (43). In the manner analogous to the synthesis of **20**, compound **42** (90 mg, 0.308 mmol) was treated with vinyllithium, (0.38 mL, 0.340 mmol). Workup and chromatography (1:1 hexanes/EtOAc) gave **43** (43 mg, 56%) as a colorless oil: ^{1}H NMR δ 6.63 (d, J = 1.1 Hz, 1H), 3.90 (d, J = 5.4 Hz, 2H), 3.56−3.54 (m, 1H), 3.32 (s, 3H), 2.78−2.70 (m, 2H), 2.68−2.65 (m, 1H), 2.63−2.55 (m, 4H), 2.48−2.42 (m, 1H), 2.25 (s, 3H), 2.20−2.13 (m, 1H), 1.53 (dddd, J = 14.1, 8.8, 5.4, 2.1 Hz, 1H); ^{13}C NMR δ 210.4, 198.0, 151.3, 141.3, 139.6, 124.0, 76.4, 58.1, 47.4 (2C), 43.7, 31.7, 30.5, 29.9, 24.5; IR (film, cm^{-1}) 1701, 1686, 1655; HRMS (CI) calcd for $C_{15}H_{20}O_3$ (M^+) 248.1412, obsd 248.1415.

(±)-2,3,3a*β*,4,6,7,-hexahydro-8-*n*-Butyl-1-(2-di-deteuroacetyl)-9-deutero-1*H*-cyclopentacyclooct-8-ene-2,5-dione (47). In the manner analogous to the synthesis of **20**, compound **44** (95 mg, 0.309 mmol) was treated with vinyllithium, (0.80 mL, 0.340 mmol). Workup and chromatography (3:1 hexanes/EtOAc) gave **47** (49 mg, 60%) as a colorless oil: ^{1}H NMR δ 3.57−3.51 (m, 1H), 2.75−2.64 (m, 3H), 2.62−2.52 (m, 4H), 2.40−2.35 (m, 1H), 2.21−2.19 (m, 1H), 2.16−2.08 (m,

3H), 1.48 (dddd, J = 14.1, 8.6, 5.4, 2.1 Hz, 1H), 1.46−1.40 (m, 2H), 1.28 (sextet, J = 7.3 Hz, 2H), 0.88 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 210.5, 198.2, 152.8, 145.7, 138.4, 121.3 (q, J = 21.6 Hz), 47.5 (2C), 43.7, 38.2, 31.5, 29.9, 29.8, 29.6 (quintet, J = 19.4 Hz), 27.4, 22.5, 13.9; IR (film, cm^{-1}) 1700, 1654; HRMS (EI) calcd for $C_{17}H_{21}O_2D_3$ (M^+) 263.1965, obsd 263.1964.

(±)-1,3ba,4,6,6a,7,7ab-Heptahydro-6aα-hydroxy-3-methyl-5-trimethylsilyl-1*H*-cyclopenta[*c*]pentalene-5-en-2-one (50). A THF (10 mL) solution (−78 °C) of compound **1** (85 mg, 0.360 mmol) was treated with 1-lithio-trimethylsilylacetylene, prepared from trimethylsilylacetylene (0.06 mL, 0.43 mmol) and *n*-BuLi (0.25 mL, 0.41 mmol) in THF (5 mL) at 0 °C. Workup and chromatography (1:1 hexanes/EtOAc) gave **50** (50 mg, 53%) as a white solid, mp = 126−127 °C. ^{1}H NMR δ 5.82 (s, 1H), 3.13−3.05 (m, 1H), 3.11 (s, 1H), 2.68−2.61 (m, 1H), 2.53 (dd, J = 18.0, 6.3 Hz, 1H), 2.38 (dd, J = 12.0, 7.2 Hz, 1H), 2.29−2.24 (m, 1H), 2.21−2.15 (br s, 1H), 2.07 (dd, J = 18.0, 2.6 Hz, 1H), 1.70 (d, J = 2.0 Hz, 3H), 1.41 (t, J = 12.1 Hz, 1H), 0.10 (s, 9H); ^{13}C NMR δ 210.0, 183.9, 149.1, 142.8, 131.3, 98.6, 49.0, 43.9, 41.2, 41.1, 40.8, 8.2, 1.9 (3C); IR (film, cm^{-1}) 3325, 1691, 1658, 1643; HRMS (EI) calcd for $C_{15}H_{23}O_{2Si}$ (MH^+) 263.1467, obsd 263.1477.

(±)-1,3bα,4,6a,7,7aβ-Heptahydro-6aα-hydroxy-5-ethoxy-3-methyl-1*H*-cyclopenta[*c*]pentalene-5-en-2-one (51). A THF (10 mL) solution (−78 °C) of compound **1** (80 mg, 0.339 mmol) was treated with 1-lithio-2-ethoxyethyne, prepared from ethoxyethyne (0.04 mL, 0.43 mmol) and *n*-BuLi (0.25 mL, 0.41 mmol) in THF (5 mL) at 0 °C. Workup and chromatography (1:1 hexanes/EtOAc) gave **51** (41 mg, 51%) as a white solid, mp = 116−117 °C. ^{1}H NMR δ 4.58 (s, 1H), 3.81 (q, J = 7.1 Hz, 2H), 3.10−3.03 (m, 1H), 3.05 (s, 1H), 2.90−2.80 (br s, 1H), 2.54 (dd, J = 18.1, 6.3 Hz, 1H), 2.33 (dd, J = 11.8, 7.1 Hz, 1H), 2.22−2.17 (m, 1H), 2.08 (dd, J = 18.1, 2.8 Hz, 1H), 2.03−2.00 (br s, 1H), 1.69 (d, J = 2.2 Hz, 3H), 1.39 (t, J = 12.1 Hz, 1H), 1.30 (t, J = 7.1 Hz, 3H); ^{13}C NMR δ 210.6, 183.0, 161.9, 132.0, 100.1, 94.0, 65.8, 46.0, 44.9, 41.6, 40.8, 36.3, 14.4, 8.2; IR (film, cm^{-1}) 3362, 2961, 1645; HRMS (EI) calcd for $C_{14}H_{18}O_3$ (M^+) 234.1256, obsd 234.1247.

4,4-Dimethoxy-2-methyl-3-(1-hexynyl)-2-cyclobuten-1-one (54). 1-Hexyne (0.374 mL, 3.26 mmol) was added to THF (25 mL) at −78 °C followed by *n*-butylithium (1.94 mL, 3.11 mmol). After 20 min, the colorless solution was transferred to a −78 °C THF (30 mL) solution of **53** (500 mg, 2.97 mmol) over 20 min. The colorless reaction mixture was warmed to 0 °C and stirred for 45 min. To the yellow reaction mixture was added trifluoroacetic anhydride (0.505 mL, 3.56 mmol), followed by $NaHCO_3$ (saturated, 50 mL) after an additional 10 min. The mixture was extracted with ether. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered and concentrated. Chromatography (8:1 hexanes/EtOAc) gave **54** (352 mg, 55%) as a yellow oil: ^{1}H NMR δ 3.51 (s, 6H), 2.53 (t, J = 7.1 Hz, 2H), 1.82 (s, 3H), 1.56 (quintet, J = 7.1 Hz, 2H), 1.47−1.40 (m, 2H), 0.87 (t, J = 7.1 Hz, 3H); ^{13}C NMR δ 195.0, 159.6, 157.2, 118.6, 115.8, 70.9, 52.8 (2C), 29.9, 21.9, 20.2, 13.4, 8.6; IR (film, cm^{-1}) 2214, 1773, 1617; HRMS (EI) calcd for $C_{13}H_{18}O_3$ (M^+) 226.1256 obsd 226.1261.

4-Hydroxy-3-methyl-2-(1-hexynyl)-4-(3-propenyl)-2-cyclobuten-1-one (55). To a −78 °C THF (15 mL) solution of **54** (350 mg, 1.50 mmol) was added allylmagnesium bromide (1.65 mL, 1.65 mmol). The initial yellow colored solution faded to cloudy gray during the course of the reaction. Dilute (10%) hydrochloric acid (10 mL) was added after 15 min, and the mixture was warmed to ambient temperature. The reaction mixture was carefully neutralized with $NaHCO_3$ and then extracted with ether. The combined organic layers were washed with brine, dried, ($MgSO_4$), filtered, and concentrated. Chromatography (3:1 hexanes/EtOAc) gave **55** (240 mg, 73%) as a pale yellow oil: ^{1}H NMR δ 5.78−5.68 (m, 1H), 5.15−5.11 (m, 1H), 5.11−5.09 (m, 1H), 3.45 (bs, 1H), 2.52 (d, J = 7.3 Hz, 2H), 2.33 (t, J = 7.1 Hz, 2H), 2.18 (s, 3H), 1.47 (quintet, J = 7.1 Hz, 2H), 1.43−1.34 (m, 2H), 0.862 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 192.4, 183.5, 133.4, 131.7, 119.4, 100.4, 93.1, 67.5, 37.9, 30.2, 21.8, 19.2, 13.4, 12.4; IR (film, cm^{-1}) 3414, 2226, 1769, 1617; HRMS (CI) calcd for $C_{14}H_{19}O_2$ (MH^+) 219.1385, obsd 219.1388.

3-Methyl-2-(1-hexynyl)-4-[(trimethylsilyl)oxy]-4-(3-propenyl)-2-cyclobuten-1-one (56). To a THF (5 mL) solution of **55** (240 mg, 1.06 mmol) was added NEt_3 (1.03 mL, 7.39 mmol) followed by TMSCl (0.90 mL, 7.10 mmol). A white precipitate of NEt_3·HCl formed immediately. After 21 h, the yellow reaction mixture was poured onto $NaHCO_3$ (saturated, 20 mL). The aqueous layer was extracted with CH_2Cl_2, and the combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. The residue was immediately chromatographed (Florisil, 4:1 hexanes/EtOAc) to provide **56** (270 mg, 89%) as a pale oil: ^{1}H NMR δ 5.64 (dddd, J = 17.3, 10.1, 7.3, 4.4 Hz, 1H), 5.08−5.05 (m, 1H), 5.04−5.02 (m, 1H), 2.48 (dt, J = 2.8, 1.4 Hz, 2H), 2.35 (t, J = 7.1 Hz, 2H), 2.15 (s, 3H), 1.50 (quintet, J = 7.1 Hz, 2H) 1.38 (sextet, J = 7.3 Hz, 2H), 0.89 (t, J = 7.3 Hz, 3H) 0.10 (s, 9H); ^{13}C NMR δ 192.0, 184.4, 133.0, 132.4, 118.3, 100.1, 95.2, 67.6, 39.4, 30.3, 21.9, 19.3, 13.5, 12.6, 1.2 (3C); IR (film, cm^{-1}) 1773, 1623; HRMS (EI) calcd for $C_{17}H_{26}O_2Si$ (M^+) 290.1702, obsd 290.1710

(±)-2-Methyl-1-(1-hexynyl)-3-[(trimethylsilyl)oxy]-bicyclo[3.2.0]hept-2-en-7-one (15). A toluene (40 mL) solution of **56** (270 mg, 0.93 mmol) was heated at reflux for 1.5 h and then cooled to ambient temperature. Concentration gave **15** as a pale oil in nearly quantitative yield in excellent purity: ^{1}H NMR δ 3.28 (dd, J = 18.2, 9.3 Hz, 1H), 2.91−2.85 (m, 1H), 2.79 (dd, J = 18.2, 5.5 Hz, 1H), 2.65−2.61 (m, 1H), 2.20 (t, J = 7.2 Hz, 3H), 1.57 (s, 3H), 1.44 (quintet, J = 7.2 Hz, 2H), 1.35 (sextet, J = 7.2 Hz, 2H), 0.87 (t, J = 7.2 Hz, 3H), 0.20 (s, 9H); ^{13}C NMR δ 202.8, 148.3, 111.7, 87.9, 75.9, 72.2, 51.7, 39.7, 31.0, 30.9, 21.9, 18.7, 13.6, 9.1, 0.60 (3C); IR (film, cm^{-1}) 1783, 1674; HRMS (CI) calcd for $C_{17}H_{25}O_2Si$ (M − H) 291.1780, obsd 291.1771.

4-(1-Hexynyl)-3-isopropoxy-3-cyclobutene-1,2-dione (57, R = n-Bu). 1-Hexyne (1.14 mL, 9.85 mmol) was added to a −78 °C THF (50 mL) solution of *n*-butylithium (7.30 mL, 9.10 mmol), and after 30 min the colorless solution was transferred to a −78 °C THF (75 mL) solution of **52** (1.5 g, 7.58 mmol) over 20 min. Trifluoroacetic anhydride (1.62 mL, 11.4 mmol) was added after 10 min, followed by $NaHCO_3$ (saturated, 25 mL) after an additional 10 min. The mixture was warmed to room temperature and extracted with ether (3 × 60 mL). The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. Chromatography (9:1 hexanes/EtOAc) gave **57** (1.47 g, 88%) as a yellow-green oil: ^{1}H NMR δ 5.74 (septet, J = 6.2 Hz, 1H), 2.58 (t, J = 7.1 Hz, 2H), 1.58 (quintet, J = 7.1 Hz, 2H), 1.48 (d, J = 6.2 Hz, 6H), 1.40 (quintet, J = 7.4 Hz, 2H), 0.91 (t, J = 7.4 Hz, 3H); ^{13}C NMR δ 196.2, 195.3, 191.5, 162.2, 122.9, 81.0, 67.7, 29.9, 22.5 (2C), 22.0, 20.5, 13.4; IR (film, cm^{-1}) 2221, 1794, 1764; HRMS (CI) calcd for $C_{13}H_{16}O_3$ (M^+) 220.1099, obsd 220.1101.

3-Isopropoxy-4-(trimethylsilylacetylene)-3-cyclobutene-1,2-dione (57, R = TMS)). In an analogous fashion, the title compound was prepared from **52** (2.0 g, 10.2 mmol), lithio-trimethylsilylacetylene (prepared from *n*-butyllithium (7.47 mL, 11.2 mmol), and trimethylsilylacetylene (1.72 mL, 12.2 mmol). Chromatography (6:1 hexanes/EtOAc) gave **57** (R = TMS) (1.96 g, 91%) as a yellow-green oil: ^{1}H NMR δ 5.33 (septet, J = 6.2 Hz, 1H), 1.50 (d, J = 6.2 Hz, 6H), 0.26 (s, 9H); ^{13}C NMR δ 196.2, 195.2, 190.3, 160.5, 127.5, 89.2, 81.1, 22.5 (2C), −0.71 (3C); IR (film, cm^{-1}) 1788, 1765; HRMS (CI) calcd for $C_{12}H_{16}O_3Si$ (M^+) 236.0867, obsd 236.0865.

3-Isopropoxy-4-(methyl propynyl ether)-3-cyclobutene-1,2-dione (57, R = CH_2OMe). In an analogous fashion, the title compound was prepared from **52** (2.0 g, 10.2 mmol), 1-lithio-propynyl methyl ether (prepared from *n*butyllithium (12.8 mL, 19.2 mmol), and methyl propynyl ether (1.70 mL, 20.2 mmol). Chromatography (2:1 hexanes/EtOAc) gave **57** (R = CH_2OMe) (1.5 g, 71%) as a yellow oil: ^{1}H NMR δ 5.31 (septet, J = 6.2 Hz, 1H), 4.42 (s, 2H), 3.39 (s, 3H), 1.46 (d, J = 6.2 Hz, 6H); ^{13}C NMR δ 195.6, 195.3, 190.2, 115.2, 81.2, 72.3, 60.4, 59.3, 58.0, 22.3 (2C); IR (film, cm^{-1}) 1791, 1767; HRMS (CI) calcd for $C_{11}H_{12}O_4$ (M^+) 208.0736, obsd 208.0736.

3-(4-Butenyl)-2-(1-hexynyl)-4-hydroxy-4-methyl-2-cyclobuten-1-one (58, R = n-Bu). To a −78 °C THF (20 mL) solution of **57** (R = n-Bu) (400 mg, 1.8 mmol) was added MeLi (1.4 mL, 2.0 mmol). After 5 min, TMSCl (0.30 mL, 2.3 mmol)

was added, and the solution was warmed to 0 °C for 20 min and then cooled to −78 °C. A THF (20 mL) solution of 4-lithio-1-butene, which was generated from 4-bromo-1-butene (0.56 mL, 5.5 mmol) and *tert*-butyllithium (6.4 mL, 11.0 mmol), was added. Hydrochloric acid (5 M aqueous, 6 mL) was added, and the solution was warmed to ambient temperature. Saturated aqueous $NaHCO_3$ (50 mL) was added, the mixture was extracted with ether, and the combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. Chromatography (2:1 hexanes/EtOAc) provided **58** (R = n-Bu) (250 mg, 60%) as a pale yellow oil: ^{1}H NMR δ 5.82 (dddd, J = 17.1, 10.2, 6.4, 2.6 Hz, 1H), 5.09 (dd, J = 17.1, 1.6 Hz, 1H), 5.03 (dd, J = 10.2, 1.4 Hz, 1H), 3.07 (br s, 1H), 2.70 (t, J = 7.4 Hz, 2H), 2.55−2.50 (m, 2H), 2.35 (t, J = 7.0 Hz, 2H), 1.54−1.47 (m, 2H), 1.46 (s, 3H), 1.43−1.38 (m, 2H), 0.87 (t, J = 7.3 Hz, 3H); ^{13}C NMR δ 193.5, 186.8, 136.9, 132.2, 115.8, 100.5, 91.5, 72.7, 68.1, 30.2, 29.9, 26.8, 21.9, 19.2, 13.5; IR (film, cm^{-1}) 3408,1769, 1642, 1612; HRMS (EI) calcd for $C_{15}H_{20}O_2$ (MH^+) 233.1541, obsd 233.1543.

3-(4-Butenyl)-4-hydroxy-4-methyl-2-(trimethylsilylacetylene)-2-cyclobuten-1-one (58, R = TMS). In an analogous fashion, the title compound was prepared from **57** (R = TMS) (700 mg, 3.3 mmol). Chromatography (6:1 hexanes/EtOAc) gave the title compound (295 mg, 41%) as a yellow oil: ^{1}H NMR δ 5.82 (dddd, J = 17.1, 10.2, 6.4, 2.6 Hz, 1H), 5.09 (dd, J = 17.1, 1.6 Hz, 1H), 5.03 (dd, J = 10.2, 1.4 Hz, 1H), 2.75 (t, J = 7.1 Hz, 2H), 2.61−2.55 (m, 2H), 2.19 (s, 1H), 1.49 (s, 3H), 0.22 (s, 9H); ^{13}C NMR δ 192.7, 189.0, 136.7, 131.1, 115.8, 104.9, 91.6, 91.3, 29.6, 27.1, 19.2, −0.52 (3C); IR (neat, cm^{-1}) 3402, 2154, 1763, 1636, 1625; HRMS (CI) calcd for $C_{14}H_{20}O_2Si$ (M^+) 248.1232, obsd 248.1232.

3-(4-Butenyl)-4-hydroxy-4-methyl-2-(methyl propynyl ether)-2-cyclobuten-1-one (58, R = CH_2OMe). In an analogous fashion the title compound was prepared from **57** (R = CH_2OMe) (349 mg, 1.7 mmol). Chromatography (2:1 hexanes/EtOAc) gave the title compound (225 mg, 61%) as a yellow oil: ^{1}H NMR δ 5.81 (dddd, J = 17.1, 10.2, 6.4, 2.6 Hz, 1H), 5.07 (dd, J = 17.1, 1.5 Hz, 1H), 5.02 (dd, J = 10.2, 1.4 Hz, 1H), 4.24 (s, 2H), 3.36 (s, 3H), 2.72 (t, J = 7.6 Hz, 2H), 2.55−2.49 (m, 2H), 1.46 (s, 3H); ^{13}C NMR δ 192.5, 188.7, 136.6, 130.5, 115.8, 93.9, 91.7, 73.7, 60.4, 57.6, 29.8, 26.9, 19.1; IR (neat, cm^{-1}) 3410, 1770, 1649; HRMS (EI) calcd for $C_{13}H_{16}O_3$ (M^+) 220.1099, obsd 220.1093.

3-(4-Butenyl)-2-(1-hexynyl)-4-methyl-4-[(trimethylsilyl)oxy]-2-cyclobuten-1-one (59, R = n-Bu)) To a THF (10 mL) solution of **58**, (R = n-Bu) (495 mg, 2.1 mmol) was added NEt_3 (2.1 mL, 14.9 mmol) followed by TMSCl (1.8 mL, 14.3 mmol). A white precipitate of NEt_3·HCl formed immediately. After 36 h, the yellow-white mixture was poured onto CH_2Cl_2 (10 mL) and $NaHCO_3$ (saturated, 10 mL). The aqueous layer was extracted with additional CH_2Cl_2, and the combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. The residue was immediately chromatographed (Florisil, 9:1 hexanes/EtOAc) to provide the title compound (507 mg, 78%) as a yellow oil: ^{1}H NMR δ 5.83 (dddd, J = 17.1, 10.2, 6.4, 2.5 Hz, 1H), 5.08 (dd, J = 17.1, 1.5 Hz, 1H), 5.02 (d, J = 10.2 Hz, 1H), 2.68−2.64 (m, 2H), 2.54−2.49 (m, 2H), 2.35 (t, J = 7.1 Hz, 2H), 1.54−1.50 (m, 2H), 1.43−1.37 (m, 2H), 1.41 (s, 3H), 0.89 (t, J = 7.3 Hz, 3H), 0.11 (s, 9H); ^{13}C NMR δ 192.7, 187.2, 137.0, 131.2, 115.5, 99.9, 92.8, 68.3, 30.3, 29.9, 26.8, 21.9, 21.0, 19.3, 13.5, 1.3 (3C); IR (film, cm^{-1}) 2219, 1772, 1656, 1642; HRMS (CI) calcd for $C_{18}H_{28}O_2Si$ (M^+) 304.1858, obsd 304.1868.

3-(4-Butenyl)-4-methyl-2-(trimethylsilylacetylene)-4-[(trimethylsilyl)oxy]-2-cyclobuten-1-one (59, R = TMS). The title compound was prepared in analogous fashion from **58** (R = TMS) (330 mg, 1.51 mmol). Chromatography (Florisil, 9:1 hexanes/EtOAc) provided the title compound (288 mg, 67%) as a yellow oil: ^{1}H NMR δ 5.83 (dddd, J = 16.7, 10.3, 6.4, 2.6 Hz, 1H), 5.10 (dd, J = 17.1, 1.6 Hz, 1H), 5.03 (dd, J = 10.3, 1.4 Hz, 1H), 2.72−2.68 (m, 2H), 2.57−2.51 (m, 2H), 1.42 (s, 3H), 0.20 (s, 9H), 0.12 (s, 9H); ^{13}C NMR δ 191.6, 189.2, 136.9, 130.4, 115.7, 104.4, 93.0, 91.6, 29.7, 27.1, 20.9, 1.3 (3C), −0.4 (3C); IR (film, cm^{-1}) 2138, 1776, 1640; HRMS (CI) calcd for $C_{17}H_{28}O_2Si_2$ (M^+) 320.1628, obsd 320.1628.

3-(4-Butenyl)-4-methyl-2-(methylpropynyl ether)-4-[(trimethylsilyl)oxy]-2-cyclobuten-1-one (59, R = CH_2-OMe). The title compound was prepared in an analogous fashion from **58** (R = CH_2OMe) (200 mg, 0.91 mmol). Chromatography (Florisil, 9:1 hexanes/EtOAc) provided the title compound (190 mg, 72%) as a pale oil: ^{1}H NMR δ 5.83 (dddd, J = 17.1, 10.2, 6.4, 2.6 Hz, 1H), 5.09 (dd, J = 17.1, 1.5 Hz, 1H), 5.04 (dd, J = 10.2, 1.3 Hz, 1H), 4.27 (s, 2H), 3.39 (s, 3H), 2.72−2.68 (m, 2H), 2.55−2.50 (m, 2H),1.43 (s, 3H), 0.11 (s, 9H); ^{13}C NMR δ 191.8, 189.0, 136.7, 129.9, 115.8, 93.8, 93.1, 73.9, 60.2, 57.8, 29.9, 27.9, 20.9, 1.3 (3C); IR (film, cm^{-1}) 1777, 1643; HRMS (CI) calcd for $C_{16}H_{24}O_3Si$ (M^+) 292.1495, obsd 292.1493.

General Procedure for the Thermolytic Rearrangement of 3-Homoallylcyclobutenones. (±)-2-(2-Methyl-2-(*E*)-[(trimethylsilyl)oxy]methylene)-1-(1-hexynyl)-bicyclo-[3.2.0]heptan-7-one (38). A *p* -xylene (50 mL) solution of **59** (R = n-Bu) (400 mg, 1.3 mmol) was heated at reflux for 1 h. Concentration and filtration through a plug of silica gel (9:1 hexanes/EtOAc) gave **38** (380 mg, 95%) as a yellow oil: ^{1}H NMR δ 2.99 (dd, J = 16.9, 8.4 Hz, 1H), 2.87 (q, J = 7.0 Hz, 1H), 2.77−2.70 (m, 1H), 2.76 (dd, J = 16.9, 7.0 Hz, 1H), 2.54−2.44 (m, 1H), 2.23 (t, J = 7.7 Hz, 2H), 2.08−2.02 (m, 1H), 1.97 (t, J = 1.9 Hz, 3H), 1.83−1.78 (m, 1H), 1.49−1.36 (m, 4H), 0.87 (t, 3H), 0.18 (s, 9H), ^{13}C NMR δ 199.9, 147.2, 119.5, 86.9, 76.3, 66.8, 47.8, 41.3, 30.9, 29.4, 27.8, 21.9, 19.9, 18.7, 13.6, 0.78 (3C); IR (film, cm^{-1}) 1776, 1672; HRMS (EI) calcd for $C_{18}H_{28}O_{2Si}$ (M^+) 304.1858, found 304.1855.

(±)-2-(2-Methyl-2-(*E*)-[(trimethylsilyl)oxy]methylene)-1-(1-trimethylsilylacetylene)-bicyclo[3.2.0]heptan-7-one (40). In the manner analogous to the synthesis of **38**, compound **59** (R = TMS) (270 mg, 0.84 mmol) gave **40** (245 mg, 91%) as a pale oil after 1 h: ^{1}H NMR δ 3.04 (dd, J = 17.1, 8.7 Hz, 1H), 3.01−2.97 (m, 1H), 2.78 (dd, J = 17.1, 6.8 Hz, 1H), 2.72 (dd, J = 17.1, 9.2 Hz, 1H), 2.52−2.44 (m, 1H), 2.12−2.03 (m, 1H), 1.98 (s, 3H), 1.78 (dd, J = 13.1, 8.0 Hz, 1H), 0.18 (s, 9H), 0.14 (s, 9H); ^{13}C NMR δ 198.8, 147.5, 119.1, 101.6, 90.9, 67.4, 48.1, 41.2, 29.5, 27.8, 20.0, 0.76 (3C), 0.01 (3C); IR (film, cm^{-1}) 2148, 1779, 1673, 1642; HRMS (CI) calcd for $C_{17}H_{28}O_2Si_2$ (M^+) 320.1628, found 320.1619.

(±)-2-(2-Methyl-2-(*E*)-[(trimethylsilyl)oxy]methylene)-1-(1-methylpropynyl ether)-bicyclo[3.2.0]heptan-7-one (42). In the manner analogous to the synthesis of **38**, compound **59** (R = CH_2OMe) (190 mg, 0.65 mmol) gave **42** (175 mg, 92%) as a pale oil after 1 h: ^{1}H NMR δ 4.14 (s, 2H), 3.34 (s, 3H), 3.02 (dd, J = 17.0, 8.6 Hz, 1H), 2.99−2.95 (m, 1H), 2.80 (dd, J = 17.0, 8.6 Hz, 1H), 2.70 (dd, J = 12.9, 7.9 Hz, 1H), 2.54−2.47 (m, 1H), 2.09−2.02 (m, 1H), 1.97 (s, 3H), 1.84−1.79 (m, 1H), 0.18 (s, 9H); ^{13}C NMR δ 198.4, 147.5, 118.8, 82.8, 74.9, 66.5, 60.1, 57.3, 48.1, 41.3, 29.4, 27.8, 20.0, 0.74 (3C); IR (film, cm^{-1}) 1774, 1671; HRMS (CI) calcd for $C_{16}H_{24}O_3Si$ (MH^+) 293.1573, found 293.1568.

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Supporting Information Available: ^{1}H and ^{13}C NMR spectra of **20**, **21**, **22**α, **22**β, **23**α, **23**β, **26**, **28**, **33**, **35**, **18**, **36**, **37**, **39**, **41**, **43**, **47**, **50**, **51**, **54**, **55**, **56**, **15**, **57**−**59** (n-Bu, TMS, CH_2OCH_3), **38**, **45**, **40**, **42**, and X-ray crystallographic data for **23**α and **37**. This material is available free of charge via the Internet at http://pubs.acs.org.

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