2920, 1640, 1600, 1495, 1440, 1380, 920, 755, 700 cm^{-1}; MS, m/z 170 (M − 18), 147 (M − 41).

3-Methyl-6-phenyl-8-nonen-4-one (31a): A, 57%; B, 74%; C, 17%; NMR ($CDCl_3$) δ 0.71–1.05 (m, 6 H), 2.1–2.3 (m, 2 H), 2.7 (d, 2 H, J = 6 Hz), 3.26 (t, 1 H, J = 6 Hz), 4.65–4.95 (m, 2 H), 5.3–5.65 (m, 1 H), 6.8–7.4 (m, 5 H); IR (film) 2960, 1710, 905, 742, 690 cm^{-1}; MS, m/z 230 (M$^+$).

3-Methyl-4-[(*E*)-2-phenylethenyl]-1-hepten-4-ol (31b): A, 20%; C, 6%; NMR ($CDCl_3$) δ 0.9–1.6 (m, 14 H), 2.15–2.3 (m, 4 H), 4.7–5.0 (m, 2 H), 5.2–5.8 (m, 1 H), 6.12 (AB q, 2 H, $\Delta\nu_{AB}$ = 36 Hz, J = 15 Hz), 6.8–7.3 (m, 5 H); IR (film) 3500, 2960, 970, 905, 738, 688 cm^{-1}; MS, m/z 230 (M$^+$).

2,2-Dimethyl-5-phenyl-7-octen-3-one (32a): A, 58%; B, 92%; C, 45%; NMR ($CDCl_3$) δ 0.96 (s, 9 H), 2.21 (t, 2 H, J = 5 Hz), 2.56 (d, 2 H, J = 7 Hz), 3.0–3.3 (m, 1 H), 4.7–5.0 (m, 2 H), 5.2–5.7 (m, 1 H), 6.9–7.3 (m, 5 H); IR (film) 2942, 1708, 989, 906, 790, 690 cm^{-1}; MS, m/z 230 (M$^+$).

3-*tert*-Butyl-1-phenyl-1,5-hexadien-3-ol (32b): A, 26%; C, 43%; NMR ($CDCl_3$) δ 0.96 (s, 9 H), 1.6 (br s, 1 H), 2.2–2.4 (m, 2 H), 4.8–5.0 (m, 2 H), 5.3–5.9 (m, 1 H), 6.30 (AB q, 2 H, $\Delta\nu_{AB}$ = 24 Hz, J = 15 Hz), 7.0–7.4 (m, 5 H); IR (film) 3550, 2960, 974, 911, 735, 689 cm^{-1}; MS, m/z 230 (M$^+$).

5-Phenyl-3,7-octadienenitrile (1,6-adduct, 33a): C, 80%; NMR ($CDCl_3$) δ 2.36 (t, 2 H, J = 6 Hz), 2.83 (d, 2 H, J = 6 Hz), 3.1–3.4 (m, 1 H), 4.70–5.90 (m, 5 H), 6.8–7.2 (m, 5 H); IR (film) 3070, 3020, 2920, 2240, 1675, 1600, 1590, 1420, 1080, 990, 906, 751 cm^{-1}; MS, m/z 197 (M$^+$), 156 (M − 41). Anal. Calcd for $C_{14}H_{15}N$: C, 85.24; H, 7.66. Found: C, 85.14; H. 7.67.

3-[(*E*)-2-Phenylethenyl]-5-hexenenitrile (1,4-adduct, 33b): A, 37%; NMR ($CDCl_3$) δ 2.2–2.7 (m, 4 H), 4.9–5.2 (m, 2 H), 5.4–5.9 (m, 1 H), 6.0 (dd, 1 H, J = 15 Hz, 12 Hz), 6.35 (d, 1 H, J = 15 Hz), 7.0–7.3 (m, 5 H); IR (film) 3070, 3020, 2910, 2225, 1640, 1620, 1600, 1595, 1450, 1000, 970, 920 cm^{-1}; MS, m/z 197 (M$^+$). Anal. Calcd for $C_{14}H_{15}N$: C, 85.24; H, 7.66. Found: C, 85.21; H, 7.68.

Ethyl 5-phenyl-3,7-octadienoate (1,6-adduct, 34a): C, 95%; NMR ($CDCl_3$) δ 1.28 (t, 3 H, J = 6 Hz), 2.39 (t, 2 H, J = 6 Hz), 2.86 (d, 2 H, J = 6 Hz), 3.23 (q, 1 H, J = 6 Hz), 3.9 (q, 2 H, J = 6 Hz), 4.7–5.0 (m, 2 H), 5.2–5.7 (m, 3 H), 7.0 (br s, 5 H); IR (film) 3070, 3030, 2980, 1730, 1640, 1600, 1495, 1455, 1370, 1030, 975, 920, 700 cm^{-1}; MS, m/z 244 (M$^+$), 203 (M − 41).

Ethyl 3-[(*E*)-2-phenylethenyl]-5-hexenoate (1,4-adduct, 34b): A, 63%; NMR ($CDCl_3$) δ 1.17 (t, 3 H, J = 6 Hz), 2.20–2.60 (m, 5 H), 4.0 (q, 2 H, J = 6 Hz), 4.9–5.3 (m, 2 H), 5.3–6.3 (m, 3 H), 7.0–7.2 (m, 5 H); IR (film) 3080, 3025, 2980, 1735, 1640, 1600, 1495, 1370, 1015, 965, 920 cm^{-1}; MS, m/z 203 (M − 41).

Methyl 5-methyl-3,7-octadienoate (1,6-adduct, 35a) [77291-11-3]:[41] C, 61%;, NMR ($CDCl_3$) δ 0.97 (d, 3 H, J = 6 Hz), 1.9–2.2 (m, 3 H), 2.89 (d, 2 H, J = 6 Hz), 3.57 (s, 3 H), 4.8–5.0 (m, 2 H), 5.3–5.8 (m, 3 H).

Methyl 3-(2-propenyl)-4-hexenoate (1,4-adduct, 35b): A, 31%; NMR ($CDCl_3$) δ 1.62 (d, 3 H, J = 6 Hz), 2.2–3.0 (m, 5 H), 3.57 (s, 3 H), 4.7–5.0 (m, 2 H), 5.3–5.6 (m, 3 H).

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Registry No. (*E*)-**7**, 1896-62-4; **7a**, 69492-29-1; (*E*)-**7b**, 100840-12-8; (*E*)-**8**, 1754-62-7; **8a**, 52129-50-7; (*E*)-**8b**, 100840-13-9; (*E*)-**9**, 1885-38-7; **9a**, 87995-21-9; (*E*)-**10**, 27829-46-5; **10a**, 87995-22-0; (*E*)-**11**, 53282-12-5; **11a**, 100840-14-0; (*E*)-**11b**, 100840-15-1; (*E*)-**12**, 6125-63-9; **12a**, 100840-16-2; (*E*)-**13**, 88312-33-8; **13a**, 100840-17-3; (*E*)-**14**, 22147-62-2; **14a**, 87995-25-3; (*E*)-**14b**, 100840-18-4; (*E*)-**14c**, 100840-19-5; (*E*)-**15**, 29582-19-2; **15a**, 87995-26-4; (*E*)-**16**, 100840-11-7; (*E*)-**17**, 2495-35-4; **17a**, 87995-27-5; (*E*)-**18**, 623-91-6; **18a**, 72140-08-0; (*E*)-**19**, 7042-33-3; **19a**, 87995-36-6; (*E*)-**19b**, 100840-20-8; (*Z*)-**19c**, 100840-21-9; **20**, 1846-76-0; **20a**, 87995-41-3; (*E*)-**21**, 623-70-1; **21a**, 63473-84-7; (*E*)-**21b**, 33698-63-4; **22**, 638-10-8; **22a**, 87995-46-8; (*E*)-**23**, 1504-72-9; **23a**, 100840-22-0; (*E*)-**23b**, 100840-23-1; **24**, 13733-50-1; **24b**, 100840-24-2; **25**, 6802-75-1; **25a**, 32119-46-3; **26**, 87995-31-1; **26a**, 87995-37-7; **26b**, 84599-56-4; **27**, 3047-38-9; **27a**, 87995-38-8; **28**, 3949-36-8; **28a**, 87995-40-2; (*E*)-**29**, 14371-10-9; (*E*)-**29b**, 79299-29-9; (*E*)-**30**, 15174-47-7; (*E*)-**30b**, 100840-25-3; (*E*)-**31**, 84319-68-6; **31a**, 87995-33-3; (*E*)-**31b**, 87995-42-4; (*E*)-**32**, 29569-91-3; **32a**, 87995-34-4; (*E*)-**32b**, 100840-26-4; (*E,E*)-**33**, 53649-66-4; (*E*)-**33a**, 100840-27-5; (*E*)-**33b**, 100840-28-6; (*E,E*)-**34**, 39806-16-1; (*E*)-**34a**, 100840-29-7; (*E*)-**34b**, 100857-97-4; (*E,E*)-**35**, 2396-84-1; i, 38868-10-9; ii, 25117-54-8; ethyl (*E*)-5-methyl-3,7-octadienoate, 100840-30-0; ethyl (*E*)-3-(2-propenyl)-4-hexenoate, 100840-31-1; lithium diallylcuprate diethyl[(*N,N*-diethylcarbamoyl)methyl]-phosphate, 21500-57-2; anion, 100840-10-6; cyclopentanone cyanohydrin, 5117-85-1; 3-furfural, 498-60-2; trimethylacetaldehyde, 630-19-3; benzaldehyde, 100-52-7; carbomethoxymethylenetriphenylphosphorane, 2605-67-6; diethyl malonate, 105-53-3; acetone, 67-64-1; acetophenone, 98-86-2; 4-*tert*-butylcyclohexanone, 98-53-3; 1-cyclopentenecarboxylic acid, 1560-11-8; methacrylic acid, 79-41-4; cinnamaldehyde, 104-55-2; *sec*-butyllithium, 598-30-1; $TiCl_4$, 429-41-4.

Allylsilane-Initiated Cyclopentane Annulations[1]

George Majetich,* Richard W. Desmond, Jr., and José J. Soria

School of Chemical Sciences, Department of Chemistry, The University of Georgia, Athens, Georgia 30602

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The utility of intramolecular allylsilane additions to various Michael acceptors for achieving cyclopentane annulation is reported. Our results revealed that fluoride ion catalysis annulated both acyclic and cyclic systems, while Lewis acid catalyses ($TiCl_4$, $EtAlCl_2$, BF_3·Et_2O) were ineffective. This divergence in reactivity is rationalized in terms of conformational and stereoelectronic effects.

Polycyclic natural products containing cyclohexanoid and cyclopentanoid systems have inspired many creative procedures for carbocyclic ring formation. Although the cyclization of cationic, radical, and stabilized anionic species can efficiently generate six-membered rings, it was soon established that such conventional methods are not always applicable to five-membered rings. Consequently, the development of versatile methods for cyclopentane annulation has been the subject of considerable activity.[2]

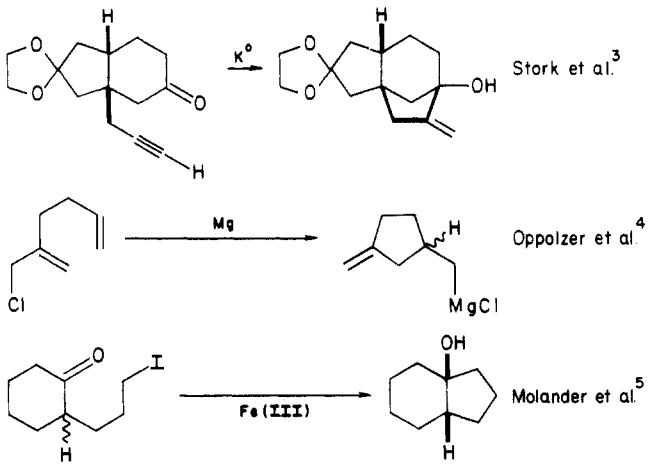
Chart I illustrates several known annulation procedures in which five-membered rings result from the intramo-

(1) This work was presented in part at the 6th Gulf Coast Conference at Pensacola, FL, in Sept 1983, and at the 35th SERMC at Raleigh, NC, in Oct 1983, and taken in part from the M.S. Thesis of Mr. Richard Desmond, University of Georgia, 1984.

(2) For two recent reviews see: (a) Ramaiah, M. *Synthesis* **1984**, 529. (b) Paquette, L. A. *Top. Curr. Chem.* **1984**, *119*, 1.

0022-3263/86/1951-1753$01.50/0

Chart I



lecular addition of a highly reactive organometallic nucleophile to an internal electrophile.[3-7] A number of related annulation procedures have been developed in which ring closure results from intramolecular conjugate addition of a nucleophile to a Michael acceptor. Unfortunately, like the intermolecular Michael reaction,[8] these intramolecular extensions experience competition from retrograde Michael reactions, secondary condensations, and the presence of relatively acidic protons. To compensate for these constraints, highly stabilized (less basic) nucleophiles have been employed: phosphonium ylides,[9] the anion of dithiane,[10] and the enolates of β-keto esters,[11] aldehydes,[12] ketones,[13] and esters.[14] In contrast, the analogous annulation using nonstabilized nucleophiles has received little attention, undoubtedly owing to difficulties associated with the specific generation of an unactivated anion in the presence of the highly reactive electrophilic olefin.[15-17] An additional complication is that the strongly basic incipient anion may cause either inter- or intramolecular proton abstraction or simply add in a 1,2-fashion, rather than favor 1,4-addition.

Chart II

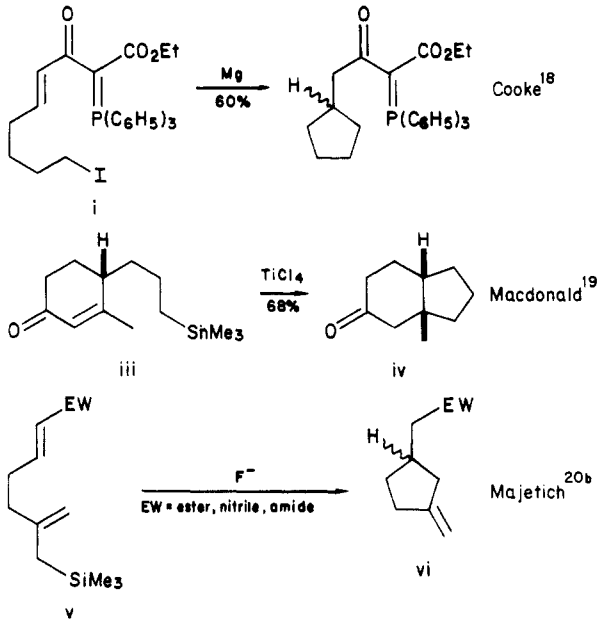
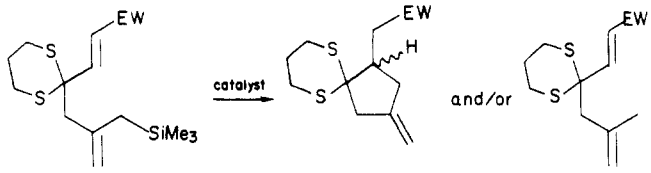


Table I[34]



EW	catalyst	yield of A, %	yield of B, %
CO_2Et (1)	F^-	52	0
CN (2)	F^-	81	0
	BF_3·Et_2O	0	23
$COCH_3$ (3)	F^-	67	0
$CON(Et)_2$ (4)	F^-	56	30
	BF_3·Et_2O	0	56

In 1979, however, Cooke[15a,18] reported the first intramolecular Michael reaction initiated by an internally generated Grignard reagent (i → ii, Chart II). Shortly thereafter, Macdonald and Mahalingam[19] effected ring formation using a latent carbanionic organotin nucleophile and an activated cyclohexenone; e.g., iii → iv. Our own work in this area[20] has focussed on the use of allylsilanes

(3) Stork, G.; Malhotra, S.; Thompson, H.; Uchibayashi, M. *J. Am. Chem. Soc.* **1965**, *87*, 1148.

(4) (a) Oppolzer, W.; Pitteloud, R.; Strauss, H. F. *J. Am. Chem. Soc.* **1982**, *104*, 6476. (b) Oppolzer, W.; Battig, K. *Tetrahedron Lett.* **1982**, *23*, 4669. (c) Oppolzer, W.; Strauss, H. F.; Simmons, D. P. *Ibid.* **1982**, *23*, 4673. (d) Oppolzer, W.; Pitteloud, R. *J. Am. Chem. Soc.* **1982**, *104*, 6478. (e) Oppolzer, W.; Pitteloud, R.; Bernardinelli, G.; Battig, K., *Tetrahedron Lett.* **1983**, *24*, 4975.

(5) Molander, G. A.; Etter, J. B. *Tetrahedron Lett.* **1984**, *25*, 3281.

(6) (a) For leading references to ring formation via organolithium, organomagnesium, organocopper, and organozirconium species, see: Chamberlin, A. R.; Bloom, S. H. *Tetrahedron Lett.* **1984**, *25*, 4901 and references cited therein. (b) For the intramolecular allylation of carbonyl compounds using organotin (or aluminum) species, see: Nokami, J.; Wakabayaski, S.; Okawara, R. *Chem. Lett.* **1984**, 869.

(7) For examples of intramolecular carbometalation of an acetylene, see: (a) Normant, J.; Alexakis, A. *Synthesis* **1981**, 841. (b) Crandall, J. K.; Michaely, W. J. *J. Org. Chem.* **1984**, *49*, 4244. (c) Fujikura, S.; Inoue, M.; Utimoto, K.; Nozaki, H. *Tetrahedron Lett.* **1984**, *25*, 1999.

(8) Posner, G. H. *Org. React. (N.Y.)* **1972**, *19*, 1.

(9) Cory, R. M.; Chan, D. M. *Tetrahedron Lett.* **1975**, 4441.

(10) Grotjahn, D. B.; Andersen, N. H., *J. Chem. Soc., Chem. Commun.* **1981**, 306.

(11) (a) Stork, G.; Taber, D. F.; Marx, M., *Tetrahedron Lett.* **1978**, 2445. (b) Stork, G.; Rosen, P.; Goldman, N.; Coombs, R. V.; Tsuji, J. *J. Am. Chem. Soc.* **1965**, *87*, 275. (c) Stork, G.; Winkler, J. D.; Saccomano, N. A. *Tetrahedron Lett.* **1983**, *24*, 4934. (d) Stork, G.; Boeckman, R. K., Jr.; Taber, D. F.; Still, W. C.; Singh, J. *J. Am. Chem. Soc.* **1979**, *101*, 7107.

(12) Stork, G.; Shiner, C. S.; Winkler, J. D. *J. Am. Chem. Soc.* **1982**, *104*, 310.

(13) Trost, B. M.; Shuey, C. D.; DiNimmo, F. *J. Am. Chem. Soc.* **1979**, *101*, 1284.

(14) Lee, R. A. *Tetrahedron Lett.* **1973**, 3333.

(15) Ring construction through the intramolecular trapping of enolates generated by conjugate addition of a nucleophile to an electrophilic olefin have been known for many years. For examples: (a) Cooke, M. P., Jr. *Tetrahedron Lett.* **1979**, 2199. (b) Posner, G. H.; Sterling, J. J.; Whitten, C. E.; Lentz, C. M.; Brunelle, D. J. *J. Am. Chem. Soc.* **1975**, *97*, 107. In fact, the term MIRC (Michael Initiated Ring Closure) is now an accepted acronym: Little, R. D.; Dawson, J. R. *Tetrahedron Lett.* **1980**, *21*, 2609 and references cited therein.

(16) The electrochemical reduction of enones in the presence of intramolecular alkylating agents represents an alternative approach for ring formation: (a) Gassman, P. G.; Rasmy, O. M.; Murdock, T. O.; Saito, K. *J. Org. Chem.* **1981**, *46*, 5455. (b) Scheffold, R.; Dike, M.; Dike, S.; Herold, T.; Walder, L. *J. Am. Chem. Soc.* **1980**, *102*, 3642.

(17) The [3 + 2] cycloaddition of [2-(trimethylsilyl)methyl]allyl derivatives to enones represents another alternative strategy for cyclopentane annulation: (a) Trost, B. M.; Nanninga, T. N. *J. Am. Chem. Soc.* **1985**, *107*, 1293 and references cited therein. See also: (b) Knapp, S.; O'Connor, U.; Mobilio, D. *Tetrahedron Lett.* **1980**, *21*, 4557.

(18) Cooke, M. P., Jr. *J. Org. Chem.* **1984**, *49*, 1146.

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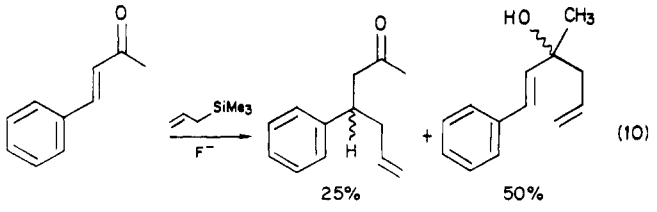
in intramolecular Michael condensations, i.e., v → vi.

The research of Sakurai, Andersen, and Fleming has stimulated the use of allylsilanes as reagents and as intermediates in organic synthesis.[21] These pioneers and others have documented the highly regiospecific reactions of allylsilanes with a wide variety of carbon electrophiles.[22] For example, Sakurai has reported that the Lewis acid catalyzed allyl transfer reactions of allylsilanes with carbonyl compounds,[23] acetals,[24] and enones[25,26] efficiently produce homoallyl alcohols, homoallyl ethers, and δ,ε-enones, respectively.

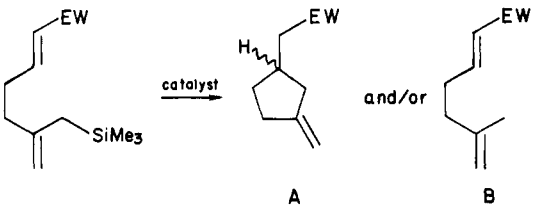
Allylsilanes are also known as allylic carbanion synthons. Independently, Sakurai[27] and Andersen[28,29] demonstrated that the allyl–silicon bond of an allylsilane moiety is readily cleaved with fluoride ion to produce a new allylic nucleophile, which adds to carbonyl compounds. Several researchers have capitalized on the ability of allylsilanes to function as "allylic carbanion equivalents" in the generation of cyclic alcohols via 1,2-addition to carbonyl compounds.[30] Prior to our investigations, the use of these reagents with Michael acceptors had been completely ignored. Such neglect is not surprising, since in the sole example reported, the fluoride-induced allyl transfer reaction with an enone was not selective.[27]

At the outset of our investigations, the intramolecular addition of an allylsilane to an electrophilic olefin using either nucleophilic or electrophilic conditions was unknown.[31,32] In this article, we report our systematic study of the scope and limitations of this new annulation strategy.



(10)

Table II[34]



A B

EW	catalyst	yield of A, %	yield of B, %
CO_2CH_2 (5)	F^-	66	0
C_6H_5	$TiCl_4$	0	78
	BF_3·Et_2O	0	45
CN (6)	F^-	59	0
$COCH_3$ (7)	F^-	40	0
	BF_3·Et_2O	no identifiable products	
$CON(Et)_2$ (8)		0	78
	BF_3·Et_2O	0	68

Results

In 1983 we reported that the intermolecular fluoride-promoted allylation of α,β-unsaturated esters, nitriles, and amides proceed in conjugate fashion in good yields, while the Lewis acid catalyzed allylation fails, in contrast with the known efficiency of this method with enones.[20a,c]

These positive results encouraged us to construct substrates capable of undergoing an intramolecular Michael reaction. Trajectory analysis of an intramolecular Michael addition requires that the nucleophile attack approximately perpendicular to the plane of the electron-deficient olefin. Cyclizations which readily accommodate this trajectory are favored.[33] Inspection of models of v suggests that this geometrical requirement is difficult to attain unless the allylsilane and the unsaturated unit are connected by at least a two-carbon tether. With this prerequisite in mind, we constructed several acyclic substrates we felt were capable of cyclizing (Table I)[34] under either electrophilic or nucleophilic conditions. The electron-withdrawing substituent of the electron-deficient olefin was either an ester (1), a nitrile (2), a methyl ketone (3), or a tertiary amide group (4). Note that the dithiane moiety precluded any problem with acidic protons.

Our intermolecular studies showed that optimum conditions for conjugate addition require only a catalytic quantity (ca. 0.2 equiv) of tetrabutylammonium fluoride[35] (TBAF) as the source of fluoride ion with *N,N*-dimethylformamide (DMF) as the solvent, in the presence of activated 4A molecular sieves. The yields of allylated products were increased slightly by the addition of 3 equiv of hexamethylphosphoramide (HMPA) (relative to Michael acceptor) to the TBAF/DMF solution prior to the addition of the substrate. These conditions were employed

(21) For comprehensive reviews of allylsilanes in organic synthesis, see: (a) Sakurai, H. *Pure Appl. Chem.* **1982**, *54*, 1. (b) Hosomi, A.; Sakurai, H. *J. Synth. Org. Chem. Jpn.* **1985**, *43*, 406.

(22) General reviews: (a) Hudrlik, P. F. "New Applications of Organometallic Reagents in Organic Synthesis", Seyferth, D., Ed.: Elsevier: Amsterdam, 1976; p 127. (b) Colvin, E. W. *Chem. Soc. Rev.* **1978**, *7*, 15. (c) Fleming, I. "Comprehensive Organic Chemistry"; Vol. 3, Barton, D., Ollis, W. D., Eds.; Pergamon Press: Oxford, 1979; p 541. (d) Fleming, I. *Chem. Soc. Rev.* **1981**, *10*, 83.

(23) Hosomi, A.; Sakurai, H. *Tetrahedron Lett.* **1976**, 1295.

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(25) Hosomi, A.; Sakurai, H. *J. Am. Chem. Soc.* **1977**, *99*, 1673.

(26) The broad synthetic applicability of the Lewis acid catalyzed allylation of enones has resulted in "Name Status" for this transformation, i.e., the Hosomi–Sakurai reaction. For a recent example of such usage, see: Blumenkopf, T.; Heathcock, C. H. *J. Am. Chem. Soc.* **1983**, *105*, 2354.

(27) Hosomi, A.; Shirahata, A.; Sakurai, H. *Tetrahedron Lett.* **1978**, 3043.

(28) Sarkar, T. K.; Andersen, N. H. *Tetrahedron Lett.* **1978**, 3513.

(29) For a comprehensive review of the use of the $CSi(CH_3)_3$ moiety as a protected carbanion, see: Andersen, N. H.; McCrae, D. A.; Grotjahn, D. B.; Gabbe, S. Y.; Theodore, L. J.; Ippolito, R. M.; Sarkar, T. K. *Tetrahedron* **1981**, *37*, 4079. For further examples of the fluoride ion induced intermolecular reaction of organosilanes with aldehydes, see: Ricci, A.; Degl'Innocent, A.; Fiorenze, M.; Taddei, M.; Spartera, M. A.; Walton, D. R. M. *Tetrahedron Lett.* **1982**, *23*, 577.

(30) For examples of the intramolecular fluoride-catalyzed addition of allylsilanes to ketones, see: (a) Ochia, M.; Sumi, K.; Fujita, E.; Shiro, M. *Tetrahedron Lett.* **1982**, *23*, 5419. (b) Trost, B. M.; Curran, D. P. *J. Am. Chem. Soc.* **1981**, *103*, 7380. (c) Trost, B. M.; Vincent, J. E. *J. Am. Chem. Soc.* **1980**, *102*, 5680.

(31) The first example of a Lewis acid catalyzed intramolecular Hosomi–Sakurai reaction was reported by: Wilson, S. R.; Price, M. F. *J. Am. Chem. Soc.* **1982**, *104*, 1124. For recent examples, see: (a) Schinzer, D. *Angew Chem., Int. Ed. Engl.* **1984**, *23*, 308. (b) Schinzer, D.; Solyom, S.; Bechker, M., *Tetrahedron Lett.* **1985**, *26*, 1831. (c) Tokoroyama, T.; Tsukamoto, M.; Ito, H. *Ibid.* **1984**, *25*, 5067.

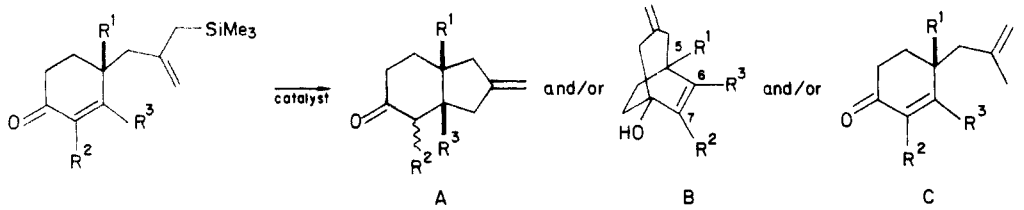
(32) While our initial manuscripts were in press[20a,b] a successful allylation of cyclohexenone using fluoride catalysis was reported: Ricci, A.; Fiorenza, M.; Grifagni, M. A.; Bartoliinie, G. *Tetrahedron Lett.* **1982**, *23*, 5079.

(33) (a) Baldwin, J. E. *J. Chem. Soc., Chem. Commun.* **1976**, 734. (b) Baldwin, J. E.; Cutting, J.; DuPont, W.; Kruse, L.; Silberman, L.; Thomas, R. C. *Ibid.* **1976**, 736. Baldwin, J. E.; Thomas, R. C.; Kruse, L.; Silberman, L. *J. Org. Chem.* **1977**, *42*, 3846. (c) Liotta, C. L.; Burgess, E. M.; Eberhardt, W. H. *J. Am. Chem. Soc.* **1984**, *106*, 4849.

(34) The preparation of the substrates presented in Tables I–IV are included in the Experimental Section.

(35) The tetraalkylammonium fluorides are extremely hygroscopic compounds. Complete removal of water is nearly impossible due to the strongly hydrogen-bonding fluoride ion and is complicated further by the fact that these compounds decompose at temperatures higher than 80 °C. For a convenient procedure to prepare "anhydrous" tetra-*n*-butylammonium fluoride, see the preceding paper.

Table III[34]



A B C

substr	R^1	R^2	R^3	catalyst	yield of A, %	yield of B, %	yield of C, %	recovd start mat.
9	H	H	H	F^-	69	0	0	0
				$EtAlCl_2$	0	0	30	45
				$TiCl_4$	0	49	0	0
10	CH_3	H	H	F^-	63	0	0	0
				$EtAlCl_2$	0	0	10	25
				$TiCl_4$	0	24	0	0
11	H	CH_3	H	F^-	57	0	0	0
				$EtAlCl_2$	0	0	50	16
				$TiCl_4$	0	34	60	0
12	CH_3	CH_3	H	F^-	55	6	0	0
				$EtAlCl_2$	0	0	70	5
				$TiCl_4$	0	0	60	0
13	H	H	CH_3	F^-	46	0	0	0
				$EtAlCl_2$	0	0	70	5
				$TiCl_4$	0	0	92	0
14	CH_3	H	CH_3	F^-	65	0	0	0
				$EtAlCl_2$	20	40	10	12
				$TiCl_4$	0	41	10	0
				$Br_3{\cdot}Et_2O$	0	0	40	0
15	H	CH_3	CH_3	F^-	43	10	10	0
				$EtAlCl_2$	0	0	20	50
				$TiCl_4$	0	50	20	0
16	CH_3	CH_3	CH_3	F^-	32	19	0	0
				$EtAlCl_2$	0	0	60	8
				$TiCl_4$	0	74	16	0

with equal success in the intramolecular cyclizations.

To test whether intra- or intermolecular deprotonation is favored over ring closure, the fluoride ion catalyzed reactions were repeated on the analogous substrates without the dithiane group (Table II).[34] Substrates **5**, **6**, and **7** underwent conjugate addition exclusively. Tertiary amide **8**, however, failed to cyclize and a 78% yield of the protodesilylation product (**8b**) was obtained.

Intramolecular processes usually proceed more readily than their bimolecular analogues. We hoped that this generalization would extend to the Lewis acid catalyzed reactions of the substrates in Tables I and II. Unfortunately, exposure of unsaturated ester **5**, nitrile **6**, and amides **7** and **8** to several Lewis acid catalysts failed to achieve cyclization, thus complementing our intermolecular studies. In our intermolecular studies, we confirmed that the Hosomi–Sakurai allylation procedure ($TiCl_4$/allyltrimethylsilane) was clearly the method of choice for allylating conjugated enones. Interestingly, both $TiCl_4$ and boron trifluoride etherate failed to promote the cyclization of enone **7**. This result inspired further study.

Our interest in the synthesis of polycyclic natural products led us to extend our study to substituted six- and five-membered rings which would form bicyclic systems, models for natural products. We found a wide divergence of reactivity with these systems, depending on whether Lewis acid or fluoride ion catalysts were used.

Cyclohexenones **9** and **10** cleanly cyclized to form the bicyclic compounds **9a** and **10a** in 69% and 63% yields, respectively. When the β-position of the enone was substituted with a methyl group, as in **11** and **12**, conjugate addition occurred in 57% and 55% yields, respectively. Cyclization of **12** also gave a small amount of a more polar compound, whose spectral data indicated the bridged bicyclic alcohol structure **12c**, resulting from 1,2-addition to the carbonyl.

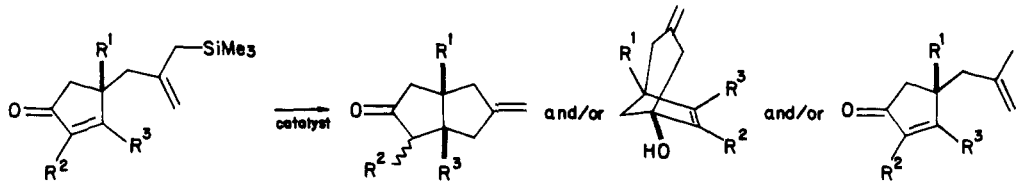
Normally, increased steric bulk at the β-position of an enone, such as a β,β-disubstituted enone, favors 1,2-addition products over Michael addition; thus the substitution of the β-position of a cyclohexenone with a methyl group represented a crucial test of this annulation procedure. Furthermore, ring closure via conjugate addition in **13** and **14** would result in the formation of a new quaternary center. These cyclizations generated bicyclic ketones **13a** and **14a** in 46% and 65% yields, respectively. In compounds **15** and **16** both the α- and the β-positions of the enone were substituted with methyl groups; cyclization generated bicyclic ketones **15a** and **16a** in 43% and 32% yields together with alcohols **15b** and **16b**, in 10% and 19% yield, respectively.

For comparison, we conducted a study of the Lewis acid initiated cyclizations on the same substrates. In all attempts, boron trifluoride etherate, stannous chloride, and titanium tetrachloride (strong Lewis acids) failed to promote conjugate addition under a variety of reaction conditions and instead resulted in either 1,2-addition or protodesilylation. We also examined milder Lewis acids such as trifluoroacetic anhydride,[36] trimethylaluminum, and diethylaluminum chloride in hopes of effecting cyclization, to no avail. Concurrent with this study,[37] we had successfully used ethylaluminum dichloride for the intramolecular addition of an allylsilane to a dienone system.[20d-f,h] Prolonged exposure of the substrates listed in

(36) Cationic π cyclization of α,β-unsaturated enones using acid anhydrides to initiate cyclization are known: (a) Harding, K. E.; Cooper, J. L. *Tetrahedron Lett.* **1977**, 3321. (b) Harding, K. E.; Cooper, J. L.; Puckett, P. M.; Ryan, J. D. *J. Org. Chem.* **1978**, *43*, 4363.

(37) The use of ethylaluminum dichloride as a catalyst for intramolecular additions of allylsilanes to enones was first reported by D. Schinzer and co-workers [186th National Meeting of the American Chemical Society, Washington, D.C., August 1983; ORGN 134]. Our independent discovery of the effectiveness of this reagent was first reported at the Southeast Regional ACS Meeting in October 1983.

Table IV[34]



A B C

substr	R^1	R^2	R^3	catalyst	yield of A, %	yield of B, %	yield of C, %	recovd start mat.[a]
17	H	H	H	F^-	64	0	0	0
				$EtAlCl_2$	0	0	84	0
				$TiCl_4$	0	0	50	10
18	CH_3	H	H	F^-	55	0	0	0
				$EtAlCl_2$	0	0	75	5
				$TiCl_4$	0	0	60	0
19	H	CH_3	H	F^-	40	4	0	0
				$EtAlCl_2$	0	0	40	50
				$TiCl_4$	0	0	95	0
20	CH_3	CH_3	H	F^-	40	10	0	0
				$EtAlCl_2$	0	0	70	15
				$TiCl_4$	0	47[b]	0	0
21	H	H	CH_3	F^-	15	0	29	0
				$EtAlCl_2$	0	0	92	0
				$TiCl_4$	0	33	0	0
22	CH_3	H	CH_3	F^-	10	45	0	0
				$EtAlCl_2$	0	0	65	20
				$TiCl_4$	0	86	0	0
23	H	CH_3	CH_3	F^-	0	22	22	0
				$EtAlCl_2$	0	0	20	55
				$TiCl_4$	0	0	86	0
24	CH_3	CH_3	CH_3	F^-	2	54	0	0
				$EtAlCl_2$	0	0	80	0
				$TiCl_4$	0	46	20	0

[a] After 2-h reaction time. [b] Exocyclic olefin rearranged.

Table III to $EtAlCl_2$ resulted in only protodesilylation products; however, in a single instance (i.e., **14**) conjugate addition was observed, albeit in low yield. Other Lewis acids were not examined.

A series of substituted cyclopentenones (Table IV) was treated with TBAF to initiate cyclization. Cyclopentenones **17** and **18** cleanly cyclized to generate bicyclic ketones **17a** and **18a** in 64% and 55% yields. Compounds **19** and **20**, in which a methyl substituent was present in the β-position, cyclized to bicyclic ketones **19a** and **20a** in 40% yield. In addition to the bicyclic ketones, the isomeric bridged bicyclic alcohols **19b** and **20b** were formed in 4% and 10% yields. Cyclopentenones **21** and **22**, in which the β-position of the enone was substituted with a methyl group, underwent cyclization via conjugate addition in low yield, unlike the cyclohexenone systems. Enone **21**, in which R^1 is a proton, gave only 15% of the bicyclic ketone **21a**; the major product of the reaction was that of protodesilylation. The cyclization of **22**, in which R^1 is a methyl group, generated the bridged bicyclic alcohol **22b** in 45% yield. In the case of the α,β-disubstituted enones **23** and **24**, little conjugate addition occurred; i.e., enone **24** gave only a 2% yield of **24a**, while the major product was bridged bicyclic alcohol **24b**, isolated in 54% yield. The major product from cyclopentenone **23** was that of protodesilylation, with a small amount of 1,2-addition product **23b**, isolated in 22% yield.

Exposure of these cyclopentenones to $TiCl_4$ and ethylaluminum dichloride under a wide variety of conditions failed to promote conjugate addition; rather, either simple protodesilylation or 1,2-addition occurred (e.g. **20b**, **21b**, and **22b**).

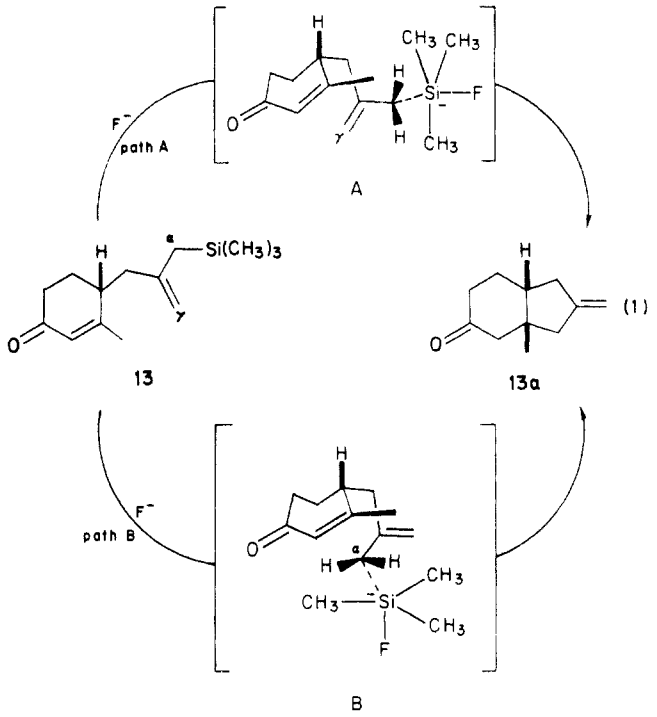
Discussion

Fluoride Catalysis. The cyclizations reported in this paper form the basis for some interesting conclusions. First, the fluoride-mediated process annulated both acyclic and cyclic unsaturated esters, nitriles, amides, and enones, in contrast to the Lewis acid catalyzed procedure. Second, these reactions proceeded despite both enolizable protons and severe steric interactions, situations presumed to be unfavorable for intramolecular Michael condensations. Finally, this annulation procedure proved capable of generating quaternary centers.

The following postulates account for these results: (1) The formation of products is under kinetic control and is not reversible. (2) Addition of a fluoride salt to an allylsilane rapidly results in the formation of a nonbasic pentacoordinate organosilicon nucleophile.[38] (3) Conjugate addition predominates if the hypervalent allylic silicon intermediate can easily adopt a spatial position favorable for 1,4-attack, via either terminus of the allylsilane moiety, leading to ring formation via a 5-exo-trig closure;[33] otherwise 1,2-addition or protodesilylation predominates.

The geometry of the transition state can normally be deduced directly from the nature of the products. However, examination of a Dreiding stereomodel of enone **13**, for instance, reveals that the flexibility of the functionalized side-chain enables, in principle, cyclization to take place at either terminus of the allyl unit (eq 1). Note that conformers A and B have the functionalized side chain constrained to an equatorial position and led to the observed cis ring fusion via the sterically favored axial approach. Here cyclization via the γ-carbon of the allylsilane would proceed via an S_E2' mechanism,[39] while the S_E2

(38) Although Hosomi and Sakurai concede the possible intermediacy of a hypervalent allylic silicon intermediate, they interpret their results in terms of an allyl anion: Sakurai, H.; Hosomi, A.; Saito, M.; Sasaki, K.; Iguchi, H.; Sakaki, J.; Araki, Y. *Tetrahedron* **1983**, *39*, 883.



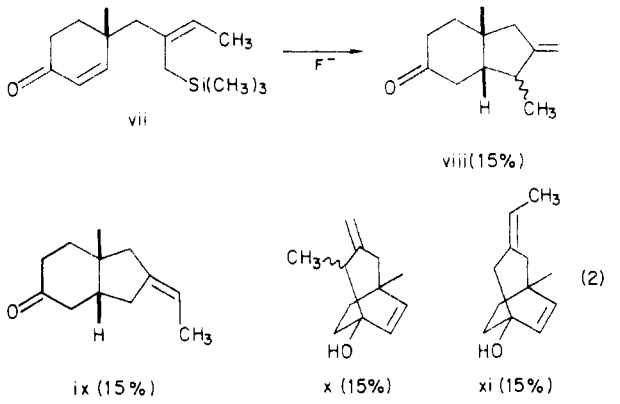
path A: attack at the γ-carbon atom of the allylsilane moiety via an S_E2' mechanism

path B: attack at the α-carbon atom of the allylsilane moiety via an S_E2 mechanism

pathway[40] would be involved if attack occurred at the silicon-containing terminus (the α-carbon).[41]

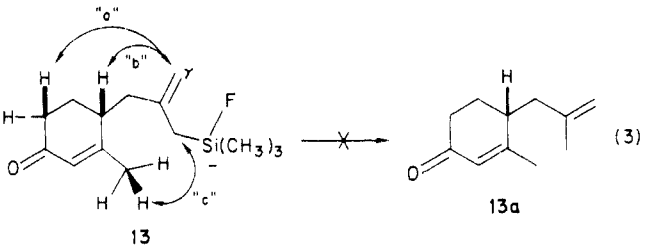
In order to determine which mechanism predominated in these cyclizations, we prepared substrate vii, with a methyl substituent to differentiate the γ-position of the allylsilane moiety. Reaction of this unsymmetrical[42] allylsilane[34] with fluoride ion resulted in both 1,4- and 1,2-adducts, consisting of roughly equal amounts of adducts viii–xi as shown in eq 2. Thus we have assumed that both S_E2' and S_E2 reaction mechanisms are in operation in the cyclizations presented in Tables I–IV. For brevity, only those transition states corresponding to the fluoride-promoted S_E2' pathway are illustrated.

The lack of 1,2-addition products in the cyclization of symmetrical allylsilanes (Tables I–IV) is particularly interesting since the intermolecular fluoride-induced allylations of several enones gave predominantly 1,2-adducts.[20a,c] Models of the transition-state complexes of enone **13** leading to 1,2-addition indicate that the side chain must assume a highly strained pseudoaxial conformation. In contrast, the formation of either transition state A and B does not require any deformation of bond angles (eq 1). Clearly, conformational preferences favor those



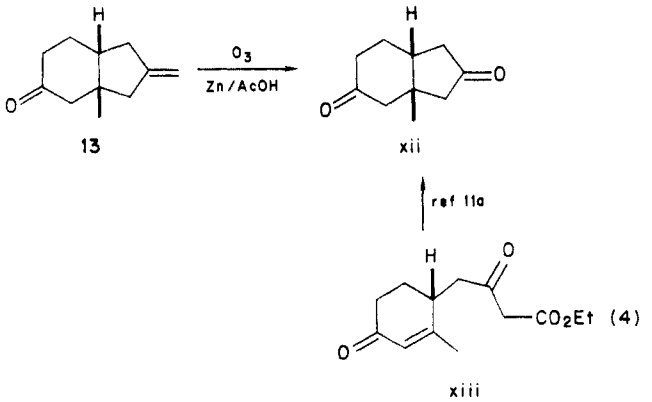
transition states leading to conjugate addition.

In the case of enone **13**, conjugate addition occurred in spite of the presence of three sets of enolizable protons; note that the disposition of reaction centers required for proton abstraction is readily accommodated in either seven- or five-centered transition states, as indicated below (eq 3). Remarkably, no products corresponding to proton



abstraction were observed. This phenomenon is consistent with our postulate that the reactive intermediate is a nonbasic nucleophile and indicates that formation of a five-membered ring via conjugate addition is favored over intramolecular proton abstraction.

Analysis of the NMR spectra was used to assign the stereochemistry of the ring junction of those compounds possessing an angular methyl group. It is well established that a cis ring junction is indicated when the resonance of the angular methyl group is greater than 1.00 ppm.[43] The cis ring junction was also confirmed by chemical means (eq 4). In 1978, Stork and co-workers reported the



formation of *cis*-hydrindandione xii via the intramolecular Michael addition of β-keto ester xiii, followed by removal of the ester group.[11a] Bicyclic ketone **13a** was ozonized to diketone xii and shown to be identical with the compound reported by Stork by comparison of spectral and chromatographic properties. It was therefore assumed that the

(39) For an example of an S_E2' mechanism, see: (a) Sleezer, B.; Winstein, R.; Young, J. *J. Am. Chem. Soc.* **1963**, *85*, 1980. Kumada and Fleming have shown that an S_E2' mechanism is involved in the electrophilic reactions of allylsilanes: (b) Hayaski, T.; Kabeta, K.; Hamachi, I.; Kumada, M., *Tetrahedron Lett.* **1983**, *24*, 2865. (c) Fleming, I.; Terrett, N. K. *Ibid.* **1983**, *24*, 4153.

(40) For examples of substitution via a three-center interaction of an organometallic intermediate, see: Negishi, E. In "Organometallics in Organic Synthesis"; Wiley-Interscience: New York, 1980; Vol. I, pp 66–73.

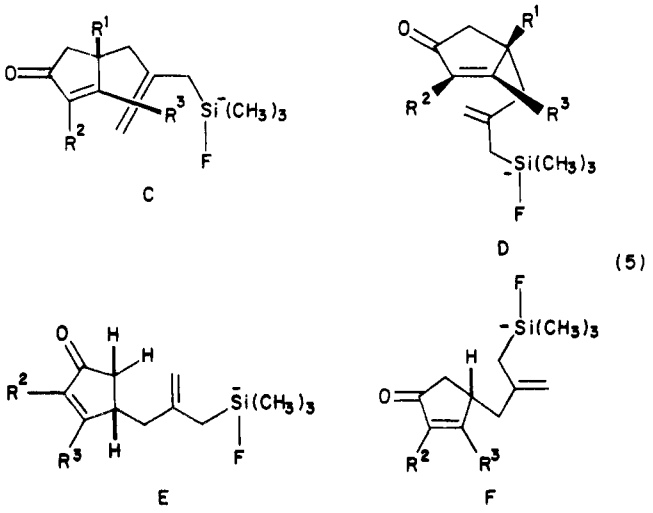
(41) Allylsilanes are intrinsically nonnucleophilic. Addition of fluoride ion to an allylsilane, however, results in the formation of a hypervalent organosilicon species, which is capable of reacting as a nucleophile. Thus from a mechanistic viewpoint, substitution of an allylsilane at either end of the π-system under *nucleophilic* conditions is more appropriately considered an addition–elimination reaction with the terms S_E2 and S_E2' aptly representing the elimination process.

(42) Unsymmetrically substituted allylsilanes have different substituents on the α- and γ-carbon atoms of the allylic systems (the $SiMe_3$ group is on the α-carbon).

(43) Jackman, L. M.; Sternhell, S. "Application of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry", 2nd ed.; Pergamon Press; Elmsford, NY, 1972; pp 241–245 and references cited therein.

other products of the cyclization study possessed the cis ring fusion because of the similarity of their spectral properties.

Conformational preferences are more pronounced in the cyclizations of the more reactive cyclopentenone substrates[44] than in the cyclohexenone series. The transition-state conformations of these substrates corresponding to 1,4-addition, 1,2-addition, and intramolecular proton abstraction are illustrated in eq 5.

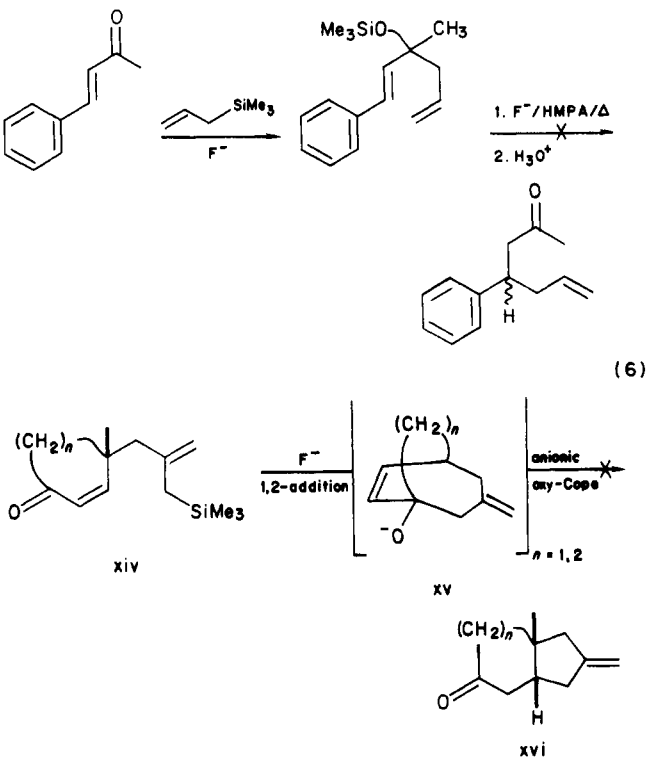


(5)

Complex C represents the preferred transition state of α-substituted and unsubstituted cyclopentenones, i.e., enones 17–20. Introduction of a methyl group at the β-position, however, leads to unfavorable nonbonded steric interactions between this substituent and the side chain, thus destabilizing this transition state and encouraging 1,2-addition. The nature of the γ-substituent influences the extent to which 1,2-addition predominates in the cyclization of β-substituted enones. Cyclopentenones **22** and **24**, in which C(4) is substituted with a methyl group, produced the strained bicyclic alcohols **22b** and **24b** in 45% and 54% yield, respectively. Formation of these adducts supports our postulate that the fluoride-induced cyclizations are under kinetic control and do not necessarily reflect the relative stability of the products. In contrast, enones **21** and **23**, in which C(4) is substituted with a proton, predominantly resulted in the loss of the trimethylsilyl moiety upon exposure to fluoride ion catalysis. We believe that intermolecular proton abstractions involving trace moisture,[45] tetra-*n*-butylammonium counterion,[46] or unreacted substrate[47] are unlikely. These substrates fail to cyclize presumably due to intramolecular proton transfer. Complex E illustrates that intramolecular proton transfer of an α'-proton via a highly favorable six-membered array is quite reasonable for each cyclopentenone substrate studied. Protodesilylation, however, predominates only when the β-position of a cyclopentenone is substituted with an alkyl group and the γ-position with a proton, e.g. enones **21** and **23**. Conformer F suggests that a five-centered transition state with a colinear relationship of the reaction centers accounts for this observation.

Our analysis of the fluoride-induced cyclizations of cyclic enones indicates that a substrate will assume a transition-state conformation leading to 1,4-addition unless this mode of reactivity is retarded by steric or stereoelectronic factors. These factors promote either 1,2-addition or intramolecular proton abstraction. These same conclusions can also be derived through analysis of the acyclic precursors presented in Table II.

Two aspects of these cyclizations remain to be discussed. First, in our intermolecular studies,[20c] we were concerned that the adduct obtained from 1,2-allylation could undergo an anionic oxy-Cope rearrangement, thus producing the same products as direct 1,4-addition.[48] We dismissed this sequence when a silylated 1,2-adduct failed to undergo rearrangement using fluoride catalysis under several vigorous thermolysis conditions. This biomolecular result, however, may not be applicable to the intramolecular reactions. If this alternative mechanistic pathway (i.e., xiv → xv → xvi) were operative, then the isolation of 1,2-adducts was solely due to the premature quenching of the anionic oxy-Cope intermediates. This hypothesis was disproved when thermolysis of the alkoxides of bicyclic alcohols **15b** and **24b** gave no reaction.[49] Finally, intramolecular addition of the allylsilane moiety to cyclic enones failed to produce the corresponding silyl enol ethers and/or silyl ethers.[50] Attempts to silylate the enolate resulting from 1,4-addition also failed. The cyclizations of α,β-unsaturated esters, nitriles, or amides (Tables I and II) were



(6)

(44) 2-Cyclopenten-1-one is more reactive toward conjugate addition than the analogous six- or seven-membered enones. This reactivity parallels the order of the half-wave potential of their respective electrolytic reductions: House, H. O.; Huber, L. E.; Umen, M. J. *J. Am. Chem. Soc.* **1972**, *94*, 8471.

(45) When we first began our investigations, we were concerned that the presence of water in the fluoride source might result in a premature quenching of the nucleophilic species. To test this possibility, we carried out the cyclization of cyclohexenone **11** using excess fluoride (greater than 3 equiv). Nevertheless, ring closure via conjugate addition occurred; no products corresponding to protodesilylation were obtained. Thus, further concern about trace amounts of moisture is unwarranted.

(46) The *n*-Bu_4N^+ counterion can act as a proton source via a β-elimination leading to the production of tri-*n*-butylamine. Andersen and co-workers have observed this competing process in their studies with 1,3-dithian-2-yl anions.[29]

(47) All fluoride-induced cyclizations were carried out by slow addition of substrate to a highly dilute solution (ca. 0.3 M) of the fluoride source.

(48) Evans, D. A.; Golob, A. M. *J. Am. Chem. Soc.* **1975**, *97*, 4765.

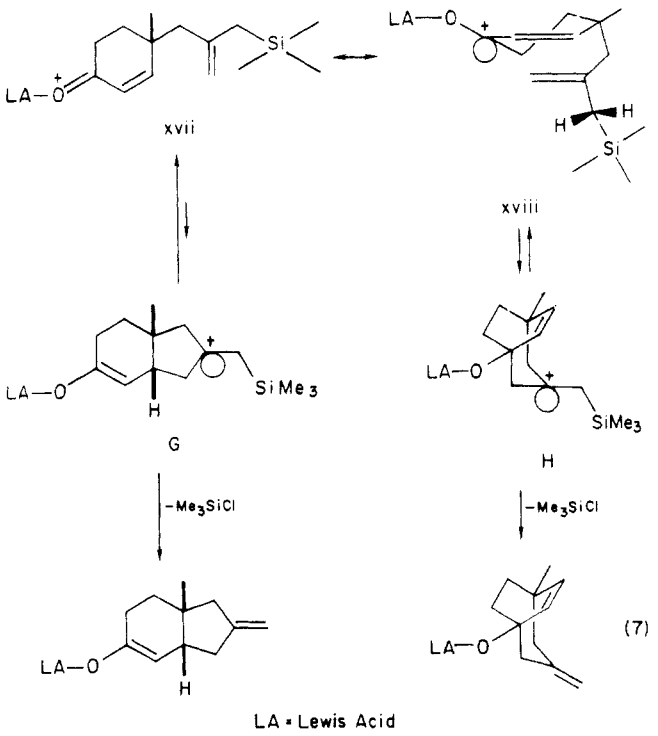
(49) Compounds known to undergo oxy-Cope rearrangement were tested for comparison.

(50) On a few occasions, workup of a fluoride catalyzed reaction furnished a silyl enol ether of the 1,4-adduct or a trimethylsilyl ether of the 1,2-adduct. This observation, however, was not reproducible.

also not complicated by related trappings.

Lewis Acid Cyclizations. Although the failure of the intramolecular Hosomi–Sakurai reaction with less-electrophilic Michael acceptors was anticipated, the inability of the enones examined to undergo conjugate addition was not. Furthermore, the formation of bicyclic alcohols cannot be attributed to conformational requirements which clearly favor conjugate addition.

Our explanation of this selectivity rests upon the relative stabilities of cationic intermediates G and H (eq 7) and



(7)

Baldwin's rules. Although the formation of intermediate H is derived from the addition of the allylsilane moiety to a highly reactive valence-bond resonance form of the activated enone (cf. xvii and xviii), the resulting carbocation is stabilized through π-delocalization.[51] Similar π-overlap stabilization is geometrically precluded in cationic intermediate G which promotes retro-Michael addition and shifts the partitioning between intermediates G and H decidedly in favor of the latter.

Baldwin's rules[33] provide an alternative explanation for these results. The equivalent of a 7-exo-trig reaction is known for cationic ring closures, cf. cationic intermediate H, whereas the "disfavored" 5-endo-trig case, cf. cationic intermediate G, is not well established for simple cations.[52]

It seems likely that either explanation also accounts for the lack of 1,4-adducts in the cyclopentenone series.

Since all Lewis acid catalyzed reactions were carried out under aprotic conditions, we attribute the formation of protodesilylation products to intramolecular proton transfer from the α'-position. These cyclizations also demonstrated a profound catalyst dependency. Although titanium tetrachloride was the most effective catalyst, this reagent undoubtedly destroys the 1,2-adducts generated upon the prolonged exposure required for complete reaction,[53] hence our somewhat low yields (yields varied from 24% up to 86%).

Conclusion

To summarize, we have shown that the fluoride-mediated process annulated both acyclic and cyclic unsaturated esters, nitriles, amides, and enones, in stark contrast to the Lewis acid catalyzed procedure.

The following advantages further enhance the versatility of this annulation procedure. 1. While preparing the various substrates examined in this study, we demonstrated the stability of an allylsilane moiety under a wide variety of conditions. 2. This annulation procedure proved capable of generating adjacent quaternary centers. 3. The exocyclic double bond of the cyclized products permits future synthetic manipulations. These advantages have been incorporated in the design of synthetic routes to a variety of natural products.

Experimental Section

All melting points were determined on a Thomas Hoover oil immersion capillary melting point apparatus and are uncorrected. Proton nuclear magnetic resonance (^{1}H NMR) spectra were recorded at 90 MHz on a Varian EM 390 spectrometer. Chemical shifts are reported in ppm on the δ scale relative to tetramethylsilane as 0 ppm. The data reported as integer numbers are accurate to within ±10% of the integer. ^{1}H NMR data are presented as follows: chemical shift (multiplicity, number of protons, coupling constants in hertz). Infrared (IR) spectra were recorded as a thin film between polished sodium chloride plates on a Perkin-Elmer 197 grating infrared spectrometer. All absorption bands are reported in wavenumbers (cm^{-1}), which were calibrated against the 1601-cm^{-1} absorption band of polystyrene. Low resolution mass spectra (MS) were recorded on a Finnigan 4023 chromatograph-mass spectrometer by a direct probe and are expressed in m/z units. High resolution mass spectra were performed at Emory University (Atlanta, GA) on a Varian Associates M-66 spectrometer. Microanalysis was performed by Atlantic Microlab, Inc., Atlanta, GA.

Anhydrous tetrahydrofuran (THF) and diethyl ether were purified by refluxing with, and distillation from, sodium/benzophenone under a nitrogen atmosphere in a recycling still. Anhydrous dimethylformamide (DMF) and hexamethylphosphoramide (HMPA) were purified by refluxing over and distillation from calcium hydride under a dry nitrogen atmosphere and stored over 4A molecular sieves. Anhydrous toluene and diisopropyl amine were purified by refluxing over and distillation from calcium hydride and stored over sodium metal and potassium hydroxide pellets, respectively. Diisobutylaluminum hydride (Aldrich) and lithium aluminum hydride are abbreviated as DIBAL and LAH, respectively. For brevity, the following Wadsworth–Emmons and Wittig reagents are abbreviated as follows: triethyl phosphonoacetate (A); diethyl (cyanomethyl)-phosphonate (B); 1-(triphenylphosphoranylidene)-2-propanone (C); and diethyl [(*N*,*N*-diethylcarbamoyl)methyl]phosphonate (D).

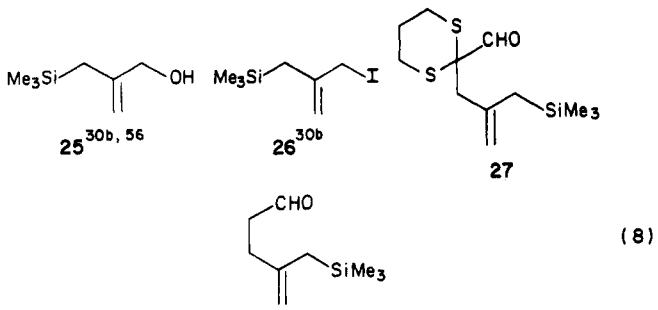
All reactions were run under an inert atmosphere of nitrogen. Unless otherwise indicated, all ethereal workups consisted of the following procedure: The reaction mixture was quenched at room temperature with saturated aqueous ammonium chloride. The solvent was removed under reduced pressure on a rotary evaporator and the residue was taken up in ether, washed with brine, and dried over anhydrous magnesium sulfate. Filtration, followed by concentration at reduced pressure on a rotary evaporator and at 0.1 torr to constant weight, afforded a crude residue which was purified by flash chromatography using MN silica gel 60 (230–400 mesh ASTM) and distilled reagent grade solvents.

(51) In a study on the stereochemistry of olefinic cyclizations, Arigoni and co-workers showed that the attacking double bond adopts an orientation in which the π-system stabilized the developing carbonium ion independent of steric considerations: Godfredsen, S.; Obrechit, J. P.; Arigoni, D. *Chimia* **1977**, *31*, 62.

(52) Acylium ions generated from γ,δ-unsaturated acids are known to produce cyclopentenones. Such a ring closure is formally a 5-endo-trig process. For other literature examples, see ref 33a and references cited therein.

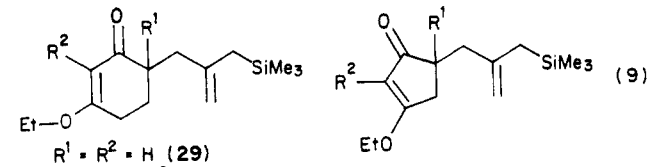
(53) Tertiary alcohols are known to rapidly solvolyze to the tertiary carbonium ion in the presence of a Lewis acid: Snider, B. B.; Rodini, D. J.; Karras, M.; Kirk, T. C.; Deutsch, E. A.; Cordova, R.; Price, R. T. *Tetrahedron* **1981**, *37*, 3927.

I. Preparation of Substrates. The precursors listed in Tables I–IV were prepared using common procedures from the intermediates shown in eq 8.



(8)

Cyclohexenones **9–16** and the analogous cyclopentenones **17–24** were prepared via the method of Stork and Danheiser from enones **29–36**.[54]



(9)

Enone vii was prepared by alkylation of the kinetic enolate of 3-ethoxy-6-methyl-2-cyclohexen-1-one with (*E*)-2-[(trimethylsilyl)methyl]-2-buten-2-yl iodide, followed by LAH reduction and acid hydrolysis. The preparation of the requiste iodide will be described in a future article.

2-Formyl-2-[2-[(trimethylsilyl)methyl]allyl]-*m*-dithiane (27). To a solution of lithium diisopropylamide prepared from 0.44 mL (3.24 mmol) of diisopropylamine in 3 mL of freshly distilled THF and 1.90 mL (3.24 mmol) of *n*-butyllithium (1.80 M in hexanes) at −78 °C was added a solution of 0.40 g (2.70 mmol) of 2-formyldithiane[55] in 2 mL of THF containing 0.47 mL (2.70 mmol) of HMPA over a 45-min period. After an additional $^1/_2$ h at −78 °C, 0.76 g (3.00 mmol) of silyl iodide **26**[30b] was added. The reaction was allowed to gradually warm to room temperature and was stirred 12 h. Standard ethereal workup gave 389 mg of crude **27**. Purification on silica gel (elution with hexanes/ether, 1:1) afforded 0.48 g (65%) of the alkylated material which was homogeneous on TLC analysis (hexane/ether, 1:1, R_f 0.86): NMR (CCl_4) δ 0.10 (s, 9 H), 1.55 (s, 2 H), 2.47 (s, 2 H), 1.7–3.4 (m, 8 H), 4.68 (s, 1 H), 4.75 (s, 1 H), 8.83 (s, 1 H).

Ethyl (*E*)-2-[2-[(Trimethylsilyl)methyl]allyl]-*m*-dithiane-2-acrylate (1). To a suspension of 31.2 mg (1.3 mmol) of sodium hydride (50%) in 5 mL of THF cooled to 0 °C was added dropwise 0.29 g (1.30 mmol) of phosphorane A over a 10-min period. The resulting mixture was stirred an additional 30 min at 0 °C. Next 0.32 g (1.17 mmol) of aldehyde **27** in 1 mL of THF was added dropwise over 15 min. Upon completion of the addition, the resulting mixture was slowly brought to reflux for 10 h. The crude product (0.26 g) was purified by chromatography on silica gel (elution with hexane/ether, 4:1) to give 150 mg (37%) of the α,β-unsaturated ester which was homogeneous on analysis (hexane/ether, 1:1, R_f(**27**) = 0.87, R_f(**1**) = 0.67): NMR ($CDCl_3$) δ 0.13 (s, 9 H), 1.4 (t, 3 H, J = 7 Hz), 1.68 (s, 2 H), 2.58 (s, 2 H), 1.60–3.40 (m, 10 H), 4.27 (q, 2 H, J = 7 Hz), 4.78 (br s, 2 H), 6.53 (AB q, 2 H, $\Delta\nu_{AB}$ = 36 Hz, J = 15 Hz); MS, m/z 344 (M^+).

(*E*)-2-[2-[(Trimethylsilyl)methyl]allyl]-*m*-dithiane-2-acrylonitrile (2). To a suspension of 31.0 mg (1.29 mmol) of sodium hydride (50%) in 5 mL of THF cooled to 0 °C was added 0.23 g of phosphorane B dropwise over 10 min. The resulting mixture was stirred an additional 30 min at 0 °C. Next, 0.30 g (1.17 mmol) of aldehyde **27** in 1 mL of THF was added dropwise over 15 min while the temperature of the reaction mixture was maintained at 0 °C. When the addition was completed the mixture was warmed slowly to reflux and then refluxed 12 h. The crude product (0.38 g) was purified on silica gel (hexanes/ether, 3:1) to give 0.150 g (43%) of the α,β-unsaturated nitrile which was homogeneous on TLC analysis (hexanes/ether, 3:1, R_f(**27**) 0.91, R_f(**2**) 0.68): NMR ($CDCl_3$) δ 0.10 (s, 9 H), 1.60 (s, 2 H), 2.45 (s, 2 H), 1.70–3.00 (m, 8 H) 4.70 (br s, 2 H), 6.15 (AB q, 2 H, $\Delta\nu_{AB}$ = 42 Hz, J = 10 Hz); IR (film) 3090, 2960, 2910, 2235, 1630, 1425, 1250, 1160, 970, 850, 615 cm^{-1}; MS, m/z 297 (M^+).

(*E*)-2-[2-[(Trimethylsilyl)methyl]allyl]-*m*-dithiane-3-propen-2-one (3). To a suspension of 30.0 mg (1.32 mmol) of sodium hydride (50%) in 5 mL of THF cooled to 0 °C was added 0.26 g (1.32 mmol) of Wittig reagent C dropwise over 10 min. The resulting mixture was stirred an additional 30 min at 0 °C. Next 0.30 g (1.10 mmol) of aldehyde **27** in 1 mL of THF was added dropwise over 15 min while the temperature of the reaction mixture was maintained at 0 °C. Upon completion of the addition, the resulting mixture was refluxed for 10 h. The crude product (0.29 g) was purified on silica gel (hexanes/ether, 3:2) to give 230 mg (67%) of the α,β-unsaturated ketone **3** which was homogeneous on TLC analysis (hexane/ether, 3:2, R_f(**27**) 0.82, R_f(**3**) 0.46): NMR ($CDCl_3$) δ 0.11 (s, 9 H), 1.70 (s, 2 H), 1.80–3.05 (m, 11 H), 2.32 (s, 3 H) 2.54 (s, 2 H), 4.72 (br s, 2 H), 6.60 (AB q, 2 H, $\Delta\nu_{AB}$ = 18 Hz); MS, m/z 187 (M − 127).

(*E*)-*N*,*N*-Diethyl-2-[2-[(trimethylsilyl)methyl]allyl]-*m*-dithiane-2-acrylamide (4). To a suspension of 168 mg (7.30 mmol) of sodium hydride (50%) in 15 mL of THF cooled to 0 °C was added 1.83 g (7.30 mmol) of Emmons reagent D in 5 mL of THF dropwise over 10 min. The resulting mixture was stirred an additional 30 min at 0 °C. Next 1.0 g (3.64 mmol) of aldehyde **27** in 5 mL of THF was added dropwise over 15 min while the temperature of the reaction mixture was maintained at 0 °C. Upon completion of the addition the resulting mixture was refluxed for 10 h. Usual reaction workup afforded 1.1 g of crude **4**. Purification on silica gel (hexanes/ether, 1:1) afforded 956 mg (71%) of the α,β-unsaturated tertiary amide which was homogeneous on TLC analysis (hexane/ether, 1:2, R_f(**27**) 0.74, R_f(**4**) 0.88): NMR ($CDCl_3$) δ 0.10 (s, 9 H), 1.27 (t, 6 H, J = 9 Hz), 6.67 (AB q, 2 H, $\Delta\nu_{AB}$ = 30 Hz, J = 15 Hz); IR (film) 3080, 2960, 2940, 2910, 1650, 1620, 1480, 1430, 1380, 1360, 1320, 1280, 1250, 1220, 1145, 980, 860 cm^{-1}; MS, m/z 371 (M^+).

4-[(Trimethylsilyl)methyl]pent-4-enal (28). To a solution of 2 g of silyl alcohol **25**[56] (12.48 mmol) in 6.91 mL (5.2 g, 74.88 mmol) of ethyl vinyl ether was added 200 mg of mercuric acetate, and the resulting mixture was heated at reflux for 48 h. The reaction vessel was fitted with a distilling head and the distillate removed until a vapor temperature of 60 °C is attained. Distillation was then continued at reduced pressure (water aspirator), providing 2.17 g (93%) of the expected vinyl enol ether as a clear oil (bp 75–80 °C, 10 torr): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.52 (s, 2 H), 3.8–4.25 (m, 4 H), 4.6–4.9 (m, 2 H), 6.27 (dd, 1 H, J = 15 Hz, 6 Hz).

The above distilled allyl vinyl ether (760 mg, 4.08 mmol) was placed in a vacuum sealed tube. This tube was placed in an oil bath and the bath temperature slowly raised to 130 °C. After 13 h, the tube was cooled to room temperature and opened. The reaction mixture was directly distilled to afford 730 mg (95%) of aldehyde **28** (bp 65–70 °C, 1 torr): NMR (CCl_4) δ 0.00 (s, 9 H), 1.43 (s, 2 H), 2.05–2.6 (m, 4 H), 4.38 (br s, 2 H), 9.5 (s, 1 H); IR (film) 3065, 2950, 1725, 1630, 1415, 1250, 1130, 1100, 850 cm^{-1}.

Benzyl (*E*)-6-Methylene-7-(trimethylsilyl)-2-heptenoate (5). To a suspension of 104 mg (2.16 mmol) of 50% sodium hydride in 10 mL of THF cooled to 0 °C was added a solution of 582 mg (2.25 mmol) of phosphorane A in 2 mL of THF dropwise over a 10-min period. The resulting mixture was stirred an additional 30 min at 0 °C. To this mixture was added a solution of 350 mg (1.88 mmol) of distilled aldehyde **28** in 3 mL of THF over a 15-min period. The resulting mixture was refluxed for 12 h. The crude product (260 mg) was purified on silica gel (elution with hexanes/ether, 3:1) to provide 396 mg (66%) of **5** which was homogeneous by TLC analysis (R_f(**28**) 0.57, R_f(**5**) 0.77): NMR (CCl_4) δ 0.00 (s, 9 H), 1.5 (s, 2 H), 1.8–2.54 (m, 4 H), 4.3–4.5 (m,

(54) Stork, G.; Danheiser, R. L. *J. Org. Chem.* **1973**, *38*, 1175.
(55) Meyers, A. I.; Strickland, R. C. *J. Org. Chem.* **1972**, *37*, 2579.
(56) Trost, B. M.; Chan, D. M. T.; Nanninga, T. N. *Org. Synth.* **1984**, *62*, 58.

2 H), 5.00 (s, 2 H), 5.7 (s, 2 H), 5.7 (d, 1 H, J = 15 Hz), 6.65–7.10 (m, 1 H), 7.2 (s, 5 H); MS, m/z 240 (M^+).

(*E*)-6-Methylene-7-(trimethylsilyl)-2-heptenenitrile (6). To a suspension of 133 mg (2.78 mmol) of 50% sodium hydride in 5 mL of THF cooled to 0 °C was added dropwise a solution of 517 mg (2.90 mmol) of phosphorane B over a 10-min period. The resulting mixture was stirred an additional 30 min at 0 °C and then a solution of 450 mg (2.42 mmol) of silyl aldehyde **28** was added dropwise over 15 min while the temperature of the reaction mixture was maintained at 0 °C. After complete addition, the mixture was refluxed for 10 h. The crude product was purified on silica gel and provided 272 mg (54%) of **6** which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**28**) 0.63, R_f(**6**) 0.50): NMR (CCl_4) δ 0.00 (s, 9 H), 1.47–1.58 (m, 2 H), 1.8–2.7 (m, 4 H), 4.55 (br s, 2 H), 5.05–5.40 (m, 1 H), 6.1–6.8 (m, 1 H); MS, m/z 178 (M − 15).

(*E*)-7-Methylene-8-(trimethylsilyl)-3-octen-2-one (7). A solution of 0.35 g (2.06 mmol) of aldehyde **28** and 0.655 g (2.06 mmol) of Wittig reagent C in 20 mL of benzene was stirred at room temperature for 20 h. The reaction mixture was quenched with reagent grade ether, filtered, concentrated, and diluted with 15 mL of water. This mixture was extracted with 3 × 25 mL portions of ether. The combined ethereal extracts were washed with brine, dried over anhydrous magnesium sulfate, and filtered, and the solvent was removed in vacuo. The crude residue obtained was purified via chromatography on silica gel (elution with hexanes/ether, 4:1) to afford 158 mg (39%) of **7**: NMR (CCl_4) δ 0.00 (s, 9 H), 1.5 (s, 2 H), 2.1 (s, 3 H), 1.8–2.2 (m, 7 H), 4.45–4.63 (m, 2 H), 5.90 (d, 1 H, J = 15 Hz), 6.52 (dt, 1 H, J = 15 Hz, J = 6 Hz).

(*E*)-*N*,*N*-Diethyl-6-methylene-7-(trimethylsilyl)-2-heptenamide (8). To a suspension of 65 mg (1.352 mmol) of 50% sodium hydride in 3 mL of THF cooled to 0 °C was added dropwise a solution of 340 mg (1.352 mmol) of phosphorane D over a 10-min period. The resulting mixture was stirred an additional 30 min at 0 °C and a solution of 230 mg (1.352 mmol) of silyl aldehyde **28** was added dropwise over 15 min while the temperature of the reaction was maintained at 0 °C. The reaction mixture was allowed to slowly warm to room temperature and stirred at room temperature for 7 h. The reaction was quenched with reagent grade ether (10 mL) and the solvent was removed under reduced pressure. Standard ethereal workup provided a crude residue. Purification of this residue on silica gel (elution with hexanes/ether, 2:1) afforded 169 mg (36%) of **8** which was homogeneous by TLC analysis (hexanes/ether, 2:1, R_f(**28**) 0.80, R_f(**8**) 0.23): NMR (CCl_4) δ 0.00 (s, 9 H), 1.15 (t, 6 H, J = 5 Hz), 1.55 (s, 2 H), 1.6–2.4 (m, 4 H), 3.35 (q, 4 H, J = 5 Hz), 4.47 (br s, 1 H), 4.55 (br s, 1 H), 6.05 (d, 1 H, J = 15 Hz), 6.65 (dt, 1 H, J = 15 Hz, J = 6 Hz); IR (film) 3080, 2965, 2930, 1660, 1620, 1480, 1435, 1380, 1360, 1265, 1145, 970, 860 cm^{-1}.

3-Ethoxy-6-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (29). To a solution of lithium diisopropylamide, prepared from 0.65 mL (4.64 mmol) of diisopropylamine in 4 mL of freshly distilled THF and 2.7 mL (4.32 mmol) of *n*-butyllithium (1.60 M in hexane) at −78 °C, was added a solution of 0.5 g (3.57 mmol) of 3-ethoxy-2-cyclohexen-1-one in 4 mL of THF containing 0.81 mL (4.64 mmol) of HMPA over 30 min (via syringe pump). After an additional $^1/_2$ h at −78 °C, the reaction mixture was warmed to 0 °C and allowed to stir at 0 °C for 3 h. The reaction mixture was again cooled to −78 °C and 1.27 g (5.00 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 1 h and then allowed to gradually warm to room temperature over 13 h. The crude product (811 mg) was purified on silica gel (hexanes/ether, 1:1) to give 0.660 g (69%) of **29** which was homogeneous on TLC analysis (hexane/ether, 1:1, R_f (starting ketone) 0.15, R_f(**29**) 0.38): NMR (CCl_4) δ 0.00 (s, 9 H), 1.28 (t, 3 H, J = 8 Hz), 1.35 (s, 2 H), 1.1–2.8 (m, 12 H), 3.75 (q, 2 H, J = 8 Hz), 4.4 (s, 2 H), 5.05 (s, 1 H); IR (film) 3060, 2950, 1660, 1610, 1480, 1455, 1425, 1380, 1360, 1315, 1250, 1200, 1120, 1040, 1030, 980, 850, 775, 700 cm^{-1}.

3-Ethoxy-6-methyl-6-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (30). To a solution of lithium diisopropylamide, prepared from 0.59 mL (4.22 mmol) of diisopropylamine in 2 mL of freshly distilled THF and 2.44 mL (3.90 mmol, 1.60 M in hexanes) of *n*-butylltihium at −78 °C, was added a solution of 0.50 g (3.25 mmol) of 3-ethoxy-5-methyl-2-cyclohexen-1-one in 3 mL of THF containing 0.70 mL (3.90 mmol) of HMPA over 25 min. After an additional 1.5 h at −78 °C, 1.15 g (4.55 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 1 h and then stirred at room temperature for 4 h. Purification of the oily residue (0.598 g) on silica gel (hexanes/ether, 3:1) afforded 0.532 g (59%) of **30** which was homogeneous on TLC analysis (hexane/ether, 3:1, R_f(**30**) 0.60): NMR (CCl_4) δ 0.00 (s, 9 H), 0.92 (s, 3 H), 1.28 (t, 3 H, J = 8 Hz), 1.30 (s, 2 H), 1.1–2.6 (m, 11 H), 3.87 (q, 2 H, J = 8 Hz), 4.38 (m, 2 H), 5.00 (s, 1 H); IR (film) 3070, 2955, 1655, 1610, 1460, 1380, 1360, 1315, 1250, 1195, 1115, 1040, 850, 790, 700, 650 cm^{-1}.

3-Ethoxy-2-methyl-6-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (31). To a solution of lithium diisopropylamide, prepared from 0.55 mL (3.90 mmol) of diisopropylamine in 5 mL of freshly distilled THF and 2.23 mL of *n*-butyllithium (3.57 mmol, 1.60 M in hexane) at −78 °C, was added a solution of 0.5 g of 3-ethoxy-2-methyl-2-cyclohexen-1-one (3.25 mmol) in 8 mL of THF containing 0.87 g (4.88 mmol) of HMPA over a 30-min period (via syringe pump). After an additional 30 min at −78 °C, 1.07 g (4.22 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 1 h and then allowed to gradually warm to room temperature over 13 h. Standard ethereal workup afforded on oily residue which was chromatographed on silica gel (elution with hexane/ether, 2:1) to provide 657 mg (72%) of **31** which was homogeneous on TLC analysis (hexane/ether, 2:1, R_f (starting ketone) 0.17, R_f(**31**) 0.77): NMR (CCl_4) δ 0.00 (s, 9 H), 1.23 (t, 3 H, J = 8 Hz), 1.38 (s, 2 H), 1.53 (br s, 3 H), 1.60–2.66 (m, 7 H), 3.80 (q, 2 H, J = 8 Hz), 4.40 (s, 2 H); IR (film) 3080, 2950, 1625, 1460, 1420, 1380, 1360, 1335, 1250, 1165, 1125, 1000, 940, 850, 790, 700 cm^{-1}.

2,6-Dimethyl-3-ethoxy-6-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (32). To a solution of lithium diisopropylamide, prepared from 0.55 mL (3.90 mmol) of diisopropylamine in 5 mL of freshly distilled THF and 2.3 mL of *n*-butyllithium (3.57 mmol, 1.55 M in hexane) at −78 °C, was added a solution of 0.5 g of 3-ethoxy-2,6-dimethyl-2-cyclohexen-1-one (3.25 mmol) in 7 mL of THF containing 582 mg (3.25 mmol) of HMPA over a 30-min period (via syringe pump). After an additional 2 h at −78 °C, 1.1 g (4.22 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 1 h and then allowed to gradually warm to room temperature overnight (12 h). The crude product (612 mg) was purified on silica gel (hexanes/ether, 3:1) and yielded 512 mg (56%) of **32** which was homogeneous on TLC analysis (hexane/ether, 2:1, R_f (starting ketone) 0.29, R_f(**32**) 0.71): NMR (CCl_4) δ 0.00 (s, 9 H), 0.93 (s, 3 H), 1.54 (br s, 3 H), 1.60–2.53 (m, 6 H), 3.64 (s, 3 H), 4.30–4.40 (bs, 2 H); IR (film) 3080, 2960, 1630, 1385, 1355, 1250, 1120, 1020, 850, 775, 700, 650 cm^{-1}.

4-[2-[(Trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (9). To a suspension of 110 mg (2.98 mmol) of LAH in 15 mL of dry THF at 0 °C was added dropwise a solution of 0.66 g (2.48 mmol) of ketone **29** in 3 mL of dry THF over a 5-min period. The reaction was stirred at 0 °C for 2 h and quenched with reagent grade ether. Evaporation of the solvent, after filtration to remove suspended matter, afforded the crude alcohol which was used without purification or characterization.

A solution of the above crude alcohol in 5 mL of THF was treated with 5 drops of 1 N aqueous HCl solution and stirred at room temperature for 30 min. The reaction was diluted with 30 mL of ether and solid anhydrous potassium carbonate was added. The reaction mixture was filtered and concentrated in vacuo. The resulting residue was chromatographed on silica gel (hexanes/ether, 1:1) to provide 370 mg (67%) of **9** which was homogeneous on TLC analysis (hexane/ether, 1:1, R_f(**29**) 0.38, R_f(**9**) 0.63): NMR (CCl_4) δ 0.00 (s, 9 H), 1.43 (s, 2 H), 1.93 (d, 2 H, J = 8 Hz), 1.40–2.50 (m, 7 H), 4.50 (s, 2 H), 5.56 (ABS, 1 H, J_{AB} = 10 Hz; J_{BX} = 3 Hz; J_{AX} = 1 Hz), 6.38 (ABX, 1 H, J_{AB} = 10 Hz; J_{BX} = 3 Hz; J_{AX} = 1 Hz); IR (film) 3080, 3030, 2950, 1680, 1635, 1455, 1420, 1390, 1350, 1290, 1255, 1215, 1160, 1070, 980, 850, 700 cm^{-1}; MS, m/z 222 (M^+).

4-Methyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (10). To a suspension of 39 mg (1.03 mmol) of LAH in 2 mL of anhydrous THF at 0 °C was added a solution of 261 mg (0.93 mmol) of ketone **30** in 1 mL of anhydrous THF over a 5-min period. The reaction was stirred at 0 °C for 2 h and quenched with reagent grade ether. Evaporation of the solvent,

after filtration to remove suspended matter, afforded 260 mg of crude alcohol which was used without further purification or characterization.

A solution of 260 mg of crude alcohol in 3 mL of THF was treated with 3 drops of 1 N aqueous HCl solution and stirred at room temperature for 30 min. The reaction was diluted with 15 mL of ether, and solid anhydrous potassium carbonate was added. The reaction solution was filtered and concentrated in vacuo. The resulting residue was chromatographed on silica gel (hexane/ether, 2:1) to afford 143 mg (65%) of **10** which was homogeneous by TLC analysis (hexane/ether, 1:1, R_f(**30**) 0.67, R_f(**10**) 0.79): IR (film) 3070, 3025, 2950, 1680, 1630, 1460, 1420, 1390, 1370, 1250, 1160, 860, 700 cm^{-1}; NMR (CCl_4) δ 0.00 (s, 9 H) 1.06 (s, 3 H), 1.45, (s, 2 H), 1.3–1.9 (m, 2 H), 2.00 (s, 2 H), 2.23 (t, 2 H, J = 6 Hz), 4.43 (br s, 1 H), 4.52 (br s, 1 H), 6.00 (AB q, 2 H, $\Delta\nu_{AB}$ = 38 Hz, J = 10 Hz); MS, m/z 236 (M^+). Anal. Calcd for $C_{14}H_{24}OSi$: C, 71.12; H, 10.23. Found: C, 70.87; H, 10.23.

2-Methyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (11). To a solution of ketone **31** (561 mg, 2.0 mmol) in 6.7 mL of anhydrous toluene cooled to 0 °C was added dropwise 2.2 mL of DIBAL (2.2 mmol, 1.0 M in toluene) over a 10-min period. The reaction was allowed to stir at 0 °C. Upon completion ($^1/_2 \rightarrow 2$ h), the reaction was quenched by the dropwise addition of a saturated aqueous solution of ammonium chloride, diluted with ether, and washed with 2 × 15 mL portions of cold 5% HCl. The ether layer was concentrated to provide the crude alcohol which was used without further purification.

The crude alcohol was diluted with 20 mL of THF and 7 drops of 10% HCl were added. The resulting solution was stirred at room temperature for 30 min. The mixture was quenched with anhydrous potassium carbonate and diluted with ether; filtration and evaporation of the solvent provided 301 mg of an oily residue. Purification on silica gel (elution with hexanes/ether, 2:1) furnished 244 mg (52%) of **11** which was homogeneous by TLC analysis (hexanes/ether, 2:1, R_f(**31**) 0.80, R_f(**11**) 0.87); NMR (CCl_4) δ 0.00 (s, 9 H), 1.46 (s, 2 H) 1.63 (d, 3 H, J = 2 Hz), 1.76–2.60 (m, 7 H), 4.53 (s, 2 H), 6.33 (br s, 1 H); IR (film) 3080, 2960, 2930, 1685, 1640, 1455, 1425, 1170, 1290, 1255, 1165, 1120, 1100, 1045, 1035, 860, 795, 760, 700 cm^{-1}; MS, m/z 236 (M^+). Anal. Calcd for $C_{14}H_{24}OSi$: C, 71.12; H, 10.23. Found: C, 70.96; H, 10.26.

2,4-Dimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (12). To a solution of **32** (512 mg, 1.83 mmol) in 6.1 mL of anhydrous toluene cooled to 0 °C was added dropwise 1.5 mL of DIBAL (2.20 mmol, 1.5 M in toluene) over a 10-min period. The reaction was allowed to stir at 0 °C. After 90 min, the reaction was quenched by the dropwise addition of a saturated aqueous solution of ammonium chloride, diluted with ether, and washed with 2 × 15 mL portions of 5% HCl. The ether layer was concentrated to provide the crude alcohol which was used without purification.

The crude alcohol was diluted with 20 mL of THF and 7 drops of 10% HCl were added. The resulting solution was stirred at room temperature for 30 min. The mixture was quenched with anhydrous potassium carbonate and diluted with ether. Filtration and evaporation of the solvent provided 291 mg of an oily residue. Purification on silica gel (elution with hexanes/ether, 2:1) furnished 223 mg (49%) of **12** which was homogeneous on TLC analysis (hexanes/ether, 3:1, R_f(**32**) 0.69, R_f(**12**) 0.80); NMR (CCl_4) δ 0.00 (s, 9 H), 1.07 (s, 3 H), 1.49 (s, 2 H), 1.68 (br s, 3 H), 2.03 (s, 2 H), 1.46–2.4 (m, 8 H), 4.44 (br s, 1 H), 4.53 (br s, 1 H), 6.23 (br s, 1 H); IR (film) 3085, 2970, 2940, 1685, 1635, 1460, 1425, 1375, 1260, 1160, 1030, 1020, 860, 780, 700 cm^{-1}; MS, m/z 250 (M^+).

3-Methyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (13). A solution of ketone **29** (547 mg, 2.06 mmol) in 2 mL of anhydrous ether was cooled to 0 °C and treated dropwise with 2.78 mL (3.09 mmol) of a 1.6 M solution of methyllithium in ether. The reaction mixture was then stirred at room temperature for 1 h. Standard ethereal workup provided 307 mg of crude residue which was used directly in the next reaction.

The above crude alcohol was dissolved in 3 mL of THF and treated with 5 drops of a 10% aqueous solution of HCl. After stirring for 1 h at room temperature, anhydrous potassium carbonate was added, and the reaction was diluted with 20 mL of ether. Following filtration and removal of the solvent, the crude enone was chromatographed on silica gel (hexanes/ether, 1:2, R_f(**29**) 0.62, R_f(**13**) 0.65): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.43 (s, 2 H), 1.87 (s, 3 H), 1.57–2.45 (m, 10 H), 4.53 (br s, 2 H), 5.70 (br s, 1 H); IR (film) 3070, 3030, 2950, 1675, 1630, 1450, 1420, 1380, 1250, 1200, 1160, 970, 920, 860 cm^{-1}; MS, m/z 236 (M^+). Anal. Calcd for $C_{14}H_{24}OSi$: C, 71.12; H, 10.23. Found: C, 70.91; H, 10.25.

3,4-Dimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (14). A solution of ketone **30** (200 mg, 0.71 mmol) in 3 mL of anhydrous ether was cooled to 0 °C and treated dropwise with 0.53 mL (0.85 mmol) of a 1.6 M solution of methyllithium in ether. The reaction mixture was then allowed to warm to room temperature and stirred at room temperature for 12 h. Standard ethereal workup provided 165 mg of crude residue which was used directly in the next reaction.

The above crude alcohol was dissolved in 3 mL of THF and treated with 2 drops of 1 N aqueous HCl solution. After being stirred at room temperature for 2 h, the reaction was diluted with 20 mL of ether, washed with brine, dried over anhydrous magnesium sulfate, and then filtered. Following removal of the solvent, the crude enone was chromatographed on silica gel (hexane/ether; 3:1) to provide 102 mg (57%) of enone **14** (hexanes/ether, 2:1, R_f(**30**) 0.52, R_f(**14**) 0.52): NMR (CCl_4) δ 0.00 (s, 9 H), 1.13 (s, 3 H), 1.50 (s, 2 H), 1.90 (br s, 3 H), 1.67–2.57 (m, 9 H), 4.50–4.67 (m, 2 H), 5.77 (br s, 1 H); IR (neat) 3070, 2950, 1670, 1615, 1380, 1330, 1250, 1160, 1005, 850, 790 cm^{-1}; MS, m/z 250 (M^+). Anal. Calcd for $C_{15}H_{26}OSi$: C, 72.04; H, 10.46. Found: C, 71.88; H, 10.49.

2,3-Dimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (15). A solution of ketone **31** (414 mg, 1.48 mmol) in 2 mL of THF was treated dropwise with 0.66 mL (1.92 mmol) of a 2.9 M solution of methylmagnesium chloride at room temperature. The reaction mixture was stirred at room temperature for 2 h, prior to ethereal workup. The crude product (421 mg) was used immediately in the next step.

The above crude alcohol was dissolved in 4 mL of THF and treated with 6 drops of a 10% aqueous solution of HCl. After stirring for 1 h at room temperature, solid anhydrous potassium carbonate was added. The resulting mixture was stirred for 10 min, diluted with 30 mL of ether, and then filtered to remove suspended matter. Following removal of the solvent, the crude enone was chromatographed on silica gel (elution with hexane/ether, 2:1) to afford 214 mg (58%) of **15** which was homogeneous on TLC analysis (hexanes/ether, 2:1, R_f(**31**) 0.77, R_f(**15**) 0.76): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.45 (s, 2 H), 1.67 (br s, 3 H) 1.85 (br s, 3 H), 1.5–2.7 (m, 13 H), 4.55 (br s, 2 H); IR (film) 3070, 2950, 1660, 1630, 1450, 1520, 1380, 1345, 1310, 1250, 1205, 1160, 1080, 920, 860, 775, 740 cm^{-1}; MS, m/z 250 (M^+). Anal. Calcd for $C_{15}H_{26}OSi$: C, 72.04; H, 10.46. Found: C, 72.18; H, 10.63.

2,3,4-Trimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-one (16). A solution of ketone **32** (264 mg, 0.90 mmol) in 2 mL of THF was treated dropwise with 0.57 mL (0.99 mmol) of a 1.75 M solution of methyllithium in ether at room temperature. The reaction mixture was allowed to stir at room temperature for 13 h, followed by warming to 50 °C for 2 h. The reaction was quenched with a solution of aqueous 10% HCl and allowed to stir for 30 min at room temperature. The reaction mixture was diluted with 70 mL of ether, dried over anhydrous potassium carbonate, and filtered, and then the solvents were removed in vacuo. The crude residue was chromatographed on silica gel (hexanes/ether, 4:1) to provide 140 mg (59%) of **16** which was homogeneous by TLC analysis (hexanes/ether, 4:1, R_f(**32**) 0.50, R_f(**16**) 0.57): NMR (CCl_4) δ 0.00 (s, 9 H), 1.17 (s, 3 H), 1.52 (s, 2 H), 1.72 (s, 3 H), 1.88 (s, 3 H), 1.6–2.35 (m, 10 H), 4.52 (br s, 1 H), 4.59 (br s, 1 H); IR (film) 3075, 2950, 1665, 1630, 1615, 1460, 1420, 1340, 1305, 1250, 1160, 850 cm^{-1}; MS, m/z 264 (M^+). Anal. Calcd for $C_{16}H_{28}OSi$: C, 72.66; H, 10.67. Found: C, 72.70; H, 10.70.

3-Ethoxy-5-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (33). To a solution of lithium diisopropylamide, prepared from 0.52 mL (3.68 mmol) of diisopropylamine in 1 mL of freshly distilled tetrahydrofuran and 2.11 mL of n-butyllithium (3.38 mmol, 1.60 M in hexanes) at −78 °C, was added a solution of 0.430 g (3.07 mmol) of 3-ethoxy-2-cyclopenten-1-one in 2 mL of THF containing 0.82 g (4.60 mmol) of HMPA dropwise over a 10-min period. After an additional 90 min at −78 °C, 1.01 g (3.99 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 1 h and then allowed to gradually warm to room temperature over 10 h. The reaction was quenched at room

temperature with solid ammonium chloride and filtered, and the solvent was removed under reduced pressure to afford 398 mg of crude **33**. Purification on silica gel (elution with hexanes/ether, 3:1) produced 0.346 g (42%) of the desired alkylated material which was homogeneous on TLC analysis (hexanes/ether, 3:1, R_f(starting ketone) 0.12, R_f(**33**) 0.29): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.13 (s, 3 H), 1.37 (t, 3 H, J = 7 Hz), 1.45 (s, 2 H), 2.15 (AB q, 2 H, $\Delta\nu_{AB}$ = 15 Hz, J = 14 Hz), 2.54 (AB q, 2 H, $\Delta\nu_{AB}$ = 28 Hz, J = 15 Hz), 3.97 (q, 2 H, J = 7 Hz), 5.00 (m, 2 H), 5.12 (s, 1 H); IR (film) 3070, 2950, 1695, 1625, 1595, 1375, 1340, 1250, 1030, 860 cm^{-1}.

3-Ethoxy-5-methyl-5-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (34). To a solution of lithium diisopropylamide, prepared from 0.89 mL (6.35 mmol) of diisopropylamine in 2 mL of freshly distilled THF and 3.64 mL of n-butyllithium (5.82 mmol, 1.60 M in hexanes) at −78 °C, was added a solution of 0.74 g (5.29 mmol) of 3-ethoxy-5-methyl-2-cyclopenten-1-one in 2 mL of THF containing 1.42 g (7.94 mmol) of HMPA dropwise over a 30-min period. After an additional 1 h at −78 °C, 1.75 g (6.88 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 90 min and then allowed to gradually warm to room temperature over 11 h. The reaction was quenched at room temperature with solid ammonium chloride. Filtration and evaporation of the solvent afforded 712 mg of crude **34**. Purification on silica gel (elution with hexanes/ether, 1:2) afforded 644 mg (50%) of **34** which was homogeneous by TLC analysis (hexanes/ether, 1:2, R_f(starting ketone) 0.26, R_f(**34**) 0.63): NMR ($CDCl_3$) δ (s, 9 H), 1.34, (t, 3 H, J = 7 Hz), 1.45 (s, 2 H), 1.54–2.85 (m, 5 H), 3.95 (q, 7 Hz), 4.48 (s, 2 H), 5.4 mg, 5012 (s, 2 H); IR (film) 3080, 2950, 1695, 1600, 1430, 1345, 1285, 1250, 1180, 1030, 860 cm^{-1}.

3-Ethoxy-2-methyl-5-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (35). To a solution of lithium diisopropylamide, prepared from 0.48 mL (3.43 mmol) of diisopropylamine in 1 mL of freshly distilled THF and 1.26 mL of n-butyllithium (3.15 mmol, 2.5 M in hexanes) at −78 °C, was added a solution of 400 mg (2.86 mmol) of 3-ethoxy-2-methyl-2-cyclopenten-1-one in 1 mL of THF containing 0.51 g (2.86 mmol) of HMPA dropwise over a 30-min period. After 90 min at −78 °C, 0.94 g (3.72 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 1 h and then gradually allowed to warm to room temperature over 10 h. The reaction was quenched with solid ammonium chloride, diluted with ether, and filtered, and the solvent was removed in vacuo to afford 420 mg of crude **35**. Purification on 10 g of silica gel (elution with hexanes/ether, 1:1) provided 359 mg (47%) of the alkylated material **35** which was homogeneous by TLC analysis (hexanes/ether, 1:1, R_f(starting ketone) 0.12, R_f(**35**) 0.68): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.33 (t, 3 H, J = 7 Hz), 1.47 (s, 2 H), 1.57 (br s, 3 H), 1.70–2.87 (m, 5 H), 4.10 (q, 2 H, J = 7 Hz), 4.49 (br s, 2 H); IR (film) 3080, 2995, 2960, 2930, 1700, 1640, 1480, 1390, 1340, 1250, 1140, 1060, 1025, 980, 860 cm^{-1}.

2,5-Dimethyl-3-ethoxy-5-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (36). To a solution of lithium diisopropylamide, prepared from 0.54 mL (3.90 mmol) of diisopropylamine in 1 mL of freshly distilled THF and 3.25 mL of n-butyllithium (3.57 mmol, 1.1 M in hexanes) at −78 °C, was added a solution of 500 mg (3.25 mmol) of 3-ethoxy-2,5-dimethyl-2-cyclopenten-1-one in 1 mL of THF containing 0.58 g (3.25 mmol) of HMPA dropwise over a 15-min period. After 90 min at −78 °C, 1.1 g (4.22 mmol) of silyl iodide **26** was added. The reaction was stirred at −78 °C for 1 h and then gradually allowed to warm to room temperature over 13 h. The reaction was quenched with solid ammonium chloride, diluted with ether, and filtered, and the solvent was removed in vacuo to afford 512 mg of crude **36**. Purification on silica gel (elution with hexanes/ether, 1:2) afforded 455 mg (50%) of **36** which was homogeneous by TLC analysis (hexanes/ether, 1:2, R_f(starting ketone) 0.37, R_f(**36**) 0.83): NMR (CCl_4) δ 0.00 (s, 9 H) 1.03 (s, 3 H), 1.30 (s, 2 H), 1.33 (t, 3 H, J = 7 Hz), 2.10 (AB q, 2 H, $\Delta\nu_{AB}$ = 13 Hz, J = 11 Hz), 2.43 (AB q, 2 H, $\Delta\nu_{AB}$ = 30 Hz, J = 16 Hz), 4.07 (q, 2 H, J = 7 Hz), 4.33–4.45 (m, 2 H).

4-[2-[(Trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (17). To a solution of ketone **33** (821 mg, 3.26 mmol) in 10.9 mL of toluene at 0 °C was added dropwise 3.6 mL of DIBAL (3.60 mmol, 1.0 M in toluene) over 20 min. The reaction was allowed to stir at 0 °C. Upon completion, ($^1/_2 \rightarrow$ 2 h), the reaction was quenched by the dropwise addition of a saturated aqueous solution of ammonium chloride, diluted with ether, and washed with 2 × 15 mL portions of 5% HCl. The ether layer was concentrated to provide the crude alcohol which was used without further purification.

The crude alcohol was diluted with 25 mL of THF and 8 drops of 10% HCl were added. The resulting solution was stirred at room temperature for 30 min. The solution was neutralized with anhydrous potassium carbonate and diluted with ether. Filtration and evaporation of the solvent provided 400 mg of oily residue. Purification on silica gel (elution with hexanes/ether, 1:2) furnished 339 mg (50%) of **17** which was homogeneous on TLC analysis (hexanes/ether, 1:2, R_f(**33**) 0.60, R_f(**17**) 0.79): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.50 ns, 2 H), 1.80–2.73 (m, 4 H), 2.70–3.0 (m, 1 H), 4.61 (s, 2 H), 6.1 (dd, 1 H J = 6 Hz, 2 Hz), 6.59 (dd, 1 H, J = 6 Hz, 2 Hz); IR (film) 3080, 2960, 1715, 1635, 1585, 1410, 1350, 1255, 1180, 850, 780, 700 cm^{-1}; MS, m/z 208 (M^+). Anal. Calcd for $C_{12}H_{20}OSi$: C, 69.16; H, 9.67. Found: C, 69.18; H, 9.63.

4-Methyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (18). To a solution of ketone **34** (509 mg, 1.91 mmol) in 6.4 mL of anhydrous toluene cooled to 0 °C was added dropwise 2.1 mL of DIBAL (2.1 mmol, 1.0 M in toluene) over a 15-min period. The reaction was allowed to stir at 0 °C. Upon completion, ($^1/_2 \rightarrow$ 2 h), the reaction was quenched by the dropwise addition of a saturated aqueous solution of ammonium chloride, diluted with ether, and washed with 2 × 15 mL portions of 5% HCl. The ether layer was concentrated to provide a crude alcohol which was used without purification.

The crude alcohol was diluted with 20 mL of THF and 6 drops of 10% HCl were added. The resulting solution was stirred at room temperature for 30 min. The solution was neutralized with anhydrous potassium carbonate and diluted with ether. Filtration and evaporation of the solvent provided 200 mg of an oily residue. Purification on silica gel (elution with hexane/ether, 1:2) furnished 242 mg (57%) of **18** which was homogeneous on TLC analysis (hexanes/ether, 1:2, R_f(**34**) 0.79, R_f(**18**) 0.93): NMR (CCl_4) δ 0.00 (s, 9 H), 1.18 (s, 3 H), 1.43 (s, 2 H), 2.10 (s, 2 H), 2.13 (AB q, $\Delta\nu_{AB}$ = 18 Hz), 4.48 (br s, 1 H), 4.51 (br s, 1 H), 5.78 (d, 1 H, J = 6 Hz), 7.23 (d, 1 H, J = 6 Hz); IR (film) 3070, 2950, 2920, 1715, 1630, 1590, 1455, 1410, 1375, 1250, 1190, 1150, 1100, 1060, 850, 800 cm^{-1}; MS, m/z 222 (M^+).

2-Methyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (19). To a solution of ketone **35** (470 mg, 1.80 mmol) in 6.0 mL of toluene cooled to 0 °C was added dropwise 1.40 mL of DIBAL (2.17 mmol, 1.50 M in toluene) over a 10-min period. The reaction was allowed to stir at 0 °C. Upon completion, the reaction was quenched by the dropwise addition of a saturated aqueous solution of ammonium chloride. Standard ethereal workup provided the crude alcohol which was used without purification.

The crude alcohol was diluted with 20 mL of THF and 6 drops of 10% HCl were added. The resulting solution was stirred at room temperature for 30 min. The solution was neutralized with anhydrous potassium carbonate and diluted with ether (60 mL). Filtration and evaporation of the solvent provided 225 mg of an oily residue. Purification on silica gel (elution was hexanes/ether, 3:1) furnished 203 mg (51%) of **19** which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**35**) 0.21, R_f(**19**) 0.36): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.43 (s, 2 H), 1.64 (br s, 3 H), 1.72–2.65 (m, 4 H), 2.7–3.0 (m, 1 H) 4.38–4.57 (m, 2 H) 6.93 (br s, 1 H); IR (film) 3070, 2960, 2930, 1705, 1630, 1410, 1380, 1335, 1250, 1200, 1160, 1080, 1000, 850, 760 cm^{-1}; MS, m/z 222 (M^+).

2,4-Dimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (20). To a solution of ketone **36** (443 mg, 1.58 mmol) in 5.3 mL of toluene cooled to 0 °C was added dropwise 1.9 mL of DIBAL (1.90 mmol, 1.0 M in toluene) over a 10-min period. The reaction was allowed to stir at 0 °C. Upon completion ($^1/_2 \rightarrow$ 2 h), the reaction was quenched by the dropwise addition of a saturated aqueous solution of ammonium chloride, diluted with ether, and washed with 2 × 15 mL portions of 5% HCl. The ether layer was concentrated to provide the crude alcohol which was used without purification.

The crude alcohol was diluted with 15 mL of THF and 5 drops of 10% HCl were added. The resulting solution was stirred at room temperature for 30 min. The solution was neutralized with anhydrous potassium carbonate and diluted with ether. Filtration

and evaporation of the solvent provided 171 mg of an oily residue. Purification on silica gel (elution with hexanes/ether, 1:2) furnished 161 mg (45%) of **20** which was homogeneous by TLC analysis (hexanes/ether, 1:2, R_f(**36**) 0.80, R_f(**20**) 0.90): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.13 (s, 3 H), 1.37 (s, 2 H), 1.63 (s, 3 H), 2.03 (s, 2 H), 4.37–4.56 (m, 2 H), 6.8 (s, 1 H); IR (film) 3080, 3050, 2970, 2940, 1715, 1635, 1500, 1460, 1420, 1380, 1330, 1210, 1160, 1080, 885, 860, 800 cm^{-1}; MS, m/z 222 (M − 15). Anal. Calcd for $C_{14}H_{24}OSi$: C, 71.12; H, 10.23. Found: C, 71.14; H, 10.20.

3-Methyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (21). A solution of **33** (200 mg, 0.79 mmol) in anhydrous ether (4 mL) at 0 °C was treated with methyllithium (1.0 mL, 1.55 M solution in ether). The reaction mixture was stirred at 0 °C for 1 h and quenched with an aqueous solution of saturated ammonium chloride. Standard ethereal workup provided an alcohol which was used without characterization.

The crude alcohol was dissolved in 5 mL of THF and treated with 5 drops of a 10% aqueous solution of HCl. After stirring for 1 h at room temperature, anhydrous potassium carbonate was added, and the reaction was diluted with 20 mL of ether. Following filtration and evaporation of the solvent, the oily residue was purified on silica gel (elution with hexanes/ether, 1:1) to afford 103 mg (62%) of **21** which was homogeneous by TLC analysis (hexanes/ether, 1:1, R_f(**33**) 0.35, R_f(**21**) 0.65): NMR (CCl_4) δ 0.00 (s, 9 H) 1.45 (s, 2 H), 2.05 (s, 3 H), 1.2–3.0 (m, 10 H), 4.5 (b, 2 H), 4.63 (br s, 1 H); IR (film) 3060, 2950, 2920, 1690, 1620, 1375, 1310, 1250, 1180, 860 cm^{-1}; MS, m/z 222 (M^+). Anal. Calcd for $C_{13}H_{22}OSi$: C, 69.69; H, 9.97. Found: C, 69.90; H, 9.99.

3,4-Dimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (22). A solution of **34** (535 mg, 2.01 mmol) in anhydrous ether (6 mL) at 0 °C was treated with methyllithium (2.70 mL, 1.55 M solution in ether). The reaction mixture was stirred at 0 °C for 1 h. Standard ethereal workup afforded a crude alcohol which was used without characterization.

The crude alcohol was dissolved in 20 mL of THF and treated with 8 drops of a 10% aqueous solution of HCl. After stirring for 1 h at room temperature, anhydrous potassium carbonate was added, and the reaction was diluted with 20 mL of ether. Following filtration and evaporation of the solvent, the oily residue was purified on silica gel (elution with hexanes/ether, 3:1) to afford 304 mg (62%) of **22** which was homogeneous by TLC analysis (hexanes/ether, 1:1, R_f(**34**) 0.53, R_f(**22**) 0.61): NMR (CCl_4) δ 0.00 (s, 9 H), 1.17 (s, 3 H), 1.40 (s, 2 H), 1.97 (br s, 3 H), 2.09 (s, 2 H), 1.5–2.6 (m, 7 H), 4.48 (br s, 1 H), 4.55 (br s, 1 H), 5.60 (br s, 1 H); IR (film) 3070, 2960, 1700, 1620, 1420, 1380, 1310, 1255, 1200, 1160, 1030, 860 cm^{-1}. Anal. Calcd for $C_{14}H_{24}OSi$: C, 71.12; H, 10.23. Found: C, 70.99; H, 10.24.

2,3-Dimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (23). A solution of **35** (520 mg, 2.06 mmol) in anhydrous ether (3 mL) at 0 °C was treated with methyllithium (2.70 mL, 1.55 M solution in ether). The reaction mixture was stirred at 0 °C for 1 h. The crude alcohol was used without characterization following standard ethereal workup.

The crude alcohol was dissolved in 20 mL of THF and treated with 8 drops of a 10% aqueous solution of HCl. After stirring for 1 h at room temperature, anhydrous potassium carbonate was added, and the reaction was diluted with 20 mL of ether. Following filtration and evaporation of the solvent, the oily residue was purified on silica gel (elution with hexanes/ether, 3:1) to afford 304 mg (62%) of **23** which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**35**) 0.31, R_f(**23**) 0.47): NMR ($CDCl_3$) δ 0.00 (s, 9 H), 1.40 (s, 2 H), 1.57 (s, 3 H), 1.90 (s, 3 H), 1.5–2.8 (m, 11 H), 4.50 (br s, 2 H); IR (film) 3080, 2970, 2930, 1700, 1655, 1390, 1330, 1290, 1225, 1165, 1080, 860 cm^{-1}; MS, m/z 236 (M^+). Anal. Calcd for $C_{14}H_{24}OSi$: C, 71.12; H, 10.23. Found: C, 71.03; H, 10.23.

2,3,4-Trimethyl-4-[2-[(trimethylsilyl)methyl]allyl]-2-cyclopenten-1-one (24). A solution of **36** (300 mg, 1.07 mmol) in anhydrous ether (5 mL) at 0 °C was treated with methyllithium (0.85 mL, 1.50 M solution in ether). The reaction mixture was stirred at 0 °C for 1 h. Standard ethereal workup provided the crude alcohol which was used without characterization.

The crude alcohol was dissolved in 15 mL of THF and treated with 5 drops of a 10% aqueous solution of HCl. After stirring for 1 h at room temperature, anhydrous potassium carbonate was added, and the reaction was diluted with 20 mL of ether. Following filtration and evaporation of the solvent, the oily residue was purified on silica gel (elution with hexanes/ether, 1:1) to afford 142 mg (53%) of **24** which was homogeneous by TLC analysis (hexanes/ether, 1:2, R_f(**36**) 0.88, R_f(**24**) 0.90): NMR (CCl_4) δ 0.00 (s, 9 H), 1.13 (s, 3 H), 1.37 (s, 2 H), 1.55 (s, 3 H), 1.85 (s, 3 H), 2.06 (s, 2 H) 4.40 (br s, 1 H), 4.50 (br s, 1 H); IR (film) 3080, 2960, 1700, 1640, 1385, 1325, 1255, 1160, 1100, 1070, 850 cm^{-1}. Anal. Calcd for $C_{15}H_{26}OSi$: C, 72.04; H, 10.46. Found: C, 71.81; H, 10.48.

II. Fluoride Ion Induced Cyclizations. General Procedures for the Fluoride-Induced Cyclizations. All cyclizations were carried out on 50 → 200 mg of substrate; scaling-up of the reaction (up to $^1/_2$ g of substrate) had little impact (±5%) upon the overall yield. *All reactions were run under an inert atmosphere with a concentration of ca. 0.3 M.* The activated 4A molecular sieves were stored in a heating oven at 130 °C (the quantity of sieves used was arbitrary). Stock solutions of anhydrous TBAF/DMF typically contained 10-30 mg of TBAF (a catalytic amount). In all cases, 3 equiv of HMPA was used relative to the quantity of substrate.

After addition of the substrate (via syringe pump) was complete, the resulting mixture was stirred at room temperature for 3→12 h (to ensure complete reaction) and then diluted with water (20 mL). This mixture was extracted with ether (3 × 40 mL), and the combined ether extracts were washed with brine (20 mL) and dried over anhydrous magnesium sulfate. Filtration and evaporation of the solvent afforded an oily residue which was directly purified via flash chromatography. The following experimental procedure is typical.

Cyclization of 1. A reaction vessel containing 4A molecular sieves was flame dried under vacuum (5 min) and placed under nitrogen. A solution of 20 mg of anhydrous TBAF/DMF (1.5 mL DMF) was then added to the flask and stirred 20 min, followed by 109 mg (0.61 mmol) of HMPA. A solution of 70 mg of α,β-unsaturated ester **1** in 1.5 mL of DMF was added dropwise via syringe pump over 45 min and the resulting mixture was stirred an additional 90 min. The reaction was diluted with 10 mL of water and extracted with 3 × 15 mL portions of ether. The combined ethereal extracts were washed with 15 mL of brine and dried over anhydrous magnesium sulfate. Filtration, followed by evaporation of the solvent, afforded 133 mg of crude **1a**. Purification on silica gel gave 29 mg (52%) of ethyl [4-methylene-2-oxo-1-cyclopentyl]acetate, cyclic trimethylene mercaptole (**1a**), which was homogeneous on TLC (hexanes/ether, 3:1, R_f(**1**) 0.61, R_f(**1a**) 0.54): NMR ($CDCl_3$) δ 1.38 (t, 3 H, J = 7 Hz), 1.6–3.6 (m, 13 H), 4.27 (q, 2 H, J = 7 Hz), 4.96 (br s, 2 H); IR (film) 2900, 1740, 1655, 1420, 1370, 1260, 1150, 1020, 880 cm^{-1}; MS, m/z 272 (M^+).

Spectral Properties of the Products. For brevity, only the quantity of substrate used and the amount of isolated cyclized product(s) obtained are provided for each reaction. Chromatographic, spectral, and analytical properties of the cyclization products are then listed.

Cyclization of 2. The cyclization of 56 mg of **2** produced 34.5 mg of crystalline [4-methylene-2-oxo-1-cyclopentyl]acetonitrile, cyclic trimethylene mercaptole (**2a**) (81%), which was homogeneous on TLC analysis (hexanes/ether, 3:1, R_f(**2**) 0.68, R_f(**2a**) 0.45): mp 88–89 °C; NMR ($CDCl_3$) δ 1.7–3.5 (m, 13 H), 5.07 (br s, 2 H); IR (film) 2950, 2900, 2825, 2250, 1650, 1440, 1425, 1415, 1360, 1275, 1215, 900, 785 cm^{-1}; MS, m/z 225 (M^+). Anal. Calcd for $C_{11}H_{15}NS_2$: C, 58.62; H, 6.70; N, 6.21. Found: C, 58.72; H, 6.75; N, 6.16.

Cyclization of 3. The cyclization of 35 mg of **3** gave 18.1 mg (67%) of 3-[4-methylene-2-oxo-1-cyclopentyl]propan-2-one, cyclic trimethylene mercaptole (**3a**), which was homogeneous on TLC analysis (hexanes/ether, 2:1, R_f(**3**) 0.71, R_f(**3a**) 0.75): NMR ($CDCl_3$) δ 1.40–3.40 (m, 13 H), 2.30 (s, 3 H), 5.00 (br s, 2 H); IR (film) 3060, 2900, 1710, 1657, 1420, 1360, 1180, 880 cm^{-1}; MS, m/z 242 (M^+).

Cyclization of 4. The cyclization of 61 mg of **4** afforded 26.7 mg (56%) of *N,N*-diethyl[4-methylene-2-oxo-1-cyclopentyl]-acetamide, cyclic trimethylene mercaptole (**4a**), which was homogeneous on TLC analysis (hexanes/ether, 1:1, R_f(**4**) 0.60, R_f(**4a**) 0.74): NMR ($CDCl_3$) δ 1.00–1.40 (m, 6 H), 1.50–3.60 (m, 17 H), 4.81 (br s, 2 H); IR (film) 3070, 2990, 2945, 2905, 1640, 1480, 1440, 1380, 1360, 1285, 1220, 1140, 1100, 910 cm^{-1}; MS, m/z 299 (M^+).

Cyclization of 5. The cyclization of 140 mg (0.463 mmol) of **5** gave 71 mg (66%) of benzyl [3-methylene-1-cyclopentyl]acetate

(**5a**) which was homogeneous on TLC analysis (hexanes/ether, 3:1, R_f(**5**) 0.71, R_f(**5a**) 0.61): NMR ($CDCl_3$) δ 1.2–3.6 (m, 9 H), 4.75 (br s, 2 H), 5.0 (s, 2 H), 7.25 (s, 5 H); MS, m/z 231 (M^+).

Cyclization of 6. The cyclization of 200 mg (0.957 mmol) of **6** provided 74 mg (59%) of [3-methylene-1-cyclopentyl]acetonitrile (**6a**) which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**6**) 0.58, R_f(**6a**) 0.42): NMR (CCl_4) δ 1.3–2.9 (m, 9 H), 4.85 (br s, 2 H); MS, m/z 121 (M^+). Anal. Calcd for $C_8H_{11}N$: C, 79.29; H, 9.14. Found: C, 79.44; H, 9.22.

Cyclization of 7. The cyclization of 85 mg (0.405 mmol) of **7** produced 32 mg (40%) of 3-[3-methylene-1-cyclopentyl]-propan-2-one (**7a**): NMR (CCl_4) δ 1.98 (s, 3 H), 1.4–2.5 (m, 12 H), 4.55–4.65 (m, 2 H). Anal. Calcd for $C_9H_{14}O$: C, 78.21; H, 10.21. Found: C, 78.00; H, 10.16.

Cyclization of 8. The cyclization of 106 mg (0.397 mmol) of **8** provided 61 mg (78%) of (*E*)-*N*,*N*-diethyl-6-methylene-2-heptenamide (**8b**) which was homogeneous by TLC analysis: NMR (CCl_4) δ 1.10 (t, 6 H, J = 5 Hz), 1.68 (s, 3 H), 1.8–2.4 (m, 4 H), 3.1–3.6 (m, 4 H), 4.55 (br s, 2 H), 5.95 (d, 1 H, J = 15 Hz), 6.55 (dt, 1 H, J = 15 Hz, 6 Hz).

Cyclization of 9. The cyclization of 200 mg (0.90 mmol) of **9** provided 93 mg (69%) of *cis*-tetrahydro-2-methylene-5(4*H*)-indanone (**9a**) as a colorless oil which was homogeneous by TLC analysis (hexanes/ether, 1:1, R_f(**9**) 0.63, R_f(**9a**) 0.50): NMR (CCl_4) δ 1.15–2.80 (m, 12 H), 4.73 (br s, 2 H); IR (film) 3080, 2930, 1715, 1660, 1435, 1250, 1230, 1145, 880, cm^{-1}; MS, m/z 150 (M^+). Anal. Calcd for $C_{10}H_{14}O$: C, 79.95; H, 9.39. Found: C, 80.07; H, 9.44.

Cyclization of 10. The cyclization of 100 mg (0.423 mmol) of **10** gave 44 mg (63%) of *cis*-tetrahydro-7a-methyl-2-methylene-5(4*H*)-indanone (**10a**) as a colorless oil which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**10**) 0.56, R_f(**10a**) 0.62): NMR (CCl_4) δ 1.18 (s, 3 H), 1.38–2.70 (m, 11 H), 4.78 (br s, 2 H); IR (film) 3070, 2920, 1720, 1655, 1430, 1240, 1170, 1135, 880 cm^{-1}; MS, m/z 164 (M^+). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.82. Found: C, 80.28; H, 9.82.

Cyclization of 11. The cyclization of 69 mg (0.29 mmol) of **11** afforded 27 mg (57%) of *cis*-tetrahydro-4-methyl-2-methylene-5(4*H*)-indanone (**11a**) as a colorless oil which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**11**) 0.72, R_f(**11a**) 0.63): NMR (CCl_4) δ 0.80–1.00 (m, 3 H), 1.30–1.80 (m, 11 H), 4.70 (br s, 2 H); IR (film) 3070, 2970, 2930, 1710, 1655, 1460, 14352, 1380, 1300, 1200, 1145, 1080, 1010, 975, 880, 785 cm^{-1}; MS, m/z 164 (M^+). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.81. Found: C, 80.22; H, 9.85.

Cyclization of 12. The cyclization of 210 mg (0.84 mmol) of **12** produced 82 mg (55%) of [3a*R**,7a*R**]-tetrahydro-4,7a-dimethyl-2-methylene-5(4*H*)-indanone (**12a**) as a colorless oil which was homogeneous by TLC analysis (hexane/ether, 3:1, R_f(**12**) 0.83, R_f(**12a**) 0.77): NMR (CCl_4) δ 1.80 (d, 2.4 H, J = 7 Hz), 1.84 (d, 0.6 H, J = 7 Hz), 1.22 (s, 3 H), 1.30–2.70 (m, 9 H), 4.69 (br s, 2 H); IR (film) 3080, 2970, 2940, 2880, 1720, 1660, 1460, 1440, 1380, 1325, 1170, 1150, 1070, 885, 795, 785 cm^{-1}; MS, m/z 192 (M^+). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.17. Found: C, 80.67; H, 10.21.

The 1,2-adduct [1*R**,5*]-5,7-dimethyl-3-methylenebicyclo-[3.2.2.]non-6-en-1-ol (**12b**) [9 mg, 6%, R_f 0.33] was also isolated: NMR (CCl_4) δ 0.90 (s, 3 H), 1.1–2.46 (m, 12 H), 1.63 (d, 3 H, J = 2 Hz), 4.54 (br s, 2 H), 5.21 (br s, 1 H); IR (film) 3800–3150, 3075, 2950, 1640, 1460, 1440, 1100, 1075, 1020, 980, 900, 840 cm^{-1}; MS m/z 178 (M^+).

Cyclization of 13. The cyclization of 67 mg (0.28 mmol) of **13** afforded 21 mg (46%) of [3a*R**,7a*S**]-tetrahydro-3a-methyl-2-methylene-5(4*H*)-indanone (**13a**) as a colorless oil which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**13**) 0.56, R_f(**13a**) 0.44): NMR ($CDCl_3$) δ 1.20 (s, 3 H), 1.30–3.10 (m, 11 H), 5.00 (br s, 2 H); IR (film) 3065, 2925, 1710, 1660, 1440, 1380, 1290, 1225, 880 cm^{-1}; MS, m/z 164 (M^+). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.81. Found C, 80.04; H, 9.84.

Cyclization of 14. The cyclization of 75 mg (0.30 mmol) of **14** gave 34 mg (65%) of [3a*R**,7a*S**]-tetrahydro-3a,7a-dimethyl-2-methylene-5(4*H*)-indanone (**14a**) as a colorless oil which was homogeneous by TLC analysis (hexanes/ether, 2:1, R_f(**14**) 0.50, R_f(**14a**) 0.36): NMR ($DCCl_3$) δ 0.93 (s, 3 H), 1.07 (s, 3 H), 1.40–2.50 (m, 10 H), 4.88 (br s, 2 H); IR (film) 3070, 2970, 2930, 1720, 1660, 1440, 1380, 880 cm^{-1}; MS, m/z 178 (M^+). Anal. Calcd for $C_{12}H_{18}O$: C, 80.84; H, 10.17. Found C, 80.72; H, 10.20.

Cyclization of 15. The cyclization of 102 mg (0.41 mmol) of **15** produced 31 mg (43%) of [3a*R**,7a*S**]-tetrahydro-3a,4-dimethyl-2-methylene-5(4*H*)-indanone (**15a**) as a colorless oil which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**15**) 0.64, R_f(**15a**) 0.65): NMR (CCl_4) δ 0.75 (s, 3 H), 0.78 (d, 3 H, J = 7 Hz), 1.20–2.70 (m, 10 H), 4.70 (b, 2 H); IR (film) 3075, 2950, 1715, 1620, 1450, 1380, 1250, 880, 845 cm^{-1}; MS, m/z 178 (M^+). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.17. Found: C, 80.69; H, 10.19.

The 1,2-adduct [1*R**,5*R**]-6,7-dimethyl-3-methylenebicyclo-[3.2.2]non-6-en-1-ol (**15b**) [7 mg, 10%, R_f 0.25] was also isolated: NMR (CCl_4) δ 1.40–2.80 (m, 9 H), 1.65 (br s, 6 H), 4.50–4.70 (m, 2 H); IR (film) 3700–3150, 3080, 2940, 1640, 1460, 1380, 1280, 1090, 1070, 1015, 975, 900, 835 cm^{-1}; MS, m/z 178 (M^+). Anal. Calcd for $C_{12}H_{18}O$: C, 80.48; H, 10.17. Found: C, 80.85; H, 10.21.

The protodesilylation product 2,3-dimethyl-4-[2-methyl-2-propenyl]-2-cyclohexen-1-one (**15c**) [7 mg, 10%, R_f 0.55] was also obtained: NMR (CCl_4) δ 1.65 (s, 3 H), 1.70 (s, 3 H), 1.85 (s, 3 H), 1.5–2.7 (m, 16 H), 4.55–4.75 (m, 2 H); IR (film) 3080, 2940, 1670, 1630, 1445, 1385, 1355, 1320, 1255, 1210, 1185, 1115, 1085, 895, 845 cm^{-1}; MS, m/z 178 (M^+).

Cyclization of 16. The cyclization of 74 mg (0.28 mmol) of **16** afforded 17 mg (32%) of [3a*R**,7a*S**]-tetrahydro-3,4,7a-trimethyl-2-methylene-5(4*H*)-indanone (**16a**) as a colorless oil which was homogeneous by TLC analysis (hexanes/ether, 6:1, R_f(**16**) 0.61, R_f(**16a**) 0.65): NMR (CCl_4) δ 0.80–0.98 (m, 6 H), 0.88 (s, 3 H), 1.15 (s, 3 H), 1.25–2.60 (m, 9 H), 4.60–4.85 (m, 2 H); IR (film) 3080, 2990, 2945, 1720, 1655, 1460, 1385, 1340, 1260, 1220, 1175, 1135, 1090, 1050, 1010, 880 cm^{-1}; MS, m/z 192 (M^+).

The 1,2-adduct [1*R**,5*R**]-3-methylene-5,6,7-trimethylbicyclo[3.2.2]non-6-en-1-ol (**16b**) [11 mg, 19%, R_f 0.32] was also isolated which was homogeneous by TLC analysis: NMR (CCl_4) δ 1.00 (s, 3 H), 1.63, (s, 3 H), 1.67 (s, 3 H), 1.15–2.50 (m, 16 H), 4.50–4.65 (br s, 2 H); IR (film) 3700–3100, 2950, 2920, 1710, 1640, 1460, 1440, 1390, 1380, 1350, 1290, 1200, 1040, 985, 900, 820 cm^{-1}; MS, m/z 192 (M^+); high resolution mass spectrum, m/z 192.1538 (calcd for $C_{13}H_{20}O$, 192.15134).

Cyclization of 17. The cyclization of 101 mg (0.48 mmol) of **17** gave 39 mg (64%) of *cis*-hexahydro-5-methylene-2(1*H*)-pentalenone (**17a**) which was homogeneous by TLC analysis (hexanes/ether, 1:2, R_f(**17**) 0.79, R_f(**17a**) 0.71): NMR ($CDCl_3$) δ 1.30–2.80 (m, 10 H), 4.70 (br s, 2 H); IR (film) 3070, 2945, 1735, 1655, 1440, 1410, 1295, 1245, 1170, 1150, 1070, 885, 790 cm^{-1}; MS, m/z 136 (M^+). Anal. Calcd for $C_9H_{12}O$: C, 79.37; H, 8.88. Found: C, 79.32; H, 8.87.

Cyclization of 18. The cyclization of 130 mg (0.58 mmol) of **18** gave 45 mg (55%) of [3a*R**,6a*S**]-hexahydro-3a-methyl-5-methylene-2(1*H*)-pentalenone (**18a**) which was homogeneous by TLC analysis (hexanes/ether, 1:2, R_f(**18**) 0.71, R_f(**18a**) 0.79): NMR (CCl_4) δ 1.07 (s, 3 H), 1.50–2.80 (m, 9 H), 4.70 (br s, 2 H); IR (film) 3075, 3010, 2960, 1740, 1655, 1455, 1435, 1405, 1380, 1270, 1175, 885 cm^{-1}; MS, m/z 150 (M^+). Anal. Calcd for $C_{10}H_{14}O$: C, 79.95; H, 9.39. Found: C, 80.03; H, 9.44.

Cyclization of 19. The cyclization of 92 mg (0.42 mmol) of **19** afforded 25 mg (40%) of *cis*-hexahydro-1-methyl-5-methylene-2(1*H*)-pentalenone (**19a**) which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**19**) 0.37, R_f(**19a**) 0.43): NMR ($CDCl_3$) δ 1.08 (d, 3 H, J = 8 Hz), 1.1–2.9 (m, 9 H), 4.8–4.9 (br s, 2 H); IR (film) 3075, 2940, 1740, 1655, 1455, 1435, 1410, 1380, 1250, 880 cm^{-1}; MS, m/z 150 (M^+). Anal. Calcd for $C_{10}H_{14}O$: C, 79.95; H, 9.39. Found: C, 79.88; H, 9.40.

The 1,2-adduct [1*R**,5*R**]-7-methyl-3-methylenebicyclo-[3.2.1]oct-6-en-1-ol (**19b**) [25 mg, 4%, R_f 0.07] was also isolated: NMR ($CDCl_3$) δ 1.6 (d, 3 H, J = 2 Hz), 1.40–2.80 (m, 12 H), 4.70 (br s, 2 H), 5.31 (br s, 1 H).

Cyclization of 20. The cyclization of 92 mg (0.42 mmol) of **20** provided 25 mg (40%) of [3a*R**,6a*S**]-hexahydro-1,3a-dimethyl-5-methylene-2(1*H*)-pentalenone (**20a**) which was homogeneous by TLC analysis (hexanes/ether, 1:2, R_f(**20**) 0.80, R_f(**20a**) 0.78): NMR (CCl_4) δ 1.11 (s, 3 H), 0.8–1.2 (m, 6 H), 1.2–2.7 (m, 8 H), 4.67 (br s, 2 H); IR (film) 3070, 2940, 2800, 1740, 1710, 1657, 1455, 1410, 1380, 1230, 870, 840 cm^{-1}; MS, m/z 164 (M^+). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.82. Found: C, 80.50; H, 9.85.

The crystalline 1,2-adduct [1*R**,5*R**]-5,7-dimethyl-3-methylenebicyclo[3.2.1]oct-6-en-1-ol (**20b**) [6 mg, 10%, mp 77–81 °C, R_f 0.20] was also isolated: NMR ($CDCl_3$) δ 1.00 (s, 3 H), 1.50

(d, 3 H, J = 1.5 Hz), 1.0–2.4 (m, 10 H), 4.53 (br s, 2 H), 4.98 (br s, 1 H); IR (film) 3600–3000, 3080, 3040, 2950, 1640, 1440, 1370, 1335, 1285, 1180, 1120, 1090, 1045, 985, 965, 880, 845, 810 cm^{-1}; MS, m/z 164 (M^+). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.81. Found: C, 80.57; H, 9.94.

Cyclization of 21. The cyclization of 135 mg (0.61 mmol) of **21** produced 14 mg (15%) of [3a*R**,6a*S**]-hexahydro-3a-methyl-5-methylene-2(1*H*)-pentalenone (**21a**) which was homogeneous by TLC analysis (hexanes/ether, 2:1, R_f(**21**) 0.45, R_f(**21a**) 0.70): NMR (CCl_4) δ 1.10 (s, 3 H), 1.3–2.8 (m, 9 H), 4.8 (br s, 2 H); IR (film) 3080, 2950, 1740, 1410, 1380, 1260, 1170, 880 cm^{-1}; MS, m/z 150 (M^+). Anal. Calcd for $C_{10}H_{14}O$: C, 79.95; H, 9.39. Found: C, 79.86; H, 9.43.

The protodesilylation product 3-methyl-4-[2-methyl-2-propenyl]-2-cyclopenten-1-one (**21c**) [26 mg, 29%, R_f 0.35] was also isolated: NMR ($CDCl_3$) δ 1.6 (s, 3 H), 2.1 (s, 3 H), 1.4–3.1 (m, 8 H), 4.55 (br s, 1 H), 4.70 (br s, 1 H), 5.71 (br s, 1 H); IR (film) 3080, 2980, 2920, 1700, 1620, 1440, 1410, 1380, 1340, 1310, 1260, 1185, 1025, 900, 840, 790, 760 cm^{-1}; MS, m/z 150 (M^+).

Cyclization of 22. The cyclization of 100 mg (0.42 mmol) of **22** gave 7 mg (10%) of [3a*R**,6a*S**]-hexahydro-3a,6a-dimethyl-5-methylene-2(1*H*)-pentalenone (**22a**) which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**22**) 0.58, R_f(**22a**) 0.77): NMR (CCl_3) δ 0.98 (s, 6 H), 2.09 (s, 2 H), 2.13 (s, 2 H), 2.23–2.40 (m, 4 H), 4.65–4.86 (m, 2 H); IR (film) 3070, 2960, 2940, 2880, 1740, 1655, 1405, 1380, 1280, 1260, 1180, 880 cm^{-1}; MS, m/z 164 (M^+).

Crystalline [1*R**,5*R**]-5,6-dimethyl-3-methylenebicyclo-[3.2.1]oct-6-en-1-ol was also isolated (**22b**) [31 mg, 45%, mp 59–61 °C, R_f 0.42]: NMR ($CDCl_3$) δ 0.99 (s, 3 H), 1.5 (s, 3 H), 1.3–2.4 (m, 10 H), 4.55 (br s, 2 H), 5.2 (br s, 1 H); IR (film) 3600–3100, 3070, 2930, 1640, 1440, 1375, 1335, 1300, 1200, 1150, 1075, 890, 820, cm^{-1}; MS, m/z 164 (M^+). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.81. Found: C, 80.20; H, 9.91.

Cyclization of 23. The cyclization of 100 mg (0.42 mmol) of **23** afforded 15 mg (22%) of [1*R**,S*R**]-6,7-dimethyl-3-methylenebicyclo[3.2.1]oct-6-en-1-ol (**23b**) which was homogeneous by TLC analysis (hexanes/ether, 2:1, R_f(**23**) 0.73, R_f(**23b**) 0.48): NMR ($CDCl_3$) δ 1.5 (s, 6 H), 1.4–2.6 (m, 8 H), 4.55 (br s, 2 H); IR (film) 3700–3000, 3060, 2900, 1635, 1370, 1315, 1295, 1110, 1060, 880, 780 cm^{-1}; MS, m/z 164 (M^+). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.82. Found: C, 80.50; H, 9.83.

The protodesilylation product 2,3-dimethyl-4-[2-methyl-2-propenyl]-2-cyclopenten-1-one (**23c**) [15 mg, 22%, R_f 0.39] was also isolated: NMR ($CDCl_3$) δ 1.65 (s, 3 H), 1.70 (s, 3 H), 2.00 (s, 3 H), 1.5–3.0 (m, 14 H), 4.6 (br s, 1 H), 4.7 (br s, 1 H); IR (film) 3070, 2950, 1680, 1640, 1380, 1320, 1070, 890, 790 cm^{-1}; MS, m/z 164 (M^+).

Cyclization of 24. The cyclization of 142 mg (0.57 mmol) of **24** afforded 2 mg (2%) of [3a*R**,6a*S**]-hexahydro-1,6a-dimethyl-2[1*H*]-pentalenone (**24a**) which was homogeneous by TLC analysis (hexanes/ether, 3:1, R_f(**24**) 0.39, R_f(**24a**) 0.51): NMR ($CDCl_3$) δ 0.98 (s, 3 H), 1.05 (s, 3 H), 0.8–1.1 (m, 9 H), 1.3–2.4 (m, 7 H), 4.7 (br s, 2 H); IR, (film) 3070, 2960, 1735, 1655, 1450, 1380, 1320, 1250, 1145, 840 cm^{-1}. Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.17. Found: C, 80.72; H, 10.19.

Crystalline [1*R**,5*R**]-5,6,7-trimethyl-3-methylenebicyclo-[3.2.1]oct-6-en-1-ol (**24b**) was also isolated [54 mg, 54%, R_f 0.29, mp 69–72 °C]: NMR ($CDCl_3$) δ 1.10 (s, 3 H), 1.45 (s, 3 H), 1.55 (s, 3 H), 1.3–2.4 (m, 13 H), 4.45 (br s, 2 H); IR (film) 3600–3100, 3070, 2950, 2930, 1640, 1440, 1330, 1290, 1200, 1180, 1115, 1040, 880 cm^{-1}; MS, m/z 178 (M^+). Anal. Calcd for $C_{12}H_{18}O$: C, 80.84; H, 10.17. Found: C, 80.59; H, 10.25.

III. General Lewis Acid Catalyzed Procedures. Three typical Lewis acid catalyzed procedures are detailed below: (A) $TiCl_4$-induced cyclizations, (B) $EtAlCl_2$-mediated cyclizations, and (C) BF_3·Et_2O-initiated cyclizations. These cyclization procedures proved highly substrate dependent. For example, $EtAlCl_2$ (B) failed to promote the cyclization of substrate **16**, while catalysis with $TiCl_4$ (A) at −78 °C resulted in only protodesilylation product **16c**; the BF_3·Et_2O-mediated procedure (C) was not examined. In another study, substrate **15** produced a mixture of the 1,2-adduct **15b** and the protodesilylation product **15c** using $TiCl_4$ catalysis; however, no reaction was observed for the $EtAlCl_2$-mediated cyclization. This information appears below in the following abbreviated format:

Cyclization of 16. (A) Protodesilylation product **16c**, 63%; (B) recovered **16**, 85%.

Cyclization of 15. (A) Protodesilylation product **15c**, 23%; 1,2-adduct **15b**, 23%; (B) recovered **15**, 80%.

Spectral data for new compounds are then listed.

(A) General Procedure for the $TiCl_4$-Induced Reactions. These cyclizations were carried out at low temperatures by using equal molar quantities of substrate and $TiCl_4$; reactions were routinely performed on 100 mg of substrate. A typical example follows.

Cyclization of 14 Using $TiCl_4$ Catalysis. $TiCl_4$ (0.1 mL, 0.91 mmol) was added dropwise to a solution of 100 mg (0.45 mmol) of **14** in 2 mL of dry methylene chloride at −78 °C. The mixture was stirred at −78 °C for 2 h. TLC analysis indicated that substrate **14** had been consumed. After the reaction was quenched with water (at −78 °C) and extracted with ether, the organic phase was washed sequentially with water, saturated aqueous ammonium chloride, and brine. After being dried with anhydrous magnesium sulfate, the solvents were evaporated in vacuo. Purification of the crude residue by chromatography on silica gel yielded 33 mg (41%) of the 1,2-adduct **14b** and 9 mg (10%) of the protodesilylation product **14c** which were homogeneous on TLC analysis (hexanes/EtOAc, 9:1, R_f(**14b**) 0.28, R_f(**14c**) 0.40).

[1*R**,5*R**]-5,6-Dimethyl-3-methylenebicyclo[3.2.2]non-6-en-1-ol (**14b**): NMR (CCl_4) δ 1.05 (s, 3 H), 1.1–2.4 (m, 12 H) 1.70 (s, 3 H), 4.60 (br s, 2 H), 5.60 (br s, 1 H); IR (film) 3600–3100, 3080, 2970, 1640, 1460, 1440, 1350, 1160, 1050, 890 cm^{-1}.

3,4-Dimethyl-4-(2-methyl-2-propenyl)-2-cyclohexen-1-one (**14c**): NMR (CCl_4) δ 1.10 (s, 3 H), 1.70 (s, 3 H), 1.80 (s, 2 H), 1.83 (s, 3 H), 1.5–2.4 (m, 12 H), 4.55 (br s, 1 H), 4.75 (br s, 1 H), 5.50 (br s, 1 H).

(B) General Procedure for the $EtAlCl_2$-Mediated Cyclizations. All ethylaluminum dichloride catalyzed reactions were carried out at low temperatures using 1 equiv of both substrate and catalyst; reactions were typically performed on 100 mg of substrate. The following experimental procedure is typical.

Cyclization of 14 Using Ethylaluminum Dichloride. To 70 mg (0.316 mmol) of **14** in 1 mL of dry toluene at 0 °C was added dropwise 0.22 mL (0.316 mmol) of a 1.4 M solution of ethylaluminum dichloride in toluene (Alfa). The reaction mixture was stirred at 0 °C for 2 h. The reaction mixture was diluted with reagent grade ether, washed with brine, dried over anhydrous magnesium sulfate, filtered, and concentrated. The crude residue was chromatographed (elution with hexanes/ethyl acetate, 9:1) to provide 10 mg (20%) of the 1,4-adduct **14a** [R_f 0.50], 8.5 mg of unreacted)**22** [R_f 0.42], and 20 mg (40%) of the 1,2-adduct **14b** [R_f 0.27].

(C) General Procedure for the Boron Trifluoride Etherate Initiated Cyclizations. BF_3·Et_2O was used to catalyze only six cyclizations. In such cases, Andersen's original procedure was employed; reactions were routinely carried out on 100 mg of substrate. A typical example follows.

Cyclization of 14 Using BF_3·Et_2O. To 100 mg (0.452 mmol) of **14** in 1 mL of dry ether at −78 °C was added dropwise 30 μL (0.497 mmol) of freshly distilled BF_3·Et_2O. The reaction mixture was kept at −78 °C for 1 h and allowed to warm gradually to room temperature over 12 h. The reaction mixture was diluted with reagent grade ether, washed with brine, and dried over anhydrous magnesium sulfate. Filtration and evaporation of the solvent furnished 65 mg of a crude residue which was purified via chromatography on silica gel. Elution with hexanes/EtOAc (9:1) gave 13 mg of unreacted starting material **14** and 32 mg (40%) of the protodesilylation product **14c** [R_f 0.27].

Cyclization of 2. (C) Protodesilylation product **2c**, 23%. 2-(2-Methyl-2-propene)-*m*-dithiane-2-acrylonitrile (**2c**): NMR ($CDCl_3$) δ 1.70 (s, 3 H), 1.6–2.2 (m, 5 H), 2.45 (s, 2 H), 2.40–2.90 (m, 6 H), 4.7 (br s, 1 H), 4.85 (br s, 1 H), 6.10 (AB q, 2 H, $\Delta\nu_{AB}$ = 39 Hz, J = 15 Hz).

Cyclization of 4. (C) Protodesilylation product **4b**, 56%. (*E*)-*N*,*N*-Diethyl-2-(2-methyl-2-propene)-*m*-dithiane-2-acrylamide (**4b**): NMR ($CDCl_3$) δ 1.30 nt, 6 H, J = 6 Hz), 1.6–2.2 (m, 4 H), 1.75 (s, 3 H), 2.4–3.0 (m, 6 H) 3.8–4.2 (q, 2 H, J = 6 Hz), 4.6–4.9 (m, 2 H), 6.4 (AB q, 2 H, $\Delta\nu_{AB}$ = 14 Hz, J = 13 Hz); MS, m/z 244 (M − 55).

Cyclization of 5. (A) Protodesilylation product **5b**, 78%), (C) **5b** (45%). Benzyl 6-methylene-2-heptenoate (**5b**): NMR ($CDCl_3$)

δ 1.62 (s, 3 H), 1.8–2.4 (m, 4 H), 4.55 (br s, 2 H), 4.95 (s, 2 H), 5.3–5.7 (m, 1 H), 6.5–6.8 (m, 1 H), 7.1 (s, 5 H).

Cyclization of 7. (C) No isolable or identifiable products obtained.

Cyclization of 8. (C) Protodesilylation product **8b**, 68%. **8b** was identical with that characterized in the fluoride ion induced cyclization.

Cyclization of 9. (A) 1,2-Adduct **9b**, 49%. (B) Recovered **9**, 45%, and protodesilylation product **9c**, 30%.

[1*R**,5*R**]-3-Methylenebicyclo[3.2.2]non-6-en-1-ol (**9b**): NMR (CCl_4) δ 1.3–2.6 (m, 10 H), 4.55 (br s, 2 H), 5.8–6.1 (m, 2 H); IR (film) 3650–3150, 3080, 2970, 1640, 1440, 1380, 1150, 1080, 890, 810 cm^{-1}; MS, *m/z* 150 (M^+).

4-(2-Methyl-2-propenyl)-2-cyclohexen-1-one (**9c**): NMR (CCl_4) δ 1.8 (s, 3 H), 1.6–2.6 (m, 10 H), 4.7–5.0 (m, 2 H), 6.0 (dd, 1 H, *J* = 10 Hz, 2 Hz), 6.85 (dd, 1 H, *J* = 10 Hz, 2 Hz).

Cyclization of 10. (A) 1,2-Adduct **10b**, 24%. (B) Recovered **10**, 25%, and protodesilylation product **10c**, 10%.

[1*R**,5*R**]-5-Methyl-3-methylenebicyclo[3.2.2]non-6-en-1-ol (**10b**): NMR (CCl_4) δ 1.00 (s, 3 H), 1.10–2.5 (m, 8 H), 4.58 (br s, 2 H), 5.73 (AB q, 2 H, $\Delta\nu_{AB}$ = 12 Hz, *J* = 8 Hz); IR (film) 3600–3100, 3080, 3040, 2940, 1670, 1640, 1450, 1365, 1120, 1080, 1050, 1010, 890 cm^{-1}; MS, *m/z* 164 (M^+).

4-Methyl-4-(2-methyl-2-propenyl)-2-cyclohexen-1-one (**10c**): NMR (CCl_4) δ 1.2 (s, 3 H), 1.75 (s, 3 H), 2.2 (s, 2 H), 1.6–2.5 (m, 9 H), 4.630 (br s, 1 H), 4.85 (br s, 1 H), 5.78 (d, 1 H, *J* = 9 Hz), 6.52 (d, 1 H, *J* = 9 Hz).

Cyclization of 11. (A) 1,2-Adduct **11b**, 34%, and protodesilylation **11c**, (60%). (B) Recovered **11** (16%) and **11c** (50%).

[1*R**,5*R**]-7-Methyl-3-methylenebicyclo[3.2.2]non-6-en-1-ol (**11b**): NMR (CCl_4) δ 1.45 (s, 3 H), 1.68 (s, 3 H), 1.3–2.6 (m, 14 H) 5.42 (d, 1 H, *J* = 14 Hz), 5.71 (d, 1 H, *J* = 7 Hz); IR (film) 3700–3100, 3020, 2950, 1650, 1450, 1070, 850 cm^{-1}.

2-Methyl-4-(2-methyl-2-propenyl)-2-cyclohexen-1-one (**11c**): NMR (CCl_4) δ 1.62 (s, 6 H), 1.7–2.6 (m, 7 H), 4.56 (br s, 1 H), 4.67 (br s, 1 H), 6.3 (br s, 1 H); IR (film) 3070, 2930, 1670, 1450, 1380, 1360, 1100, 900 cm^{-1}.

Cyclization of 12. (A) Protodesilylation product **12c**, 60%. (B) Recovered **12** (5%) and **12c** (70%).

2,4-Dimethyl-4-(2-methyl-2-propenyl)-2-cyclohexen-1-one (**12c**): NMR (CCl_4) δ 1.05 (s, 3 H), 1.3–2.5 (m, 12 H), 1.62 (s, 3 H), 1.67 (s, 3 H), 2.08 (s, 2 H), 2.27 (t, 2 H, *J* = 6 Hz), 4.55 (br s, 1 H), 4.72 (br s, 1 H), 6.21 (br s, 1 H); IR (film) 3080, 2950, 2930, 1670, 1450, 1380, 1360, 1120, 1080, 1020, 900, 800 cm^{-1}; MS, *m/z* 178 (M^+).

Cyclization of 13. (A) Protodesilylation product **13c**, 92%. (B) Recovered **13** (65%) and **13c** (20%).

3-Methyl-4-(2-methyl-2-propenyl)-2-cyclohexen-1-one (**13c**): NMR (CCl_4) δ 1.68 (s, 3 H), 1.80 (s, 3 H), 1.55–2.4 (m, 13 H), 4.63 (br s, 1 H), 4.68 (br s, 1 H), 5.55 (br s, 1 H); IR (film) 3070, 2930, 1670, 1445, 1380, 1250, 1200, 900 cm^{-1}.

Cyclization of 14. (A) 1,2-Adduct **14b** (41%) and protodesilylation product **14c** (10%). (B) Recovered **14** (12%), 1,4-adduct **14a** (20%), 1,2-adduct **14b** (40%), and **14c** (10%). (C) **14c** (40%).

Cyclization of 15. (A) 1,2-Adduct **15b** (50%) and protodesilylation product **15c** (20%). (B) Recovered **15** (55%) and **15c** (20%).

The 1,2-adduct **15b** was identical with that characterized in the fluoride ion induced cyclization.

Cyclization of 16. (A) 1,2-Adduct **16b** (74%) and protodesilylation product **16c** (16%). (B) Recovered **16** (8%) and protodesilylation product **16c** (60%).

The 1,2-adduct **16b** was identical with that characterized in the fluoride ion induced cyclization.

4-(2-Methyl-2-propenyl)-2,3,4-trimethyl-2-cyclohexen-1-one (**16c**): NMR (CCl_4) δ 1.10 (s, 3 H), 1.60 (s, 3 H), 1.65 (s, 3 H), 1.4–2.4 (m, 15 H), 4.50 (br s, 1 H), 4.68 (br s, 1 H); IR (film) 3080, 2930, 1660, 1620, 1450, 1380, 1340, 1300, 1220, 1120, 900, 800 cm^{-1}.

Cyclization of 17. (A) Protodesilylation product **17c** (50%). (B) Recovered **17** (10%) and **17c** (84%).

4-(2-Methyl-2-propenyl)-2-cyclopenten-1-one (**17c**): NMR (CCl_4) δ 1.65 (s, 3 H), 1.75–2.4 (m, 4 H), 2.8–3.1 (m, 1 H), 4.55 (br s, 1 H), 4.65 (br s, 1 H), 5.85 (dd, 1 H, *J* = 6 Hz, 2 Hz), 7.26 (dd, 1 H, *J* = 6 Hz, 2 Hz); IR (film) 2930, 2850, 1720, 1585, 1180, 800 cm^{-1}.

Cyclization of 18. (A) Protodesilylation product **18c** (60%). (B) Recovered **18** (5%) and **18c** (75%).

4-Methyl-4-(2-methyl-2-propenyl)-2-cyclopenten-1-one (**18c**): NMR (CCl_4) δ 1.18 (s, 3 H), 1.65 (s, 3 H), 2.15 (AB q, 2 H, $\Delta\nu_{AB}$ = 20 Hz, *J* = 18 Hz), 2.20 (s, 2 H), 4.58 (br s, 1 H), 4.75 (br s, 1 H), 5.75 (d, 1 H, *J* = 6 Hz), 7.23 (d, 1 H, *J* = 6 Hz); IR (film) 2920, 2850, 1715, 1340, 1240, 1000, 800 cm^{-1}.

Cyclization of 19. (A) Protodesilylation product **19c** (95%). (B) Recovered **19** (50%) and **19c** (40%).

2-Methyl-4-(2-methyl-propenyl)-2-cyclopenten-1-one (**19c**): NMR ($CDCl_3$) δ 1.70–1.80 (m, 6 H), 1.9–2.7 (m, 5 H), 2.7–3.0 (m, 1 H), 4.5–4.8 (m, 2 H), 6.9–7.0 (br s, 1 H); IR (film) 3080, 2970, 2930, 1705, 1640, 1445, 1410, 1380, 1330, 1200, 1070, 1000, 900 cm^{-1}.

Cyclization of 20. (A) 1,2-Adduct **20b** with olefin rearrangement (47%). (B) Recovered **20** (15%) and protodesilylation product **20c** (70%).

3,7-Dimethylbicyclo[3.2.1]octa-4,6-dien-1-ol (**20b**): NMR (CCl_4) δ 1.5–1.8 (m, 8 H), 1.5–2.7 (m, 11 H), 2.8–3.05 (m, 1 H), 6.95 (br s, 2 H); IR (film) 3700–3100, 2930, 1620, 1635, 1260, 910, 790 cm^{-1}.

2,4-Dimethyl-4-(2-methyl-propenyl)-2-cyclopenten-1-one (**20c**): NMR ($CDCl_3$) δ 1.13 (s, 3 H), 1.6–1.65 (s, 6 H), 2.15 (s, 2 H), 2.18 (AB q, $\Delta\nu_{AB}$ = 16 Hz, *J* = 17 Hz); 4.75 (br s, 1 H), 6.85 (br s, 1 H); IR (film) 3080, 2970, 2920, 2870, 1710, 1640, 1450, 1410, 1380, 1330, 1200, 1070, 990, 890, 800 cm^{-1}.

Cyclization of 21. (A) 1,2-Adduct **21b** (33%). (B) Protodesilylation product **21c** (91%).

5-Methyl-3-methylenebicyclo[3.2.1.]oct-5-en-ol (**21b**): NMR (CCl_4) δ 2.0–2.2 (br s, 7 H), 2.0–2.8 (m, 10 H), 4.0 (br s, 1 H), 4.9 (br s, 1 H), 5.15 (br s, 1 H), 5.75 (br s, 1 H); IR (film) 3700–3150, 2930, 1620, 1535, 1505, 1260, 1180, 910, 800 cm^{-1}.

Protodesilylation product **21c** was identical with that characterized in the fluoride ion induced cyclization.

Cyclization of 22. (A) 1,2-Adduct **22b** (86%). (B) Recovered **22** (20%) and protodesilylation product **22c** (65%).

The 1,2-adduct **22b** was identical with that characterized in the fluoride ion induced cyclization.

3,4-Dimethyl-4-(2-methyl-propenyl)-2-cyclopenten-1-one (**22c**): NMR (CCl_4) δ 1.2 (s, 3 H), 1.5–2.6 (m, 10 H), 1.65 (s, 3 H), 2.0 (s, 3 H), 2.2 (s, 2 H), 4.55 (br s, 1 H), 4.85 (br s, 1 H), 5.65 (br s, 1 H); IR (film) 3070, 2970, 2930, 1700, 1620, 1440, 1380, 1260, 1030, 900 cm^{-1}.

Cyclization of 23. (A) Protodesilylation product **23c** (86%). (B) Recovered **23** (55%) and **23c** (20%).

Protodesilylation product **23c** was identical with that characterized in the fluoride ion induced cyclization.

Cyclization of 24. (A) 1,2-Adduct **24b** (46%) and protodesilylation product **24c** (20%). (B) **24c** (80%).

The 1,2-adduct **24b** was identical with that characterized in the fluoride ion induced cyclization.

2,3,4-Trimethyl-4-(2-methyl-propenyl)-2-cyclopenten-1-one (**24c**): NMR (CCl_4) δ 1.10 (s, 3 H), 1.53 (s, 3 H), 1.58 (s, 3 H), 1.85 (s, 3 H), 2.15 (s, 2 H), 2.12 (AB q, $\Delta\nu_{AB}$ = 16 Hz, *J* = 18 Hz), 4.50 (br s, 1 H), 4.8 (br s, 1 H); IR (film) 3080, 2970, 2920, 2870, 1700, 1645, 1450, 1380, 1320, 1070, 900, 790 cm^{-1}.

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100812-55-3; **14**, 100812-56-4; **14a**, 100812-57-5; **14b**, 100812-58-6; **14c**, 100812-59-7; **15**, 100812-60-0; **15a**, 100812-61-1; **15b**, 100812-62-2; **15c**, 100812-63-3; **16**, 100812-64-4; **16a**, 100812-65-5; **16b**, 100812-66-6; **16c**, 100812-67-7; **17**, 100812-68-8; **17a**, 100812-69-9; **17c**, 100812-70-2; **18**, 100812-71-3; **18a**, 59463-21-7; **18c**, 59463-14-8; **19**, 100812-72-4; **19a**, 100812-73-5; **19b**, 100812-74-6; **19c**, 100812-75-7; **20**, 100812-76-8; **20a**, 100812-77-9; **20b**, 100812-78-0; **20c**, 100812-79-1; **21**, 100812-80-4; **21a**, 59463-21-7; **21b**, 100812-81-5; **21c**, 100812-82-6; **22**, 100812-83-7; **22a**, 100812-84-8; **22b**, 100812-85-9; **22c**, 100812-86-0; **23**, 100812-87-1; **23b**, 100812-88-2; **23c**, 100812-89-3; **24**, 100812-90-6; **24a**, 100812-91-7; **24b**, 100812-92-8; **24c**, 100812-93-9; **25**, 81302-80-9; **26**, 80121-73-9; **27**, 100812-94-0; **28**, 87603-80-3; **29**, 100812-95-1; **30**, 100812-96-2; **31**, 100812-97-3; **32**, 100812-98-4; **33**, 100812-99-5; **34**, 100813-00-1; **35**, 100813-01-2; **36**, 100813-02-3; 2-formyldithiane, 34906-12-2; triethyl phosphonoacetate, 867-13-0; diethyl (cyanomethyl)phosphonate, 2537-48-6; 1-(triphenylphosphoranylidene)-2-propanone, 1439-36-7; diethyl [(*N*,*N*-diethylcarbamoyl)methyl]phosphonate, 3699-76-1; 3-(trimethylsilyl)-2-methylenepropyl vinyl ether, 87603-79-0; 3-ethoxy-2-cyclohexen-1-one, 5323-87-5; 3-ethoxy-5-methyl-2-cyclohexen-1-one, 35023-83-7; 3-ethoxy-2-methyl-2-cyclohexen-1-one, 20643-20-3; 3-ethoxy-2,6-dimethyl-2-cyclohexen-1-one, 76192-88-6; 3-ethoxy-1,2-dimethyl-6-[2-[(trimethylsilyl)methyl]allyl]-2-cyclohexen-1-ol, 100813-03-4; 3-ethoxy-2-cyclopenten-1-one, 22627-70-9; 3-ethoxy-5-methyl-2-cyclopenten-1-one, 100813-04-5; 3-ethoxy-2-methyl-2-cyclopenten-1-one, 25112-86-1; 3-ethoxy-2,5-dimethyl-2-cyclopenten-1-one, 100813-05-6.

Selective Reduction of Cyclic Conjugate Enones with $NaBH_4$ in the Presence of Cyclodextrins[1]

Roberto Fornasier, Vittorio Lucchini, Paolo Scrimin,* and Umberto Tonellato*

Centro C.N.R. Meccanismi di Reazioni Organiche, Dipartimento di Chimica Organica dell'Università, 35131 Padova, Italy

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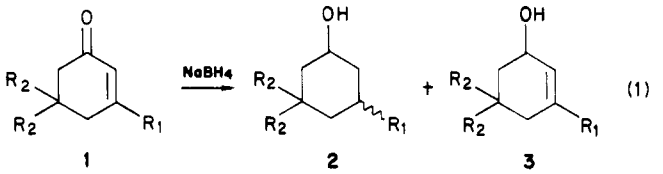
The $NaBH_4$ reduction of 2-cyclohexenone (**1a**), 3-methyl-2-cyclohexenone (**1b**), and 3,5,5-trimethyl-2-cyclohexenone (**1c**) to the corresponding cyclohexanols (**2**) and cyclohexenols (**3**) has been investigated in aqueous alkaline media, in the absence and in the presence of α- and β-cyclodextrins (CD) and two modified β-CDs. Changes in the [**2**]/[**3**] ratios are induced by substrate inclusion in the CD's cavities. The reduction (**1b**) is accelerated in the presence of β-CD. The strength and mode of substrate insertion into the CD's cavities have been inferred from a ^1H NMR spectroscopy investigation. The formation of a ternary complex made of CD, substrate, and boron hydride species is suggested to account for the observed selectivities.

Cyclodextrins (CDs), doughnut-shaped macrocycles composed of six or more glucose units, have been extensively investigated as simple enzyme models owing to their ability to form inclusion complexes with a variety of substrates.[2] High rate accelerations have been observed for the hydrolytic cleavage of activated substrates.[3] More recently, inclusion complexes have been reported to undergo selective reactions.[4-7] The common feature of these reactions is the critical dependance on the geometry of the complexes which can be modulated by modifying both the guest and host molecules.

We report herewith the selectivity effects, resulting from CD inclusion, in the $NaBH_4$ reduction of α,β-unsaturated cyclic ketones **1a–c**. These are known[8] to undergo a $NaBH_4$ reduction to give the corresponding alkanols (**2**) or alkenols (**3**) (eq 1), formally related to a hydride attack



(1)

a, $R_1 = R_2 = H$
b, $R_1 = CH_3$; $R_2 = H$
c, $R_1 = R_2 = CH_3$

at C_3 or C_1, the product ratio depending on the reagent structures or reaction conditions.[9]

The study of regioselectivity effects in the presence of α- and β-CD and also, in the case of enone **1b**, in the presence of two modified β-CDs, i.e., heptakis(2,6-di-*O*-methyl)-β-CD and heptakis(6-*N*-methyl-*N*-acetyl)-β-CD, has been complemented by a NMR spectroscopy investigation aimed at defining the mode of inclusion of the substrates in the CD complexes and the strength of binding.

Results

Selective Reduction of Cyclohexenones 1a–c in the Presence of CDs. Table I shows the cyclohexanol (**2**)/cyclohexenol (**3**) mole ratios observed in the reduction products for aqueous 0.2 M Na_2CO_3 solutions using different CD/substrate ratios. The table also includes an indication of the fraction of bound substrate as evaluated from the binding constants, K_b, determined by NMR measurements (see below).

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