400-W medium-pressure mercury-arc lamp (placed 2 ft from the pressure tube) through two layers of Pyrex. Bromine was completely consumed in 5 min. ^{1}H NMR analysis of this solution showed that 9-chloro-10-(α-bromocyclopropyl)anthracene was formed in 95% yield. The remaining 5% was comprised of 1,3-dibromo-1-(9-chloroanthryl)propane (3%) and unidentified products (2%). Spectral data for 9-chloro-10-(α-bromocyclopropyl)anthracene: ^{1}H NMR ($CDCl_3/CCl_4$) δ 1.45 (m, 2 H, *cis*-cyclopropylmethylene hydrogens), 2.06 (m, 2 H, *trans*-cyclopropylmethylene hydrogens), 7.57–7.71 (m, 4 H, 2-, 3-, 6-, and 7-H anthryl hydrogens), 8.56 (m, 2 H, 1- and 8-H anthryl hydrogens), 8.81 (m, 2 H, 4- and 5-H anthryl hydrogens); ^{13}C NMR ($CDCl_3$) δ 20.30 and 28.00 (cyclopropyl carbons), 125.00–136.00 (m, anthryl carbons). Repeated attempts to isolate pure 9-chloro-10-(α-bromocyclopropyl)anthracene by column and thin-layer chromatography were unsuccessful due to the rapid decomposition of the compound.

Photobromination of 9-Bromo-10-cyclopropylanthracene. This reaction was carried out at 15 °C by using the same procedure described for 9-chloro-10-cyclopropylanthracene. The yield of 9-bromo-10-(α-bromocyclopropyl)anthracene was determined by ^{1}H NMR analysis to be 95%. ^{1}H NMR ($CDCl_3/CCl_4$) δ 1.47 (m, 2 H, *cis*-cyclopropylmethylene hydrogens), 2.08 (m, 2 H, *trans*-cyclopropylmethylene hydrogens), 7.44–7.69 (m, 4 H, 2-, 3-, 6-, and 7-H anthryl hydrogens), 8.61 (m, 2 H, 1- and 8-H anthryl hydrogens), 8.81 (m, 2H, 4- and 5-H anthryl hydrogens).

Dark Bromination of 9-Bromo-10-cyclopropylanthracene. 9-Bromo-10-cyclopropylanthracene (70.0 mg, 0.23 mmol), NBS (20.5 mg, 0.12 mmol), and 5 mL of CCl_4 were placed in a 30-mL pressure tube that was equipped with a magnetic stirring bar and carefully wrapped with aluminum foil. Bromine (5.8 μL, 0.11 mmol) was distilled into the pressure tube via a vac-line. The pressure tube was sealed with an O-ringed Teflon needle valve and immersed in a water bath maintained at 15 °C. After 1 h, the contents of the pressure tube were evaporated to dryness under reduced pressure. ^{1}H NMR analysis indicated the presence of only one product, 1,3-dibromo-1-(9-bromoanthryl)propane. ^{1}H NMR ($CCl_4/CDCl_3$) δ 2.8 (m, 1 H), 3.4–3.5 (m, 2 H), 3.7 (m, 1 H), 7.5–7.7 (m, 4 H, 2-, 3-, 6-, and 7-H anthryl hydrogens), 8.4 (d, 1 H, J = 9 Hz, 4-H anthryl hydrogen), 8.7 (dd, 2 H, 1- and 8-H anthryl hydrogens), 8.8 (d, 1 H, J = 10 Hz, 5-H anthryl hydrogen). Reduction of a reaction residue with an excess amount of n-Bu_3SnH in benzene afforded only 9-propylanthracene.

Dark Bromination of 9-Chloro-10-cyclopropylanthracene. This experiment was carried out in an analogous manner as the dark bromination of 9-bromo-10-cyclopropylanthracene. Only one product, 1,3-dibromo-1-(9-chloroanthryl)propane, was obtained after 1 h of reaction time. ^{1}H NMR ($CCl_4/CDCl_3$) δ 2.77 (m, 1 H), 3.38–3.49 (m, 2 H), 3.66 (m, 1 H), 7.65–7.54 (m, 4 H, 2-, 3-, 6-, and 7-H anthryl hydrogens), 8.36 (d, 1 H, J = 8.7 Hz, 4-H anthryl hydrogen), 8.60 (dd, 2 H, 1- and H-8 anthryl hydrogens), 8.79 (d, 1 H, J = 9.8 Hz, 5-H anthryl hydrogen). ^{13}C NMR (CDCl) δ 31.24, 41.65 and 45.79, 123.08–131.8.

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Comparative Analysis of Diastereoselection Levels Attainable during Controlled Exo and Endo Addition of Chiral Cyclopentenyl Organometallics to Optically Pure and Racemic 1-Vinylnorbornan-2-ones

Leo A. Paquette,* Donald T. DeRussy, Thierry Vandenheste, and Robin D. Rogers[1]

Contribution from the Evans Chemical Laboratories, The Ohio State University, Columbus, Ohio 43210, and the Department of Chemistry, Northern Illinois University, DeKalb, Illinois 60115. *Received October 18, 1989*

Abstract: The levels of diastereoselection attainable during endo addition to (+)-**8** and of exo addition to (−)-**9** and (±)-**10** have been tested with five differently substituted cyclopentenyl anions. The extent of intermolecular recognition reaches useful levels when an endo attack is involved. In contrast, diastereomeric differentiation is significantly reduced when an exo trajectory is followed. These data are concisely rationalized in terms of an essentially coplanar arrangement of the reactants with appropriate stacking during the endo face-selective process. In contrast, a knife-edge alignment is adopted by the cyclopentenyl species as exo attack on the norbornanone carbonyl group begins. Structural assignments to the product alcohols were realized by direct X-ray crystallographic analysis of these or their anionic oxy-Cope products. The balance of the structural information evolved from diagnostic ^{1}H NMR correlations involving the cyclopentenyl olefinic proton and those of the vinyl group when recorded in benzene-d_6 solution. In each example, oxy-Cope rearrangement took place stereospecifically to deliver a single product. Whereas an endo chair transition state was followed by the exo alcohols, an exo boat arrangement was adopted in the endo norbornanol series.

The determination of diastereoselection levels attainable during nucleophilic capture of chiral β,γ-unsaturated ketones by chiral vinyl organometallics has gained increasing significance in recent years.[2] The interest accorded these condensations has been spurred by the considerable practical import that such processes can bring to the stereospecific synthesis of natural products via subsequent anionic oxy-Cope rearrangement.[3] Since the level of preferred C–C bond formation is recognized to hinge on the subtle interplay of several factors, a deeper understanding of individual controlling influences is essential for more rational utilization of the protocol.

(1) Author to whom inquiries relating to the X-ray crystallographic analyses should be directed at Northern Illinois University.

(2) (a) Paquette, L. A.; Learn, K. S. *J. Am. Chem. Soc.* **1986**, *108*, 7873. (b) Paquette, L. A. In *Organic Synthesis: Modern Trends*; Chizhov, O., Ed.: Blackwell Scientific Publictions: Oxford, 1988; pp 1–12. (c) Paquette, L. A.; Learn, K. S.; Romine, J. L. *Tetrahedron* **1987**, *43*, 4989. (d) Paquette, L. A.; Learn, K. S.; Romine, J. L.; Lin, H.-S. *J. Am. Chem. Soc.* **1988**, *110*, 879. (e) Paquette, L. A.; DeRussy, D. T.; Cottrell, C. E. *Ibid.* **1988**, *110*, 890. (f) Paquette, L. A.; DeRussy, D. T.; Gallucci, J. C. *J. Org. Chem.* **1989**, *54*, 2278. (g) Paquette, L. A.; He, W.; Rogers, R. D. *Ibid.* **1989**, *54*, 2291.

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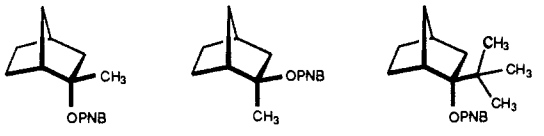
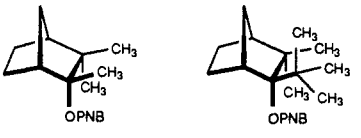
In continuation of a program designed to probe these discriminatory factors, we have now investigated the consequences of 1,2-addition to select 1-vinyl-2-norbornanones from the exo (A) and endo surfaces (B). Molecular mechanics have also been applied to the observed stereochemical trends in order to develop a qualitative, though reliable predictive model.

Background Considerations. Nucleophilic and electrophilic additions to norbornyl systems have been intensively studied by a number of research groups.[4] Exo addition clearly enjoys an unrivaled kinetic advantage, unless the singly bridged atom (C-7) is disubstituted. Where 7,7-dimethylnorbornene is concerned, reactions that proceed via cyclic transition states are directed preferentially endo, while those that proceed stepwise with minimal steric demands continue to favor the exo trajectory.[5] Nucleophilic additions to 7,7-disubstituted norbornan-2-ones do not follow this trend and proceed exclusively from the endo direction.[3c,d,6]

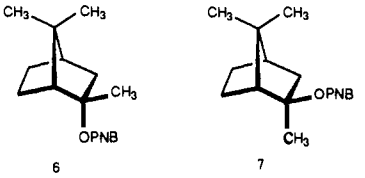
Differing degrees and modes of compression have been invoked to account for the solvolytic behavior of 2-norbornyl systems. Thus, the rigidity of the bicyclo[2.2.1]heptane framework has been held responsible for steric impedance to ionization in **1** relative to **2**.[7] Quite respectable acceleration of carbocation generation can be realized by steric congestion of the exo surface as in **3**.[8] Introduction of *gem*-dimethyl groups into the 3-position greatly increases the strain level and substantially raises the impact of *tert*-butyl versus methyl in **4** and **5**.[9] Finally, placement of the *gem*-dimethyl pair at C-7 as in **6** and **7** heightens crowding in the exo environment while maintaining endo space roughly constant. This structural modification essentially levels the exo–endo solvolysis rate ratio.[9]



rel. rate (25°C) 1.00 885 39600



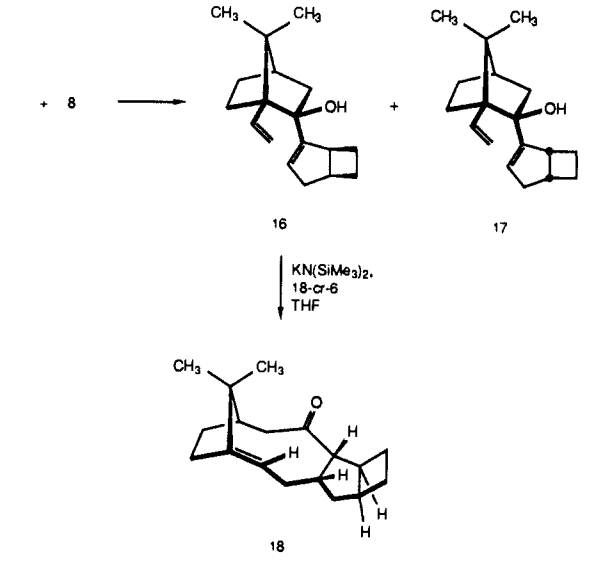
rel. rate (25°C) 1.00 1,120,000

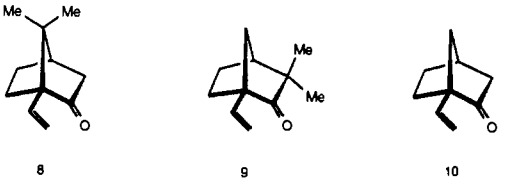


rel. rate (25°C) 1.00 6.1

On this basis, the degree of nucleophilic accessibility to 2-norbornanones can be anticipated likewise to be subject to considerable steric control. To the extent that such interactions play a major role in determining transition-state energies, a corresponding distinction in the magnitudes of diastereoselection observed for exo and endo addition could exist. Therefore, ketones **8–10** were selected as appropriate substrates. For **9** and **10**, exo attack prevails.[11] However, the doubly neopentyl nature of the carbonyl group in **9** brings to this ketone a heightened level of steric crowding not available to **10**. Is this distinction sufficient to cause **9** to be appreciably more diastereoselective than **8** in its reactions with chiral nucleophiles? How will it compare with **8** in the extent to which discrimination between the enantiomeric forms of the incoming nucleophilic species is made?

Scheme I





(+)-7,7-Dimethyl-1-vinyl-2-norbornanone (8). This optically pure ketone, available in two steps from D-camphor-10-sulfonyl chloride,[12] has previously been shown to experience rapid enolization when exposed to Grignard and lithium reagents.[10] Dichlorocerates were therefore employed to take advantage of their reduced basicity.[13] In order to maximize the potential for kinetic resolution,[2b,e] **8** was consistently introduced slowly to 3 equiv of the particular cerium reagent in cold (−78 °C to −30 °C) tetrahydrofuran. Earlier results have shown this relative amount of organometallic to be adequate to realize maximum stereoselection while minimizing the unproductive consumption of vinyl bromide.[2e]

Vinyl bromides **11–15** were chosen as suitable probes. All have been described elsewhere.[2] Bromide **14**, the only monosubstituted nucleophile, has been found in other circumstances to provide high diastereoselective discrimination.[2e,f] Recourse to **15** holds interest due to the unique nature of the bicyclo[2.2.1]heptene ring as discussed above.

Slow addition of **8** to the dichlorocerate of **13** gave rise to two alcohols (ratio 3.2:1) which were readily separated chromatographically. The absolute configuration of the major isomer was identified as **16** on the strength of its anionic oxy-Cope rear-

(4) Lajunen, M. *Acc. Chem. Res.* **1985**, *18*, 254 and the many citations given therein.
(5) (a) Brown, H. C.; Kawakami, J. H. *J. Am. Chem. Soc.* **1970**, *92*, 1990. (b) Brown, H. C.; Kawakami, J. H.; Ikegami, S. *Ibid.* **1970**, *92*, 6915. (c) Brown, H. C.; Kawakami, J. H.; Liu, K.-T. *Ibid.* **1973**, *95*, 2209. (d) Brown, H. C.; Kawakami, J. H. *Ibid.* **1973**, *95*, 8665.
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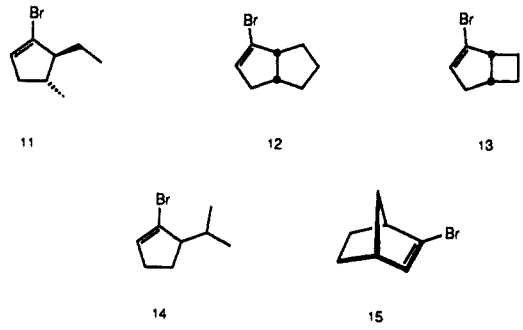
(10) Paquette, L. A.; Pegg, N. A.; Toops, D.; Maynard, G. D.; Rogers, R. D. *J. Am. Chem. Soc.* **1990**, *112*, 277.
(11) Paquette, L. A.; Teleha, C. A.; Taylor, R. T.; Maynard, G. D.; Rogers, R. D.; Gallucci, J. C.; Springer, J. P. *J. Am. Chem. Soc.* **1990**, *112*, 265.
(12) Fischer, N.; Opitz, G. *Organic Synthesis* 1973; Collect. Vol. V., p 877.
(13) (a) Imamoto, T.; Sugiura, Y.; Takiyama, N. *Tetrahedron Lett.* **1984**, *25*, 4233. (b) Imamoto, T.; Sugiura, Y. *J. Organomet. Chem.* **1985**, *285*, C21. (c) Imamoto, T.; Takiyama, N.; Nakamura, K. *Tetrahedron Lett.* **1985**, *26*, 4762. (d) Imamoto, T.; Takiyama, N.; Nakamura, K.; Hatajima, T.; Kamiya, Y. *J. Am. Chem. Soc.* **1989**, *111*, 4392.



rangement to **18** (Scheme I) and X-ray analysis of this nicely crystalline ketone. The [3,3]sigmatropic process within **16** occurred rapidly at room temperature, giving rise exclusively to **18** (91% isolated) within only 15 min. An independent precedent involving structurally related 1-vinyl-2-cyclohexenyl-*exo*-norbornan-2-ols has shown that of four possible transition states only the "endo-chair" option is utilized.[10,14] The stereochemical characteristics of **18** define operation of the identical pathway.

Progression to the *cis*-bicyclo[3.3.0]octenyl system (Scheme II), with care to reproduce reaction conditions as closely as possible, was seen to exhibit continued preference for formation of the "β-alcohol", viz. **19**. The relevant product distribution (8.6:1) indicated that enlargement of the adjoining ring by one methylene group sufficed to have a considerable impact on diastereoselection. The distinction between **19** and **20** was achieved on the basis of ^{1}H NMR shift correlations of a type found suitable in other contexts.[2] These data are compiled in Table I. In general, the absorptions due to H_a and H_c are positioned to lower field, and H_b and H_d are more shielded in the β-alcohols (major) relative to their α counterparts (minor). While a few discrepancies have surfaced, two additional X-ray analyses were obtained to enhance the acceptability of the correlation.

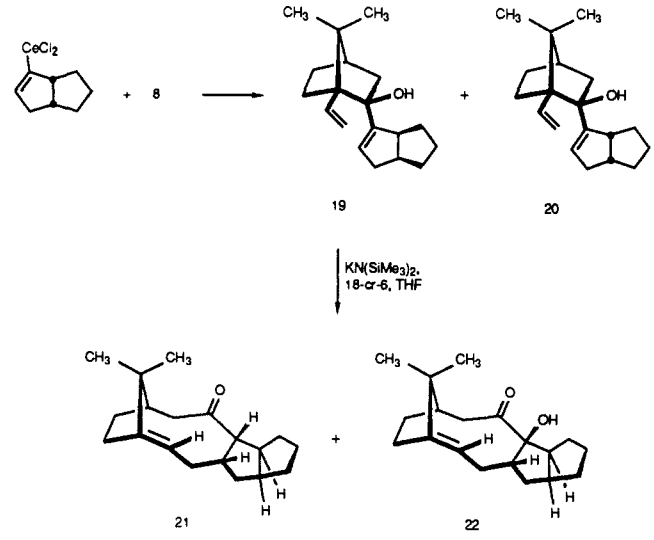
Oxy-Cope rearrangement within **19** was subsequently carried out without particular care being given to rid the reaction vessel of oxygen. As a result, α-hydroxy ketone **22** was produced (30%) in addition to **21** (53%). The ability of those regiospecifically generated enolates produced under such conditions to react readily with adventitious oxygen has recently been documented.[14] The structural assignments to **21** and **22** follow from NOE studies and dirrect spectral comparisons to closely related bridgehead olefinic ketones.[10,14]

The effect of the nucleophile structure on product distribution was next extended to encompass **14**. As anticipated, the increased steric bulk of the flanking isopropyl substituent in this dichlorocerate gave rise to the highest level of kinetic resolution (15.7:1) encountered in this study (Scheme III). As before, alcohols **23** and **24** were initially defined as to their stereochemisty by their ^{1}H NMR features (Table I). The validity of these conclusions was subsequently confirmed by conversion of **23** to **25**, two-step transformation of this enone to the highly crystalline **26**, and three-dimensional X-ray analysis of this triol. The configurations of the seven stereogenic centers in **26** necessitate that **25** be its progenitor and that "endo chair" topography be adopted during the isomerization of **23**.

The consequences of trans-4,5-disubstitution in the nucleophile proved to be attenuating as witnessed by the 7.0:1 ratio of **27** to **28** (Scheme IV). The reduced diastereoselectivity may stem in part from the untoward impact of the methyl substituent in the cerate working in opposition to the steric bias promoted by the ethyl group. The ^{1}H NMR shift data for the two alcohols follow established precedent (Table I). Furthermore, the oxy-Cope rearrangement of **27** proceeded rapidly, furnishing ketone **29** in 95% yield after 30 min at 20 °C.

The condensation of **8** with the 2-norbornenyl cerate provided the lowest diastereomer ratio encountered for this ketone (**30**:**31** = 2.2:1, Scheme V). Clearly, the structural characteristics of this nucleophilic species are not well suited to the realization of useful diastereoselective discrimination. The absolute stereochemistries of **30** and **31** follow from the chemical shifts of their diagnostic protons (Table I) and X-ray analysis of ketone **32**, which was produced efficiently (85%) upon exposure of **30** to potassium

Scheme II



Scheme III

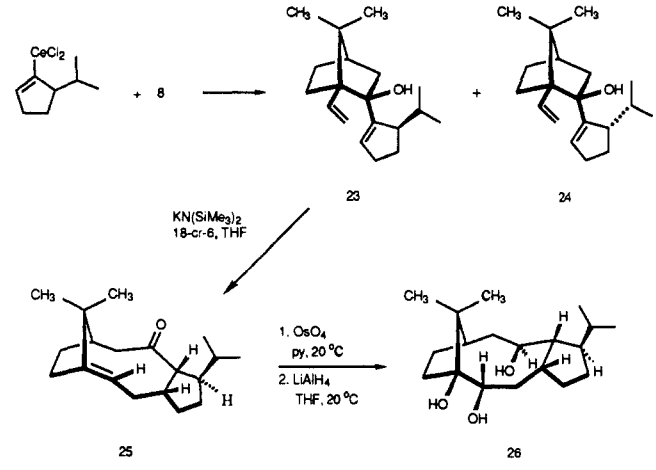
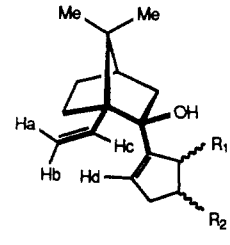


Table I. Selected by ^{1}H NMR Chemical Shift Data for the Exo Alcohols Derived from **8**[a]

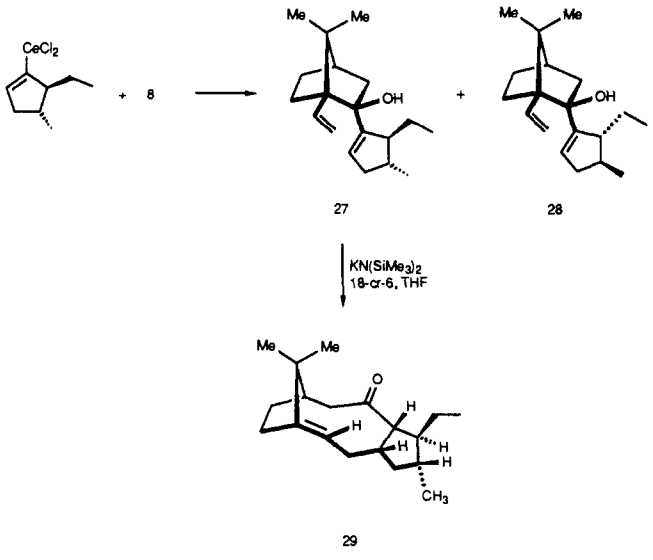


		chemical shift, δ			
diastereomer	series	H_a	H_b	H_c	H_d
16	β	6.35	5.26	4.98	5.60
17	α	6.34	5.21	5.05	5.57
19	β	6.35	5.26	5.04	5.53
20	α	6.48	5.22	5.08	5.38
23	β	6.34	5.26	5.06	5.75
24	α	6.48	5.19	5.06	5.60
27	β	6.37	5.26	5.05	5.57
28	α	6.46	5.22	5.08	5.46
30	β	6.29	5.23	5.00	5.63
31	α	6.40	5.24	5.09	5.66

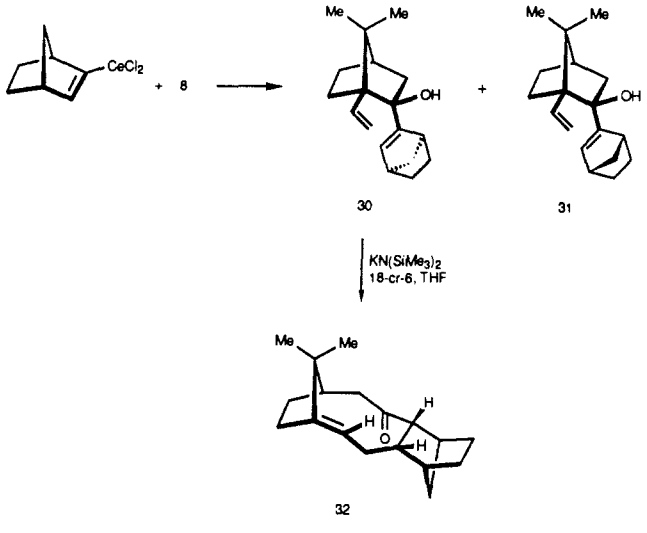
[a] 300 MHz, C_6D_6 solution.

(14) Paquette, L. A.; DeRussy, D. T.; Pegg, N. A.; Taylor, R. T.; Zydowsky, T. M. *J. Org. Chem.* **1989**, *54*, 4576.

Scheme IV



Scheme V



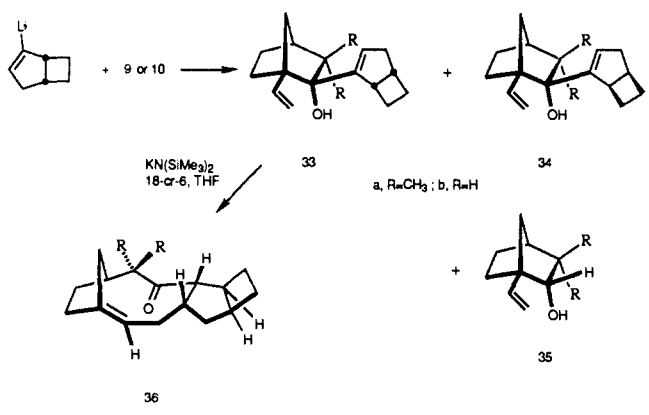
hexamethyldisilazide and 18-crown-6 in tetrahydrofuran. Chirality transfer had clearly again occurred by operation of an endo chair transition state.

(−)-3,3-Dimethyl-1-vinyl-2-norbornanone (9). Ketone **9** was conveniently secured as its optically pure 1*R* enantiomer in four steps from (1*R*)-(−)-fenchone as previously described.[11] The nonsusceptibility of **9** to competing enolization negated the need for cerium trichloride as an additive. Furthermore, the rates of condensation of vinyllithium reagents with **9** were found to be acceptably rapid at −78 °C. These conditions were therefore adopted. As before, a 3-fold excess of the organometallic was employed in order to maximize the opportunity for kinetic resolution.

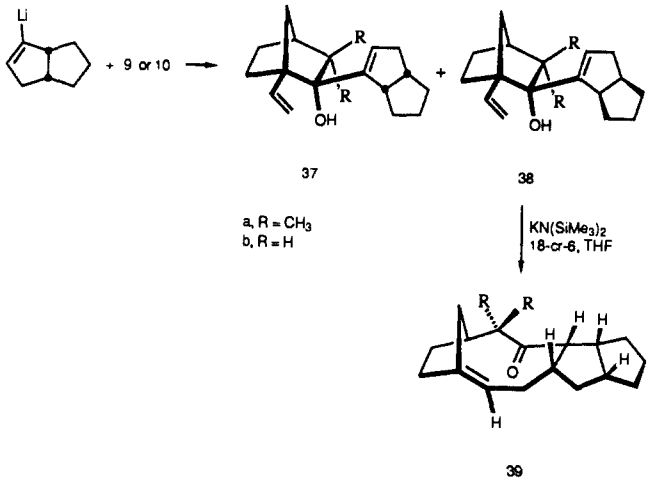
Condensation of the bicyclo[3.2.0]heptenyllithium reagent with **9** afforded alcohols **33a** and **34a** in a ratio of 1.1:1 as determined by analytical HPLC methods (Scheme VI). The low yield of desired products (52–54%) is presumed to be due in large part to the steric impedance to capture of a relatively bulky nucleophile. In fact, alcohol **35a** (endo stereochemistry assumed) was also isolated (10–13%), thereby revealing that the reduction of **9** by means of an electron-transfer mechanism now becomes a competing process.

Although **33a** and **34a** could be cleanly separated by chromatography, convincing relative (and absolute) stereochemical information could not be derived from ^{1}H NMR data alone. In order to resolve this issue, **33a** was subjected to anionic oxy-Cope rearrangement. The reaction was complete in only 40 min at room temperature and gave **36a** (97%), the crystallinity of which made

Scheme VI



Scheme VII



X-ray crystallographic analysis possible. In accord with evidence arrived at in a recent study,[11] **33a** experiences [3.3]sigmatropy via an "exo boat" transition state, thus giving rise to *Z* olefin geometry and to a cis,anti,cis arrangement at those stereogenic centers within the bicyclo[3.1.0]heptane subunit.

Condensation of **9** with the bicyclo[3.3.0]octenyllithium reagent resulted in a switch in product distribution (**37a**:**38a** = 1:1.1, Scheme VII), although the dominance by the "β-stereoisomeric alcohol" is only slightly greater than purely statistical. A small amount (6–11%) of **35a** was again isolated.

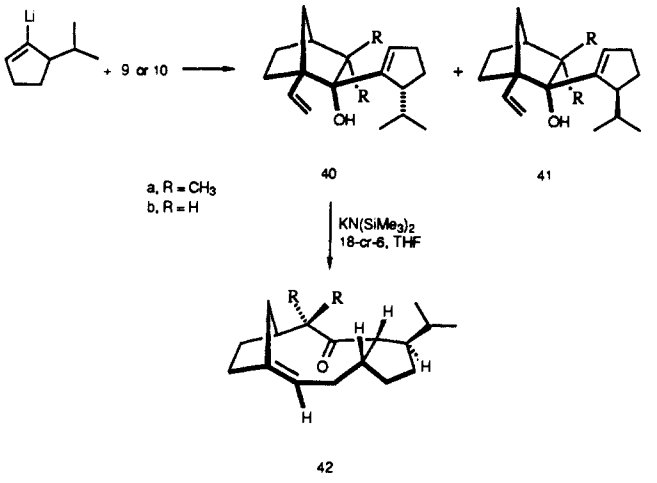
Compound **38a** was one of the few crystalline tertiary alcohols encountered in the course of this study, and an X-ray analysis was therefore performed. This molecule, in fact, precisely adopts that spatial disposition of double bonds directly conducive to [3.3]sigmatropy via the "exo boat" pathway that is so prevalent with substrates of this type.[11] Customary adoption of this boat-like geometry, hardly predictable in light of rather extensive precedent,[15] may originate from preferred ground-state geometries with proper allowance for the tenets of the Curtin–Hammett principle.[16]

Exposure of **9** to the lithio derivative of **14** brought about return of the "α-stereoisomeric alcohol" as the major product. The very modest diastereoselection (**40a**:**41a** = 1.2:1, Scheme VIII) was accompanied by the lowest yield of desired products (22–36%) and the greatest amount of **35a** (14–31%) observed to this point. It was becoming clear that **9** is devoid of a level of steric bias that is capable of insuring large diastereomer ratios during 1,2-addition by cyclopentenyl anions.

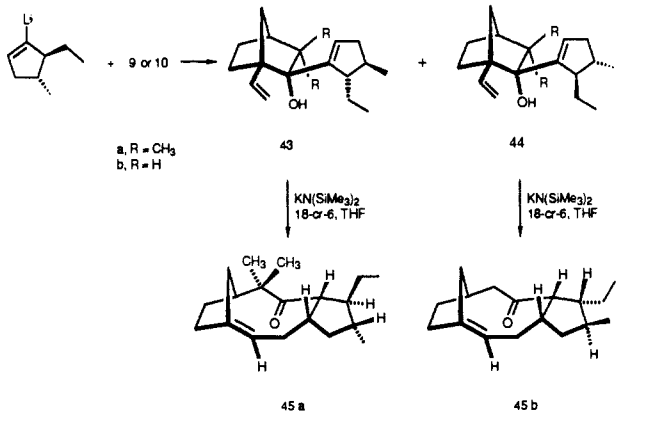
Trends in the ^{1}H NMR shift data for **40a**, **41a**, and their analogues were used to assign stereochemistry in these examples (Table II). The oxy-Cope rearrangement of **40a** proceeded

(15) (a) Hill, R. K. *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: 1984; Vol. 3A, p 503. (b) Hill, R. K. In *Comprehensive Organic Synthesis*; Pergamon Press: In press.
(16) Curtin, D. Y. *Rec. Chem. Prog.* **1954**, *15*, 111.

Scheme VIII



Scheme IX

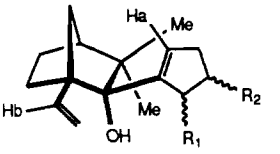


smoothly to afford **42a** (96%). Particularly notable features of the trans-4,5-disubstituted example (Scheme IX) are as follows: (a) the now customary low level discrimination (1.1:1) that slightly favors **43a**, (b) the heightened product yields (60–76%), and (c) the total absence of **35a** in the product mixture. From these data, it can be concluded that the lithium reagent derived from **11** is comparatively less sterically demanding in its exo approach to **9**. Following suitable chromatographic separation of **43a** from **44a**, structural assignments were made on the strength of ^{1}H NMR data (Table II). The stereochemistry of **45a** derives logically from the consistent exo boat transition-state pathway adopted by molecules such as **43a** during anionically promoted ring expansion.

The capture by **9** of the 2-norbornenyllithium reagent was particularly efficient (91–93%), though comparably low in diastereoselective discrimination (**46a**:**47a** = 1.2:1, Scheme X). Since ^{1}H NMR methods were of little utility in the present circumstances (Table II), **46a** was isomerized quantitatively to ketone **48a**, the epoxide of which proved especially crystalline. X-ray analysis of **49a** revealed that, although the exo boat transition-state trajectory was indeed followed, protonation of the resulting regiospecifically formed enolate materialized exclusively exo to the norbornyl framework. A trans fused ring juncture was thereby generated. It is of some interest that the usual kinetic advantage associated with exo proton delivery to 2-norbornyl centers does not materialize during the formation of **32a** (Scheme V). We assume that the *E* double bond geometry in the anion of **48a** provides for relatively greater conformational latitude and less steric structure than is present within the *Z* series represented by **32a**.

(±)-1-Vinyl-2-norbornanone (10). In light of the ease with which racemic **10** can be prepared from (±)-2-oxonorbornane-1-carboxylic acid,[11] no attempt was made to obtain optically active material in this phase of the investigation. Consequently, all of the structural formulae describing the products of reaction with **10** represent only one component of the racemate. To conform

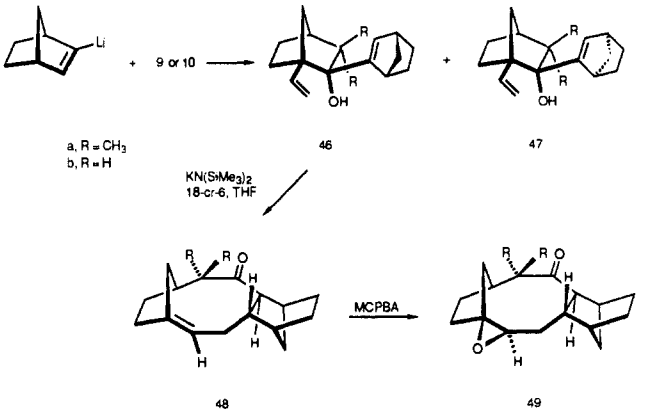
Table II. Selected ^{1}H NMR Chemical Shift Data for the Endo Alcohols Derived from **9**[a]



diastereomer	series	chemical shift, δ H_a	chemical shift, δ H_b
33a	α	5.35	6.03
34a	β	5.46	6.23
37a	α	5.19	6.06
38a	β	5.28	6.18
40a	α	5.40	5.98
41a	β	5.59	6.19
43a	α	5.21	6.01
44a	β	5.51	6.29
46a	α	5.70	5.98
47a	β	5.70	5.99

[a] 300 MHz, C_6D_6 solution.

Scheme X



with earlier phases of this investigation, all nucleophilic additions to **10** were performed on the identical scale, and the diastereoselectivity ratios cited represent the average of several repeat experimental determinations. As usual, the correspondence from run to run was quite satisfactory. Because **10** is also particularly susceptible to enolization, recourse was again made to dichlorocerium reagents. Furthermore, to optimize alcohol production, each reaction mixture was ultimately quenched with 1 equiv of methanol, exposed anew to a second aliquot of the cyclopentenyllithium reagent, and finally subjected one additional time to treatment in this way. A 1:1 ratio of **10** to nucleophile was universally adopted at each stage since double diastereoselection and not kinetic resolution was now at stake.[2b,e] The diastereomeric ratios were established by analytical HPLC methods.

The response of **10** to the cerates derived from bromides **11–15** follows a pattern surprisingly similar to that previously established for **9**. The one exception to surface involves the 5-isopropyl system **14**. In this instance, condensation afforded a 1:3.7 mixture of **40b** and **41b** (Scheme VIII). It will be recalled that the α-stereoisomeric alcohol **40a** predominates slightly (1.2:1) when starting from **9**. Although the vinyl protons of **40b** and **41b** (Table III) provided suggestive evidence for the stereochemical features of these alcohols, added confirmation was sought by means of anionic oxy-Cope chemistry. When **40b** was treated with KHMDS and 18-crown-6 in customary fashion, a near 1:1 mixture of **50** and its epimer **51** was produced (Scheme XI). Since neither of these ketones was adequately crystalline, **50** was epoxidized to give **52**. The correctness of the original assignments was confirmed by X-ray crystallographic analysis of **52**.

Quite striking was the persistence of relatively low diastereoselectivity ratios in the four additional examples (Table IV). The substantive similarity in the intermolecular recognition factors

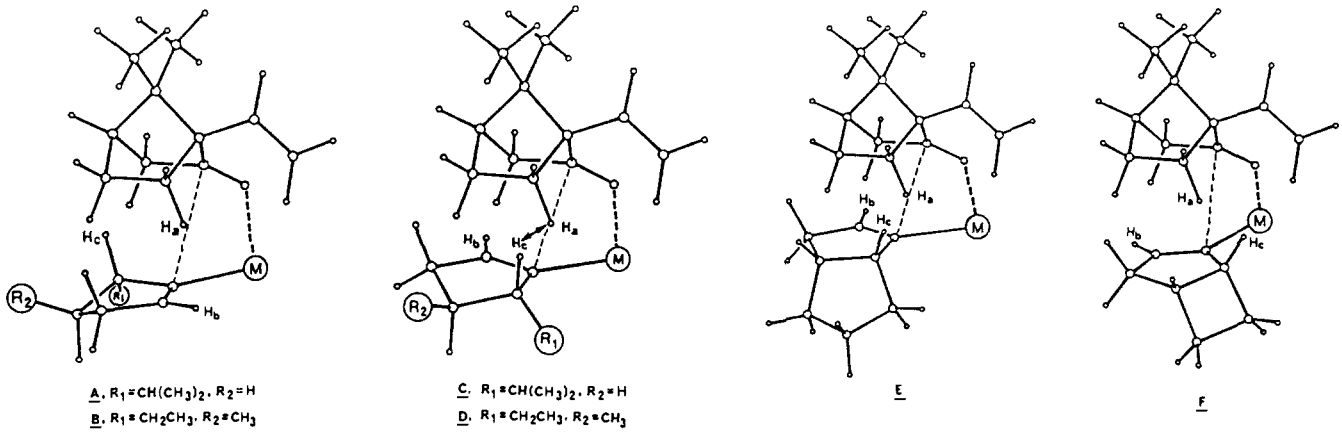
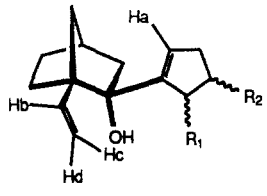


Figure 1. Selected transition-state models for the 1,2-addition of cyclopentenyl organometallics to **8** resulting in the major (A, B) and minor (C–F) alcohols. The intermolecular distance has been arbitrarily selected.

Table III. Selected ^{1}H NMR Chemical Shift Data for the Endo Alcohols Derived from **10**[a]



		chemical shift, δ			
diastereomer	series	H_a	H_b	H_c	H_d
33b	α	5.35	6.09	5.00	
34b	β	5.76	6.10	5.06	
37b	α	5.32	5.98	4.90	
38b	β	5.60	6.05	4.96–5.07	
40b	α	5.11	6.06	5.00	
41b	β	5.42	6.08	4.99, 5.01	
43b	α	5.20	6.10	4.93–5.01	
44b	β	5.51	6.10	4.97–5.05	
46b	α	5.49	6.14	5.00	
47b	β	5.73	6.10	5.06	

[a] 300 MHz, C_6D_6 solution.

Table IV. Summary of Diastereoselectivity Ratios

	ketone[a]		
vinyl bromide	**8**	**9**	**10**
13	3.2:1	1.1:1	1.5:1
12	8.6:1	1:1.1	1:2.2
14	15.7:1	1.2:1	1:3.7
11	7.0:1	1.1:1	1.5:1
15	2.2:1	1.2:1	1.1:1

[a] The value for the β-stereoisomer (as defined in the text) is given first.

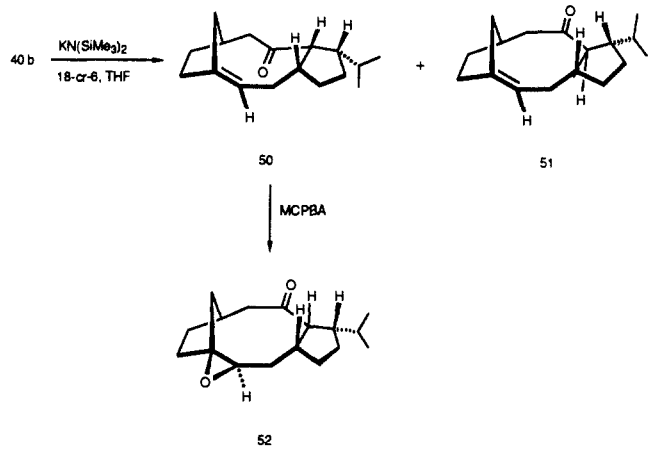
exhibited by the attacking nucleophiles does not on the whole bring them into that region of space occupied by the 3-exo substituent (CH_3 for **9**; H for **10**) until after the critical bond-forming event is passed. This revealing point will be elaborated upon in the Discussion.

The resulting *endo*-2-norbornanols were identified on the basis of the sequencing of their vinyl proton absorptions (Table III) and multiplicities. The ketonic oxy-Cope products exhibited NMR spectra that permitted direct comparison with their dimethyl analogues in the "a" series. Despite the satisfactory degree of correlation, which again demands adoption of the "exo boat" sigmatropic pathway, independent confirmation was sought by obtaining crystallographic verification in two additional examples (**36b** and **45b**).

Discussion

Heightened Capacity for Kinetic Resolution Surrounds Endo Attack. In this study, optically pure samples of the 1-vinyl-2-

Scheme XI

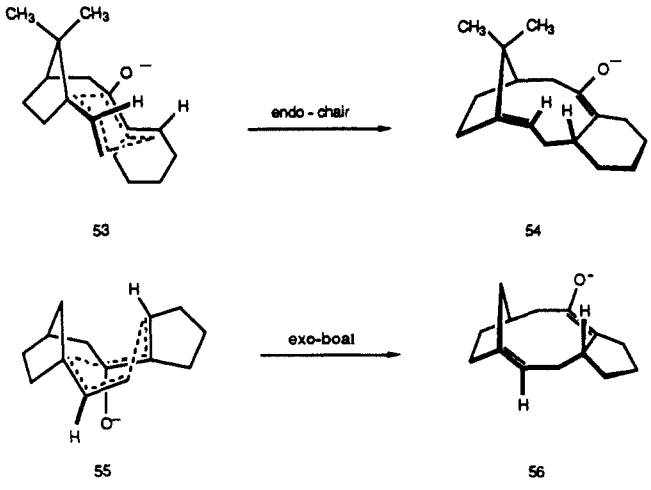


norbornanones **8** and **9** have been allowed to react with a 3-fold excess of several cyclopentenyl organometallics. The ensuing coupling reactions proceed under kinetic control via a pair of diastereomeric transition states. The extent to which one of these trajectories dominates over the second equates to the level of kinetic resolution attainable in the specific example. The data acquired herein (Table IV) clearly reveal that the endo approach pathway sterically enforced on the approaching nucleophile in the case of **8** is much more responsive to the two diastereomeric options. The greater spread in the relative energies of the rate-determining steps when **8** is involved is believed to stem from the greater steric blockade present on the *endo*-norbornyl surface as discussed in the introduction.

The existing state of affairs can be suitably appreciated by application of the Bürgi–Dunitz model for the directionality of nucleophilic capture by the carbonyl group[17] in combination with a simplified depiction of cerium–oxygen complexation.[2d,f,g] The transition-state models given in Figure 1, where appropriate stacking of the reagent pair is illustrated,[2f,g] are representative of our current thinking. Thus, the strong discrimination shown for A over C (15.7:1) likely has its origins in the severe nonbonded steric interaction involving H_a/H_c in the latter. In A, proximal vinylic proton H_b on the cyclopentenyl ring does not experience a comparable level of steric compression. Also, the bulkiness of the isopropyl group ensures its quasi-equatorial disposition, thus maximizing the H_a/H_c congestion in C. This compression can be expected to persist irrespective of whether the two reagents are oriented in mutually co-planar fashion (as shown) or at a somewhat different dihedral angle. This is because the rather obtuse trajectory associated with impending C–C bond formation

(17) (a) Bürgi, H. B.; Dunitz, J. D.; Lehn, J. M.; Wipff, G. *Tetrahedron* **1974**, *30*, 1563. (b) Scheiner, S.; Lipscomb, W. N.; Kleier, D. A. *J. Am. Chem. Soc.* **1976**, *98*, 4770. (c) Eisenstein, O.; Schlegel, H. B.; Kayser, M. M. *J. Org. Chem.* **1983**, *47*, 2886.

Scheme XII



53 54

55 56

necessarily maximizes this particular steric interaction.

When the isopropyl substituent is replaced by ethyl and a *trans*-methyl group is introduced at C-4 as in B and D, the diastereoselectivity is more than halved (Table IV). Models show that the effect of this substitution plan is to orient H_c almost in-plane to the five-membered ring because the cyclopentene cannot conveniently accommodate the C–Ce bond, R_1, and R_2 in a contiguous fashion along its outer equatorial perimeter. The decreased steric compression in D consequently allows for formation of a higher proportion of the "α-diastereomeric alcohol" **24**.

Transition-state models E and F, both of which lead to the less dominant alcohol, illustrate the important structural distinction that separates the bicyclo[3.3.0]octen-1-yl and bicyclo[3.2.0]-hepten-1-yl frameworks. Reduction of the adjoining ring size from cyclopentane to cyclobutane brings about a significant dihedral angle change between the two central tertiary C–H bonds, the smaller ring enforcing the greater degree of outward splaying as illustrated. On this basis, the all-important H_a/H_c interaction will be less severe in F than in E. When translated into rate considerations, this means that the extent of kinetic resolution should be greater in the bicyclo[3.3.0]octenyl example, since F should be capable of more favorable competition with its diastereomeric transition state than can E. At the experimental level, this structural modification translates into almost 3-fold greater diastereoselection (Table IV).

Near Comparable Diastereoselection Accompanies Exo Bonding to 9 and 10. With the exception of those condensations involving **12** with **9** and **10**, and **14** with **10**, an otherwise consistent preference for formation of "α-stereoisomeric alcohols" has been observed. Consequently, the two diastereomeric transition-state models associated with attack on the exo face of these ketones must (a) prove to be biased in the α-matching direction so often encountered, (b) account logically for the three examples of stereochemical crossover, and (c) make evident the cause(s) underlying these trend "violations".

Let us first consider the probable relative orientation of the two reactants at that point along either reaction trajectory where compact approach has been realized. Mere scrutiny of molecular models reveals that the syn apical proton at C-7 in these norbornanones plays a major role in deterring adoption of a mutually coplanar arrangement. As a result, the orientations depicted in Figure 2 feature an orthogonal arrangement in order to avoid this primary element of steric crowding. In general circumstances, utilization of such an approach angle should favor the adoption of G instead of H, irrespective of whether R is methyl or hydrogen. Once the vinyl C–H unit in the nucleophile becomes positioned between C-3 and C-7 as well as atop C-4 as shown, the group R_1 in G becomes projected above and beyond the oxygen atom. In actuality, these substituents constitute an outer boundary of the activated complex. As a result, any nonbonded interaction with the 1-vinyl and exo C-3 groups (CH_3 or H) is minimized. By way of contrast, the involvement of H necessarily incurs the added energy costs associated with positioning R_1 in that region of space proximal to the vinyl substituent in the ketone.

The abnormal response of **12** to this scenario stems from the steric bulk of its fused five-membered ring, the pronounced concave shape of this nucleophile, and the spatial demands of its methylene triad. In this set of circumstances, passage to product alcohol via H is somewhat favored over G because the fold of the bicyclo-[3.3.0]octenyl unit exerts less steric interaction with the vinyl group in the former than with the exo C-3 substituent in the latter. It is noteworthy that the reduced size of the four-membered ring in **13** already brings about a return to the norm.

This directing influence becomes most apparent in those reactions involving **14**. The well-recognized steric bulk of the isopropyl substituent (A = 2.1) is lowered in I because it finds itself projected outwardly. Where norbornanone **9** is concerned, $(CH_3)_2CH$– finds itself roughly midway between vinyl and exo 3-methyl, a state of affairs considerably better than that resident in alternative option J (in particular, note the proximity of isopropyl to vinyl). As a consequence, condensation between **9** and **14** proceeds to deliver a somewhat greater amount of the α-alcohol via I.

In contrast, the absence of the C-3 methyls in **10** results in substantive steric decompression in J (not possible in I) of a magnitude that is conducive to product formation preferably along this reaction channel.

We anticipate that this basis for reversing the preferred diastereomeric course of these carbonyl 1,2-addition reactions should be amenable to fine-tuning and control, thereby allowing for direct application of this chemistry to the stereocontrolled synthesis of complex polycyclic systems including natural products.

Conclusions. The trajectories followed by chiral (racemic) 1-cyclopentenyl nucleophiles as they approach a 2-norbornanone carbonyl group from its endo and exo surfaces are herein demonstrated to be widely divergent. The endo topography of these ketones is such that useful levels of diastereoselective discrimination can often be found to operate. In contrast, elevated levels of diastereomeric imbalance are difficult to achieve via exo bonding. These differences contribute to a fuller appreciation of the role that π-facial selectivity can have on diastereoselectivity ratios.

The accumulated data are most succinctly rationalized in terms of an almost coplanar orientation of the nucleophile–electrophile pair in the appropriate stacking mode when endo bonding is about to materialize. This transition-state model places the burden of steric discrimination on the endo protons of the ethano bridge in the norbornanone and the allylic protons of the cyclopentenyl organometallic (Figure 1). Exo attack cannot avail itself of a comparable intermolecular setting because of the presence of the syn 7-H atom. The current view is one where a knife-edge alignment of the cyclopentene is adopted vis-a-vis the norbornanone such that the extent to which the C-5 substituent can be accommodated from either surface dictates the product ratios (Figure 2). As a result, a 3-exo substituent of modest size makes little impact on product distribution.

It remains to ascertain whether the features peculiar to these trajectories are unique to norbornane derivatives. We hope to

(18) Sheldrick, G. M. SHELX76, a system of computer programs for X-ray structure determination as locally modified, University of Cambridge, England, 1976.

(19) Sheldrick, G. M. SHELXS In *Crystallographic Computing 3*; Sheldrick, G. M., Kruger, C., Goddard, R., Eds.; Oxford University Press: 1985; pp 175–189.

(20) *International Tables for X-ray Crystallography*; Kynoch Press, Birmingham, England, 1974; Vol. IV, pp 72, 99, 149. (Present distributor: Kluwer Academic Publishers, Dordrect and Boston).

(21) TEXSAN, TEXRAY Structure Analysis Package, Version 2.1, Molecular Structure Corporation, College Station, TX, 1987.

(22) Gilmore, C. J. MITHRIL: A Computer Program for the Automatic Solution of Crystal Structures from X-ray Data. University of Glasgow, Scotland, 1983.

(23) Beurskens, P. T. DIRDIF: Direct Methods for Difference Structures—An Automatic Procedure for Phase Extension and Refinment of Difference Structure Factors. Technical Report 1984/1. Crystallography Laboratory, Toernooiveld, 6525 Ed Nijmegen, The Netherlands.

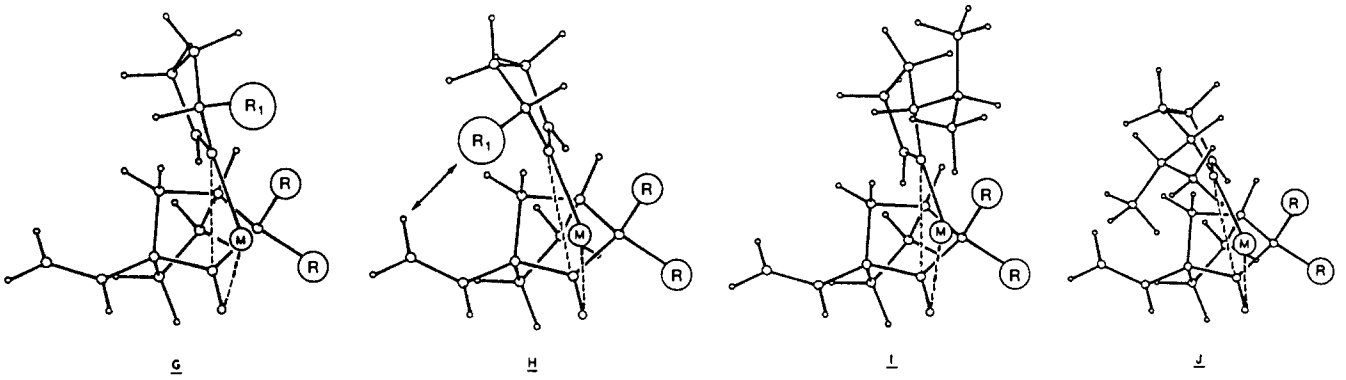


Figure 2. Transition-state models for the 1,2-addition of cyclopentenyl organometallics to 9 and **10**. Representations G and H relate to the full range of nucleophiles, while I and J related specifically to **14**. The intermolecular distance has been arbitrarily selected.

be in a position to provide enlightenment on this question at a future date.

Experimental Section

Prototypical Dichlorocerate Addition to Ketone 8. Cerium trichloride heptahydrate (1.84 g, 4.95 mmol) was dried by heating at 140–150 °C and 0.1 Torr for 2 h, slurried overnight in 15 mL of anhydrous tetrahydrofuran, and cooled to −78 °C. The lithium reagent prepared from vinyl bromide **13** (778 mg, 4.50 mmol) and *tert*-butyllithium (5.39 mL of 1.7 M, 9.0 mmol) as described below was transferred via cannula to this slurry, which was in turn stirred magnetically for 1 h. A solution of **8** (246 mg, 1.50 mmol) in 2 mL of tetrahydrofuran was added slowly over 10 min, and stirring was continued at −78 °C for 30 min before warming to −30 °C. An additional 3.5 h elapsed before 5 mL of saturated ammonium chloride solution was introduced. The mixture was partitioned between ether and brine, and the aqueous phase was extracted three times with ether. The combined organic layers were washed with brine, dried, and evaporated. MPLC of the residue on silica gel (elution with 1% ether in petroleum ether) furnished 87 mg (22%) of **17** followed by 270 mg (70%) of **16**, both as colorless oils. The average **16**/**17** ratio determined by HPLC on unpurified mixtures from several runs was 3.2:1.

For **16**: IR (neat, cm^{-1}) 3616, 3581, 3081, 2961, 2936, 2844, 1633, 1456; ^1H NMR (300 MHz, C_6D_6) δ 6.35 (dd, J = 17.8, 11.0 Hz, 1 H), 5.60 (s, 1 H), 5.26 (dd, J = 11.0, 2.3 Hz, 1 H), 4.98 (dd, J = 17.7, 2.2 Hz, 1 H), 3.10 (br s, 1 H), 2.66 (quint, J = 7.6 Hz, 1 H), 2.45 (ddt, J = 16.8, 8.3, 1.9 Hz, 1 H), 2.31–2.16 (m, 2 H), 2.12–1.89 (m, 4 H), 1.73–1.53 (m, 5 H), 1.43 (s, 3 H), 1.38–0.86 (m, 2 H), 0.84 (s, 3 H); ^{13}C NMR (75 MHz C_6D_6) ppm 154.82, 136.88, 126.51, 116.51, 82.27, 60.44, 51.12, 48.39, 46.32, 45.50, 40.84, 35.67, 28.59, 27.35, 26.80, 26.36, 21.96, 21.36; MS m/z (M^+) calcd 258.1984, obsd 258.1962; $[\alpha]^{22}_D$ −46.9° (c 1.04, $CHCl_3$). Anal. Calcd for $C_{18}H_{26}O$: C, 83.67; H, 10.14. Found: C, 83.75; H, 10.17.

For **17**: IR (neat, cm^{-1}) 3608, 3496, 3081, 3053, 2946, 2886, 2884, 1632, 1455; ^1H NMR (300 MHz, C_6D_6) δ 6.34 (dd, J = 17.8, 11.0 Hz, 1 H), 5.57 (s, 1 H), 5.21 (dd, J = 11.1, 2.2 Hz, 1 H), 5.04 (dd, J = 17.8, 2.2 Hz, 1 H), 3.46–3.41 (m, 1 H), 2.75–2.67 (m, 1 H), 2.45–2.26 (m, 2 H), 2.16–1.95 (series of m, 5 H), 1.76–1.52 (m, 4 H), 1.38 (s, 3 H), 1.24–1.16 (m, 2 H), 1.04–0.96 (m, 1 H), 0.83 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 151.77, 138.01, 126.34, 115.40, 83.69, 58.77, 51.26, 46.82, 46.39, 45.52, 39.98, 36.61, 29.16, 27.53, 26.75, 26.04, 23.14, 21.54; MS m/z (M^+) calcd 258.1984, obsd 258.2011; $[\alpha]^{25}_D$ −72° (c 0.81, $CHCl_3$).

Prototypical Anionic Oxy-Cope Rearrangement. Isomerization of 16. In an oven-dried 25-mL flask flushed with argon was placed 102 mg (0.395 mmol) of **16**, 125 mg (0.474 mmol) of 18-crown-6, and 5 mL of anhydrous tetrahydrofuran. Potassium hexamethyldisilazide (0.95 mL of 0.5 M in toluene, 0.5 mmol) was introduced dropwise via syringe, and the reaction mixture was stirred at room temperature for 15 min, cooled to 0 °C, and treated with 1 mL of saturated ammonium chloride solution. The mixture was partitioned between petroleum ether and ammonium chloride solution, and the organic phase was washed with brine and dried. Solvent evaporation and MPLC purification (silica gel, elution with 1% ether in petroleum ether) gave 93 mg (91%) of **18** as colorless crystals, mp 76–77 °C (from ethanol): IR ($CHCl_3$, cm^{-1}) 2959, 2936, 1680; ^1H NMR (300 MHz, C_6D_6) δ 5.35–5.28 (m, 1 H), 3.33–3.01 (m, 1 H), 2.78–2.66 (m 2 H), 2.61–2.54 (m, 1 H), 2.48–1.92 (series of m, 9 H), 1.85–1.58 (m, 4 H), 1.49–1.35 (m, 2 H), 1.13 (s, 3 H), 1.06 (m, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 213.12, 144.58, 124.50, 63.95, 51.52, 48.10, 45.07, 43.89, 42.56, 41.21, 40.44, 30.54, 25.10, 24.98, 24.76, 24.70, 22.78, 22.53; MS m/z (M^+) calcd 258.1984, obsd 258.2001; $[\alpha]^{22}_D$ −68.3° (c 1.06, $CHCl_3$).

The structure of **18**, determined by X-ray crystallography, is displayed in Figure 3 (supplementary material).

Addition of 12 to 8. Ketone 8 (246 mg, 1.50 mmol) was treated with the dichlorocerate prepared as described above from 842 mg (4.50 mmol) of **12**, 9.0 mmol of *tert*-butyllithium, and 1.84 g (4.95 mmol) of cerium trichloride heptahydrate. The crude product was purified by MPLC on silica gel (elution with 1% ether in petroleum ether) to give 347 mg (85%) of a mixture of **19** and **20**. Analytical HPLC analysis showed the average **19**/**20** ratio from several runs to be 8.6:1. Pure samples of the alcohols were obtained by means of analytical HPLC.

For **19**: colorless oil; IR (neat, cm^{-1}) 3611, 3596, 3080, 2944, 2860, 2851, 1633, 1453; ^1H NMR (300 MHz C_6D_6) δ 6.35 (dd, J = 17.8, 11.0 Hz, 1 H), 5.53 (d, J = 1.6 Hz, 1 H), 5.26 (dd, J = 11.0, 2.2 Hz, 1 H), 5.04 (dd, J = 17.7, 2.2 Hz, 1 H), 2.98–2.94 (m, 1 H), 2.54–2.45 (m, 2 H), 2.26 (dt, J = 13.5, 3.0 Hz, 1 H), 1.94–1.57 (series of m, 8 H), 1.50–1.22 (m, 5 H), 1.43 (s, 3 H), 1.11–0.84 (m, 1 H), 0.84 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 154.06, 137.59, 125.61, 116.32, 82.09, 60.68, 53.98, 51.25, 46.13, 45.46, 40.89, 40.69, 35.65, 33.23, 27.50, 26.24, 25.78, 22.02, 21.35; MS m/z (M^+) calcd 272.2140, obsd 272.2173; $[\alpha y^{22}_D$ −31.2° (c 1.05, $CHCl_3$). Anal. Calcd for $C_{19}H_{28}O$: C, 83.77; H, 10.36. Found: C, 83.77; H, 10.37.

For **20**: colorless oil; IR ($CHCl_3$, cm^{-1}) 3602, 3012, 2950, 2852; ^1H NMR (300 MHz, C_6D_6) δ 6.48 (dd, J = 17.8, 11.1 Hz, 1 H), 5.38 (s, 1 H), 5.22 (dd, J = 11.1, 2.3 Hz, 1 H), 5.08 (dd, J = 17.8, 2.2 Hz, 1 H), 3.22–3.15 (m, 1 H), 2.62–2.59 (m, 1 H), 2.46–2.36 (m, 1 H), 2.03–0.85 (series of m, 15 H), 1.40 (s, 3 H), 0.85 (s, 3 H); ^{13}C NMR (125 MHz, C_6D_6) ppm 150.93, 138.35, 125.16, 115.00, 83.02, 58.72, 51.72, 51.21, 46.39, 45.36, 42.71, 39.11, 35.20, 34.85, 27.74, 26.63, 25.74, 22.13, 21.45; MS m/z (M^+) calcd 272.2140, obsd 272.2135; $[\alpha y^{22}_D$ −87.5° (c 0.20, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 19. Stirring 34 mg (0.125 mmol) of **19** with 1.0 mL of a 0.5 M solution of potassium hexamethyldisilazide in toluene (0.5 mmol) and 66 mg (0.252 mmol) of 18-crown-6 in tetrahydrofuran (2 mL) for 2.5 h and MPLC purification (silica gel, 1% ether in petroleum ether) furnished 18 mg (53%) of **21**. Flushing the column with 10% ether in petroleum ether gave 11 mg (30%) of **22**.

For **21**: colorless solid, mp 79–80 °C (from ethanol); IR ($CHCl_3$, cm^{-1}) 2986, 2954, 2866, 1678, 1463, 1453; ^1H NMR (300 MHz, C_6D_6) δ 5.18 (d, J = 11.0 Hz, 1 H), 2.71–2.59 (m, 2 H), 2.40–2.12 (series of m, 6 H), 1.96–1.87 (m, 1 H), 1.81–1.44 (m, 5 H), 1.29–0.93 (series of m, 7 H), 1.08 (s, 3 H), 1.01 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 214.03, 144.64, 124.33, 64.19, 51.67, 48.55, 47.73, 45.06, 44.64, 44.19, 40.89, 35.91, 35.27, 30.70, 27.84, 25.08, 24.77, 22.81, 22.54; MS m/z 272.2140, obsd 272.2131; $[\alpha]^{22}_D$ −28.8° (c 1.03, $CHCl_3$). Anal. Calcd $C_{19}H_{28}O$: C, 83.77; H, 10.36. Found: C, 83.66; H, 10.40.

For **22**: white solid, mp 162–163 °C (from ethanol); IR ($CHCl_3$, cm^{-1}) 3616, 2991, 2956, 2921, 2871, 1677, 1453; ^1H NMR (300 MHz, C_6D_6) δ 5.51–5.46 (m, 1 H), 3.16–3.12 (m, 1 H), 2.68–2.56 (m, 1 H), 2.48–2.29 (m, 2 H), 2.25–1.65 (series of m, 9 H), 1.49–1.01 (series of m, 8 H), 1.40 (s, 3 H), 1.09 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 215.48, 144.64, 121.88, 89.46, 56.05, 54.06, 50.06, 44.02, 42.35, 39.58, 35.15, 34.40, 30.37, 28.06, 26.49, 24.76, 23.81, 21.92, 20.30; MS m/z (M^+) calcd 288.2089, obsd 288.2082; $[\alpha]^{22}_D$ −16° (c 1.0, $CHCl_3$).

Addition of 14 to 8. From 850 mg (4.50 mmol) of **14**, 9.0 mmol of *tert*-butyllithium, 1.84 (4.95 mmol) of cerium trichloride heptahydrate, and 246 mg (1.50 mmol) of **8** there was isolated following MPLC (silica gel, 1% ether in petroleum ether) 226 mg (55%) of **23** and 14 mg (3%) of **24**, both as colorless oils. The average analytical HPLC ratio was 15.7:1. Flushing the column with 10% ether in petroleum ether returned 10 mg (4%) of **8**. The overall yield based on recovered **8** was therefore 62%.

For **23**: IR (neat, cm^{-1}) 3614, 3082, 2962, 2935, 2884, 2856, 1634, 1469; ^1H NMR (300 MHz, C_6D_6) δ 6.34 (dd, J = 17.8, 11.0 Hz, 1 H), 5.75 (s, 1 H), 5.26 (dd, J = 11.0, 2.1 Hz, 1 H), 5.06 (dd, J = 17.7, 2.2 Hz, 1 H), 2.60–2.59 (m, 1 H), 2.26 (ddd, J = 13.3, 4.0, 3.2 Hz, 1 H), 2.21–2.04 (m, 3 H), 1.84 (d, J = 13.4 Hz, 1 H), 1.78–1.52 (m, 5 H), 1.49–1.21 (m, 2 H), 1.42 (s, 3 H), 1.02–0.73 (m, 1 H), 0.92 (d, J = 7.0 Hz, 3 H), 0.84 (s, 3 H), 0.68 (d, J = 6.7 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 152.91, 137.74, 127.17, 116.30, 81.90, 60.84, 54.28, 51.20, 46.01, 45.12, 33.18, 29.92, 27.44, 26.17, 23.33, 22.39, 22.09, 21.44, 15.65; MS m/z (M^+) calcd 274.2297, obsd 274.2275; $[\alpha]^{22}_D$ −34.7° (c 1.79, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 83.45; H, 11.04.

For **24**: IR (neat, cm^{-1}) 3612, 3510, 3078, 3055, 2960, 2936, 2875, 2853, 1632, 1467; ^{1}NMR (300 MHz, C_6D_6) δ 6.48 (dd, J = 17.9, 11.1 Hz, 1 H), 5.60 (s, 1 H), 5.19 (dd, J = 11.0, 1.9 Hz, 1 H), 5.06 (dd, J = 17.9, 2.0 Hz, 1 H), 2.88 (m, 1 H), 2.41–2.34 (m, 1 H), 2.07–1.93 (m, 3 H), 1.82–0.69 (series of m, 9 H), 1.38 (s, 3 H), 0.92 (d, J = 6.9 Hz, 3 H), 0.83 (s, 3 H), 0.70 (d, J = 6.9 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 150.73, 138.26, 127.90, 114.51, 93.02, 58.81, 51.30, 51.10, 46.40, 46.19, 31.33, 30.32, 26.30, 25.30, 24.58, 22.10, 21.73, 21.41, 15.69; MS m/z (M^+) calcd 274.2297, obsd 274.2283; $[\alpha]^{22}_D$ −15° (c 0.18, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 23. Stirring 132 mg (0.482 mmol) of **23** with potassium hexamethyldisilazide (1.16 mL of a 0.5 M solution in toluene, 0.6 mmol) and 18-crown-6 (153 mg, 0.578 mmol) in tetrahydrofuran (5 mL) for 1 h and MPLC (silica gel, elution with 1% ether in petroleum ether) gave 116 mg (88%) of **25**, a colorless oil: IR (neat, cm^{-1}) 2954, 2864, 1674, 1462; ^1H NMR (300 MHz, C_6D_6) δ 5.14 (ddd, J = 11.6, 2.9, 2.6 Hz, 1 H), 2.58 (dd, J = 8.6, 5.2 Hz, 1 H), 2.46–2.13 (m, 5 H), 1.99–1.58 (series of m, 9 H), 1.30–0.96 (m, 2 H), 1.08 (s, 3 H), 1.02 (s, 3 H), 0.78 (d, J = 6.5 Hz, 3 H), 0.76 (d, J = 6.5 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 214.77, 145.21, 123.89, 59.21, 54.86, 51.98, 51.78, 44.87, 44.18, 34.02, 33.99, 33.03, 30.66, 25.00, 24.80, 22.68, 22.60, 21.97, 21.25; MS m/z (M^+) calcd 274.2296, obsd 274.2313; $[\alpha]^{22}_D$ −31.6° (c 1.27, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 83.18; H, 11.05.

Sequential Osmylation–Lithium Aluminum Hydride Reduction of 25. In an oven-dried 25-mL flask flushed with argon was placed ketone **25** (38 mg, 0.139 mmol) and 2.5 mL of pyridine. Osmium tetroxide (0.83 mL of a 0.20 M solution in pyridine, 0.17 mmol) was introduced, and the black solution was stirred overnight. The pyridine was removed by evaporation in vacuo, and the flask was sequentially charged with 5 mL of anhydrous tetrahydrofuran and lithium aluminum hydride (53 mg, 1.39 mmol). After overnight stirring, the reaction mixture was treated with 2 mL of ethyl acetate followed by a few drops of a 1 M aqueous solution of sodium hydroxide. The mixture was filtered through Celite (elution with ethyl acetate). Solvent evaporation and column chromatography (silica gel, elution with 10% ethanol in petroleum ether) gave 41 mg (95%) of **26**, colorless crystals, mp 146–147 °C (from CH_2Cl_2); IR ($CHCl_3$, cm^{-1}) 3632, 3540, 3012, 2964, 2936, 2877, 1467; ^1H NMR (300 MHz, C_6D_6) δ 4.07 (dd, J = 5.6, 2.5 Hz, 1 H), 3.68 (d, J = 6.9 Hz, 1 H), 2.97–2.86 (m, 1 H), 2.73 (br s, 1 H), 2.49–2.36 (m, 2 H), 2.26–1.07 (series of m, 16 H), 1.04 (s, 3 H), 1.02 (s, 3 H), 0.88 (d, J = 6.6 Hz, 3 H), 0.83 (d, J = 6.6 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 86.74, 79.73, 78.08, 55.84, 48.41, 48.17, 45.21, 43.86, 39.31, 38.96, 33.31, 32.96, 32.79, 32.27, 28.16, 24.53, 21.94, 20.48, 19.40; MS m/z (M^+) 310.2508, obsd 310.2492; $[\alpha]^{22}_D$ +17.4° (c 1.37, $CHCl_3$).

The structure of **26**, determined by X-ray crystallography, is displayed in Figure 4 (supplementary material).

Addition of 11 to 8. The dichlorocerium reagent was prepared as before with 850 mg (4.50 mmol) of **11**, 9.0 mmol of *tert*-butyllithium, and 1.84 g (4.95 mmol) of cerium trichloride heptahydrate. Condensation with **8** (246 mg, 1.50 mmol) and subsequent MPLC on silica gel (elution with 1% ether in petroleum ether) afforded 347 mg (84%) of **27** and 46 mg (11%) of **28**. The overall yield was therefore 95%, and the average **27**/**28** ratio was 7.0:1.

For **27**: colorless oil; IR (neat, cm^{-1}) 3710, 3614, 3080, 2952, 2930, 2878, 2853, 1632; ^1H NMR (300 MHz, C_6D_6) δ 6.37 (dd, J = 17.8, 11.0 Hz, 1 H), 5.57 (d, J = 2.2 Hz, 1 H), 5.26 (dd, J = 11.0, 2.2 Hz, 1 H), 5.05 (dd, J = 17.7, 2.2 Hz, 1 H), 2.42 (ddt, J = 16.7, 7.6, 2.2 Hz, 1 H), 2.92–2.22 (m, 1 H), 2.04 (d, J = 9.3 Hz, 1 H), 1.91–1.58 (series of m, 7 H), 1.46–1.39 (m, 1 H), 1.43 (s, 3 H), 1.29 (s, 1 H), 1.16–0.99 (m, 2 H), 0.95 (d, J = 7.0 Hz, 3 H), 0.87 (t, J = 7.4 Hz, 3 H), 0.84 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 153.44, 137.69, 124.78, 116.23, 81.71, 60.97, 58.43, 51.31, 46.06, 45.12, 39.99, 35.84, 27.37, 26.86, 26.16, 23.40, 22.06, 21.34, 12.22; MS m/z (M^+) calcd 274.2296, obsd 274.2289; $[\alpha]^{22}_D$ −39.8° (c 1.05, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 83.21; H, 10.97.

For **28**: colorless oil; IR (neat, cm^{-1}) 3715, 3610, 3082, 3059, 2960, 2925, 2880, 2837, 1633; ^1H NMR (300 MHz, C_6D_6) δ 6.46 (dd, J = 17.8, 11.1 Hz, 1 H), 5.46 (s, 1 H), 5.22 (dd, J = 11.0, 2.1 Hz, 1 H), 5.08 (dd, J = 17.9, 2.2 Hz, 1 H), 2.46–2.37 (m, 2 H), 2.02–1.57 (series of m, 6 H), 1.38 (s, 3 H), 1.35–0.99 (m, 5 H), 1.02 (s, 1 H), 0.94 (d, J = 7.0 Hz, 3 H), 0.88 (t, J = 7.3 Hz, 3 H), 0.82 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 150.82, 138.27, 125.54, 114.96, 82.86, 58.81, 55.58, 51.26, 46.46, 46.31, 38.33, 37.32, 27.32, 26.79, 25.17, 23.37, 22.18, 21.46, 11.85; MS m/z (M^+) calcd 274.2296, obsd 274.2278; $[\alpha]^{22}_D$ −1.3° (c 1.26, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 27. Alcohol **27** (110 mg, 0.401 mmol) was stirred in tetrahydrofuran (3 mL) with potassium hexamethyldisilazide (0.96 mL of a 0.5 M solution in toluene, 0.5 mmol) and 18-crown-6 (127 mg, 0.481 mmol) for 0.5 h. The usual workup followed by MPLC (silica gel, elution with 1% ether in petroleum ether) led to the isolation of 105 mg (95%) of **29**, a colorless oil: IR (neat, cm^{-1}) 2988, 2966, 2927, 2876, 1683, 1464; ^1H NMR (300 MHz, C_6D_6) δ 5.11 (d, J = 11.3 Hz, 1 H), 2.54 (dd, J = 8.7, 5.0 Hz, 1 H), 2.43–2.32 (m, 3 H), 2.24–1.58 (series of m, 10 H), 1.54–1.37 (m, 3 H), 1.08 (s, 3 H), 1.02 (s, 3 H), 1.00 (d, J = 6.1 Hz, 3 H), 0.79 (t, J = 7.4 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 214.64, 145.32, 123.79, 62.04, 56.64, 51.84, 50.16, 44.91, 44.14, 42.72, 42.59, 30.46, 28.38, 25.05, 24.82, 22.72, 22.64, 18.92, 13.51; MS m/z (M^+) calcd 274.2296, obsd 274.2311; $[\alpha]^{22}_D$ −65.3° (c 1.43, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 83.01; H, 11.02.

Addition of 15 to 8. Condensation of the dichlorocerate derived from **15** (778 mg, 4.50 mmol), 9.0 mmol of *tert*-butyllithium, and cerium trichloride heptahydrate (1.84 g, 4.95 mmol) with **8** (246 mg, 1.50 mmol) gave rise after MPLC on silica gel (elution with 1% ether in petroleum ether) to 198 mg (51%) of **30** and 91 mg (24%) of **31**. The overall yield of 75% was accompanied by an average HPLC-derived **30**/**31** ratio of 2.2:1.

For **30**: colorless solid, mp 31–32 °C; IR (thin film, cm^{-1}) 3611, 3082, 3059, 2956, 2874, 1633, 1455; ^1H NMR (300 MHz, C_6D_6) δ 6.29 (dd, J = 17.6, 11.0 Hz, 1 H), 5.63 (d, J = 2.7 Hz, 1 H), 5.23 (ddd, J = 11.0, 1.9, 1.6 Hz, 1 H), 5.00 (ddd, J = 17.6, 2.0, 1.5 Hz, 1 H), 2.81–2.80 (m, 1 H), 2.67–2.66 (m, 1 H), 2.09–2.05 (m, 1 H), 1.77–0.88 (series of m, 13 H), 1.42 (s, 3 H), 0.84 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 154.90, 136.69, 129.28, 116.10, 83.27, 59.31, 51.57, 49.99, 46.20, 45.08, 43.92, 42.45, 27.08, 26.67, 25.35, 25.05, 22.18, 21.56; MS m/z (M^+) calcd 258.1984, obsd 258.2032; $[\alpha]^{22}_D$ +8.1° (c 1.20, $CHCl_3$).

For **31**: colorless oil; IR (neat, cm^{-1}) 3605, 3592, 3082, 2060, 2790, 2875, 1632, 1453; ^1H NMR (300 MHz, C_6D_6) δ 6.40 (dd, J = 17.8, 11.1 Hz, 1 H), 5.66 (d, J = 3.0 Hz, 1 H), 5.24 (dd, J = 11.0, 2.1 Hz, 1 H), 5.09 (dd, J = 17.8, 2.1 Hz, 1 H), 3.15 (s, 1 H), 2.66 (s, 1 H), 1.97 (dt, J = 13.2, 3.1 Hz, 1 H), 1.80–1.32 (series of m, 8 H), 1.38 (s, 3 H), 1.08–0.83 (m, 5 H), 0.83 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 154.48, 138.19, 129.49, 115.95, 82.93, 58.71, 51.07, 48.85, 46.26, 44.06, 43.04, 42.65, 26.73, 26.58, 26.47, 26.30, 22.04, 21.54; MS m/z (M^+) calcd 258.1984, obsd 258.1994; $[\alpha]^{22}_D$ −118° (c 1.03, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 30. Stirring 108 mg (0.419 mmol) of **30** with potassium hexamethyldisilazide (1.1 mL of a 0.5 M solution in toluene, 0.5 mmol) and 18-crown-6 (145 mg, 0.548 mmol) in tetrahydrofuran (3 mL) for 15 min and MPLC (silica gel, elution with 1% ether in petroleum ether) gave 92 mg (85%) of **32** as colorless crystals, mp 107–108 °C (from ethanol): IR ($CHCl_3$, cm^{-1}) 2989, 2957, 2927, 2878, 1679, 1465, 1455; ^1H NMR (300 MHz, C_6D_6) δ 4.89–4.85 (m, 1 H), 2.60 (d, J = 9.7 Hz, 1 H), 2.50 (ddd, J = 12.0, 9.2, 2.7 Hz, 1 H), 2.24–1.02 (series of m, 14 H), 1.64 (dd, J = 12.7, 6.1 Hz, 1 H), 1.52 (t, J = 6.2 Hz, 1 H), 1.02 (s, 3 H), 1.00 (s, 3 H), 0.92–0.79 (m, 1 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 212.24, 146.35, 122.26, 59.82, 57.28, 51.44, 45.00, 44.23, 43.57, 40.35, 35.96, 31.45, 30.66, 29.01, 25.63, 24.74, 22.80, 22.40; MS m/z (M^+) calcd 258.1984, obsd 258.1982; $[\alpha]^{22}_D$ −89.5° (c 1.33, $CHCl_3$).

The structure of **32**, determined by X-ray crystallography, is displayed in Figure 10 (supplementary material).

Prototypical Organolithium Addition to Ketone 9. In an oven-dried 50-mL flask flushed with argon was placed **13** (778 mg, 4.50 mmol) and 15 mL of anhydrous tetrahydrofuran. This solution was cooled to −78 °C, treated dropwise with *tert*-butyllithium (5.29 mL of 1.7 M, 9.0 mmol) in pentane, and stirred for 30 min. A solution of **9** (246 mg, 1.50 mmol) in 2 mL of tetrahydrofuran was added slowly over 10 min, and tirring was continued at −78 °C for an additional 2.5 h before 5 mL of saturated ammonium chloride solution was introduced. The mixture was partitioned between ether and brine, and the aqueous phase was extracted three times with ether. The combined organic layers were washed with brine, dried, and evaporated. MPLC of the residue on silica gel (elution with 1% ether in petroleum ether) furnished 91 mg (24%) of **34a** followed by 115 mg (30%) of **33a**, both as colorless oils. Flushing the column wih 10% ether in petroleum ether returned 33 mg (13%) of unreacted **9** and 33 mg (13%) of the reduction product **35a**, also a colorless oil. The overall yield based on recovered **9** was therefore 67% (taking **35a** into

account, 80%). The average **33a**/**34a** ratio determined by HPLC on purified mixtures from several runs was 1.1:1.

For **33a**: IR (neat, cm^{-1}) 3625, 3078, 3066, 2968, 2936, 2890, 2841, 1634, 1470, 1463; ^1H NMR (300 MHz, C_6D_6) δ 6.03 (dd, J = 17.2, 11.0 Hz, 1 H), 5.35 (s, 1 H), 4.98–4.90 (m, 2 H), 3.19 (br m, 1 H), 2.67–2.37 (m, 3 H), 2.22–1.98 (m, 4 H), 1.82–0.95 (series of m, 8 H), 1.02 (s, 3 H), 0.95 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 148.47, 141.83, 127.07, 112.42, 84.10, 61.47, 49.17, 48.64, 45.46, 41.26, 39.27, 35.46, 30.17 (2 C), 27.37, 26.99, 24.66, 21.55; MS m/z (M^+) calcd 258.1984, obsd 258.1962; $[\alpha]^{22}_D$ −32.9° (c 1.39, $CHCl_3$).

For **34a**: IR (neat, cm^{-1}) 3626, 3077, 3066, 3036, 2986, 2844, 1634, 1463; ^1H NMR (300 MHz, C_6D_6) δ 6.26 (dd, J = 17.0, 11.5 Hz, 1 H), 5.46 (s, 1 H), 5.04 (dd, J = 11.3, 2.1 Hz, 1 H), 5.03 (dd, J = 17.1, 2.0 Hz, 1 H), 3.12–3.06 (m, 1 H), 2.69–2.62 (m, 1 H), 2.59–1.59 (series of m, 9 H), 1.52–0.86 (m, 4 H), 1.05 (s, 3 H), 0.84–0.72 (m, 1 H), 0.78 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 148.22, 142.49, 127.16, 112.07, 84.23, 60.15, 49.75, 49.23, 45.20, 41.45, 38.76, 35.03, 31.41, 29.57, 29.06, 27.56, 24.71, 22.46; MS m/z (M^+) calcd 259.1984, obsd 258.1957; $[\alpha]^{22}_D$ −63.1° (c 1.24, $CHCl_3$). Anal. Calcd for $C_{18}H_{26}O$: C, 83.67; H, 10.14. Found: C, 83.59; H, 10.25.

For **35a**: IR (neat, cm^{-1}) 3462, 3080, 2957, 2937, 2880, 1638; ^1H NMR (300 MHz, C_6D_6 δ 5.95 (dd, J = 17.4, 10.8 Hz, 1 H), 5.04 (dd, J = 17.5, 1.8 Hz, 1 H), 5.01 (dd, J = 10.8, 1.8 Hz, 1 H), 3.28 (s, 1 H), 1.92–1.83 (m, 1 H), 1.70–1.46 (m, 3 H), 1.36–0.92 (m, 4 H), 0.89 (s, 3 H), 0.87 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 141.95, 113.42, 83.03, 56.43, 48.27, 39.75, 39.10, 30.87, 25.88, 22.88, 20.39; MS m/z (M^+) calcd 166.1358, obsd 166.1361; $[\alpha]^{22}_D$ +12.0° (c 2.61, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 33a. In an oven-dried 25-mL flask flushed with argon was placed 115 mg (0.446 mmol) of **33a**, 141 mg (0.535 mmol) of 18-crown-6, and 5 mL of anhydrous tetrahydrofuran. Potassium hexamethyldisilazide (1.07 mL of a 0.5 M solution in toluene, 0.5 mmol) was added dropwise, and the reaction mixture was stirred at room temperature for 40 min, cooled to 0 °C, and treated with 1 mL of saturated ammonium chloride solution via injection. The mixture was partitioned between petroleum ether and ammonium chloride solution, and the organic phase was washed with brine and dried. Solvent evaporation and MPLC purification (silica gel, elution with 1% ether in petroleum ether) gave 112 mg (97%) of **36a** as colorless crystals, mp 112–113 °C (from ethanol): IR ($CHCl_3$, cm^{-1}) 3012, 2966, 2926, 2858, 1678; ^1H NMR (300 MHz, C_6D_6) δ 5.32–5.27 (m, 1 H), 2.96–2.92 (m, 1 H), 2.85 (d, J = 5.3 Hz, 1 H), 2.68–2.36 (m, 5 H), 2.24–1.96 (series of m, 6 H), 1.82–1.75 (m, 1 H), 1.65 (td, J = 8.8, 2.0 Hz, 1 H), 1.58–1.32 (m, 3 H), 1.16 (dd, J = 11.2, 5.4 Hz, 1 H), 1.06 (s, 3 H), 1.01 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 219.96, 143.44, 119.67, 54.50, 49.34, 48.40, 46.04, 45.56, 38.77, 36.28, 32.24, 30.64, 28.80, 27.89, 25.72, 24.71, 23.99, 23.62; MS m/z (M^+) calcd 258.1984, obsd 258.1989; $[\alpha]^{22}_D$ −72.9° (c 1.01, $CHCl_3$).

The structure of **36a**, determined by X-ray crystallography, is displayed in Figure 11 (supplementary material).

Addition of 12 to 9. The organolithium reagent was prepared from 842 mg (4.50 mmol) of **12** and 9.0 mmol of *tert*-butyllithium as described above and reacted with 9 (246 mg, 1.50 mmol). Following MPLC (silica gel, elution with 1% ether in petroleum ether), there were isolated 97 mg (24%) of **38a** as a white solid, mp 45–46 °C (from hexane), and 86 mg (21%) of **37a** as a colorless oil. In addition, 62 mg (25%) of 9 and 27 mg (11%) of **35a** were recovered for an overall yield of 81%. The average **37a**/**38a** HPLC ratio for several runs was determined to be 1:1.1.

For **38a**: IR ($CHCl_3$, cm^{-1}) 3626, 3076, 2941, 2868, 1635; ^1H NMR (300 MHz, C_6D_6) δ 6.18 (dd, J = 18.2, 10.3 Hz, 1 H), 5.28 (s, 1 H), 5.00 (dd, J = 18.1, 2.0 Hz, 1 H), 5.00 (dd, J = 10.3, 2.0 Hz, 1 H), 2.77–2.70 (m, 1 H), 2.66–2.38 (m, 3 H), 2.04–1.93 (m, 2 H), 1.90–1.52 (m, 5 H), 1.50–1.34 (m, 4 H), 1.31–1.11 (m, 3 H), 1.09 (s, 3 H), 0.87 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 148.22, 142.59, 125.90, 111.92, 83.34, 60.10, 54.48, 49.95, 45.32, 41.95, 40.05, 38.74, 35.48, 34.12, 31.90, 28.99, 27.52, 24.64, 22.48; MS m/z (M^+) calcd 272.2140, obsd 272.2157; $[\alpha]^{22}_D$ −63.3° (c 1.11, $CHCl_3$).

The structure of **38a**, determined by X-ray crystallography, is displayed in Figure 12 (supplementary material).

For **37a**: IR (neat, cm^{-1}) 3636, 3596, 3526, 3081, 3071, 2936, 2868, 2848, 1635, 1420; ^1H NMR (300 MHz, C_6D_6) δ 6.06 (dd, J = 17.5, 10.9 Hz, 1 H), 5.19 (d, J = 1.9 Hz, 1 H), 4.98 (dd, J = 11.0, 2.0 Hz, 1 H), 4.92 (dd, J = 17.6, 2.1 Hz, 1 H), 3.06–3.03 (m, 1 H), 2.67–2.57 (m, 1 H), 2.52–2.32 (m, 2 H), 2.08–1.95 (m, 2 H), 1.82–1.68 (m, 1 H), 1.66–1.10 (series of m, 11 H), 1.05 (s, 3 H), 0.86 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 147.77, 142.01, 126.25, 112.27, 83.92, 62.02, 53.16, 49.29, 45.33, 40.91, 40.04, 39.20, 35.66, 32.45, 30.42, 30.32, 26.36, 24.59, 21.82; MS m/z (M^+) calcd 272.2141, obsd 272.2123; $[\alpha]^{22}_D$ −12.7° (c 2.10, $CHCl_3$). Anal. Calcd for $C_{19}H_{28}O$: C, 83.77; H, 10.36. Found: C, 83.83; H, 10.40.

Anionic Oxy-Cope Rearrangement of 38a. Stirring 99 mg (0.364 mmol) of **38a** with potassium hexamethyldisilazide (0.85 mL of a 0.5 M solution in toluene, 0.4 mmol) and 18-crown-6 (116 mg, 0.437 mmol) in tetrahydrofuran (3 mL) for 1 h and MPLC (silica gel, elution with 1% ether in petroleum ether) gave 96 mg (97%) of **39a** as colorless crystals, mp 111–111.5 °C: IR ($CDCl_3$, cm^{-1}) 3006, 2964, 2916, 2871, 1681, 1461; ^1H NMR (300 MHz, C_6D_6) δ 5.26 (dd, J = 9.6, 6.2 Hz, 1 H), 3.23 (dd, J = 7.2, 5.6 Hz, 1 H), 2.55–2.23 (m, 6 H), 2.11–1.86 (m, 5 H), 1.18–1.37 (series of m, 7 H), 1.14–0.95 (m, 2 H), 1.06 (s, 3 H), 1.00 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 219.65, 143.27, 119.78, 52.62, 50.91, 49.57, 49.35, 48.40, 45.62, 34.85, 32.46, 32.23, 30.46, 30.43, 29.98, 27.95, 27.83, 24.20, 23.73; MS (M^+) m/z calcd 272.2140, obsd 272.2158; $[\alpha]^{22}_D$ −82.0° (c 1.26, $CHCl_3$). Anal. Calcd for $C_{19}H_{28}O$: C, 83.77; H, 10.36. Found: C, 83.34; H, 10.35.

Addition of 14 to 9. From 850 mg (4.50 mmol) of **14**, 9.0 mmol of *tert*-butyllithium, and 246 mg (1.50 mmol) of **9**, there were obtained after MPLC (silica gel, 1% ether in petroleum ether) 86 mg (21%) of **40a**, 61 mg (15%) of **41a**, and 31 mg (31%) of reduction product **35a** for an overall yield of 67%. The average HPLC ratio of **40a**/**41a** was determined to be 1.2:1 on the basis of several runs.

For **40a**: colorless oil; IR (neat, cm^{-1}) 3616, 3593, 3079, 2974, 2934, 2869, 2852, 1637, 1468; ^1H NMR (300 MHz, C_6D_6) δ 5.98 (dd, J = 17.5, 10.8 Hz, 1 H), 5.40 (s, 1 H), 4.96 (dd, J = 10.9, 1.7 Hz, 1 H), 4.87 (dd, J = 17.5, 1.8 Hz, 1 H), 2.58 (br s, 1 H), 2.33–2.17 (m, 3 H), 2.00–1.97 (m, 2 H), 1.75–1.61 (m, 4 H), 1.42–1.24 (m, 4 H), 1.02 (s, 3 H), 0.96 (s, 3 H), 0.94 (d, J = 6.9 Hz, 3 H), 0.80 (d, J = 6.9 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 148.80, 141.71, 112.49, 84.42, 62.48, 53.60, 49.09, 45.86, 39.31, 34.01, 30.95, 30.04, 29.78, 24.52, 23.25, 23.19, 22.15, 16.42 (1 C obscured by C_6D_6); MS m/z (M^+) calcd 274.2296, obsd 274.2311; $[\alpha]^{22}_D$ −2.9° (c 1.65, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 83.18; H, 10.96.

For **41a**: colorless oil; IR (neat, cm^{-1}) 3616, 3081, 2964, 2936, 2891, 2856, 1634, 1468; ^1H NMR (300 MHz, C_6D_6) δ 6.19 (dd, J = 17.0, 11.5 Hz, 1 H), 5.59 (s, 1 H), 5.02–4.96 (m, 2 H), 2.48–2.24 (m, 4 H), 2.21–2.04 (m, 1 H), 1.98 (d, J = 10.4 Hz, 1 H), 1.77–1.63 (m, 4 H), 1.43–1.28 (m, 2 H), 1.25–1.05 (m, 2 H), 1.02 (s, 3 H), 0.96 (d, J = 6.9 Hz, 3 H), 0.85 (s. 3 H), 0.82 (d, J = 7.0 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 147.18, 142.57, 129.98, 112.01, 84.37, 60.66, 54.74, 49.97, 45.57, 38.75, 32.62, 32.19, 32.05, 29.32, 24.39 (2 C), 22.84, 22.28, 16.49; MS m/z (M^+) calcd 274.2296, obsd 274.2335; $[\alpha]^{22}_D$ −54° (c 0.83, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 40a. Stirring 25 mg (0.091 mmol) of **40a** with potassium hexamethyldisilazide (0.27 mL of a 0.5 M solution in toluene, 0.1 mmol) and 18-crown-6 (36 mg, 0.136 mmol) in tetrahydrofuran (2 mL) for 1 h and subsequent MPLC on silica gel (elution with 1% ether in petroleum ether) afforded 24 mg (96%) of **42a** as a colorless solid, mp 75–76 °C (from ethanol): IR ($CHCl_3$, cm^{-1}) 3962, 2912, 2874, 1679, 1467, 1454; ^1H NMR (30 MHz, C_6D_6) δ 5.29–5.24 (m, 1 H), 3.01 (dd, J = 6.1, 2.2 Hz, 1 H), 2.57 (d, J = 12.9 Hz, 1 H), 2.50–1.95 (series of m, 8 H), 1.80–1.48 (m, 3 H), 1.44–0.97 (m, 4 H), 1.20 (s, 3 H), 1.05 (s, 3 H), 0.82 (d, J = 6.6 Hz, 3 H), 0.77 (d, J = 6.6 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 220.95, 143.32, 119.74, 53.59, 51.73, 49.85, 49.16, 47.91, 33.27, 32.23, 30.99, 29.41, 29.19, 28.32, 28.03, 26.64, 23.50, 22.15, 20.58; MS m/z (M^+) calcd 274.2296, obsd 274.2294; $[\alpha]^{22}_D$ −2.0° (c 1.10, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 82.74; H, 10.95.

Addition of 11 to 9. A combination of 850 mg (4.50 mmol) of **11**, 9.0 mmol of *tert*-butyllithium, and ketone 9 (246 mg, 1.50 mmol) gave after MPLC (silica gel, 1% ether in petroleum ether) 163 mg (40%) of **43a** and 148 mg (36%) of **44a**. The average **43a**/**44a** ratio determined by HPLC on unpurified mixtures from several runs was 1.1:1.

For **43a**: colorless oil; IR (neat, cm^{-1}) 3587, 3077, 2960, 2932, 2874, 2848, 1632, 1461; ^1H NMR (300 MHz, C_6D_6) δ 6.01 (dd, J = 17.5, 10.8 Hz, 1 H), 5.21 (s, 1 H), 4.96 (d, J = 10.9, 2.0 Hz, 1 H), 4.88 (dd, J = 17.5, 1.8 Hz, 1 H), 2.65 (ddt, J = 16.5, 7.9, 2.2 Hz, 1 H), 2.28–2.20 (m, 1 H), 2.02–1.98 (m, 2 H), 1.90–1.64 (series of m, 5 H), 1.54–1.20 (m, 4 H), 1.10–0.87 (m, 1 H), 1.06 (s, 3 H), 0.98 (d, J = 7.0 Hz, 3 H), 0.92 (t, J = 7.1 Hz, 3 H), 0.88 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 147.99, 142.06, 125.33, 112.33, 83.68, 62.17, 58.25, 49.23, 45.33, 40.39, 39.31, 34.83, 30.19, 30.09, 27.09, 24.53, 23.72, 21.78, 13.30; MS m/z (M^+) calcd 274.2296, obsd 274.2265; $[\alpha]^{22}_D$ −21.3° (c 1.88, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 83.21, H, 11.08.

For **44a**: colorless oil; IR (Neat, cm^{-1}) 3629, 3079, 2964, 2924, 2876, 2849, 1636, 1464; ^1H NMR (300 MHz, C_6D_6) δ 6.29 (dd, J = 17.4, 11.0 Hz, 1 H), 5.51 (t, J = 2.3 Hz, 1 H), 5.12 (dd, J = 11.0, 1.9 Hz, 1 H), 5.09 (dd, J = 17.3, 2.0 Hz, 1 H), 2.71 (ddt, J = 16.7, 7.4, 2.1 Hz, 1 H), 2.43–2.33 (m, 1 H), 2.20 (d, J = 8.3 Hz, 1 H), 2.09 (dq, J = 10.2, 2.2 Hz, 1 H), 2.04–1.72 (series of m, 5 H), 1.65–1.42 (m, 3 H), 1.39–1.29 (m, 2 H), 1.11 (s, 3 H), 1.09 (d, J = 7.3 Hz, 3 H), 1.04 (s, 3 H), 1.01

(t, J = 7.8 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 146.32, 142.70, 126.86, 111.91, 84.07, 61.05, 58.56, 49.76, 46.03, 39.73, 38.85, 37.25, 31.67, 29.56, 28.46, 24.55, 23.62, 22.49, 11.97; MS m/z (M^+) calcd 274.2296, obsd 274.2300; $[\alpha]^{22}_D$ −10.1° (c 1.15, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 43a. A 35-mg (0.128 mmol) sample of **43a** was stirred in tetrahydrofuran (2 mL) with potassium hexamethyldisilazide (0.38 mL of a 0.5 M solution in toluene, 0.2 mmol) and 18-crown-6 (51 mg, 0.19 mmol) for 1 h. MPLC purification (silica gel, 1% ether in petroleum ether) gave 33 mg (94%) of **45a** as a colorless oil: IR (neat, cm^{-1}) 2954, 2904, 2894, 1680, 1451; ^{1}H NMR (300 MHz, C_6D_6) δ 5.29–5.23 (m, 1 H), 2.82 (q, J = 5.8 Hz, 1 H), 2.54 (q, J = 12.8 Hz, 1 H), 2.46–2.32 (m, 2 H), 2.30–1.95 (m, 4 H), 1.80–1.43 (m, 4 H), 1.37–0.77 (series of m, 5 H), 1.24 (d, J = 6.5 Hz, 3 H), 1.13 (s, 3 H), 1.03 (s, 3 H), 0.83 (t, J = 7.4 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 222.11, 143.24, 119.91, 56.80, 54.47, 49.75, 49.01, 48.37, 40.54, 38.26, 32.11, 30.82, 30.73, 29.66, 28.09, 26.60, 23.52, 20.65, 13.09; MS m/z (M^+) calcd 274.2296, obsd 274.2315; $[\alpha]^{22}_D$ −36.6° (c 1.33, $CHCl_3$). Anal. Calcd for $C_{19}H_{30}O$: C, 83.15; H, 11.02. Found: C, 83.24; H, 11.06.

Addition of 15 to 9. In line with the predescribed procedure, 778 mg (4.50 mmol) of **15** was allowed to react with 9.0 mmol of *tert*-butyllithium. Following the subsequent addition of **9** (246 mg, 1.5 mmol) and the usual workup, there was isolated 198 mg (51%) of **46a** and 164 mg (42%) of **47a**, both as colorless oils. HPLC analysis showed the average ratio of these alcohols to be 1.2:1, respectively.

For **46a**: IR (neat, cm^{-1}) 3616, 3588, 3495, 3081, 2964, 2874, 1633, 1463; ^{1}H NMR (300 MHz, C_6D_6) δ 5.98 (dd, J = 17.6, 10.8 Hz, 1 H), 5.70 (d, J = 2.7 Hz, 1 H), 4.97 (dd, J = 17.6, 1.8 Hz, 1 H), 4.94 (dd, J = 10.8, 2.0 Hz, 1 H), 2.83 (s, 1 H), 2.67 (s, 1 H), 2.50–2.41 (m, 1 H), 1.94 (dd, J = 10.3, 1.9 Hz, 1 H), 1.85–1.76 (m, 1 H), 1.68–1.67 (m, 1 H), 1.61–1.34 (series of m, 6 H), 1.19 (dd, J = 12.3, 4.3 Hz, 1 H), 1.14–0.90 (m, 3 H), 1.02 (s, 3 H), 0.85 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 155.87, 142.33, 130.01, 112.72, 84.03, 60.34, 49.94, 48.66, 46.71, 45.58, 42.19, 38.91, 30.96, 30.17, 26.54, 25.88, 24.96, 22.10; MS m/z (M^+) calcd 258.1983, obsd 258.2002; $[\alpha]^{22}_D$ +71.0° (c 1.09, $CHCl_3$). Anal. Calcd for $C_{18}H_{26}O$: C, 83.67; H, 10.14. Found: C, 83.67; H, 10.11.

For **47a**: IR (neat, cm^{-1}) 3626, 3584, 3078, 2966, 2872, 1634, 1454; ^{1}H NMR (300 MHz, C_6D_6) δ 5.99 (dd, J = 17.6, 10.9 Hz, 1 H), 5.70 (d, J = 3.5 Hz, 1 H), 4.94 (dd, J = 17.6, 2.0 Hz, 1 H), 4.92 (dd, J = 10.9, 1.9 Hz, 1 H), 2.68 (d, J = 1.5 Hz, 1 H), 2.39–2.30 (m, 1 H), 1.86 (ddd, J = 10.0, 2.2, 2.0 Hz, 1 H), 1.75–1.07 (series of m, 12 H), 1.05 (s, 3 H), 0.94 (s, 1 H), 0.90 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 150.44, 142.87, 129.52, 111.64, 82.97, 59.51, 49.78, 47.14, 45.44, 44.28, 42.92, 37.91, 31.58, 30.00, 26.88, 26.08, 25.29, 22.53; MS m/z (M^+) calcd 258.1984, obsd 258.1954; $[\alpha]^{22}_D$ −54.3° (c 1.20, $CHCl_3$).

Anionic Oxy-Cope Rearrangement of 46a. Stirring of **46a** (107 mg, 0.415 mmol) with potassium hexamethyldisilazide (1.0 mL of a 0.5 M solution in toluene, 0.5 mmol) and 18-crown-6 (132 mg, 0.498 mmol) in anhydrous tetrahydrofuran (5 mL) for 1 h and MPLC of the product mixture (silica gel, 1% ether in petroleum ether) gave rise to **48a** (106 mg, 99%) as a colorless oil: IR (neat, cm^{-1}) 2944, 2872, 1689, 1455; ^{1}H NMR (300 MHz, C_6D_6) δ 5.07–5.03 (m, 1 H), 3.10–3.07 (m, 1 H), 2.46–2.45 (m, 1 H), 2.30–2.26 (m, 1 H), 2.20–1.86 (m, 6 H), 1.73–1.46 (series of m, 7 H), 1.26–1.14 (m, 2 H), 1.12 (s, 3 H), 1.12–0.98 (m, 1 H), 1.01 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 219.31, 145.86, 118.15, 52.54, 50.86, 47.06, 46.12, 45.84, 42.23, 39.89, 35.73, 33.05, 32.63, 29.95, 28.64, 26.27, 23.51, 23.27; MS m/z (M^+) calcd 258.1984, obsd 258.1963; $[\alpha]^{22}_D$ −43.1° (c 1.40, $CHCl_3$). Anal. Calcd for $C_{18}H_{26}O$: C, 83.67; H, 10.14. Found: C, 83.68; H, 10.24.

Epoxidation of 48a. To a cold (0 °C), magnetically stirred solution of **48a** (42 mg, 0.16 mmol) in anhydrous dichloromethane (5 mL) containing disodium hydrogen phosphate (35 mg, 0.24 mmol) and sodium dihydrogen phosphate (34 mg, 0.24 mmol) was added *m*-chloroperbenzoic acid (42 mg, 0.24 mmol) in portions during 5 min. The reaction mixture was stirred at room temperature for 2.75 h, and the organic layer was washed in turn with saturated sodium thiosulfate (2 × 5 mL), saturated sodium bisulfite (2 × 5 mL), and brine (2 × 5 mL) solutions before drying and solvent evaporation. MPLC purification of the residue on silica gel (elution with 20% ether in petroleum ether) furnished **49a** (44 mg, 98%) as colorless needles, mp 159 °C (from ethanol): IR ($CHCl_3$, cm^{-1}) 3016, 2961, 2879, 1691, 1459; ^{1}H NMR (300 MHz, C_6D_6) δ 3.17–3.14 (m, 1 H), 2.59 (dd, J = 10.1, 4.8 Hz, 1 H), 2.14 (s, 1 H), 2.02–1.14 (series of m, 15 H), 1.11 (s, 1 H), 1.09 (s, 3 H), 0.98–0.88 (m, 1 H), 0.81 (s, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 215.20, 67.80, 61.63, 52.44, 52.17, 46.67, 43.94, 43.24, 42.45, 41.93, 33.53, 33.05, 32.10, 29.46, 28.25, 25.56, 22.15, 22.04; MS m/z (M^+) calcd 274.1933, obsd 274.1911; $[\alpha]^{22}_D$ −36.4° (c 1.52, $CHCl_3$).

The structure of **49a**, determined by X-ray crystallography, is displayed in Figure 13 (supplementary material).

Prototypical Addition to Ketone 10. Into a 25-mL, two-necked flask was placed 820 mg (2.05 mmol) of cerium trichloride heptahydrate, which was heated overnight at 160 °C under high vacuum. After returning to room temperature, dry tetrahydrofuran (10 mL) was introduced, and the mixture was stirred for 3 h. In another flask, a solution of **14** (100 mg, 0.53 mmol) in dry tetrahydrofuran (1.5 mL) was cooled to −78 °C and treated slowly with *tert*-butyllithium (0.65 mL of 1.7 M hexanes, 1.1 mmol). This solution was stirred for 30 min at −78 °C and then transferred to the cold (−78 °C) cerium chloride slurry via cannula. Stirring was continued for 3 h at −78 °C, after which a solution of **10** (60 mg, 0.44 mmol) in tetrahydrofuran (2 mL) was added. Two hours later, 21 μL of methanol was injected via syringe, 30 min was allowed to elapse, and another 0.53 mmol of vinyllithium reagent was added. This procedure was repeated a second time, and the reaction mixture was allowed to warm slowly to room temperature overnight. Saturated ammonium chloride solution was added, and the products were extracted into ether, washed with brine, dried, and evaporated to leave a yellow oil. MPLC of this material on silica gel gave 11 mg of **40b** and 50 mg of **41b** (61% combined yield).

For **40b**: colorless oil; IR (C_6D_6, cm^{-1}) 3605, 3065, 2955, 1725, 1635, 1465, 1380, 1280, 1125, 915; ^{1}H NMR (300 MHz, C_6D_6) δ 6.09 (dd, J = 17.0, 11.1 Hz, 1 H), 5.35 (s, 1 H), 5.00 (m, 2 H), 4.95–4.99 (m, 1 H), 2.65 (s, 1 H), 2.45 (m, 1 H), 2.38–2.00 (m, 4 H), 1.79 (m, 3 H), 1.57 (m, 2 H), 1.42–1.10 (m, 5 H), 0.97 (d, J = 6.9 Hz, 3 H), 0.81 (d, J = 6.9 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 152.93, 140.03, 126.82, 113.59, 82.15, 60.37, 52.97, 50.05, 41.87, 36.18, 32.82, 31.09, 30.08, 28.24, 24.76, 22.65, 16.29; MS m/z calcd 246.1984, obsd 246.1995.

For **41b**: colorless crystals, mp 43 °C (from ether–petroleum ether); IR (C_6D_6, cm^{-1}) 3560, 3080, 2950, 1730, 1636, 1468, 1378, 1290, 1010, 915; ^{1}H NMR (300 MHz, C_6D_6) δ 6.10 (dd, J = 17.0, 6.7 Hz, 1 H), 5.75 (s, 1 H), 5.06 (m, 2 H), 2.71 (m, 1 H), 2.48 (m, 1 H), 2.24 (m, 4 H), 1.74 (m, 4 H), 1.30 (m, 6 H), 0.92 (d, J = 6.8 Hz, 3 H), 0.75 (d, J = 6.8 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 151.96, 140.76, 127.27, 113.02, 81.53, 59.40, 52.40, 48.16, 42.24, 36.63, 32.08, 31.03, 30.26, 30.19, 25.08, 22.59, 15.92; MS m/z (M^+) calcd 246.1984, obsd 246.1970. Anal. Calcd for $C_{17}H_{26}O$: C, 82.87; H, 10.64. Found: C, 82.69; H, 10.61.

Anionic Oxy-Cope Rearrangement of 41b. Isomerization of **41b** (30 mg) in the predescribed manner gave a yellow oil, the MPLC of which on silica gel (elution with 2% ether in petroleum ether) provided 11.3 mg of **51** and 13.3 mg of **50** (63% combined yield).

For **50**: colorless solid, mp 89–90 °C (from ether); IR (C_6D_6, cm^{-1}) 2925, 2865, 1725, 1690, 1450, 1380, 1370, 1350, 1280, 1120, 1080, 1045, 955; ^{1}H NMR (300 MHz, C_6D_6) δ 5.34 (m, 1 H), 2.72 (t, J = 4.6 H, 1 H), 2.55–2.44 (m, 2 H), 2.35 (d, J = 12.8 Hz, 1 H), 2.20–1.37 (series of m, 15 H), 0.80 (t, J = 6 Hz, 6 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 216.64, 148.48, 120.79, 58.12, 55.76, 53.43, 50.30, 36.26, 33.54, 32.18, 29.93, 29.61, 28.87, 27.15, 26.45, 23.28, 22.12; MS m/z (M^+) calcd 246.1984, obsd 246.1977. Anal. Calcd for $C_{17}H_{26}O$: C, 82.87; H, 10.64. Found: C, 82.81; H, 10.51.

For **51**: colorless oil; IR (C_6D_6, cm^{-1}) 2955, 2870, 1698, 1470, 1370, 1265, 1070, 880; ^{1}H NMR (300 MHz, C_6D_6) δ 5.16 (d, J = 11 Hz, 1 H), 2.85 (d, J = 12 Hz, 1 H), 2.40–0.85 (series of m, 17 H), 0.80 (d, J = 6.6 Hz, 3 H), 0.74 (d, J = 6.6 Hz, 3 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 218.51, 140.42, 124.43, 58.90, 53.42, 50.81, 48.29, 35.03, 34.30, 33.98, 33.68, 32.08, 31.97, 30.24, 28.51, 21.94, 21.29; MS m/z (M^+) calcd 246.1984, obsd 246.1962.

Epoxidation of 50. To a magnetically stirred mixture of **50** (40 mg, 0.17 mmol), monobasic sodium phosphate hydrate (39 mg, 0.28 mmol), dibasic sodium phosphate (100 mg, 0.28 mmol), and dichloromethane (4 mL) was added 35.5 mg (0.21 mmol) of MCPBA. After 1 h, an additional 36 mg of peracid was added. Stirring was continued for 1 h, 5 mL of saturated sodium thiosulfate solution was transferred in the reaction flask, and the mixture was poured into a separtory funnel. The organic phase was washed with sodium bicarbonate solution and brine and then dried. Evaporation of the solvent left a white solid that was purified by MPLC to give 35 mg (82%) of **52** as colorless crystals, mp 110 °C (from ether): IR ($CHCl_3$, cm^{-1}) 3510, 3010, 2960, 2870, 2250, 1685, 1448, 1435, 1380, 1365, 1278, 1215, 1143, 1113, 1020, 745; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.24 (t, J = 5.12 Hz, 1 H), 2.93 (dd, J = 11.5, 5.3 Hz, 1 H), 2.85 (dd, J = 10.8, 3.0 Hz, 1 H), 2.57–2.52 (m, 1 H), 2.40–1.41 (series of m, 14 H), 1.34–1.24 (m, 2 H); 0.89 (d, J = 6.5 Hz, 3 H), 0.81 (d, J = 6.5 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 219.84, 69.22, 63.95, 58.82, 55.89, 52.03, 44.71, 36.70, 32.29, 30.32, 29.96, 29.85, 28.13, 26.78, 26.64, 22.83, 21.58; MS m/z (M^+) calcd 262.1933, obsd 262.1920.

The structure of **52**, determined by X-ray crystallography is displayed in Figure 14 (supplementary material).

Addition of 13 to 10. The organocerium reagent was prepared from **13** as described above and added to **10** (60 mg, 0.4 mmol). After two methanol quench–vinyllithium addition cycles, the reaction mixture was

quenched, and the resulting yellow oil was subjected to MPLC. There were obtained 27 mg of **34b** and 30 mg of **33b** (56% combined).

For **33b**: colorless solid, mp 49–50 °C (from ether–petroleum ether); IR (C_6D_6, cm^{-1}) 3560, 3070, 2940, 2860, 2830, 1630, 1445, 1280, 1075, 1000, 915, 740; ^1H NMR (300 MHz, C_6D_6) δ 5.98 (dd, J = 18.0, 9.9 Hz, 1 H), 5.32 (s, 2 H), 4.90 (s, 2 H), 3.28 (s, 1 H), 2.76 (m, 1 H), 2.40 (m, 1 H), 2.24–1.94 (m, 6 H), 1.79–1.13 (m, 7 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 154.25, 140.30, 126.21, 113.77, 82.42, 59.74, 49.29, 47.47, 42.01, 41.00, 36.34, 36.22, 30.23, 29.23, 27.51, 27.43; MS m/z (M^+) calcd 230.1671, obsd 230.1688. Anal. Calcd for $C_{16}H_{22}O$: C, 83.43; H, 9.63. Found: C, 83.08, H, 9.85.

Anionic Oxy-Cope Rearrangement of 33b. Isomerization of **33b** (70 mg) in the predescribed manner gave a yellow oil, purification of which by MPLC (silica gel, elution with 2% ether in petroleum ether) gave 45 mg (64%) of **36b**, a colorless crystalline solid, mp 96–97 °C (from ether): IR (C_6D_6, cm^{-1}) 2925, 2845, 1685, 1440, 1360, 1275, 1215, 1105, 1035, 1000, 915, 870, 740; ^1H NMR (300 MHz, C_6D_6) δ 5.30 (m, 1 H), 2.91 (m, 1 H), 2.69–1.08 (series of m, 20 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 216.74, 142.63, 120.56, 60.90, 50.65, 45.92, 43.70, 37.35, 34.93, 32.44, 30.77, 28.02, 26.72, 23.72, 23.08 (one signal not observed); MS m/z (M^+) calcd 230.1671, obsd 230.1651.

The structure of **36b**, determined by X-ray crystallography, is displayed in Figure 15 (supplementary material).

Addition of 12 to 10. The organocerium reagent was prepared from **12** as described above and added to **10** (60 mg, 0.44 mmol). After two methanol quench–vinyllithium addition cycles, workup gave a yellow oil that was purified by MPLC on silica gel. There were isolated 21 mg of **37b** and 45 mg of **38b** (61% combined yield).

For **37b**: colorless oil; IR (C_6D_6, cm^{-1}) 3600, 3045, 2945, 2860, 1740, 1630, 1450, 1285, 1125, 1085, 1015, 920, 740; ^1H NMR (300 MHz, C_6D_6) δ 6.06 (dd, J = 18.6, 9.5 Hz, 1 H), 5.11 (s, 1 H), 5.00 (m, 2 H), 3.00 (m, 2 H), 2.72–0.89 (series of m, 18 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 153.85, 140.30, 124.80, 113.65, 81.74, 60.11, 52.40, 49.52, 42.50, 41.92, 40.19, 36.19, 34.94, 34.80, 30.21, 27.65, 27.07; MS m/z (M^+) calcd 244.1827, obsd 244.1868.

For **38b**: colorless oil; IR (C_6D_6, cm^{-1}) 3580, 3080, 2940, 2860, 1745, 1635, 1475, 1445, 1420, 1290, 1125, 1080, 915, 755, 680; ^1H NMR (300 MHz, C_6D_6) δ 6.08 (dd, J = 17.4, 10.8 Hz, 1 H), 5.42 (s, 1 H), 5.01 (dd, J = 17.5, 1.9 Hz, 1 H), 4.99 (dd, J = 10.7, 1.9 Hz), 3.00 (m, 2 H), 2.65–1.10 (series of m, 18 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 152.90, 140.77, 124.58, 113.05, 81.45, 59.33, 52.61, 48.57, 48.24, 42.84, 39.69, 36.88, 34.82, 34.17, 30.23, 29.89, 27.53; MS m/z (M^+) calcd 244.1827, obsd 244.1821. Anal. Calcd for $C_{17}H_{24}O$: C, 83.55; H, 9.90. Found: C, 83.41; H, 10.15.

Anionic Oxy-Cope Rearrangement of 38b. Isomerization of **38b** (115 mg) in the predescribed manner gave a yellow oil that was purified by MPLC (silica gel, elution with 2% ether in petroleum ether) to give 60 mg (52%) of **39b**, a colorless oil: IR (C_6D_6, cm^{-1}) 2920, 2830, 1690, 1445, 1380, 1350, 1280, 1240, 1190, 1120, 1105, 1040, 1010, 870, 710; ^1H NMR (300 MHz, C_6D_6) δ 5.32 (m, 1 H), 2.83 (m, 1 H), 2.56–1.10 (series of m, 22 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 217.25, 143.43, 121.97, 58.39, 53.29, 53.23, 48.78, 45.35, 35.95, 34.71, 33.44, 32.46, 31.82, 30.28, 30.17, 28.06, 27.68; MS m/z (M^+) calcd 244.1827, obsd 244.1807. Anal. Calcd for $C_{17}H_{24}O$: C, 83.55; H, 9.90. Found: C, 83.45; H, 9.80.

Addition of 11 to 10. The organocerium reagent was prepared from **11** as described above and added to **10** (60 mg, 0.44 mmol). After two methanol quench–vinyllithium addition cycles, workup and chromatographic separation delivered 26 mg of **43b** and 21 mg of **44b** (43% combined yield).

For **43b**: colorless oil; IR (C_6D_6, cm^{-1}) 3600, 3080, 2950, 2870, 1630, 1450, 1380, 1285, 1120, 1010, 920; ^1H NMR (300 MHz, C_6D_6) δ 6.10 (dd, J = 17.0, 11.4 Hz, 1 H), 5.20 (s, 1 H), 5.01–4.93 (m, 2 H), 2.60–2.51 (m, 2 H), 2.31–0.88 (series of m, 20 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 152.90, 140.49, 124.46, 113.82, 81.51, 60.44, 56.82, 50.62, 41.87, 39.72, 37.44, 36.16, 30.17, 28.81, 27.96, 23.19, 12.16; MS m/z (M^+) calcd 246.1984, obsd 246.1953. Anal. Calcd for $C_{17}H_{26}O$: C, 82.87; H, 10.64. Found: C, 82.59; H, 10.40.

For **44b**: colorless oil; IR (C_6D_6, cm^{-1}) 3580, 3080, 2950, 2870, 1725, 1635, 1445, 1375, 1290, 1200, 1125, 995, 915; ^1H NMR (300 MHz, C_6D_6) δ 6.10 (dd, J = 17.5, 9.9 Hz, 1 H), 5.51 (s, 1 H), 5.05–4.97 (m, 2 H), 2.57–2.34 (m, 2 H), 2.16–0.79 (series of m, 20 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 151.92, 140.92, 124.59, 113.12, 81.07, 59.45, 56.55, 48.42, 42.26, 38.96, 37.40, 37.00, 30.68, 30.17, 26.99, 22.88, 12.15; MS m/z (M^+) calcd 246.1984, obsd 246.1989.

Anionic Oxy-Cope Rearrangement of 44b. Isomerization of **44b** (110 mg) in the predescribed manner afforded 43 mg (39%) of **45b** as a colorless solid, mp 91–92 °C (from ether); IR (C_6D_6, cm^{-1}) 2935, 2860, 1685, 1450, 1370, 1100, 1035, 870; ^1H NMR (300 MHz, C_6D_6) δ 5.34 (m, 1 H), 2.57–2.54 (m, 1 H), 2.50 (m, 2 H), 2.41 (d, J = 10 Hz, 1 H), 2.21–0.83 (series of m, 21 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 219.18, 143.46, 122.12, 61.84, 56.30, 51.48, 49.28, 40.62, 38.41, 36.26, 34.00, 31.61, 30.22, 29.85, 27.30, 20.10, 13.28; MS m/z (M^+) calcd 246.1984, obsd 246.2010.

The structure of **45b**, determined by X-ray crystallography, is displayed in Figure 16 (supplementary material).

Addition of 15 to 10. The organocerium reagent was prepared from **15** as described above and added to **10** (60 mg, 0.44 mmol). After two methanol quench–vinyllithium addition cycles, workup and chromatographic purification gave 28 mg of **46b** and 31 mg of **47b** (58% combined yield).

For **46b**: colorless oil; IR (C_6D_6, cm^{-1}) 3580, 2960, 2870, 1730, 1640, 1445, 1420, 1090, 1125, 1075, 1020, 1000, 965; ^1H NMR (300 MHz, C_6D_6) δ 6.10 (dd, J = 18.0, 10.0 Hz, 1 H), 5.73 (d, J = 3.0 Hz, 1 H), 5.06 (m, 2 H), 2.91 (d, J = 1.2 Hz, 1 H), 2.74 (m, 1 H), 2.54 (m, 1 H), 2.14 (m, 1 H), 2.05–1.98 (m, 1 H), 1.86 (dd, J = 9.9, 1.9 Hz, 1 H), 1.72–0.90 (series of m, 12 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 156.07, 140.71, 127.88, 112.86, 80.76, 59.01, 48.93, 46.67, 44.87, 42.79, 42.63, 36.75, 30.30, 29.77, 26.35, 25.80; MS m/z (M^+) calcd 230.1671, obsd 230.1692.

For **47b**: colorless oil; IR (C_6D_6, cm^{-1}) 3585, 3080, 2960, 2870, 1730, 1640, 1450, 1420, 1290, 1090, 1010, 920; ^1H NMR (300 MHz, C_6D_6) δ 6.14 (dd, J = 18.0, 10.1 Hz, 1 H), 5.50 (d, J = 3.1 Hz, 1 H), 5.00 (m, 1 H), 4.90 (m, 1 H), 2.86 (s, 1 H), 2.71 (s, 1 H), 2.30–1.83 (m, 2 H), 1.65–0.97 (series of 14 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 155.59, 140.23, 129.49, 113.70, 80.96, 59.19, 49.06, 46.41, 44.34, 42.84, 41.33, 35.96, 30.59, 27.10, 26.65, 25.81; MS m/z (M^+) calcd 230.1671, obsd 230.1676. Anal. Calcd for $C_{16}H_{20}O$: C, 83.43; H, 9.63. Found: C, 83.05; H, 9.51.

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Supplementary Material Available: X-ray experimental details, ORTEP diagrams, tables of bond distances and angles, final fractional coordinates, and thermal parameters for all compounds examined, and a numbering scheme for **38a** (66 pages). Ordering information is given on any current masthead page.