Appropriate fractions are combined and concentrated. The product is dried in a desiccator under vacuum. The yield is less than 0.05 g. The ^{13}C NMR spectrum is identical with that of unenriched dipalmitoyl-PC (Figure 2b) except for the intensities of the downfield carbonyl resonances. The latter are discussed in Results and Discussion.

Acknowledgment. L. M. Loew is the recipient of a Research Career Development Award CA-677 from the National Cancer Institute. This investigation was supported by the Research Corporation and USPHS Grant CA23838. The 360-MHz NMR facility at Syracuse University was funded under NIH Grant 1P41 RRO1317.

Registry No. **1**, 87728-50-5; **2**, 87728-51-6; **4**, 21991-64-0; **5**, 59414-94-7; **6**, 77075-58-2; **7**, 87728-52-7; **8**, 87728-53-8; **9**, 87728-54-9; **10**, 77075-52-6; **11**, 34688-34-1; **12**, 87728-55-0; **13**, 87728-56-1; **14**, 87760-76-7; dimethylethanolamine, 108-01-0; methyl dichlorophosphate, 677-24-7; methyl propyl 2-(dimethylamino)ethyl phosphate, 87728-57-2; methyl 2-(dimethylamino)ethyl 1,2-*O*-isopropylideneglyceryl phosphate, 77075-57-1; allyl methyl chlorophosphate, 77075-53-7; methyl allyl 2-(dimethylamino)ethyl phosphate, 77075-56-0; palmitoyl chloride, 112-67-4; 10-undecenoic acid, 112-38-9; lauric acid, 143-07-7; palmitic-*1*-^{13}C acid, 57677-53-9.

Chelation Control of Enolate Geometry. Acyclic Diastereoselection via the Enolate Claisen Rearrangement

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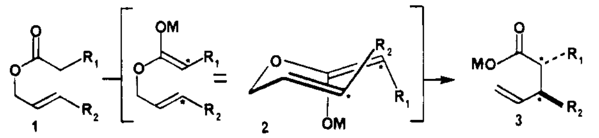
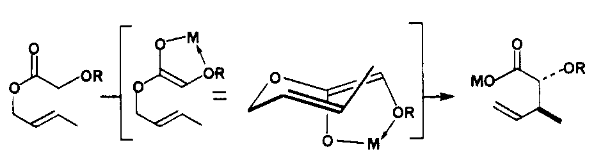
The Ireland–Claisen rearrangements of a variety of O-protected allylic glycolate esters are described. Vicinal diastereoselectivities ranging from 7.2:1 to >20:1 were observed, indicating that chelation control of enolate geometry is operational in the conversion of substrates **4a–c**, **6a–c**, and **8a,b** to the corresponding methyl 2-alkoxy-3-methyl-4-pentenoates **5a–c** and **7a–c** and to the sesquiterpene synthons **9a,b**. Four methods were developed for the preparation of the O-protected (*E*)- and (*Z*)-2-butenyl glycolate esters **4a–c** and **6a–c** and of the substrates **8a,b**. The assignment of relative vicinal stereochemistry in the rearrangement products **5a–c**, **7a–c**, and **9a,b** was accomplished by a combination of chemical and spectroscopic correlations, including a synthesis of (±)-verrucarinolactone (**12**).

The concept of "acyclic stereoselection" has recently received substantial experimental study, with impressive results.[1] A common rationale in many of the diastereoselective reactions thus developed is the coupling of sp^2-hybridized carbon centers via cyclic transition states. Accordingly, advantage is drawn from two sources: (1) the ready availability of reactive trigonal carbon sites (carbonyls, enolates, olefins), often with controlled local geometry; (2) the well-known conformational and stereochemical biases associated with cyclic structures, especially six-centered transition states.

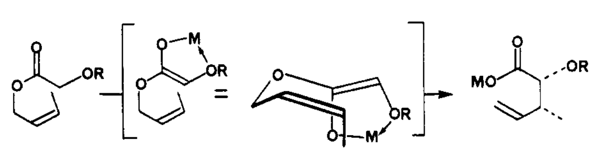
The [3,3]-sigmatropic rearrangement of enolates (or trialkylsilyl ketene acetals) derived from esters of allylic alcohols is such a reaction and enjoys the stated advantages. In these Ireland–Claisen rearrangements (eq 1),[2] the sp^2 geometry at remote olefin and enolate carbons (asterisks in **2**) is transformed into vicinal sp^3-carbon stereochemistry (asterisks in **3**) via a chairlike pericyclic transition state.[3,4] We felt that if R_1 in **1** was a heteroatomic substituent, the enolate geometry would be controlled by intramolecular coordination, as illustrated in eq 2 and 3. With the enolate geometry thus set, selective entry into either diastereomeric series would depend only upon the geometry about the olefin linkage, as shown. A systematic study of such "chelation-controlled" Ireland–Claisen rearrangements on a variety of O-protected allylic glycolate ester substrates is herein reported in full detail. Several reports have appeared recently describing related



(1)



(2)



(3)

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(1) (a) Bartlett, P. A. *Tetrahedron* **1980**, *36*, 2. (b) Evans, D. A.; Nelson, J. V.; Taber, T. R. *Top. Stereochem.* **1982**, *13*, 1. (c) Heathcock, C. H. *Science (Washington D.C.)* **1981**, *214*, 395. (d) Masamune, S.; Choy, W. *Aldrichimica Acta* **1982**, *15*, 47. (e) Mukaiyama, T. *Org. React.* **1982**, *28*, 203. (f) Kishi, Y. *Aldrichimica Acta* **1980**, *13*, 23.

(2) (a) Ireland, R. E.; Daub, J. P. *J. Org. Chem.* **1981**, *46*, 479. (b) Ireland, R. E.; Vevert, J.-P. *Ibid.* **1980**, *45*, 4259. (c) Ireland, R. E.; Thaisrivongs, S.; Vanier, N.; Wilcox, C. S. *Ibid.* **1980**, *45*, 48. (d) Ireland, R. E.; Thaisrivongs, S.; Wilcox, C. S. *J. Am. Chem. Soc.* **1980**, *102*, 1155. (e) Ireland, R. E.; Mueller, R. H.; Willard, A. K. *Ibid.* **1976**, *98*, 2868. (f) Ireland, R. E.; Mueller, R. H. *Ibid.* **1972**, *94*, 5897.

(3) A boatlike transition state becomes favorable in the face of certain structural features which have recently been elucidated. See: (a) References 2b,c. (b) Bartlett, P. A.; Pizzo, C. F. *J. Org. Chem.* **1981**, *46*, 3896. (c) Cave, R. J.; Lythgoe, B.; Metcalfe, D. A.; Waterhouse, I. *J. Chem. Soc., Perkin Trans. 1* **1977**, 1218.

(4) For general reviews of the Claisen rearrangement, see: (a) Rhoads, S. J.; Raulins, N. R. *Org. React.* **1975**, *22*, 1. (b) Ziegler, F. E. *Acc. Chem. Res.* **1977**, *10*, 227.

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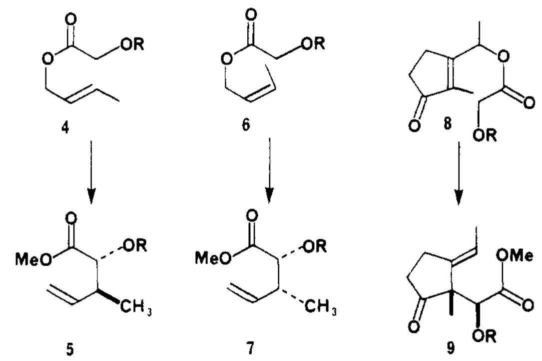
Table I[6]



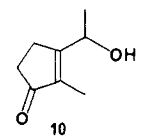
substrate ester	prep proced[a] (% yield)	major product	diastereomer ratio	isolated yield, %
4a, R = Me	A (97)	5a, R = Me	10.2:1[b]	65
4b, R = CH_2Ph	A (97)	5b, R = CH_2Ph	9.6:1[c]	77
4c, R = MEM	B (87)	5c, R = MEM	7.2:1[b]	70
4d, R = H	ref 5a	5d, R = H	2.4:1[d]	38
6a, R = Me	C (75)	7a, R = Me	23:1[b]	64
6b, R = CH_2Ph	C (86)	7b, R = CH_2Ph	18.6:1[c]	79
6c, R = MEM	D (85)	7c, R = MEM	11.4:1[b]	70
6d, R = H	ref 5a	7d, R = H	1.4:1[d]	47
8a, R = Me	A (95)	9a, R = Me	≥20:1[e]	57
8b, R = CH_2Ph	A (97)	9b, R = CH_2Ph	≥20:1[e]	60

[a] See text and experimental for description of procedures A-D. [b] Measured by glass capillary GLC. [c] Measured by analytical HPLC. [d] Measured by integration of distinctive resonances in ^1H NMR at 400 MHz. [e] None of diastereomer detected by ^1H NMR at 400 MHz or by ^{13}C NMR.

studies in this general area.[5] Of these, the studies by Bartlett[5a,g] and Fujisawa[5b] are the most closely analogous (vide infra).

The rearrangement substrates **4a–c**, **6a–c**, and **8a,b** were prepared by one of four procedures, as indicated in Table I.[6] Procedure A involved the straightforward acylation of the appropriate allylic alcohol with the corresponding alkoxyacetyl chloride in CH_2Cl_2/pyridine (0–25 °C). Rearrangement substrates **4a,b** and **8a,b** were conveniently prepared in this manner in isolated yields of ≥95%. This method was not applicable to the synthesis of the (2-methoxyethoxy)methyl (MEM)-protected[7] allylic glycolates **4c** and **6c**, in that we found the requisite [(2-methoxyethoxy)methoxy]acetyl chloride difficult to prepare. However, the MEM-protected ethyl glycolate was readily available.[8] Accordingly (procedure B), substrate **4c** was prepared in 87% yield by the Ti(O-*i*-Pr)$_4$-catalyzed[9] transesterification of $MEMOCH_2CO_2Et$ with (*E*)-2-buten-1-ol in refluxing benzene. In the allylic ester substrates **6a–c**, the *Z* olefin stereochemistry was established by semihydrogenation of an acetylene linkage with H_2/Lindlar's catalyst. Due to experimental[10] difficulties associated with the clean production of (*Z*)-2-buten-1-ol from 2-butyn-1-ol, we chose (procedure C) to first acylate 2-butyn-1-ol with the appropriate alkoxyacetyl chloride in CH_2Cl_2/pyridine (0–25 °C) and to then semihydrogenate the acetylenic ester [H_2 (1 atm), Lindlar's catalyst, EtOAc, 25 °C]. In this way, substrates **6a** and **6b** were prepared in 75% and 86% yields, respectively.[11] Finally, the reliable production of the MEM-protected (*Z*)-2-butenyl ester **6c** required a combination of the Ti(O-*i*-Pr)$_4$-catalyzed[9] transesterification of (MEM)OCH_2CO_2Et with 2-butyn-1-ol, followed by semihydrogenation of the acetylenic ester [H_2 (1 atm), Lindlar's catalyst, EtOAc, 25°C]. This method (procedure D) gave the desired ester **6c** in 85% overall yield.

The synthesis of substrates **4a,b** and **8a,b** required the availability of the corresponding allylic alcohols. Stereoisomerically homogeneous (*E*)-2-buten-1-ol was prepared by reduction ($LiAlH_4$, Et_2O, 0–25 °C) of *trans*-crotonaldehyde. 3-(1-Hydroxyethyl)-2-methylcyclopent-2-en-1-one (**10**) required for the synthesis of **8a,b** was prepared by the method described previously.[12]



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The Ireland–Claisen rearrangements of the O-protected allylic glycolate esters **4a–c**, **6a–c**, and **8a,b** were carried

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(5) For related studies in this general area, see: (a) Bartlett, P. A.; Tanzella, D. J.; Barstow, J. F. *J. Org. Chem.* **1982**, *47*, 3941. (b) Sato, T.; Tajima, K.; Fujisawa, T. *Tetrahedron Lett.* **1983**, *24*, 729. (c) Whitesell, J. K.; Helbling, A. M. *J. Org. Chem.* **1980**, *45*, 4135. (d) References 2c,d. (e) Ager, D. J.; Cookson, R. C. *Tetrahedron Lett.* **1982**, *23*, 3419. (f) Mikami, K.; Fujimoto, K.; Nakai, T. *Ibid.* **1983**, *24*, 513. (g) Bartlett, P. A.; Barstow, J. F. *J. Org. Chem.* **1982**, *47*, 3933. (h) Jones, D. N.; Kogan, T. P.; Murray-Rust, P.; Murray-Rust, J.; Newton, R. F. *J. Chem. Soc., Perkins Trans. 1* **1982**, 1325.

(6) In the table, schemes, and equations, all chiral substances were produced as racemates; a single enantiomer is shown for simplicity. All structural assignments are supported by IR, ^1H NMR, ^{13}C NMR, mass spectrometry, and elemental analysis.

(7) Corey, E. J.; Gras, J.-L.; Ulrich, P. *Tetrahedron Lett.* **1976**, 809.

(8) $MEMOCH_2CO_2Et$ (bp 139–142 °C, 18 mmHg) was easily prepared by the protection of ethyl glycolate with the crystalline triethylammonium salt $MEMNEt_3^+Cl^-$ in refluxing acetonitrile as described in ref 7. A representative procedure afforded 53 g of distilled product (79%).

(9) (a) Seebach, D.; Hungerbühler, E.; Naef, R.; Schnurrenberger, P.; Weidmann, B.; Züger, M. *Synthesis* **1982**, 138. (b) Schnurrenberger, P.; Züger, M. F.; Seebach, D. *Helv. Chim. Acta* **1982**, *65*, 1197. (c) Seebach, D.; Züger, M. *Ibid.* **1982**, *65*, 495.

(10) We found the direct semihydrogenation of 2-butyn-1-ol to be capricious, giving varying small amounts of (*E*)-2-buten-1-ol. However, there are reports where this reduction has been effected with very high stereoselectivity. For example, see ref 2e. For a case in which an esterification–reduction sequence similar to ours was employed, see: Bartlett, P. A.; Tanzella, D. J.; Barstow, J. F. *Tetrahedron Lett.* **1982**, *23*, 619.

(11) None of the corresponding *E* isomers **4a** and **4b** could be detected by ^1H NMR or ^{13}C NMR analysis of **6a** and **6b**, respectively.

(12) Burke, S. D.; Shearouse, S. A.; Burch, D. J.; Sutton, R. W. *Tetrahedron Lett.* **1980**, *21*, 1285.

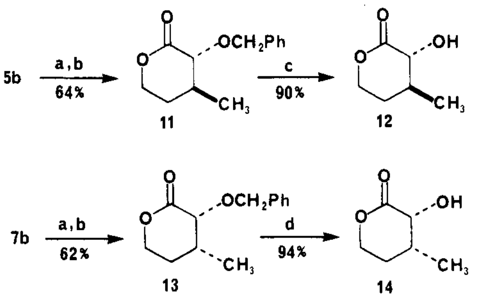
out via the intermediacy of the trimethylsilyl ketene acetals. Thus, deprotonation of the ester substrates with lithium diisopropylamide (LDA) in tetrahydrofuran (THF) at −100 °C for 1 h was followed by addition of chlorotrimethylsilane (Me_3SiCl) in Et_3N. After the reaction mixtures had stirred an additional 1 h at −100 °C (higher temperatures allowed C-silylation to compete with O-silylation), they were allowed to warm to 25 °C and were stirred for several hours. For the purpose of purification and analysis, the crude products of the rearrangements were hydrolyzed with 5% aqueous NaOH and, after standard biphasic partitioning, were esterified with CH_2N_2/Et_2O. The methyl esters thus produced were isolated as diastereomeric mixtures by chromatography on silica gel and were subjected to analysis.

The product ratios were determined by one of four methods. For substrates **4a**, **4c**, **6a**, and **6c**, the rearrangement diastereoselectivities were measured by GLC.[13a] The ratios of the products derived from substrates **4b** and **6b** were determined by analytical HPLC with UV detection.[13b] The product ratios derived from substrates **4d** and **6d** were measured by integration of distinctive resonances in the 400-MHz ^1H NMR spectra.[14] For substrates **8a** and **8b**, the product ratios of ≥20:1 cited in Table I represent lower limits, in that only a single diastereomer could be detected by ^{13}C NMR and by ^1H NMR at 400 MHz.

For the O-protected (*E*)-2-butenyl glycolate esters **4a–c**, the derived product ratios ranged from 10.2:1 to 7.2:1 as shown (Table I), with decreasing diastereoselectivity in the order of R = Me > CH_2Ph > $CH_2OCH_2CH_2OCH_3$. The chemical yields cited are for the isolated mixtures of diastereomers and are uniformly good. For the O-protected (*Z*)-2-butenyl glycolate ester substrates **6a–c**, the product ratios ranged from 23:1 downward to 11.4:1, with the same order of decreasing diastereoselectivity (R = Me > CH_2Ph > $CH_2OCH_2CH_2OCH_3$). The rearrangement products **9a** and **9b** were produced from the substrates **8a** and **8b**, respectively, as diastereomerically homogeneous substances (vide supra).

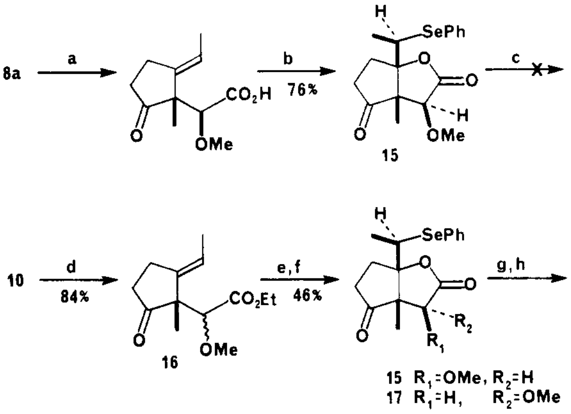
We also briefly investigated the rearrangement of the free hydroxyl substrates **4d** and **6d** via the corresponding enediolates. Our observations for the substrate **4d** mirrored those published in the interim by other investigators,[5a,b] reflecting diminished yields and drastically reduced diastereoselectivities. In our experience, a solution of (*E*)-2-butenyl glycolate (**4d**) in THF was treated first with 2.5 equiv of LDA for 1 h at −100 °C and then with excess Me_3SiCl/Et_3N. After the reaction mixture had been stirred for 1 h at −100 °C and 4 h at 25 °C, it was heated at reflux for 2 h. After an aqueous acid workup followed by extraction and esterification with CH_2N_2/Et_2O, a mixture of epimers **5d** and **7d** was isolated in 38% yield in a ratio of 2.4:1. Under similar circumstances with the same substrate, Bartlett reported[5a] a yield of 38% and a diastereomer ratio of 1.4:1, and Fujisawa reported[5b] a **5d**/**7d** ratio of 2.3:1 in 40% yield. It should be noted that Fujisawa observed greatly enhanced yields and diastereoselectivities by using lithium hexamethyldisilazide for the formation of enediolates from **4d** and **6d**.[5b]

Scheme I[a]



[a] (a) Disiamylborane, CH_2Cl_2, 0 °C; H_2O_2, OH^-, 0-25 °C. (b) Camphorsulfonic acid, PhH, reflux. (c) H_2 (1 atm), 10% Pd/C, EtOH. (d) H_2 (1 atm), 10% Pd/C, 4:1 EtOH-aqueous HCl.

Scheme II[a]



[a] (a) LDA, THF, −100 °C; Me_3SiCl, −100-25 °C; aqueous OH^-. (b) PhSeCl, CH_2Cl_2, Et_3N, −78-25 °C. (c) DBU, PhH, 25 °C, 50 h. (d) $MeOCH_2C(OEt)_3$, $CH_3CH_2CO_2H$ (catalytic), 120 °C, 36 h. (e) K_2CO_3, MeOH, H_2O, 25 °C, 14 h. (f) PhSeCl, EtOAc, 0-25 °C (**15**/**17**, 43:57). (g) DBU, PhH, 25 °C 72 h (**15**/**17** 59:41). (h) DBU, PhH, 52 °C, 56 h (**15**/**17** 80:20).

The relative stereochemical assignments for the rearrangement products **5b** and **7b** were established by chemical and spectroscopic correlation with the known methyl 2-hydroxy-3-methyl-4-pentenoates **5d** and **7d**.[15] The stereochemical assignments for **5a,c** and **7a,c** were made by analogy. To this end, the crude carboxylic acid from the enolate Claisen rearrangement of substrate **4b** was subjected to reductive debenzylation with lithium in liquid ammonia. Esterification with CH_2N_2/Et_2O then gave **5d** in predominance. Similarly, the crude carboxylic acid derived from enolate Claisen rearrangement of **6b** provided **7d** as the major product. The ^1H NMR spectra of these methyl 2-hydroxy-3-methyl-4-pentenoates were in essential agreement with those reported by Snider.[14,15]

An additional structural correlation for isomers **5b** and **7b** is shown in Scheme I, including a synthesis of (±)-verrucarinolactone (**12**), a degradation product of the macrocyclic tricothecene verrucarin A.[16] Hydroboration

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(13) (a) These GLC analyses were carried out on a 20 m × 0.25 mm i.d. column, static coated (0.25-μm film thickness) with SUPEROX-4 (Alltech Assoc., Inc., Deerfield, IL). We are indebted to Professor Stephen L. Morgan and Matthew Przybyciel for their advice and assistance with these measurements. (b) These HPLC analyses were carried out on an IBM 9533 HPLC on a silica gel column (elution with 1% (v/v) ethyl acetate in cyclohexane).

(14) Distinctive diagnostic resonances in the ^1H NMR spectra at 400 MHz ($CDCl_3$) for **5d** and **7d** are as follows. **5d**: δ 4.17 (dd, 1 H, *J* = 6.4, 3.8 Hz, MeO_2CCHOC), 1.00 (d, 3 H, *J* = 6.9 Hz, H_3CCHCC). **7d**: δ 4.11 (dd, 1 H, *J* = 6.2, 2.8 Hz, MeO_2CCHOC), 1.14 (d, 3 H, *J* = 7.0 Hz, H_3CCHCC).

(15) Snider, B. B.; van Straten, J. W. *J. Org. Chem.* **1979**, *44*, 3567.

(16) For other syntheses of verrucarinolactone (12) or functional equivalents thereof, see: (a) Achini, R.; Meyer, U.; Tamm, C. *Helv. Chim. Acta* **1968**, *51*, 1702. (b) Mohr, P.; Tori, M.; Grossen, P.; Herold, P.; Tamm, C. *Ibid.* **1982**, *65*, 1412. (c) Trost, B. M.; McDougal, P. G. *Tetrahedron Lett.* **1982**, *23*, 5497. (d) Roush, W. R.; Blizzard, T. A.; Basha, F. Z. *Ibid.* **1982**, *23*, 2331. (e) Still, W. C.; Ohmizu, H. *J. Org. Chem.* **1981**, *46*, 5242. (f) Trost, B. M.; Ochiai, M.; McDougal, P. G. *J. Am. Chem. Soc.* **1978**, *100*, 7103. (g) Tomioka, K.; Sato, F.; Koga, K. *Heterocycles* **1982**, *17*, 311. (h) Herold, P.; Mohr, P.; Tamm, C. *Helv. Chim. Acta* **1983**, *66*, 744. (i) Yamamoto, U.; Maeda, N.; Maruyama, K. *J. Chem. Soc., Chem. Commun.* **1983**, 774.

of **5b** with disiamylborane[17] in CH_2Cl_2 followed by an oxidative workup (H_2O_2, aqueous NaOH) and lactonization (camphorsulfonic acid, PhH, reflux) afforded lactone **11**: mp 64–65 °C; 64% yield. The ^1H NMR vicinal coupling of 9.3 Hz between the methine hydrogens was consistent with the assigned *trans*-2,3-disubstitution in **11**. This was confirmed by hydrogenolysis of the benzyl ether [H_2 (1 atm), 10% Pd/C, EtOH] to give (±)-verrucarinolactone (**12**): mp 72–73 °C (lit. mp 71–72.5 °C,[16a] 71–72 °C[16d]); 90% yield. Application of the hydroboration–lactonization sequence to **7b** gave the lactone **13** in 62% yield, wherein the 5.3-Hz coupling between the vicinal methine hydrogens in the ^1H NMR spectrum correlated with the cis relationship shown. Reductive debenzylation [H_2 (1 atm), 10% Pd/C, EtOH/aqueous HCl] afforded the hydroxy lactone **14**: mp 67–68 °C; 94% yield.

The single products observed from the enolate Claisen rearrangements of substrates **8a,b** were assigned the structures **9a,b** on the basis of the concept of chelation control of enolate geometry. Support for these relative configurational assignments was garnered as shown in Scheme II. Treatment of the crude carboxylic acid rearrangement product from substrate **8a** with phenylselenenyl chloride in CH_2Cl_2/Et_3N[18] gave the crystalline seleno lactone **15**: mp 134 °C; 76% yield. With the cis-fused bicyclo[3.3.0] ring system thus established, it was felt that the thermodynamically favored exo orientation of substituents could be exploited. In fact, attempted epimerization of the methoxyl-bearing carbon in **15** [1,5-diazabicyclo[5.4.0]undec-5-ene (DBU), PhH, 25 °C, 50 h] afforded no change. Of course, assuming the stereochemistry shown for **15** was correct, such an epimerization would be in the contrathermodynamic sense and would require deprotonation from the hindered endo face. In order to validate this negative result, we prepared a mixture of **15** and its epimer. The allylic alcohol **10**[12] was subjected to standard ortho ester Claisen rearrangement conditions[19] with triethyl 2-methoxyorthoacetate[20] [propionic acid (catalytic), 120 °C, 36 h]. The product **16** was isolated as a mixture of epimers in 84% yield. Ester hydrolysis (K_2CO_3, $MeOH/H_2O$, 25 °C, 14 h) followed by selenolactonization (PhSeCl, EtOAc, 0–25 °C, 24 h)[18] afforded a mixture of epimeric lactones **15** and **17** in a ratio of 43:57. A sluggish epimerization was accomplished with DBU in benzene. After 72 h at 25 °C, the **15**/**17** ratio had increased to 59:41, and an additional 56 h at 52 °C left the ratio at 80:20 in favor of **15**. This epimerization process was most easily monitored by ^1H NMR in that the methine hydrogens at the inverting center appear as distinctive singlets at δ 3.79 and 3.86 for **15** and **17**, respectively, in $CDCl_3$. The crystalline lactone **17** (mp 122–123 °C) was also isolated and fully characterized as a single isomer. The assignment of exo orientation for the methoxy substituent in **15** and of the side-chain relative configuration as shown in **9** is thus supported.

In summary, the Ireland–Claisen rearrangement of O-protected allylic glycolates has been shown to proceed in good yields (57–79%) with moderate to high diastereoselectivities (7.2:1->20:1). Chelation control of enolate geometry is apparently responsible for the direction and magnitude of the stereoselection observed. The rearrangement products **5a–c**, **7a–c**, and **9a,b** contain vicinal sp^3-carbon stereocenters that are formed in a stereocontrolled manner. These new asymmetric centers are flanked by differentially reactive functionality for extension or modification of the carbon chain. Further refinement and application of this method is underway.

Experimental Section

General Procedures. Melting points were recorded on a Büchi capillary melting point apparatus. Melting and boiling points are uncorrected. Infrared (IR) spectra were recorded on a Beckman IR 4210 or a Perkin-Elmer Model 621 spectrometer. Proton nuclear magnetic resonance (^1H NMR) spectra were recorded at 90 (Varian EM 390) or 400 MHz (Bruker WH-400) as indicated. Carbon magnetic resonance (^{13}C NMR) spectra were recorded on a Varian CFT-20, an IBM NR-80, or a Bruker WH-400 spectrometer. Chemical shifts for proton and carbon resonances are reported in parts per million (δ) relative to Me_4Si (δ 0.0).

Analytical thin-layer chromatography (TLC) was done on Analtech TLC plates precoated with silica gel GHLF (250-μm layer thickness). Column chromatography was done on Merck silica gel 60 (70–230-mesh ASTM).

Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl immediately before use. Benzene was distilled from CaH_2 and stored over sodium ribbon. Methylene chloride was distilled from P_2O_5 and passed through a column of alumina. Diisopropylamine and pyridine were distilled from CaH_2 and stored over KOH pellets.

(*E*)-2-Butenyl 2-Methoxyacetate (4a). Procedure A. To a solution of 1.00 g (13.8 mmol) of (*E*)-2-buten-1-ol in 50 mL of CH_2Cl_2 and 2.2 mL (27.5 mmol) of pyridine at 0 °C was added 1.55 mL (16.6 mmol) of 2-methoxyacetyl chloride[21] in a dropwise fashion via syringe. After the reaction mixture had been stirred at 0 °C for 1 h and 25 °C for 12 h, it was poured into ether and washed with H_2O followed by 0.5 N aqueous HCl. The ether layer was dried ($MgSO_4$) and concentrated. Purification by elution through a column of 100 g of silica gel with 1:4 ether–hexanes afforded 1.92 g (97%) of the ester **4a** as an oil: homogeneous by TLC and spectroscopic analysis; R_f 0.84 (2:3 ether–hexanes); IR (neat film) 3020, 2940, 2918, 2875, 2856, 2823, 1745, 1676, 1450, 1422, 1380, 1360, 1261, 1190, 1127, 1085, 1022, 964, 920 cm^{-1}; ^1H NMR (90 MHz, CCl_4) δ 5.62 (m, 2 H), 4.49 (d, 2 H, J = 6.0 Hz), 3.87 (s, 2 H), 3.37 (s, 3 H), 1.72 (d, 3 H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) δ 169.32, 131.21, 124.19, 69.08, 64.69, 58.52, 17.04. Anal. Calcd for $C_7H_{12}O_3$: C, 58.32; H, 8.39. Found: C, 58.08; H, 8.33.

(*E*)-2-Butenyl 2-(Benzyloxy)acetate (4b). (*E*)-2-Buten-1-ol (1.0 g, 13.8 mmol) was acylated with 2-(benzyloxy)acetyl chloride[23] by procedure A as described above, except that stirring was maintained at 0 °C for 2 h and at 25 °C for 48 h. Purification by elution through a column of 100 g of silica gel with 1:5 ethyl acetate–hexanes gave 2.94 g (97%) of the ester **4b** as an oil: homogeneous by TLC and spectroscopic criteria; R_f 0.80 (1:1 ether–hexanes); IR (neat film) 3069, 3043, 3012, 2923, 2895, 2863, 2835, 1740, 1663, 1484, 1441, 1380, 1365, 1343, 1253, 1181, 1115, 1067, 1017, 954, 894 cm^{-1}; ^1H NMR (90 MHz, CCl_4) δ 7.22 (m, 5 H), 5.62 (m, 2 H), 4.56 (s, 2 H), 4.47 (d, 2 H, J = 6.0 Hz), 3.96 (s, 2 H), 1.70 (d, 3 H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) δ 169.84, 136.87, 131.76, 128.16, 127.70, 124.37, 72.99, 66.88, 65.17, 17.46. Anal. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.67; H, 7.56.

(*E*)-2-Butenyl 2-[(2-Methoxyethoxy)methoxy]acetate (4c). Procedure B. A solution of 3.0 g (0.042 mol) of (*E*)-2-buten-1-ol, 1.92 g (0.010 mol) of $MEMOCH_2CO_2Et$,[8] and several drops of $Ti(O\text{-}i\text{-}Pr)_4$ in 70 mL of dry benzene was heated at reflux under a Dean–Stark condenser for 9 h. Concentration at reduced

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(17) Prepared from the borane–dimethyl sulfide complex and 2-methyl-2-butene in CH_2Cl_2 at 0 °C.

(18) (a) Clive, D. L. J.; Russell, C. G.; Chittattu, G.; Singh, A. *Tetrahedron* **1980**, *36*, 1399. (b) Nicolaou, K. C.; Seitz, S. P.; Sipio, W. J.; Blount, J. F. *J. Am. Chem. Soc.* **1979**, *101*, 3884.

(19) Johnson, W. S.; Werthemann, L.; Bartlett, W. R.; Brocksom, T. J.; Li, T.-t.; Faulkner, D. J.; Petersen, M. R. *J. Am. Chem. Soc.* **1970**, *92*, 741.

(20) Prepared from methoxyacetonitrile (Scarrow, J. A.; Allen, C. F. H. "Organic Syntheses"; Wiley: New York, 1943; Collect. Vol. II, p 387) according to the procedure described in: DeWolfe, R. H. *Synthesis* **1974**, 153.

(21) Aldrich Chemical Co.

(22) Farchan Labs.

(23) Prepared from 2-(benzyloxy)acetic acid (Benington, F.; Morin, R. D. *J. Org. Chem.* **1961**, *26*, 194) by treatment with oxalyl chloride at 0 °C.

pressure followed by chromatography on 150 g of silica gel (elution with 1:3 ether–hexanes) gave 1.89 g (87%) of the transesterification product **4c** as an oil: homogeneous by TLC and spectroscopic analysis; R_f 0.40 (1:1 ether–hexanes); IR (neat film) 3014, 2937, 2920, 2884, 2817, 1750, 1676, 1450, 1407, 1379, 1364, 1278, 1262, 1242, 1200, 1173, 1136, 1122, 1057, 1021, 966, 932, 852 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 5.65 (m, 2 H), 4.64 (s, 2 H), 4.48 (d, 2 H, J = 6.0 Hz), 4.04 (s, 2 H), 3.53 (m, 4 H), 3.28 (s, 3 H), 1.71 (d, 3 H, J = 5.8 Hz); ^{13}C NMR ($CDCl_3$) δ 169.12, 131.04, 124.14, 94.60, 70.98, 66.59, 64.64, 63.56, 58.06, 16.96. Anal. Calcd for $C_{10}H_{18}O_5$: C, 55.03; H, 8.31. Found: C, 54.88; H, 8.56.

Methyl (*R,*S**)-2-Methoxy-3-methyl-4-pentenoate (5a).** To a solution of 3.9 mmol of LDA in 25 mL of THF at −100 °C was added 0.50 g (3.5 mmol) of the ester **4a** in 6 mL of THF. After the reaction mixture had stirred for 1 h at −100 °C, there was added 1.0 mL of the supernatant from the centrifugation of a 1:1 mixture of Me_3SiCl and Et_3N. The mixture was allowed to stir an additional 1 h at −100 °C, was then allowed to warm to 25 °C, and was stirred for 12 h. The solution was then poured into 75 mL of 5% aqueous NaOH and stirred for 10 min, and the aqueous layer was washed with ether. The aqueous phase was acidified with concentrated HCl at 0 °C and was extracted repeatedly with CH_2Cl_2. The combined extracts were dried ($MgSO_4$) and concentrated. The crude carboxylic acid was dissolved in 50 mL of Et_2O at 0 °C and was esterified with an ethereal solution of diazomethane. Chromatography on silica gel (elution with 1:9 ether–hexanes) gave 330 mg (65%) of the rearrangement product **5a**, together with the diastereomeric ester **7a** as a minor product. The diastereomer ratio **5a**/**7a** was found to be 10.2:1 by glass capillary GLC (85 °C, isothermal):[13a] R_f 0.66 (2:3 ether–hexanes); IR (neat film) 3080, 2981, 2955, 2936, 2880, 2832, 1755, 1642, 1457, 1436, 1420, 1376, 1358, 1269, 1198, 1180, 1134, 1108, 1077, 1003, 921 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 5.72 (m, 1 H), 4.97 (m, 2 H), 3.64 (s, 3 H), 3.49 (d, 1 H, J = 6.0 Hz), 3.29 (s, 3 H), 2.50 (m, 1 H), 0.99 (d, 3 H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) δ 172.10, 139.09, 115.23, 84.59, 58.46, 51.45, 41.06, 15.03. Anal. Calcd for $C_8H_{14}O_3$: C, 60.74; H, 8.92. Found: C, 60.58; H, 9.04.

Methyl (*R,*S**)-2-(Benzyloxy)-3-methyl-4-pentenoate (5b).** The substrate ester **4b** (0.30 g, 1.36 mmol) was rearranged and esterified as described above for the preparation of **5a**. Chromatography on 40 g of silica gel (elution with 1:4 ether–hexanes) gave 246 mg (77%) of the rearrangement products **5b** (major) and **7b** (minor) in a ratio of 9.6:1, as determined by analytical HPLC:[13b] R_f 0.75 (1:2 ether–hexanes); IR (neat film) 3082, 3059, 3027, 2946, 2924, 2857, 1746, 1633, 1491, 1447, 1428, 1414, 1391, 1368, 1343, 1262, 1196, 1157, 1128, 1091, 1056, 1024, 990, 915, 837, 731, 691 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (m, 5 H), 5.77 (m, 1 H), 5.05 (m, 2 H), 4.55 (AB q, 2 H, J_{AB} = 11.7 Hz, $\Delta\nu_{AB}$ = 120.5 Hz), 3.82 (d, 1 H, J = 6.0 Hz), 3.73 (s, 3 H), 2.65 (br q, 1 H), 1.09 (d, 3 H, J = 6.8 Hz); ^{13}C NMR ($CDCl_3$) δ 172.18, 139.10, 137.34, 128.13, 127.76, 127.64, 115.25, 82.04, 72.40, 51.41, 41.17, 15.29. Anal. Calcd for $C_{14}H_{18}O_3$: C, 71.77; H, 7.74. Found: C, 71.92; H, 7.85.

Methyl (*R,*S**)-2-[(2-Methoxyethoxy)methoxy]-3-methyl-4-pentenoate (5c).** The substrate ester **4c** (200 mg, 0.92 mmol) was rearranged and esterified as described above for the **4a**–**5a** conversion. Chromatographic purification on 40 g of silica gel (elution with 1:3 ether–hexanes) gave 147 mg (70%) of the rearrangement products **5c** (major) and **7c** (minor) in a ratio of 7.2:1, as determined by glass capillary GLC (148 °C, isothermal):[13a] R_f 0.42 (1:1 ether–hexanes); IR (neat film) 2952, 2930, 2890, 2821, 1750, 1641, 1461, 1453, 1438, 1367, 1268, 1203, 1175, 1120, 1096, 1044, 924, 850 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 5.73 (m, 1 H), 5.01 (m, 2 H), 4.62 (br s, 2 H), 3.89 (d, 1 H, J = 6.0 Hz), 3.64 (s, 3 H), 3.57 (m, 2 H), 3.41 (m, 2 H), 3.27 (s, 3 H), 2.58 (br q, 1 H), 1.04 (d, 3 H, J = 7.0 Hz); ^{13}C NMR ($CDCl_3$) δ 171.98, 139.03, 115.42, 95.27, 79.46, 71.50, 67.38, 58.83, 51.45, 40.83, 14.90. Anal. Calcd for $C_{11}H_{20}O_5$: C, 56.88; H, 8.68. Found: C, 57.17; H, 8.62.

Methyl (*R,*S**)-2-Hydroxy-3-methyl-4-pentenoate (5d). (A) From (*E*)-2-Butenyl 2-Hydroxyacetate (4d).** To a solution of 1.44 mmol of LDA in 20 mL of THF at −100 °C was added 75 mg (0.58 mmol) of ester **4d** in 5 mL of THF. After the reaction mixture had stirred at −100 °C for 1 h, there was added 1 mL of the supernatant from the centrifugation of a 1:1 mixture of Me_3SiCl and Et_3N. The reaction mixture was then stirred 1 h at −100 °C, 4.5 h at 25 °C, and 3 h at reflux, at which time it was cooled and acidified with cold, concentrated HCl to pH 4.5. The aqueous layer was extracted three times with CH_2Cl_2, and the combined organic layers were dried ($MgSO_4$) and concentrated. The crude product thus obtained was dissolved in 50 mL of ether and was esterified with an ethereal solution of diazomethane. Chromatographic purification on 14 g of silica gel (elution with 1:3 ether–hexanes) gave 32 mg (38%) of the esters **5d** and **7d** in a ratio of 2.4:1, as determined by integration of distinctive resonances in the 400-MHz ^{1}H NMR spectrum:[14,15] R_f 0.68 (1:1 ether–hexanes); IR (neat film) 3485, 3080, 2965, 2934, 2880, 1736, 1640, 1438, 1421, 1380, 1262, 1215, 1125, 1076, 1024, 998, 917, 860, 846, 733 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.83 (m, 1 H), 5.11 (m, 2 H), 4.17 (dd, 1 H, J = 6.4, 3.8 Hz), 3.77 (s, 3 H), 2.78 (d, 1 H, J = 6.4 Hz), 2.63 (m, 1 H), 1.00 (d, 3 H, J = 6.9 Hz).

(B) From (*E*)-2-Butenyl 2-(Benzyloxy)acetate (4b). The substrate ester **4b** (500 mg, 2.27 mmol) was rearranged as described for the preparation of **5b**, up to the point of diazomethane esterification. Instead, the crude carboxylic acid was dissolved in 30 mL of liquid ammonia (distilled from lithium) at −78 °C. To this solution was added 400 mg of lithium wire cut in short pieces, and the reaction mixture was allowed to warm to −33 °C. The reaction mixture turned deep blue after 20 min, and was allowed to stir an additional 20 min, at which time it was cooled to −78 °C and quenched with isoprene. The ammonia was allowed to evaporate, and the residue was acidified with cold, concentrated HCl and ice–water to pH 3.5. The aqueous layer was extracted five times with CH_2Cl_2, and the combined organic extracts were dried ($MgSO_4$) and concentrated. The crude product thus obtained was dissolved in 30 mL of ether and was esterified with an ethereal solution of diazomethane. Chromatography on 12 g of silica gel (1:3 ether–hexanes) gave the ester **5d** (100 mg, 31% overall from **4b**), identical with that described above and elsewhere.[15]

(*Z*)-2-Butenyl 2-Methoxyacetate (6a). Procedure C. To a solution of 1.0 g (0.014 mol) of 2-butyn-1-ol[22] and 2.6 mL (2.55 g, 0.032 mol) of pyridine in 55 mL of dry CH_2Cl_2 at 0 °C was added 1.6 mL (1.9 g, 0.018 mol) of 2-methoxyacetyl chloride[21] in a dropwise manner. After the reaction mixture had stirred for 1 h at 0 °C and for 12 h at 25 °C, it was poured into 100 mL of ether. The organic layer was washed with H_2O, aqueous $CuSO_4$, and H_2O again, and was then dried ($MgSO_4$) and concentrated. Chromatographic purification of the residue on 110 g of silica gel (elution with 1:4 ether–hexanes) gave 1.90 g (95%) of 2-butynyl 2-methoxyacetate, homogeneous by TLC analysis, R_f 0.49 (2:3 ether–hexanes).

Into a 250 mL Morton flask were placed 150 mg of Lindlar's catalyst[21] and 20 mL of EtOAc. The system was flushed and charged with H_2 and was allowed to equilibrate for 10 min, at which time 1.90 g (0.013 mol) of 2-butynyl 2-methoxyacetate in 10 mL of EtOAc was added via syringe. The mixture was stirred vigorously at 25 °C and the uptake of H_2 was monitored. After 280 mL (~85% of theory) of H_2 had been taken up, the reaction mixture was filtered through Celite with ether. Removal of the solvents under reduced pressure and chromatography on 100 g of silica gel (elution with 1:4 ether–hexanes) afforded 1.50 g (79%) of the ester **6a** as an oil: homogeneous by TLC and spectroscopic analysis; R_f 0.56 (2:3 ether–hexanes); IR (neat film) 3016, 2971, 2916, 2883, 2814, 1745, 1725, 1649, 1439, 1412, 1401, 1372, 1362, 1339, 1267, 1179, 1118, 1012, 981, 951, 912 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 5.58 (m, 2 H), 4.57 (d, 2 H, J = 6 Hz), 3.87 (s, 2 H), 3.34 (s, 3 H), 1.70 (d, 3 H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) δ 169.83, 129.81, 123.41, 69.47, 59.99, 58.95, 12.77. Anal. Calcd for $C_7H_{12}O_3$: C, 58.32; H, 8.39. Found: C, 58.17; H, 8.32.

(*Z*)-2-Butenyl 2-(Benzyloxy)acetate (6b). The substrate ester **6b** was prepared according to the procedure described above for **6a** (procedure C) by using 2-(benzyloxy)acetyl chloride.[23] In this way 0.75 g (10.7 mmol) of 2-butyn-1-ol and 3.0 g (16 mmol) of 2-(benzyloxy)acetyl chloride were converted to 1.40 g (86% over two steps) of the ester **6b**: R_f 0.79 (2:3 ether–hexanes); IR (neat film) 3081, 3058, 3022, 2933, 2853, 1753, 1657, 1602, 1583, 1494, 1451, 1425, 1407, 1389, 1346, 1274, 1192, 1123, 1078, 1026, 959, 904, 785, 736, 694 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 7.26 (br s, 5 H), 5.56 (m, 2 H), 4.64 (d, 2 H, J = 7.0 Hz), 4.56 (s, 2 H), 3.98 (s, 2 H), 1.73 (d, 3 H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) δ 169.92, 136.83, 129.81, 128.16, 127.73, 123.47, 72.99, 66.88, 60.01, 12.82. Anal. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.73; H, 7.56.

(*Z*)-2-Butenyl 2-[(2-Methoxyethoxy)methoxy]acetate (6c). Procedure D. A solution of 4.2 g (0.06 mol) of 2-butyn-1-ol, 3.0 g (0.016 mol) of (MEM)OCH_2CO_2Et,[8] and several drops of Ti(O-*i*-Pr)$_4$ in 80 mL of dry benzene was heated at reflux under a Dean–Stark condenser for 10 h. Concentration under reduced pressure followed by chromatography on 150 g of silica gel (elution with 1:3 ether–hexanes) gave 3.2 g (95%) of 2-butynyl 2-[(2-methoxyethoxy)methoxy]acetate, homogeneous by TLC analysis, R_f 0.52 (1:1 ether–hexanes).

Into a 250-mL Morton flask were placed 200 mg of Lindlar's catalyst[21] and 15 mL of EtOAc The system was flushed and charged with H_2. The acetylenic ester from above (0.50 g, 2.4 mmol) was added in 15 mL of EtOAc via syringe. The mixture was stirred vigorously at 25 °C, and the uptake of H_2 was monitored. After 50 mL (~93% of theory) of H_2 had been taken up, the reaction mixture was filtered through Celite with ether. Concentration at reduced pressure followed by chromatography on 100 g of silica gel (elution with 1:2 ether–hexanes) afforded 0.45 g (89%) of the ester **6c** as an oil: homogeneous by TLC and spectroscopic criteria; R_f 0.69 (2:1 ether–hexanes); IR (neat film) 3030, 2922, 2886, 2820, 1753, 1658, 1449, 1412, 1383, 1368, 1356, 1280, 1200, 1175, 1122, 1097, 1062, 1026, 964, 933, 850 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 5.63 (m, 2 H), 4.75 (s, 2 H), 4.69 (d, 2 H, J = 7.5 Hz), 4.19 (s, 2 H), 3.62 (m, 4 H), 3.37 (s, 3 H), 1.71 (d, 3 H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) 169.53, 129.60, 123.37, 94.88, 71.20, 66.87, 63.88, 59.86, 58.43, 12.62. Anal. Calcd for $C_{10}H_{18}O_5$: C, 55.03; H, 8.31. Found: C, 54.93; H, 8.31.

Methyl (*R,*R**)-2-Methoxy-3-methyl-4-pentenoate (7a).** To a solution of 0.83 mmol of LDA in 20 mL of THF at −100 °C was added 100 mg (0.69 mmol) of the substrate ester **6a** in 6 mL of THF. After the reaction mixture had stirred at −100 °C for 1 h, there was added an excess of Me_3SiCl in the form of the supernatant from the centrifugation of a 1:1 mixture of Me_3SiCl and Et_3N. The reaction mixture was allowed to stir 1 h at −100 °C and 6 h at 25 °C. The reaction was quenched by adding concentrated HCl until pH 4.5 was reached. The reaction mixture was then partitioned between water and CH_2Cl_2, and the combined organic layers were dried ($MgSO_4$) and concentrated. The crude product thus obtained was dissolved in 50 mL of ether and was esterified with an ethereal solution of diazomethane. Chromatography on 12 g of silica gel [elution with 22% ether in pentane (v/v)] gave 70 mg (64%) of the product esters **7a** (major) and **5a** (minor) in a ratio of 23:1, as determined by glass capillary GLC (85 °C, isothermal):[13a] R_f 0.66 (2:3 ether–hexanes); IR (neat film) 3080, 2947, 2918, 2867, 2822, 1744, 1727, 1629, 1448, 1426, 1365, 1346, 1261, 1189, 1170, 1120, 1087, 1051, 1007, 989, 910, 837 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 5.74 (m, 1 H), 4.91 (m, 2 H), 3.65 (s, 3 H), 3.52 (d, 1 H, J = 5.5 Hz), 3.31 (s, 3 H), 2.56 (m, 1 H), 1.04 (d, 3 H, J = 7.0 Hz); ^{13}C NMR ($CDCl_3$) δ 171.98, 138.44, 115.18, 84.73, 58.48, 51.34, 40.84, 15.94. Anal. Calcd for $C_8H_{14}O_3$: C, 60.74; H, 8.92. Found: C, 61.04; H, 9.10.

Methyl (*R,*R**)-2-(Benzyloxy)-3-methyl-4-pentenoate (7b).** The substrate ester **6b** (300 mg, 1.36 mmol) was rearranged and esterified as described for the preparation of **7a**. Chromatography of the crude product thus obtained on 40 g of silica gel (elution with 1:4 ether–hexanes) gave 250 mg (79%) of the esters **7b** (major) and **5b** (minor) in a ratio of 18.6:1, as determined by analytical HPLC:[13]: R_f 0.75 (1:2 ether–hexanes); IR (neat film) 3064, 3029, 2973, 2949, 2929, 2868, 1752, 1637, 1604, 1496, 1452, 1433, 1420, 1394, 1372, 1345, 1268, 1202, 1177, 1138, 1090, 1057, 1028, 1016, 996, 917, 844, 740, 696 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (m, 5 H), 5.85 (m, 1 H), 5.05 (m, 2 H), 4.56 (AB q, 2 H, J_{AB} = 12 Hz, $\Delta\nu_{AB}$ = 139 Hz), 3.85 (d, 1 H, J = 5.0 Hz), 3.74 (s, 3 H), 2.67 (m, 1 H), 1.08 (d, 3 H, J = 7.0 Hz); ^{13}C NMR ($CDCl_3$) δ 172.00, 138.59, 137.30, 128.05, 127.73, 127.55, 115.16, 81.90, 72.32, 51.32, 40.95, 16.17. Anal. Calcd for $C_{14}H_{18}O_3$: C, 71.77; H, 7.74. Found: C, 71.89; H, 7.67.

Methyl (*R,*R**)-2-[(2-Methoxyethoxy)methoxy]-3-methyl-4-pentenoate (7c).** The substrate ester **6c** (100 mg, 0.46 mmol) was rearranged and esterified as described for the preparation of **7a**. Chromatographic purification on 12 g of silica gel (elution with 1:3 ether–hexanes) gave 76 mg (70%) of the esters **7c** (major) and **5c** (minor) in a ratio of 11.4:1, as determined by glass capillary GLC (148 °C, isothermal):[13a] R_f 0.66 (2:1 ether–hexanes); IR (neat film) 3078, 2966, 2950, 2930, 2891, 2820, 1750, 1638, 1452, 1435, 1416, 1366, 1268, 1201, 1172, 1122, 1100, 1043, 997, 921, 848 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.78 (m, 1 H), 5.03 (m, 2 H), 4.74 (m, 2 H), 4.06 (d, 1 H, J = 5.0 Hz), 3.71 (m, 2 H), 3.70 (s, 3 H), 3.50 (m, 2 H), 3.36 (s, 3 H), 2.66 (m, 1 H), 1.08 (d, 3 H, J = 6.8 Hz); ^{13}C NMR ($CDCl_3$) δ 171.80, 138.50, 115.42, 95.19, 79.51, 71.48, 67.37, 58.74, 51.39, 40.75, 16.11. Anal. Calcd for $C_{11}H_{20}O_5$: C, 56.88; H, 8.68. Found: C, 56.87; H, 8.81.

Methyl (*R,*R**)-2-Hydroxy-3-methyl-4-pentenoate (7d). (A) From (*Z*)-2-Butenyl 2-Hydroxyacetate (6d).** The substrate ester **6d** (75 mg, 0.58 mmol) was rearranged and esterified as described for the preparation of **5d** from **4d**. Chromatography on 12 g of silica gel (elution with 1:3 ether–pentane) gave 39 mg (47%) of the product esters **7d** and **5d** in a ratio of 1.4:1, as determined by integration of distinctive resonances in the 400-MHz ^{1}H NMR spectrum:[14,15] R_f 0.68 (1:1 ether–hexanes); IR (CCl_4) 3547, 3086, 2963, 2940, 2882, 2866, 1736, 1652, 1452, 1440, 1420, 1376, 1277, 1258, 1222, 1132, 1092, 1072, 1024, 1000, 922 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.73 (m, 1 H), 5.04 (m, 2 H), 4.11 (dd, 1 H, J = 6.2, 2.8 Hz), 3.76 (s, 3 H), 2.71 (d, 1 H, J = 6.2 Hz), 2.63 (m, 1 H), 1.14 (d, 3 H, J = 7.0 Hz).

(B) From (*Z*)-2-Butenyl 2-(Benzyloxy)acetate (6b). The substrate ester **6b** (300 mg, 1.36 mmol) was subjected to the enolate Claisen rearrangement, reductive debenzylation, and diazomethane esterification sequence as described for the conversion **4b** → **5d**. Chromatographic purification on 13 g of silica gel (elution with 1:4 ether–hexanes) gave 61 mg (31% overall) of the product ester **7d**, identical with that described above and elsewhere.[15]

3-[1-(2-Methoxyacetoxy)ethyl]-2-methylcyclopent-2-en-1-one (8a). 3-(1-Hydroxyethyl)-2-methylcyclopent-2-en-1-one (**10**;[12] 1.0 g, 7.1 mmol) was acylated with 2-methoxyacetyl chloride[21] by procedure A as detailed for the preparation of **4a**. Purification by elution through a column of 100 g of silica gel with 1:1 ether–hexanes gave 1.43 g (95%) of the ester **8a** as an oil: homogeneous by TLC and spectroscopic criteria; R_f 0.75 (ether); IR (neat film) 2976, 2915, 2818, 1752, 1731, 1700, 1647, 1432, 1417, 1402, 1373, 1331, 1288, 1260, 1180, 1150, 1122, 1050, 1028, 1000, 970, 937, 870, 838, 816 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 5.80 (br q, 1 H, J = 6.0 Hz), 3.95 (s, 2 H), 3.36 (s, 3 H), 2.40 (m, 4 H), 1.71 (br s, 3 H), 1.41 (d, 3 H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$) δ 208.93, 169.07, 167.98, 136.23, 69.28, 68.54, 59.02, 33.21, 24.61, 18.01, 7.76. Anal. Calcd for $C_{11}H_{16}O_4$: C, 62.25; H, 7.60. Found: C, 61.98; H, 7.73.

3-[1-[2-(Benzyloxy)acetoxy]ethyl]-2-methylcyclopent-2-en-1-one (8b). The allylic alcohol **10**[12] (0.50 g, 3.6 mmol) was acylated with 2-(benzyloxy)acetyl chloride[23] by procedure A as detailed for the preparation of **4a**. Chromatographic purification on 60 g of silica gel (elution with 1:3 ether–hexanes) gave 1.0 g (97%) of the ester **8b** as an oil: homogeneous by TLC and spectroscopic criteria; R_f 0.68 (ether); IR (neat film) 3060, 3025, 2980, 2920, 2862, 1752, 1700, 1647, 1492, 1440, 1404, 1377, 1332, 1292, 1273, 1191, 1126, 1077, 1052, 1029, 1002, 968, 907, 876, 843, 819, 739, 697 cm^{-1}; ^{1}H NMR (90 MHz, CCl_4) δ 7.22 (br s, 5 H), 5.80 (br q, 1 H, J = 6.2 Hz), 4.55 (s, 2 H), 4.00 (s, 2 H), 2.32 (m, 4 H), 1.71 (br s, 3 H), 1.40 (d, 3 H, J = 6.2 Hz); ^{13}C NMR ($CDCl_3$) δ 208.64, 169.05, 136.73, 136.08, 128.03, 127.52, 72.95, 68.51, 66.70, 33.17, 24.57, 17.89, 7.66. Anal. Calcd for $C_{17}H_{20}O_4$: C, 70.81; H, 6.99. Found: C, 71.09; H, 7.19.

Methyl (*S,*R**)-*α*-Methoxy-(*E*)-2-ethylidene-1-methyl-5-oxocyclopentaneacetate (9a).** The substrate ester **8a** (75 mg, 0.35 mmol) was rearranged and esterified as described for the preparation of **5a**. Chromatography on 14 g of silica gel (elution with 1:3 ether–hexanes) gave 45 mg (57%) of the product ester **9a** as an oil: homogeneous by TLC and spectroscopic criteria; R_f 0.69 (1:1 ether–hexanes); IR (neat film) 2987, 2956, 2926, 2863, 2835, 1744, 1673, 1443, 1407, 1377, 1366, 1349, 1292, 1269, 1201, 1131, 1114, 1071, 1032, 1013, 965, 900, 838, 785, 735 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.66 (br q, 1 H), 3.93 (s, 1 H), 3.66 (s, 3 H), 3.50 (s, 3 H), 2.51 (br m, 4 H), 1.61 (d, 3 H, J = 6.9 Hz), 1.18 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 219.19, 171.16, 142.03, 119.90, 85.67, 60.51, 55.14, 51.56, 36.07, 23.13, 22.13, 13.52. Anal. Calcd for $C_{12}H_{18}O_4$: C, 63.70; H, 8.02. Found: C, 64.01; H, 8.20.

Methyl (*S,*R**)-*α*-(Benzyloxy)-(*E*)-2-ethylidene-1-methyl-5-oxocyclopentaneacetate (9b).** The substrate ester **8b** (100 mg, 0.35 mmol) was rearranged and esterified as described for the preparation of **5a**. Chromatography on 14 g of silica gel (elution with 1:3 ether–hexanes) gave 63 mg (60%) of the product ester **9b** as an oil: homogeneous by TLC and spectroscopic criteria; R_f 0.63 (1:1 ether–hexanes); IR (neat film) 3087, 3062, 3033, 2952, 2923, 2862, 1747, 1672, 1494, 1452, 1436, 1404, 1378, 1364, 1342, 1290, 1269, 1208, 1178, 1132, 1082, 1065, 1030, 1014, 965, 912, 839, 747, 737, 698 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 (m, 5 H), 5.68 (br q, 1 H), 4.66 (AB q, 2 H, J = 11.5 Hz, $\Delta\nu_{AB}$ = 180 Hz), 4.18 (s, 1 H), 3.68 (s, 3 H), 2.49 (br m, 4 H), 1.61 (d, 3 H, J = 6.8 Hz), 1.18 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 220.71, 172.73, 143.60, 129.71, 129.38, 129.22, 121.38, 84.78, 80.10, 56.56, 53.09, 37.58, 24.65, 23.80, 15.08. Anal. Calcd for $C_{18}H_{22}O_4$: C, 71.50; H, 7.33. Found: C, 71.62; H, 7.46.

(*R,*S**)-*α*-(Benzyloxy)-*β*-methyl-*δ*-valerolactone (11).** To a solution of 100 mg (0.43 mmol) of the rearrangement product **5b** in 15 mL of CH_2Cl_2 at 0 °C was added 14 mL of a 0.5 M solution of disiamylborane in CH_2Cl_2.[17] The reaction mixture was stirred at 0 °C for 20 h, at which time there was added 1.2 mL of 3 M aqueous NaOH followed by 2.2 mL of 30% H_2O_2, all at 0 °C. The cloudy reaction mixture was allowed to warm to 25 °C and was stirred for 18 h. The clear reaction mixture was then added to 50 mL of CH_2Cl_2 and 15 mL of 5% aqueous HCl. The aqueous phase was extracted once with CH_2Cl_2, and 20 mL of saturated aqueous NaCl was added to the aqueous layer, which was then extracted twice more with CH_2Cl_2. The combined organic extracts were then dried ($MgSO_4$) and concentrated. The crude product thus obtained was taken up in 50 mL of benzene together with 25 mg of camphorsulfonic acid. This mixture was heated at reflux for 18 h under a Dean–Stark trap. After removal of the solvent via rotary evaporator, the product was chromatographed on 12 g of silica gel (elution with 1:3 ether–hexanes) to give 60 mg (64%) of the crystalline lactone **11**: mp 64–65 °C; homogeneous by TLC and spectroscopic criteria; R_f 0.46 (1:1 ether–hexanes); IR (neat film) 3090, 3064, 3030, 2962, 2928, 2874, 1748, 1606, 1585, 1494, 1453, 1402, 1380, 1259, 1217, 1191, 1122, 1064, 1031, 994, 932, 860, 790, 700 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 (br m, 5 H), 4.79 (AB q, 2 H, J_{AB} = 11.3 Hz, $\Delta\nu_{AB}$ = 175 Hz), 4.25 (m, 2 H), 3.59 (d, 1 H, J = 9.3 Hz), 2.14–2.01 (br m, 2 H), 1.56 (br m, 1 H), 1.08 (d, 3 H, J = 6.5 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171. 37, 137.36, 128.20, 128.05, 127.74, 79.27, 73.37, 66.67, 32.72, 29.88, 18.92. Anal. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.77; H, 7.50.

(*R,*S**)-*α*-Hydroxy-*β*-methyl-*δ*-valerolactone [(±)-Verrucarinolactone] (12).** The benzyl ether **11** (50 mg, 0.23 mmol) was placed in 15 mL of ethanol, together with 30 mg of 10% Pd/C,[21] under H_2 (1 atm). After the reaction mixture had stirred at 25 °C for 40 h, TLC analysis indicated that all of the starting material **11** had been consumed. The catalyst was removed by filtration through a pad of Celite. The EtOH was removed by rotary evaporator to leave 27 mg (90%) of (±)-verrucarinolactone (**12**): mp 72–73 °C (lit. mp 71–72.5 °C,[16a] 71–72 °C,[16d]); homogeneous by TLC and spectroscopic criteria; R_f 0.53 (1:1 ethyl acetate–hexanes); IR ($CHCl_3$) 3522, 3020, 2959, 2923, 2870, 2850, 1730, 1474, 1450, 1393, 1375, 1354, 1309, 1250, 1169, 1109, 1084, 1059, 1040, 1010, 991, 910, 852 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.32 (br m, 2 H), 3.83 (d, 1 H, J = 10.4 Hz), 3.25 (br s, 1 H), 2.02 (br m, 2 H), 1.68 (br m, 1 H), 1.23 (d, 3 H, J = 6.3 Hz); ^{13}C NMR ($CDCl_3$) δ 175.02, 72.61, 67.50, 33.56, 29.93, 19.07. Anal. Calcd for $C_6H_{10}O_3$: C, 55.37; H, 7.75. Found: C, 55.12; H, 8.03.

(*R,*R**)-*α*-(Benzyloxy)-*β*-methyl-*δ*-valerolactone (13).** The rearrangement product **7b** (530 mg, 2.27 mmol) was subjected to the hydroboration–oxidation–lactonization sequence as described for the preparation of lactone **11**. Purification by chromatography on 50 g of silica gel (elution with 1:3 ether–hexanes) gave 309 mg (62%) of the lactone **13** as an oil: homogeneous by TLC and spectroscopic criteria; R_f 0.51 (1:1 ether–hexanes); IR (neat film) 3083, 3062, 3026, 2957, 2924, 2868, 1746, 1606, 1587, 1494, 1452, 1403, 1377, 1310, 1275, 1250, 1205, 1152, 1124, 1080, 1063, 1045, 1027, 994, 911, 859, 802, 734, 696 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23 (m, 5 H), 4.65 (AB q, 2 H, J_{AB} = 12.0 Hz, $\Delta\nu_{AB}$ = 122 Hz), 4.30 (m, 1 H), 4.14 (m, 1 H), 3.90 (d, 1 H, J = 5.3 Hz), 2.25 (m, 1 H), 1.88 (m, 1 H), 1.67 (m, 1 H), 1.00 (d, 3 H, J = 6.9 Hz); ^{13}C NMR ($CDCl_3$) δ 170.67, 137.42, 128.23, 127.72, 76.18, 72.21, 66.72, 30.74, 27.71, 15.95. Anal. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.67; H, 7.48.

(*R,*R**)-*α*-Hydroxy-*β*-methyl-*δ*-valerolactone (14).** The benzyl ether **13** (72 mg, 0.33 mmol) was dissolved in a solution of 8 mL of ethanol and 2 mL of 2 N HCl. To this was added 20 mg of 10% Pd/C,[21] and the resulting mixture was stirred under 1 atm of H_2. After 2.5 h at 25 °C, TLC analysis indicated that all of the **13** had been consumed. The catalyst was removed by filtration through Celite with ethyl acetate. The solvent was removed by rotary evaporator, and the aqueous residue was extracted with ethyl acetate. The combined organic extracts were dried ($MgSO_4$) and concentrated to give 40 mg (94%) of the crystalline hydroxy lactone **14**: mp 67–68 °C; homogeneous by TLC and spectroscopic criteria; R_f 0.25 (1:1 ethyl acetate–hexanes); IR ($CHCl_3$) 3524, 3024, 2986, 2960, 2925, 2854, 1736, 1483, 1459, 1450, 1383, 1264, 1171, 1117, 1093, 1028, 1000, 897, 858 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.35 (br m, 2 H), 3.24 (br s, 1 H), 2.55 (br m, 1 H), 2.22 (br m, 1 H), 1.72 (br m, 1 H), 1.22 (br s, 1 H), 0.99 (d, 3 H, J = 7.1 Hz); ^{13}C NMR ($CDCl_3$) δ 175.20, 69.64, 66.09, 30.07, 28.95, 14.85.

Preparation and Attempted Epimerization of the Phenylseleno Lactone 15. By use of the published procedure,[18] the crude carboxylic acid derived from rearrangement of substrate **8a** (220 mg, 1.03 mmol) was dissolved in 40 mL of CH_2Cl_2 at 0 °C. After the addition of 0.17 mL (1.25 mmol) of Et_3N, the reaction mixture was stirred at 0 °C for 1 h and was then cooled to −78 °C. There was added 0.24 g (1.25 mmol) of phenylselenenyl chloride, and the reaction mixture was stirred at −78 °C for 1 h and at 25 °C for 72 h. After removal of the solvent by rotary evaporator, the residue was chromatographed on silica gel (elution with 1:3 ether–hexanes) to give 249 mg (76%) of the crystalline phenylseleno lactone **15**: mp 134 °C; homogeneous by TLC and spectroscopic criteria; R_f 0.51 (1:1 ether–hexanes); IR ($CHCl_3$) 3017, 2986, 2941, 2879, 2842, 1761, 1577, 1448, 1438, 1409, 1378, 1324, 1302, 1178, 1145, 1100, 1075, 1020, 977, 932, 896 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59–7.29 (br m, 5 H), 3.79 (s, 1 H), 3.60 (s, 3 H), 3.40 (q, 1 H, J = 7.0 Hz), 2.59 (br m, 3 H), 2.26 (br m, 1 H), 1.60 (d, 3 H, J = 7.0 Hz), 1.20 (s, 3 H);^{13}C NMR ($CDCl_3$) δ 216.16, 172.12, 134.81, 129.22, 128.48, 128.12, 95.91, 79.99, 60.61, 59.76, 44.37, 35.03, 30.04, 18.29, 11.31. A solution of 13.3 mg (0.037 mmol) of the lactone **15** and 4 μL of 1,5-diazabicyclo[5.4.0]undec-5-ene (DBU) in 15 mL of benzene was stirred at 25 °C for 50 h. At this time, the reaction mixture was poured into ethyl acetate, and the organic layer was washed with 0.5 N HCl, dried ($MgSO_4$), and concentrated. Analysis by TLC and ^{1}H NMR indicated that no epimerization had taken place at the methoxyl-bearing carbon.

Preparation of the Mixture of Phenylseleno Lactones 15 and 17. A mixture of the allylic alcohol **10** (0.60 g, 4.2 mmol), 4.2 mL of triethyl 2-methoxyorthoacetate,[20] and 180 μL of propionic acid was stirred at 120 °C for 36 h. Chromatographic purification on 110 g of silica gel (elution with 1:3 ether–hexanes) gave 0.84 g (84%) of the Claisen rearrangement product **16** as a mixture of epimers [R_f 0.77 (1:1 ether–hexanes)]. A solution of 200 mg (0.83 mmol) of **16** in 60 mL of wet methanol was stirred with excess K_2CO_3 for 14 h at 25 °C. The methanol was removed by rotary evaporator, the residue was taken up in 20 mL of H_2O, and the aqueous layer was washed once with ether. The aqueous layer was then acidified with concentrated HCl and was extracted twice with CH_2Cl_2 and twice with ether. The organic extracts were dried ($MgSO_4$) and concentrated to leave 150 mg of crude carboxylic acid product. This was dissolved in 60 mL of ethyl acetate at 0 °C, and 0.18 g (0.94 mmol) of phenylselenenyl chloride was added. The reaction mixture was allowed to stir at 0 °C for 30 min and at 25 °C for 24 h. The solvent was removed by rotary evaporator, and the residue was purified by chromatography on 45 g of silica gel (elution with 1:3 ethyl acetate–hexanes) to give 140 mg (46% overall from **16**) of a mixture of the epimeric lactones **15** and **17** in a ratio of 43:57, as determined by ^{1}H NMR integration of the methine singlets at δ 3.79 and 3.86, respectively, in $CDCl_3$. For the purpose of independent characterization, the lactone **17** was isolated in pure form by chromatography of the **15**/**17** mixture on silica gel (elution with 1:4 ethyl acetate–hexanes). The crystalline phenylseleno lactone **17** (mp 122–123 °C) thus isolated was homogeneous by TLC and spectroscopic criteria; R_f 0.41 (1:1 ether–hexanes); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58–7.26 (br m, 5 H), 3.86 (s, 1 H), 3.62 (s, 3 H), 3.34 (q, 1 H, J = 7.0 Hz), 2.54 (br m, 3 H), 2.14 (br m, 1 H), 1.62 (d, 3 H, J = 7.0 Hz), 1.39 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 211.65, 171.64, 134.78, 129.28, 128.24, 94.92, 84.49, 60.01, 57.77, 44.45, 37.58, 31.50, 18.73, 16.24. Anal. Calcd for $C_{17}H_{20}O_4Se$: C, 55.59; H, 5.48. Found: C, 55.53; H, 5.74.

Epimerization Study on the Mixture of Lactones 15 and 17. To a solution of 66 mg (0.18 mmol) of the mixture of epimeric lactones **15** and **17** (ratio 43:57 by ^{1}H NMR) in 30 mL of benzene was added 10 μL of DBU. The reaction mixture was stirred at 25 °C for 72 h, at which time it was poured into 80 mL of ethyl acetate, and the organic layer was washed with 0.5 N HCl. The organic layer was dried ($MgSO_4$) and concentrated. Integration of the methine resonances at δ 3.79 and 3.86 in the ^{1}H NMR showed that the ratio of **15** to **17** had increased to 59:41. This new mixture was redissolved in 30 mL of benzene, and 10 μL of DBU was added. The reaction mixture was heated at 52 °C for 56 h, cooled, and poured into 150 mL of ethyl acetate. After having been washed with 2.5% aqueous HCl, the organic layer was dried ($MgSO_4$) and concentrated. Integration of the ^{1}H NMR resonances at δ 3.79 and δ 3.86 for **15** and **17**, respectively, showed that the ratio had further increased to 80:20 in favor of **15**.

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Registry No. **4a**, 87763-61-9; **4b**, 87763-62-0; **4c**, 87763-63-1; **4d**, 82731-58-6; (±)-**5a**, 87763-64-2; (±)-**5b**, 87763-65-3; (±)-**5c**, 87763-66-4; (±)-**5d**, 71215-27-5; **6a**, 87763-67-5; **6b**, 87763-68-6; **6c**, 87763-69-7; **6d**, 85970-67-8; (±)-**7a**, 87763-70-0; (±)-**7b**, 87763-71-1; (±)-**7c**, 87763-72-2; (±)-**7d**, 71215-25-3; (±)-**8a**, 87763-73-3; (±)-**8b**, 87763-74-4; (±)-**9a**, 87763-75-5; (±)-**9b**, 87763-76-6; (±)-**10**, 87763-84-6; (±)-**11**, 87763-77-7; (±)-**12**, 83057-87-8; (±)-**13**, 87763-78-8; (±)-**14**, 87828-38-4; (±)-**15**, 87763-79-9; (±)-**16** (isomer 1), 87763-80-2; (±)-**16** (isomer 2), 87763-85-7; (±)-**17**, 87828-39-5; $MEMOCH_2CO_2Et$, 87763-81-3; (benzyloxy)acetyl chloride, 19810-31-2; (*E*)-2-buten-1-ol, 504-61-0; 2-butynyl 2-methoxyacetate, 87763-82-4; 2-butynyl 2-[(2-methoxyethoxy)methoxy]acetate, 87763-83-5; 2-methoxyacetyl chloride, 38870-89-2; 2-butyn-1-ol, 764-01-2.

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^{19}F NMR Study on the Conformation Changes of 1,1,2,2-Tetrafluoro-1,2-disilacyclohexanes

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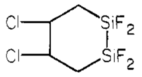
Four 1,1,2,2-tetrafluoro-1,2-disilacyclohexane derivatives are synthesized. The conformation changes associated with ring inversion of these compounds are studied by full line-shape analyses of their ^{19}F DNMR spectra. The activation parameters, $\Delta G^\ddagger$, $\Delta H^\ddagger$, and $\Delta S^\ddagger$, are obtained with reasonable accuracy. The results show that the activation energy barrier of the ring inversion process is closely affected by the nature of the substituents at the 4 and 5 positions in cis orientation. A plausible mechanism for the ring inversion process, which involves a semiplanar transition state and a boat form intermediate, is proposed.

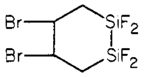
The use of DNMR full line-shape analysis for investigation of conformational equilibria and rates of ring inversion in cyclic compounds is well-known.[1] A great number of cyclohexane derivatives and other ring systems have been studied by this method, the results have provided valuable insight to the mechanisms of conformational changes in ring systems which are difficult to obtain by other methods.[1] Information about heterocyclic compounds is comparatively less complete; for example, there have been only a few studies on silacyclic compounds in the literature.[2,3] One of the reasons is that, unlike the cyclohexane system in which the stable form of the ring structure is well-known, the information of the basic static structures of heterocyclic compounds is often lacking. Besides, within the temperature range that the DNMR technique normally accesses, strained ring compounds often can not exibit their low temperature limiting spectra for analysis.

It is usually possible to work with much larger chemical shifts by replacing one or more hydrogens on a cyclic compound by fluorine atoms and study the ^{19}F NMR spectra. This "fluorine labeling" technique has already been used for determination of the rate of ring inversion of a number of fluorocyclic compounds.[4]

In the present study, ^{19}F NMR spectroscopy was used for studying the conformation change of four 1,1,2,2-tetrafluoro-1,2-disilacyclohexane derivatives I to IV, among which the structure of I has been determined by a single crystal X-ray diffraction study,[5] and compound II has not been reported previously.



cis-I



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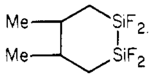

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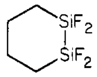

IV

Experimental Section

Preparation of Compounds I, III, and IV. Compounds I, III, and IV were prepared and purified following the procedures reported previously.[6-8] Purification of III was improved by GC separation.

Preparation of Compound II. Compound II was obtained from the cocondensation reaction of difluorosilylene with vinyl bromide. The reaction and purification conditions were very similar to those used in the reaction of difluorosilylene with vinyl

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