resulting solution and the buffered bleach (160 mL, pH = 11.25) were cooled separately in an ice bath and then combined at 4 °C. The two-phase mixture was stirred for 12 h. *tert*-Butyl methyl ether (500 mL) was then added to the solution, and the organic phase was separated and filtered through a Celite pad, washed with water (2 × 400 mL) and brine (2 × 400 mL), and then dried over Na_2SO_4. The solvent was removed under vacuum, and GC analysis of the residue indicated the presence of cis and trans epoxides in a 3.5:1 ratio. The ee of the cis epoxide was determined to be 95–97% by ^1H NMR analysis with $Eu(hfc)_3$ as chiral shift reagent, and the ee of the trans isomer was determined to be 78% by the same method. The residue was purified by short-path distillation (104–105 °C (0.5 mm)) to afford 4.0 g of a mixture containing 70% cis epoxide (56% yield), 13% trans epoxide (10% yield), and remaining trace impurities arising from starting material (all yields determined by GC analysis). This material was suitable for subsequent reactions and was used without further purification. Alternatively, for smaller scale procedures the residue was purified by flash chromatography (petroleum ether/ether (87:13), v/v) to afford the epoxides in a 10:1 cis/trans ratio. *cis*-Ethyl-3-phenylglycidate: ^1H NMR ($CDCl_3$) δ 1.02 (t, J = 7.2 Hz, 3 H), 3.83 (d, J = 4.8 Hz, 1 H), 3.9–4.1 (m, 2 H), 4.27 (d, J = 4.8 Hz, 1 H), 7.2–7.5 (aromatic, 5 H); *trans*-ethyl 3-phenylglycidate: ^1H NMR ($CDCl_3$) δ 1.33 (t, J = 7.2 Hz, 3 H), 3.51 (d, J = 2.1 Hz, 1 H), 4.09 (d, J = 1.8 Hz, 1 H), 4.2–4.4 (m, 2 H), 7.2–7.5 (aromatic, 5 H).

(2*R*,3*S*)-3-Phenylisoserinamide. The (2*R*,3*R*)-ethyl 3-phenylglycidate obtained as described above (3.9 g of a mixture containing 14.2 mmol of *cis*-ethyl 3-phenylglycidate) was dissolved in a solution of 60 mL of ethanol saturated with ammonia (prepared by passing NH_3 through ethanol at −15 °C). This solution was placed in a stainless steel Parr reactor and heated to 100 °C for 3 H with mechanical stirring. After the solution was cooled to room temperature, solvent was removed under vacuum and the residue was dissolved in 70 mL of boiling methanol. The solution was cooled to −20 °C and a first crop of beige crystals (1.6 g) was collected after 8 h. The mother liquor was concentrated to approximately 20 mL and then cooled to −20 °C, and a second crop of crystals was collected (0.5 g). The two crops were combined and found to contain 5–7% of the anti diastereomer by integration of the ^1H NMR spectrum. Recrystallization from methanol (50–60 mL) following the same protocol described above led to isolation of diastereomerically pure product (1.66 g, 65%): mp 172–173 °C; ^1H NMR (DMSO-d_6/D_2O) δ 3.87 (d, J = 3.3 Hz, 1 H), 4.08 (d, J = 3.3 Hz, 1 H), 7.0–7.5 (aromatic, 5 H); ^{13}C NMR (DMSO-d_6) δ 57.3, 75.6, 126.3, 127.0, 127.7, 144.4, 174.9. Anal. Calcd for $C_9H_{12}O_2N_2$: C, 60.00; H, 6.67; N, 15.55. Found: C, 59.90; H, 6.71; N, 15.25.

The corresponding racemate was synthesized by an analogous sequence with epoxide prepared with (±)-4: mp 192–193 °C (lit.[16] mp 187–188 °C).

(2*R*,3*S*)-3-Phenylisoserine. The literature procedure was followed with minor modifications.[16] (2*R*,3*S*)-3-Phenylisoserinamide (1.63 g, 9.05 mmol) was combined with 2.88 g (9.1 mmol) of $Ba(OH)_2 \cdot 8H_2O$ and water (16 mL). The resulting suspension was heated to reflux under nitrogen for 8 h. The release of ammonia from the reaction mixture was monitored periodically by holding a strip of moistened pH paper above the solution, and the reaction was judged to be complete once the vapor above the solution was neutral. The reaction mixture was then cooled to 80 °C, and water (120 mL) was added. The temperature of the solution was maintained at 80 °C for 20 min before a solution of 910 mg of H_2SO_4 in 8 mL of water was added. The acidified solution was determined to have a pH between 5 and 7. Heating at 80 °C was maintained for another 10 min, and the mixture was then cooled to room temperature. The resulting precipitate ($BaSO_4$) was removed by centrifugation, the supernatant liquid was separated, and the solvent was removed under vacuum to provide the desired product as a white solid (1.51 g, 92% yield), mp 238 °C dec: ^1H NMR (D_2O/NaOD) δ 3.94 (d, J = 3.9 Hz, 1 H), 4.01 (d, J = 3.9 Hz, 1 H), 7.0–7.5 (aromatic, 5 H). Anal. Calcd for $C_9H_{11}NO_3$: C, 59.66; H, 6.07; N, 7.73. Found: C, 59.33; H, 6.13; N, 7.67.

***N*-Benzoyl-(2*R*,3*S*)-3-phenylisoserine (3).** (2*R*,3*S*)-3-Phenylisoserine (1.50 g, 8.25 mmol) was dissolved in 10% aqueous $NaHCO_3$ (200 mL) with stirring. The solution was cooled to 4 °C, and benzoyl chloride (3 mL, 3.57 g, 25 mmol) was added. This mixture was stirred for 6 h at 4 °C and then acidified to pH = 1 by addition of aqueous HCl solution (18%). This resulted in formation of a white precipitate suspended in the aqueous solution. The aqueous mixture was extracted with THF/CH_2Cl_2 (4:1, 3 × 250 mL), and the organic phases were combined, dried over Na_2SO_4, and removed under reduced pressure to provide a white crystalline mixture containing both desired product and benzoic acid. The latter was removed by dissolution of the mixture in a minimum amount of acetone (40 mL) and subsequent addition of 800 mL of hexane. The resulting product **3** was isolated as a white solid by filtration (1.74 g, 74% yield) and was determined to be diastereomerically pure by ^1H NMR: mp 177–179 °C (lit.[5c] mp 167–169 °C). FABMS m/z 286 (M^+ + 1); ^1H NMR (DMSO-d_6) δ 4.37 (d, J = 4.5 Hz, 1 H), 5.46 (dd, J = 8.7, 4.5 Hz, 1 H), 5.3–5.7 (b, 1 H), 7.2–7.6 (m, 9 H), 7.84 (d, J = 7.5 Hz, 1 H), 8.58 (d, J = 9.0 Hz, 1 H), 12.5–13.0 (br, 1 H); ^{13}C NMR (acetone-d_6) δ 56.5, 74.3, 128.0, 128.1, 129.0, 129.2, 132.2, 135.5, 141.0, 167.1, 173.9; FABHRMS calcd for $C_{16}H_{16}NO_4$ 286.1079, obsvd 286.1068; $[\alpha]^{25}_D$ −35.9° (*c* 0.565, EtOH) (lit.[5c] $[\alpha]^{25}_D$ +36.5° (*c* 1.45, EtOH) (for the 2*S*,3*R* isomer); $[\alpha]^{25}_D$ −37.78° (*c* 0.9, EtOH) (for the 2*S*,3*S* isomer)). Anal. Calcd for $C_{11}H_{15}NO_4$: C, 67.36; H, 5.30; N, 4.91. Found: C, 67.31; H, 5.26; N, 4.87.

Acknowledgment. This work was supported by the National Institutes of Health (GM-43214). Awards to E.N.J. from the National Science Foundation (PYI program), the David and Lucille Packard Foundation, the Lilly Grantee Program, the Sloan Foundation, and the Merck Faculty Development Program are gratefully acknowledged.

Registry No. 1, 33069-62-4; 3, 132201-33-3; 3 (de-benzoyl derivative), 136561-53-0; 3 amide (de-benzoyl derivative), 141901-21-5; (*R*,*R*)-4, 138124-32-0; PhC≡CCO_2Et, 2216-94-6; (*Z*)-PhCH=$CHCO_2$Et, 4610-69-9; (*E*)-PhCH=$CHCO_2$Et, 4192-77-2; $Ph(CH_2)_2CO_2$Et, 2021-28-5; $Mn(OAc)_2 \cdot (H_2O)_4$, 6156-78-1; ethyl (2*R*,3*R*)-3-phenylglycidate, 126060-73-9; ethyl *trans*-3-phenylglycidate, 2272-55-1; 2,4-di-*tert*-butylphenol, 96-76-4; 3,5-di-*tert*-butylsalicaldehyde, 37942-07-7; (1*R*-*trans*)-1,2-diaminocyclohexane, 20439-47-8.

Ireland–Claisen Rearrangements of Chiral (*Z*)-Vinylsilanes. Highly Diastereoselective Synthesis of *anti*-α-Alkoxy-β-(dimethylphenylsilyl)-(*E*)-hex-4-enoates

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Introduction

Recent reports from our laboratory have described the use of functionalized (*E*)-crotylsilanes as carbon nucleophiles in diastereo- and enantioselective addition reactions to acetals and aldehydes.[3] We have reported the stereo-

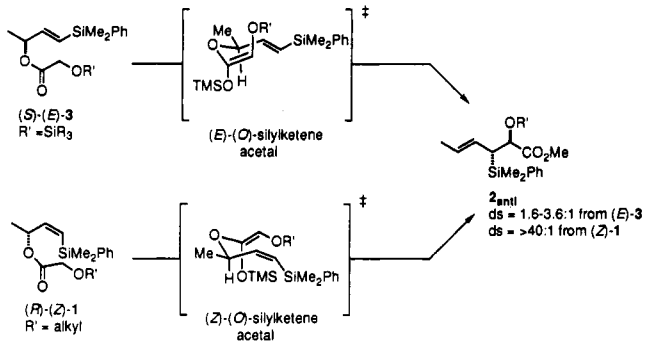
(1) Recipient of a James Flack Norris Award, 1991, Northeast Section of the American Chemical Society.

(2) (a) Panek, J. S.; Yang, M. *J. Am. Chem. Soc.* **1991**, *113*, 6594–6600. (b) Panek, J. S.; Yang, M. *J. Org. Chem.* **1991**, *56*, 5755–5758. (c) Panek, J. S.; Yang, M. *J. Am. Chem. Soc.* **1991**, *113*, 9868–9870.

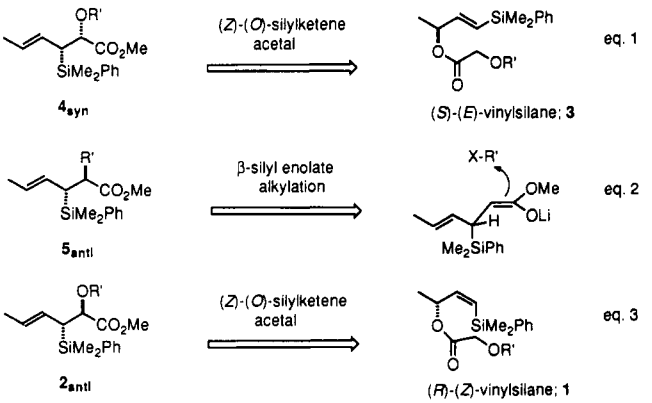
(3) Reviews on allylmetal chemistry: (a) Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 555–566. (b) Yamamoto, Y.; Maruyama, K. *Heterocycles* **1982**, *18*, 357. For detailed reports of the use of chiral crotylboronates in addition reactions to aldehydes, see: (c) Roush, W. R.; Hoong, L. K.; Palmer, M. A. J.; Straub, J. A.; Palkowitz, A. D. *J. Org. Chem.* **1990**, *55*, 4117–4126. (e) Roush, W. R.; Ando, K.; Powers, D. B.; Palkowitz, A. D.; Halterman, R. L. *J. Am. Chem. Soc.* **1990**, *112*, 6339–6348. (f) Roush, W. R.; Palkowitz, A. D.; Ando, K. *J. Am. Chem. Soc.* **1990**, *112*, 6348–6359 and references cited therein.

0022-3263/92/1957-4323$03.00/0

Scheme I

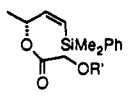
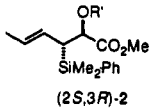
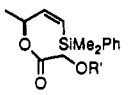
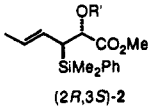


selective synthesis of such crotylsilanes through the Ireland–Claisen rearrangement of highly enantiomerically enriched (*R*)- and (*S*)-(*E*)-1-(trialkylsilyl)-1-buten-3-ol glycolate ester derivatives to yield *syn*-α-alkoxy-β-(trialkylsilyl)-(*E*)-hex-4-enoates **4**.[4] By using enolization conditions that favor the formation of the (*Z*)-O-silylketene acetal, the (*E*)-crotylsilane was obtained with high levels of syn diastereoselection (>1:25 anti/syn, eq 1). We have shown in a related study that chiral β-silyl enolates undergo highly selective electrophillic addition reactions with a variety of alkyl halides to produce anti-α-alkyl-β-silylhexenoates, with levels of diastereoselection ranging between 24 and 100:1 (eq 2).[5] In order to further explore this class of organosilane reagents in stereoselective reactions that may be useful in natural product synthesis we required access to the complementary *anti*-α-alkoxy-β-(trialkylsilyl)-(*E*)-hexenoates **2**.



The Ireland–Claisen strategy involving the illustrated vinylsilanes presented us with two potential routes to the desired *anti*-α-alkoxy series. One approach which was explored in our previous report involved reversing the configuration of the silyl ketene acetal from *Z* to *E* in the rearrangement of O-silylated glycolate esters of (*E*)-vinylsilanes **3**, as illustrated in Scheme I for (*S*)-(*E*)-**3** and (*R*)-(*Z*)-**1**. Unfortunately, the strong chelating ability of the glycolate oxygen made it difficult to obtain useful levels of selectivity in the enolization step; therefore, the subsequent sigmatropic rearrangement yielded the desired anti product with only moderate levels of diastereoselection (1.6–3.6:1 anti:syn). The second option involved changing the configuration of the vinylsilane from the *E* to the *Z* stereoisomer. This option seemed particularly attractive because it would allow us to selectively form the (*Z*)-*O*-silyl ketene acetal by taking advantage of the strong chelating ability of the glycolate oxygen in the enolization step, a strategy which had previously proved successful in the case of the (*E*)-vinylsilanes (eq 1). According to literature precedent, the formation of the (*Z*)-*O*-silyl ketene acetal of (*Z*)-vinylsilanes should lead to the anti diastereomers after bond reorganization (eq 3 and Scheme I).[6]

Table I. Ireland–Claisen Rearrangement of Chiral (*R*)- and (*S*)-(*Z*)-vinylsilanes

(*Z*)-vinylsilane	(*E*)-crotylsilane product,[a,b]	compd no.	yield, %[c]
	 (2*S*,3*R*)-2		
(*R*)-**1a**	R' = CH_3	**2a**	69
(*R*)-**1b**	CH_2Ph	**2b**	76
(*R*)-**1c**	$CH_2C_6H_4OMe$-*p*	**2c**[d]	91
(*R*)-**1d**	CH_2OCH_3	**2d**[d]	76
	H	**2e**[e]	64
	 (2*R*,3*S*)-2		
(*S*)-**1f**	R' = CH_3	**2f**	82
(*S*)-**1g**	CH_2Ph	**2g**	74

[a] Refers to the diastereomerically pure major (*E*)-crotylsilane product after esterification and chromatography on SiO_2. [b] For the cases examined the diastereomeric ratios were shown to be at least 40:1 anti/syn as determined by ^1H NMR analysis (270 MHz). [c] Combined yield for two steps: Claisen rearrangement and esterification [MeOH, $SOCl_2$ (1.5 equiv)]. [d] The methyl esters **2c** and **2d** were obtained by esterification with CH_2N_2 in Et_2O at 0 °C → rt. [e] Compound **2e** was obtained through exposure of the carboxylic acid derived from the Claisen rearrangement of **1d** to the esterification conditions ($MeOH/SOCl_2$), resulting in the loss of the MOM protecting group.

Results and Discussion

The purpose of this paper is to report the results of our experiments concerning the Ireland–Claisen rearrangement of O-protected glycolate esters of (*R*)- and (*S*)-(*Z*)-1-(dimethylphenylsilyl)-1-buten-3-ol derivatives **1**. After esterification ($MeOH/SOCl_2$) the reactions gave *anti*-α-alkoxy-β-(dimethylphenylsilyl)-(*E*)-hex-4-enoates (**2**), with high levels of diastereoselection (Scheme I and eq 3).[7] The success of this study was based on the availability of useful quantities of (*R*)- and (*S*)-(*Z*)-1-(dimethylphenylsilyl)-1-buten-3-ol derivatives. We have previously reported that a crude enzymic extract of Pseudomonas AK catalyzes an enantioselective transesterification of the corresponding (*E*)-vinylsilanes, producing a nearly enantiomerically pure (*S*)-alcohol.[8] Unfortunately, lipase extracts failed to promote a transesterification of the corresponding (*Z*)-vinylsilanes, and only racemic alcohol was recovered. The requisite optically pure (*R*)- and (*S*)-(*Z*)-vinylsilanes used to prepare glycolate esters **1** were therefore obtained through an enzyme-mediated resolution of racemic 1-(dimethylphenylsilyl)-1-butyn-3-ol with Pseudomonas AK lipase, followed by a Lindlar reduction.[9]

(4) Sparks, M. A.; Panek, J. S. *J. Org. Chem.* **1991**, *56*, 3431–3438.
(5) Panek, J. S.; Beresis, R.; Xu, F.; Yang, M. *J. Org. Chem.* **1991**, *56*, 7341–7344.
(6) For Claisen rearrangements of glycolate esters of racemic (*E*)- and (*Z*)-vinylstannanes, see: Ritter, K. *Tetrahedron Lett.* **1990**, *31*, 869–873.
(7) Publications concerning the Ireland–Claisen rearrangement: (a) Ireland, R. E.; Mueller, R. H.; Willard, A. K. *J. Am. Chem. Soc.* **1976**, *98*, 2868–2877. (b) Ireland, R. E. *Aldrichimica Acta* **1988**, *21*, 59. (c) Ireland, R. E.; Wipf, P.; Armstrong, J. D. *J. Org. Chem.* **1991**, *56*, 650–657. (d) Marshall, J. A. *Chemtracts: Org. Chem.* **1991**, *4*, 154–157.
(8) Sparks, M. A.; Panek, J. S. *Tetrahedron Lett.* **1991**, *32*, 4085–4088.

The results of our study concerning the Ireland–Claisen rearrangements of (*R*)- and (*S*)-(*Z*)-vinylsilanes are summarized in Table I. These results are complementary to our earlier published reports concerning the Claisen rearrangements of (*E*)-vinylsilanes and related stereoselective alkylation reactions of β-silyl enolates.

For the cases examined the (*Z*)-*O*-silyl ketene acetals derived by the low-temperature enolization and subsequent silylation [(i) $LiN(TMS)_2$ (1.2 equiv), THF, −78 °C, 15 min; (ii) TMSCl (6.0 equiv), −78 °C → rt; (iii) 5% HCl] afforded the *anti*-(*E*)-crotylsilanes as their carboxylic acids. The acids were then converted to the corresponding methyl esters [absolute MeOH, $SOCl_2$ (1.5 equiv), 0 °C → rt] in high yield. In the case of the carboxylic acid derived from the Claisen rearrangement of **1d**, the thionyl chloride promoted esterification conditions resulted in loss of the methoxymethoxy protecting group and provided a convenient route to the α-hydroxyhexenoate **2e** in 83% yield (Table I). As expected the bond reorganization was highly stereoselective for the generation of the *E*-double bond with no trace of the *Z*-stereoisomer.[10]

Assignment of Relative Stereochemistry. The assignment of relative stereochemistry is based on comparison of three bond coupling constant data between the anti and syn diastereomers **2** and **4**. The assignment of relative stereochemistry for the *anti*-(*E*)-crotylsilanes **2a–f** is based on the measurement of three-bond coupling constants between the C2/C3-stereogenic centers ($^3J_{H2,H3}$)[11] and the results of our previous studies.[4,5] For two examples, authentic samples of the corresponding syn diastereomers were available from an Ireland–Claisen rearrangement of the (*E*)-vinylsilanes, which permitted the direct comparison of the three-bond coupling constant values between both 2,3-anti and 2,3-syn diastereomers. For these functionalized (*E*)-crotylsilanes the measured $^3J_{H2,H3}$ values for the anti diastereomers (2*S*,3*R*)-**2e** and (2*S*,3*R*)-**2a** were smaller in magnitude than those of the syn diastereomer.[4]

In summary, the use of the Ireland–Claisen rearrangement of optically active (*Z*)-vinylsilanes provides access to *anti*-α-alkoxy-β-(dimethylphenylsilyl)-(*E*)-hex-4-enoates in good yield with high levels of diastereoselection and demonstrates the expanded scope that is provided by reversing the configuration of the vinylsilane. The application of these reagents in asymmetric addition reactions will be reported in due course.

Experimental Section[12]

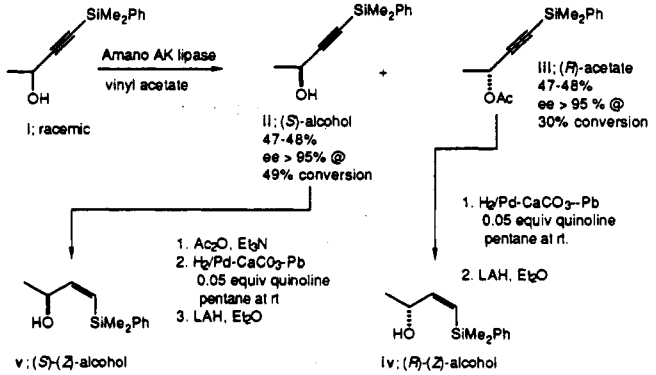
Representative Procedure for the Dicyclohexylcarbodiimide (DCC) Promoted Esterification of (*R*)- and (*S*)-(*Z*)-Vinylsilanes. (3*R*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-yl (Benzyloxy)acetate (1b). To a stirred solution of (*R*)-1-(dimethylphenylsilyl)-1-buten-3-ol (1.04 g, 5.05 mmol) in freshly distilled CH_2Cl_2 (10 mL) were added (benzyloxy)acetic acid[13] (1.09 g, 6.57 mmol, 1.3 equiv), DCC (1.25 g, 6.07 mmol, 1.2 equiv), and 4-(dimethylamino)pyridine (DMAP, 5–10 mg) at 0 °C. The resulting reaction mixture was allowed to warm slowly to room temperature. After being stirred for 12 h, the mixture was cooled to 0 °C and filtered through silica gel to remove the precipitated urea. The crude product was chromatographed on SiO_2 (0–3% EtOAc–petroleum ether gradient elution) to afford 1.71 g (4.83 mmol, 95%) of pure **1b** as a colorless oil: ^1H NMR (270 MHz, $CDCl_3$) δ 7.55–7.27 (m, 10 H), 6.28 (dd, 1 H, *J* = 8.8, 14.7 Hz), 5.83 (d, 1 H, *J* = 14.7 Hz), 5.46 (m, 1 H), 4.57 (s, 2 H), 4.00 and 3.93 (AB q, 2 H, *J* = 16.1 Hz), 1.16 (d, 3 H, *J* = 6.4 Hz), 0.46 (s, 3 H), 0.41 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 169.2, 147.0, 138.6, 137.1, 133.6, 130.7, 129.0, 128.4, 128.0, 127.9, 127.8, 73.2, 71.7, 67.2, 20.4, −1.1, −1.4; IR (neat) 2970, 1755; CIMS (NH_3) 372.2, 91.0; CIHRMS M + NH_4^+ calculated for $C_{21}H_{26}O_3Si$ 372.1994, found 372.2000; $[\alpha]^{23}_D$ = −30.1° (*c* 1,36, CH_2Cl_2).

The following compounds were prepared according to the representative procedure described above and in the indicated isolated yield.

(3*R*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-yl methoxyacetate (1a, 89% yield): ^1H NMR (270 MHz, $CDCl_3$) δ 7.54–7.51 (m, 2 H), 7.35–7.31 (m, 3 H), 6.29 (dd, 1 H, *J* = 8.5, 14.7 Hz), 5.83 (d, 1 H, *J* = 14.7 Hz), 5.45 (m, 1 H), 3.93 and 3.85 (AB q, 2 H, *J* = 16.6 Hz), 3.39 (s, 3 H), 1.15 (d, 3 H, *J* = 6.8 Hz), 0.45 (s, 3 H), 0.40 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 169.2, 147.0, 138.6, 133.7, 130.8, 129.1, 127.9, 71.7, 69.9, 59.2, 20.5, −1.1, −1.4); IR (neat) 2970, 1745; CIMS (NH_3) 296.2, 189.1, 147.0, 73.0; CIHRMS M + NH_4^+ calculated for $C_{15}H_{22}O_3Si$ 296.1682, found 296.1678; $[\alpha]^{23}_D$ = −28.8° (*c* 1.36, CH_2Cl_2).

(3*R*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-yl ((4-methoxybenzyl)oxy)acetate (1c, 92% yield): ^1H NMR (270 MHz,

(9) A general procedure for the preparation of (*R*)- and (*S*)-(*Z*)-vinylsilanes **iv** and **v** is as follows [for the preparation of propargylic alcohol **i** and related compounds, see: (a) Fleming, I.; Takai, K.; Thomas, A. P. *J. Chem. Soc., Perkin Trans. 1* **1987**, 2269–2273. (b) Colvin, E. W. *Silicon Reagents in Organic Synthesis*, Academic Press; London, 1988; Chapter 16, pp 124–125]: To a 0.5 M pentane solution of racemic alcohol **i** was added a crude extract of *Pseudomonas* AK lipase (0.5 wt equiv) and vinyl acetate (5.0 equiv), and the resulting suspension was stirred at rt for 4 h. Chromatography of the crude reaction mixture on SiO_2 (0 to 5% EtOAc/petroleum ether) provided nearly optically pure (*S*)-propargylic alcohol, (*S*)-**ii**, and (*R*)-propargylic acetate, **iii**, as illustrated in the scheme. The absolute stereochemistry of the resolved alcohol was assigned by analogy with prior published reports involving similar structural types (see Burgess, K.; Jennings, L. D. *J. Am. Chem. Soc.* **1991**, *113*, 6129–6139). The (*R*)-(*Z*) alcohol was obtained employing a two-step procedure: Lindlar reduction [1 atm of H_2, Pd–$CaCO_3$–Pb, 10% by weight, 0.05 equiv of quinoline, 2–4 h, rt, 0.5 M in pentane, *Z*:*E* = 14:1 by capillary GLC; Lindlar reduction of the unprotected alcohol resulted in poor stereoselection (*Z*:*E* = 5–7:1)] followed by lithium aluminum hydride reduction afforded the desired (*R*)-(*Z*) alcohol **iv** in 90% yield from the acetate. The (*S*)-(*Z*) alcohol **v** was obtained in 91% isolated yield by using a similar three-step procedure as illustrated below.



(10) Three other laboratories have reported (10a, 10b–d, 10i) the use of (*E*)-vinylsilanes in Claisen rearrangements: (a) Murphy, P. J.; Spencer, J. L.; Procter, G. *Tetrahedron Lett.* **1990**, *31*, 1051–1054. (b) Procter, G.; Russel, A. T.; Murphy, P. J.; Tan, T. S.; Mather, A. N. *Tetrahedron* **1988**, *44*, 3953–3973. (c) Russel, A. T.; Procter, G. *Tetrahedron Lett.* **1987**, *28*, 2041–2044. (d) Jenkins, P. R.; Gut, R.; Wetter, H.; Eschenmoser, A. *Helv. Chim. Acta* **1979**, *62*, 1922–1931. Examples of Claisen rearrangements of chelated glycolate derivatives: (e) Burke, S. D.; Fobare, W. F.; Pacofsky, G. J. *J. Org. Chem.* **1983**, *48*, 5221–5228. (f) Sato, T.; Tajima, K.; Fujisawa, T. *Tetrahedron Lett.* **1983**, *24*, 729–733. (g) Fujisawa, T.; Tajima, K.; Sato, T. *Chem. Lett.* **1984**, 1669–1672. (h) Gould, T. J.; Balestra, M.; Wittmann, M. D.; Gary, J. A.; Rossano, L. T.; Kallmerten, J. *J. Org. Chem.* **1987**, *52*, 3889–3901. (i) For Claisen rearrangements of racemic glycolate esters of (*E*)-vinylsilanes: Sato, T.; Tsunekawa, H.; Kohama, H.; Fujisawa, T. *Chem. Lett.* **1986**, 1553–1556.

(11) Doyle, M. P.; Bagheri, V.; Harn, N. K. *Tetrahedron Lett.* **1988**, *29*, 5119–5122.

(12) (a) All reactions were run in oven-dried glassware, sealed with a rubber septum, and stirred with a magnetic stirring bar under N_2. Unless otherwise noted, commercial reagents were purchased and used without prior purification. Hexamethyldisilazane and *n*-butyllithium were purchased from Aldrich Chemicals. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl prior to use. Methylene chloride was distilled from calcium hydride prior to use. TLC plates used for monitoring reaction progress were plastic sheets precoated with SiO_2 60 F_{254} as purchased from E. Merck, Darmstadt. Flash chromatography (see Still, W. C.; Khan, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923–2925) was performed on E. Merck silica gel 230–400 mesh.

(13) Manhas, M. S.; Amin, S. G.; Chawla, H. P. S.; Bose, A. K. *J. Heterocycl. Chem.* **1978**, *15*, 601–604.

$CDCl_3$) δ 7.56–6.86 (m, 9 H), 6.29 (dd, 1 H, J = 9.3, 14.2 Hz), 5.84 (d, 1 H, J = 14.2 Hz), 5.47 (m, 1 H), 4.52 (s, 2 H), 3.95 and 3.91 (AB q, 2 H, J = 16.6 Hz), 3.81 (s, 3 H), 1.17 (d, 3 H, J = 6.4 Hz), 0.47 (s, 3 H), 0.42 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 169.3, 159.4, 147.1, 138.6, 133.6, 130.7, 129.7, 129.2, 129.1, 127.8, 113.8, 72.8, 71.7, 66.9, 55.2, 20.5, –1.1, –1.4; IR (neat) 2990, 1760; CIMS (NH_3) 402.2, 195.1, 121.1; CIHRMS M + NH_4^+ calculated for $C_{23}H_{28}O_4Si$ 402.2102, found 402.2078; $[\alpha]^{23}_D$ = –39.7° (*c* 1.36, CH_2Cl_2).

(3*R*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-yl (methoxymethoxy)acetate (1d, 94% yield): ^1H NMR (270 MHz, $CDCl_3$) δ 7.54–7.49 (m, 2 H), 7.36–7.31 (m, 3 H), 6.27 (dd, 1 H, J = 9.3, 14.2 Hz), 5.82 (d, 1 H, J = 14.2 Hz), 5.44 (m, 1 H), 4.66 (s, 2 H), 4.06 and 4.00 (AB q, 2 H, J = 16.6 Hz), 3.36 (s, 3 H), 1.15 (d, 3 H, J = 6.8 Hz), 0.45 (s, 3 H), 0.40 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 169.0, 147.0, 138.6, 133.6, 130.7, 129.1, 127.8, 96.3, 71.8, 64.3, 55.7, 20.4, –1.1, –1.4; IR (neat) 2980, 1755; CIMS (NH_3) 326.1, 247.1, 189.1, 145.1; CIHRMS M + NH_4^+ calculated for $C_{16}H_{24}O_4Si$ 326.1788, found 326.1767; $[\alpha]^{23}_D$ = –32.2° (*c* 1.12, CH_2Cl_2).

(3*S*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-yl methoxyacetate (1f, 86% yield): ^1H NMR (270 MHz, $CDCl_3$) δ 7.54–7.51 (m, 2 H), 7.35–7.31 (m, 3 H), 6.29 (dd, 1 H, J = 8.5, 14.7 Hz), 5.83 (d, 1 H, J = 14.7 Hz), 5.45 (m, 1 H), 3.93 and 3.85 (AB q, 2 H, J = 16.6 Hz), 3.39 (s, 3 H), 1.15 (d, 3 H, J = 6.8 Hz), 0.45 (s, 3 H), 0.40 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 169.2, 147.0, 138.6, 133.7, 130.8, 129.1, 127.9, 71.7, 69.9, 59.2, 20.5, –1.1, –1.4; IR (neat) 2970, 1745; CIMS (NH_3) 296.2, 221.1, 189.1 147.1; CIHRMS M + NH_4^+ calculated for $C_{15}H_{26}O_3Si$ 296.1682, found 296.1682; $[\alpha]^{23}_D$ = +24.6° (*c* 1.36, $CHCl_3$).

(3*S*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-yl (benzyloxy)acetate (1g, 81% yield): ^1H NMR (270 MHz, $CDCl_3$) δ 7.55–7.27 (m, 10 H), 6.28 (dd, 1 H, J = 8.8, 14.7 Hz), 5.83 (d, 1 H, J = 14.7 Hz), 5.46 (m, 1 H), 4.57 (s, 2 H), 4.00 and 3.93 (AB q, 2 H, J = 16.1 Hz), 1.16 (d, 3 H, J = 6.4 Hz), 0.46 (s, 3 H), 0.41 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 169.2, 147.0, 138.6 137.1, 133.6, 130.7, 129.0, 128.4, 128.0, 127.9, 127.8, 73.2 71.7, 67.2, 20.4, –1.1, –1.4; IR (neat) 2970, 1755; CIMS (NH_3) 372.2, 91.0; CIHRMS M + NH_4^+ calculated for $C_{21}H_{26}O_3Si$ 372.1994, found 372.1998; $[\alpha]^{23}_D$ = + 32.39° (*c* = 1.40, CH_2Cl_2).

Representative Procedure for the Ireland–Claisen Rearrangement of Enantiomerically Enriched (*R*)- and (*S*)-(*Z*)-Vinylsilanes. (2*S*,3*R*)-(*E*)-Methyl 2-(Benzyloxy)-3-(dimethylphenylsilyl)-(*E*)-hex-4-enoate (2b). To a magnetically stirred THF/hexanes solution of $LiN(TMS)_2$ (1.6 equiv, 2.26 mmol, 0.4 M) at –78 °C under N_2 was added a THF solution of (3*R*)-(*Z*)-1-(dimethylphenylsilyl)-1-buten-3-yl (benzyloxy)acetate (500 mg, 1.4 mmol, 1.0 equiv, 0.26 M). The resulting mixture was stirred for 15 min before being trapped with freshly distilled TMSCl (1.07 mL, 8.4 mmol, 6.0 equiv). The mixture was then allowed to slowly reach room temperature and was stirred for 12 h, at which time it was treated with 5% HCl (20 mL). The reaction mixture was extracted with Et_2O (3 × 20 mL). The combined organic layers were dried over Na_2SO_4 and filtered, and the solvent was removed under reduced pressure to give the crude acid. Chromatography on SiO_2 (100% petroleum ether → 50% EtOAc–petroleum ether gradient elution) afforded (2*S*,3*R*)-(*E*)-2-(benzyloxy)-3-(dimethylphenylsilyl)hex-4-enoic acid (428 mg, 86% yield). A portion of the carboxylic acid (168 mg, 0.47 mmol, 1 equiv) was dissolved in absolute MeOH (3.0 mL), cooled to 0 °C, and treated with $SOCl_2$ (52 μL, 0.71 mmol, 1.5 equiv), and the reaction mixture was allowed to stir for 12 h before the solvent was removed under reduced pressure. The crude product was chromatographed on SiO_2 (100% petroleum ether → 20% EtOAc–petroleum ether) to afford 154 mg of pure **2b** as a colorless oil: ^1H NMR (270 MHz, $CDCl_3$) δ 7.45–7.26 (m, 10 H), 5.54–5.19 (m, 2 H), 4.54 and 4.03 (AB q, 2 H, J = 10.8 Hz), 3.93 (d, 1 H, J = 3.4 Hz), 3.61 (s, 3 H), 2.17 (dd, J = 3.4, 10.3 Hz), 1.62 (d, 3 H, J = 6.4 Hz), 0.25 (s, 3 H), 0.22 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 172.8, 137.6, 134.0, 129.0, 128.2, 128.1, 128.0, 127.6, 126.3, 125.9, 79.5, 72.5, 51.4, 38.1, 18.1, –3.5, –4.4; IR (neat) 2960, 1750; CIMS (NH_3) 386.2, 261.1, 242.1, 164.1, 135.1; CIHRMS M + NH_4^+ calculated for $C_{22}H_{28}O_3Si$ 386.2151, found 386.2160; $[\alpha]^{23}_D$ = –35.3° (*c* 1.22, CH_2Cl_2).

(2*S*,3*R*)-(*E*)-Methyl 2-methoxy-3-(dimethylphenylsilyl)-hex-4-enoate (2a): ^1H NMR (270 MHz, $CDCl_3$) δ 7.53–7.49 (m, 2 H), 7.36–7.31 (m, 3 H), 5.46–5.20 (m, 2 H), 3.64 (d, 1 H, J = 3.4 Hz), 3.61 (s, 3 H), 3.19 (s, 3 H), 2.11 (dd, 1 H, J = 3.4, 10.7 Hz), 1.61 (dd, 3 H, J = 1.5, 6.3 Hz) 0.35 (s, 3 H), 0.26 (s, 3 H); ^{13}C NMR (60 MHz $CDCl_3$) δ 172.7, 137.5, 134.0, 129.0, 127.6, 126.5, 125.7, 81.7, 58.2, 51.4, 38.2, 18.0, –3.6, –4.5; IR (neat) 2950, 1750, CIMS (NH_3) 310.2, 261.2, 126.1, 95.1; CIHRMS M + NH_4^+ calculated for $C_{16}H_{24}O_3Si$ 310.1838, found 310.1821; $[\alpha]^{23}_D$ = –43.0° (*c* 0.89, CH_2Cl_2).

(2*S*,3*R*)-(*E*)-Methyl 2-((4-methoxybenzyl)oxy)-2-(dimethylphenylsilyl)hex-4-enoate (2c): ^1H NMR (270 MHz, $CDCl_3$) δ 7.45–6.83 (m, 9 H), 5.53–5.18 (m, 2 H), 4.47 and 3.99 (AB q, 2 H, J = 10.6 Hz), 3.92 (d, 1 H, J = 3.3 Hz), 3.80 (s, 3 H), 3.61 (s, 3 H), 2.16 (dd, 1 H, J = 3.3, 10.6 Hz), 1.61 (dd, 3 H, J = 1.1, 6.2 Hz), 0.25 (s, 3 H), 0.21 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 172.9, 159.2, 137.6, 134.0, 129.8, 129.7, 128.9, 127.6, 126.2, 125.9, 123.6, 79.1, 72.1, 55.2, 51.4, 38.1, 18.1, –3.5, –4.5; IR (neat) 2950, 1745; CIMS (NH_3) 416.2, 121.1; CIHRMS M + NH_4^+ calculated for $C_{23}H_{30}O_4Si$ 416.2257, found 416.2248; $[\alpha]^{23}_D$ = –28.1° (*c* 1.39, CH_2Cl_2).

(2*S*,3*R*)-(*E*)-Methyl 2-(methoxymethoxy)-3-(dimethylphenylsilyl)hex-4-enoate (2d): ^1H NMR (270 MHz, $CDCl_3$) δ 7.51–7.48 (m, 2 H), 7.34–7.30 (m, 3 H), 5.49–5.18 (m, 2 H), 4.53 and 4.41 (AB q, 2 H, J = 7.0 Hz), 4.12 (d, 1 H, J = 4.0 Hz), 3.55 (s, 3 H), 3.29 (s, 3 H), 2.20 (dd, 1 H, J = 4.0, 10.6 Hz), 1.62 (dd, 3 H, J = 1.5, 6.2 Hz), 0.37 (s, 3 H), 0.27 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 172.5, 137.4, 134.0, 129.0, 127.6, 126.6, 125.8, 96.9, 77.3, 56.6, 51.4, 37.5, 18.1, –3.3, –4.6; IR (neat) 2950, 1750; CIMS (NH_3) 340.3, 261.2, 245.2; CIHRMS M + NH_4^+ calculated for $C_{17}H_{26}O_4Si$ 340.1994, found 340.1931; $[\alpha]^{23}_D$ = –46.3° (*c* 1.45, CH_2Cl_2).

(2*S*,3*R*)-(*E*)-Methyl 2-hydroxy-3-(dimethylphenylsilyl)-hex-4-enoate (2e): ^1H NMR (270 MHz, $CDCl_3$) δ 7.56–7.54 (m, 2 H), 7.35–7.32 (m, 3 H), 5.40–5.26 (m, 2 H), 4.20 (d, 1 H, J = 2.4 Hz), 3.65 (s, 3 H), 2.75 (bs, 1 H), 2.08 (dd, 1 H, J = 2.4, 10.0 Hz), 1.61 (d, 3 H, J = 6.4 Hz), 0.38 (s, 3 H), 0.30 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 175.7, 137.7, 134.1, 129.0, 127.6, 126.9, 125.0, 71.7, 52.2, 38.2, 18.2, –3.8, –4.2; IR (neat) 3500, 2980, 1735; CIMS (NH_3) 296.2, 261.1, 201.1, 126.1; CIHRMS M + NH_4^+ calculated for $C_{15}H_{22}O_3Si$ 296.1682, found 296.1675; $[\alpha]^{23}_D$ = –81.6° (*c* 1.0, CH_2Cl_2).

(2*R*,3*S*)-(*E*)-Methyl 2-methoxy-3-(dimethylphenylsilyl)-hex-4-enoate (2f): ^1H NMR (270 MHz, $CDCl_3$) δ 7.53–7.49 (m, 2 H), 7.36–7.31 (m, 3 H), 5.46–5.20 (m, 2 H), 3.64 (d, 1 H, J = 3.4 Hz), 3.61 (s, 3 H), 3.19 (s, 3 H), 2.11 (dd, 1 H, J = 3.4, 10.7 Hz), 1.61 (dd, 3 H, J = 1.5, 6.3 Hz), 0.35 (s, 3 H), 0.26 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 172.7, 137.5, 134.0, 129.0, 127.6, 126.5, 125.7, 81.7, 58.2, 51.4, 38.2, 18.1, –3.6, –4.4; IR (neat) 2950, 1750; CIMS (NH_3) 310.2, 261.1, 126.1; CIHRMS M + NH_4^+ calculated for $C_{16}H_{24}O_3Si$ 310.1838, found 310.1830; $[\alpha]^{23}_D$ = +45.2° (*c* 0.89, CH_2Cl_2).

(2*R*,3*S*)-(*E*)-Methyl 2-(benzyloxy)-3-(dimethylphenylsilyl)-hex-4-enoate (2g): ^1H NMR (270 MHz, $CDCl_3$) δ 7.45–7.26 (m, 10 H), 5.54–5.19 (m, 2 H), 4.54 and 4.03 (AB q, 2 H, J = 10.8 Hz), 3.93 (d, 1 H, J = 3.4 Hz), 3.61 (s, 3 H), 2.17 (dd, J = 3.4, 10.3 Hz), 1.62 (d, 3 H, J = 6.4 Hz), 0.25 (s, 3 H), 0.22 (s, 3 H); ^{13}C NMR (60 MHz, $CDCl_3$) δ 172.8, 137.6, 134.0, 129.0, 128.2, 128.1, 128.0, 127.6, 126.3, 125.9, 79.5, 72.5, 51.4, 38.1, 18.1, –3.5, –4.5; IR (neat) 2960, 1750; CIMS (NH_3) 386.2, 261.1; CIHRMS M + NH_4^+ calculated for $C_{22}H_{28}O_3Si$ 386.2151, found 386.2149; $[\alpha]^{23}_D$ = +32.5° (*c* 1.21, CH_2Cl_2).

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Supplementary Material Available: Spectral data for iv and v and all carboxylic acids from the Claisen rearrangement and ^{13}C and ^1H NMR spectra of **1a–g** and **2a–g** (29 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.