a colorless oil. Column chromatography on silica gel (gradient elution with ethyl acetate–hexanes) afforded 0.065 g (77%) of **48** as a colorless oil: IR (film) 3320 (br), 2964, 2922, 2858, and 1658 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 4.13 (s, 2 H), 2.23 (app t, J = 5.1 Hz, 2 H), 2.17 (app t, J = 5.1 Hz, 2 H), 1.76 (s, 3 H), and 1.48–1.65 (m, 7 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 138.0, 124.3, 63.2, 30.5, 29.9, 28.2, 27.6, 26.6, and 15.9. Anal. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50. Found: C, 76.97; H, 11.78.

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Optically Active Ketones as Chiral Auxiliaries in the [2,3]-Wittig Rearrangement

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The stereochemical aspects of the [2,3]-Wittig rearrangement of optically active tertiary allyl ethers derived from (+)-camphor and (−)-fenchone were investigated. The rearrangement of the (+)-camphor derivative yielded two olefin products in a 70/30 E/Z ratio. The geometry of the trisubstituted olefin produced during the rearrangement was assigned by NOE experiments. The configuration of the newly formed carbinol center of the products was established by kinetic resolution, Mosher's method, and conversion to derivatives of known absolute configuration. The absolute configuration of the carbinol center for the Z isomer was assigned to be S and that of the E isomer to be R. The (−)-fenchone derivative gave only a single Z olefin product, which was assigned the S configuration at the carbinol center.

Introduction

The efficient conservation of chiral elements during sigmatropic rearrangements has made possible the development of many useful methods for asymmetric synthesis.[1] Several variants of the [2,3]-Wittig rearrangement have been found to be particularly useful members of this class of reactions.[2] The use of chiral auxiliaries adjacent to the carbanion center[3] and the rearrangement of optically active secondary allyl ethers[4] are two of the most successful strategies investigated. In the interest of expanding the scope of the [2,3]-Wittig rearrangement, we have undertaken a project to investigate preparation and rearrangement of optically active tertiary bis-allyl ethers.

Our strategy was to prepare these substrates by the addition of organometallic reagents to readily available optically active ketones (Figure 1). The optically active allyl alcohols produced may be converted to bis-allyl ethers under modified Williamson ether synthesis conditions.[5] Treatment of the bis-allyl ethers with an appropriate base would effect the [2,3]-Wittig rearrangement. The terminal olefin of the product serves as a convenient handle for further elaboration of the substrate. Cleavage of the newly formed trisubstituted double bond regenerates the chiral auxiliary and produces a new optically active chiral fragment. (+)-Camphor and (−)-fenchone were the ketones chosen for the initial evaluation of this strategy.

Discussion

The addition of vinyl Grignard reagent to (+)-camphor in the presence of $CeCl_3$ provided the optically active tertiary exo alcohol **2** in high yield (Figure 2).[6] Exclusion addition of the Grignard reagent to the endo face of the bicyclic ketone is due to the steric impairment of approach to the exo face of the carbonyl group by the *gem*-dimethyl group on the methylene bridge of the rigid terpene skeleton. Optically active allyl ether **3** was prepared by using modified Williamson conditions as reported by Marshall.[5] The rearrangement of the bis-allyl ether was attempted under the conditions we had employed previously[4a] (*n*-BuLi, THF, −78 °C to room temperature) for the [2,3]-Wittig rearrangement of optically active secondary allyl ethers. However, only starting material was recovered. After an extensive search for a base that would effect the desired rearrangement, it was found that *t*-BuOK/*t*-BuLi would induce the [2,3]-Wittig rearrangement.[7] When a solution of *t*-BuLi was added slowly to a mixture of *t*-BuOK and **3** in THF at −85 °C followed by warming to 0 °C, two products were produced in a 2.3:1 ratio. Examination of the products by ^1H and ^{13}C NMR indicated that they were the E and Z isomers (**4a** and **5a**) of the allylic alcohol product.

The geometry of the trisubstituted double bond was established by NOE studies on a 500-MHz NMR spectrometer. The proton NMR spectrum of the E isomer (**4a**) contained three signals for the methyl groups on the bicyclic terpene skeleton. Irradiation of the bridgehead methyl signals at δ 0.906 produced a NOE effect on the olefin resonance at δ 5.04. This observation demonstrates that the olefin proton is configurationally close to the

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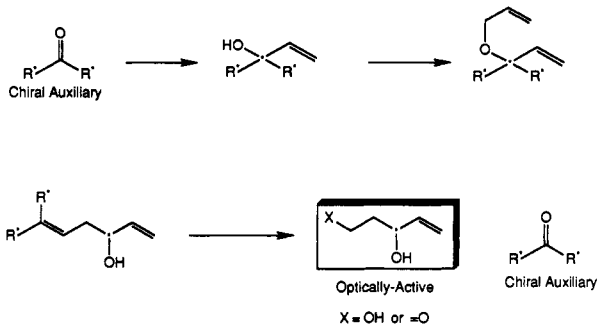

Figure 1. Strategy for the [2,3]-Wittig rearrangement of tertiary allyl ethers.

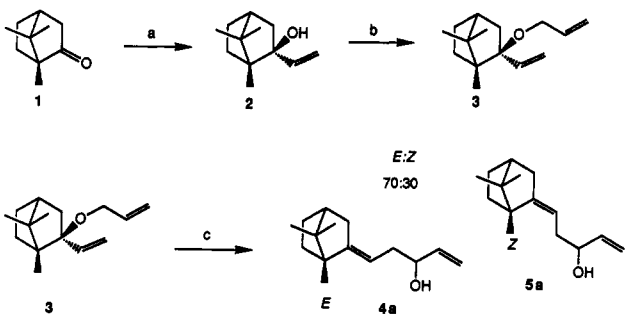

Figure 2. Conditions: (a) CH_2=$CHMgBr$, $CeCl_3$; (b) NaH, NaI, allyl bromide, DME; (c) *t*-BuOK, *t*-BuLi, THF/pentane, −85 °C.

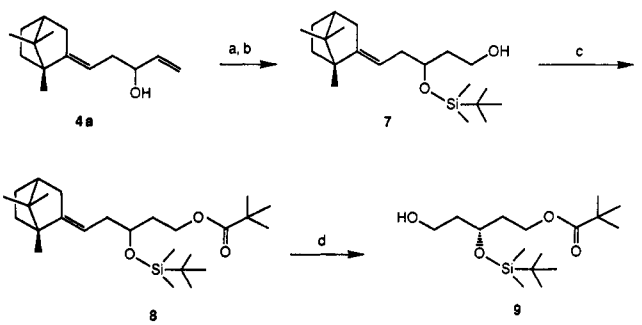

Figure 3. Conditions: (a) TBDMSCl, imidazole, DMF; (b) 9-BBN, THF, NaOH/HOOH; (c) pivaloyl chloride, pyridine; (d) O_3, CH_2Cl_2–MeOH–pyridine, $NaBH_4$.

bridgehead methyl group as would be expected for the *E* isomer (**4a**). Conversely, the irradiation of the bridgehead methyl resonance of the *Z* isomer (**5a**) resulted in an effect on the methylene signal at δ 2.44, thus, indicating a close spatial arrangement of the methylene and bridgehead methyl group as is expected for the *Z* isomer (**5a**).

The absolute configuration at the carbinol center of the *E* product (**4a**) was determined by a four-step conversion to the known compound (*R*)-3-(*tert*-butyldimethylsiloxy)-5-pivaloyl-1-pentanol (Figure 3).[8] The product alcohol **4a** was protected as the TBDMS ether[9] **6** and the terminal olefin was hydroborated with 9-BBN followed by oxidative workup with basic hydrogen peroxide to produce primary alcohol **7**.[10] Conversion to the pivalate ester[11] **8** and subsequent ozonolysis employing the sodium borohydride workup gave the known protected triol **9**.[8] This compound was identical by ^1H and ^{13}C NMR with that

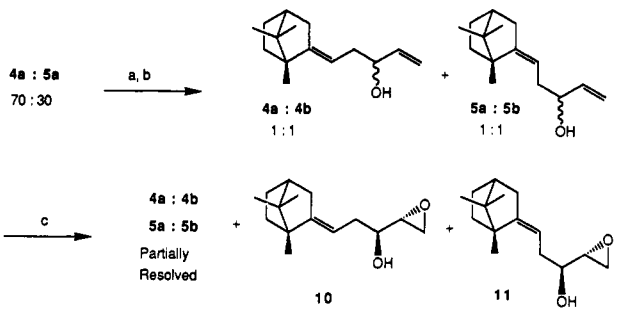

Figure 4. Conditions: (a) Dess–Martin oxidation;[13] (b) Luche reduction;[14] (c) Sharpless kinetic resolution.[12]

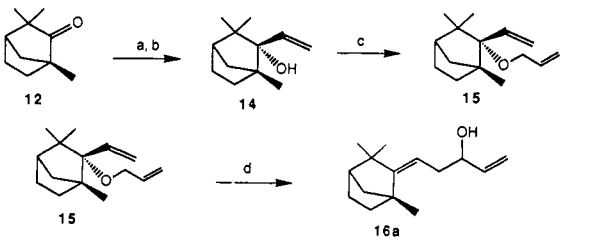

Figure 5. Conditions: (a) lithium acetylide, THF, −78 °C; (b) H_2, 5% $Pd/BaSO_4$, quinoline; (c) NaH, NaI, allyl bromide, DME; (d) *t*-BuOK, HMPA, *t*-BuLi, THF/pentane, −78 °C.

reported in the literature. The optical rotation indicated that the carbinol center was of the *R* configuration.

This assignment was confirmed by the Sharpless kinetic resolution[12] of an epimeric mixture of both the *Z* and *E* products (Figure 4). The epimeric mixture of alcohols was prepared by oxidation of the product mixture with Dess–Martin periodinane[13] followed by reduction with $NaBH_4$ in the presence of $CeCl_3$.[14] The four diastereomeric allylic alcohols were distinguishable in the 500-MHz ^1H NMR spectrum. The upfield methyl resonances for **4a** and **4b** were at δ 0.713 and 0.722, respectively. The corresponding resonances for **5a** and **5b** were δ 0.818 and 0.814. Comparison of the spectrum of the original product mixture with the spectra of the mixture of diastereomers (**4a**/**4b**, **5a**/**5b**) and the partially resolved mixture of these diastereomers demonstrated the faster disappearance of the methyl peaks corresponding to **4b** and **5a** than those of **4a** and **5b** under the Sharpless epoxidation conditions. From this analysis the configuration of the *E* isomer (**4a**) was judged to be *R*. This method also provided evidence that the configuration of the carbinol center of the *Z* isomer (**5a**) was *S*.

The addition of vinyl Grignard reagent to (−)-fenchone was slow, even in the presence of $CeCl_3$. An alternative route to the tertiary allyl alcohol employed the addition of lithium acetylide[15] to the optically active (−)-fenchone (**12**). The addition occurred to the less sterically hindered exo face of the ketone.[16] The endo propargyl alcohol **13** was then reduced to an allylic alcohol by catalytic hydrogenation (5% palladium on barium sulfate poisoned with quinoline) to yield **14**. The optically active bis-allyl ether **15** was prepared by the same methods as employed for the (+)-camphor-derived bis-allyl ether. However, the rearrangement of this substrate using conditions employed for

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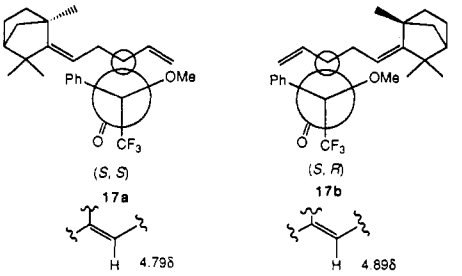

Figure 6. Mosher's ester configurational correlation model.

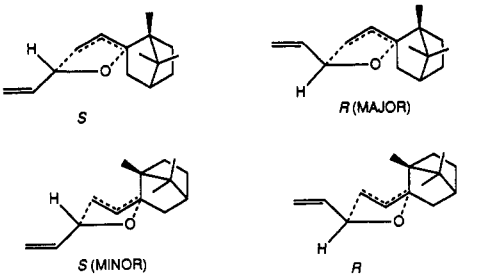

Figure 7. Transition-state models for the [2,3]-Wittig rearrangement.

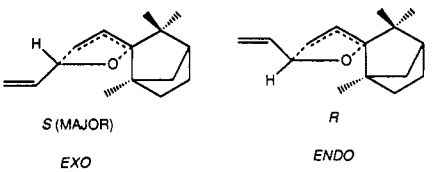

Figure 8. Transition-state models for the (−)-fenchone derivative.

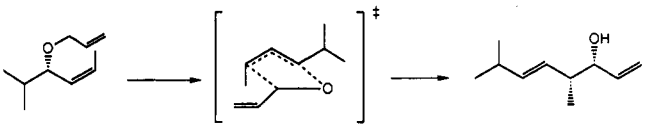

Figure 9. [2,3]-Wittig rearrangements of secondary allyl ether derivatives.

the (+)-camphor derivative did not provide a clean rearrangement product. Significant amounts of the parent allylic alcohol were obtained under these conditions. It was found that the undesirable cleavage could be significantly suppressed by using 5 equiv of HMPA in the reaction mixture.[5] The rearrangement provided a single product (**16a**) (Figure 5).

A mixture of the epimers (**16a** and **16b**) was prepared by the oxidation/reduction sequence employed for the rearrangement products of the (+)-camphor derivative. Both isomers were readily distinguished by a separate set of methyl resonances in the 500-MHz ^{1}H NMR spectrum. Comparison of the NMR spectrum of the product (**16a**) with that of the epimeric mixture of the rearrangement product (**16a**:**16b**, 1:1), indicated that the product was a single diastereomer (>95/5). A lanthanide shift reagent study using Eu(hfc)$_3$ on the mixture of epimers **16a**/**16b** produced two resonances for the carbinol proton. The complimentary experiment on the [2,3]-Wittig rearrangement product was unable to detect the presence of the minor diastereomer **16b**. Spiking the product sample with the epimeric mixture produced a downfield resonance that was only previously observed in the spectrum of the epimers with shift reagent. From these observations we have established that the product must be at least a 95:5 mixture of diastereomers.

The *Z* geometry of the trisubstituted double bond was established by NOE experiments. Irradiation of the upfield methyl resonance at δ 1.10 enhanced only the olefin resonance at δ 4.90, while irradiation of the downfield bridghead methyl resonances at δ 1.19 caused an NOE on the methylene resonance at δ 2.35 in accord with the *Z* designation.

The diastereomeric mixture of **16a** and **16b** was subjected to the Sharpless kinetic resolution process.[12] Isomer **16a** reacted faster than **16b**, indicating that the configuration of the carbinol center of **16a** was *S*. This observation was confirmed by the conversion of the [2,3]-Wittig product and the epimeric mixture of product alcohols to the corresponding α-methoxy-α-(trifluoromethyl)phenylacetate esters (**17a** and **17b**).[17] Although all the resonances for the protons on the side chain of the bicyclic terpene skeleton displayed differences in chemical shift in the spectrum of the mixture of epimers, the most striking of these was the difference observed for the vinyl resonance of the trisubstituted double bond. The upfield shift of 0.1 ppm for this vinyl proton resonance in the ^{1}H NMR spectrum of the minor diastereomer is consistent with the *S* configuration at the C-3 carbinol center using the model put forth by Mosher (Figure 6).[17]

An attempt was made to further confirm the assignment of the absolute configuration of the carbinol center by conversion of the product to (*S*)-3-(*tert*-butyldimethylsiloxy)-5-(pivaloyloxy)-1-pentanol.[8] Following the methodology employed for the product of the (+)-camphor derivatives, the desired product was not obtained from ozonolysis of the trisubstituted olefin. Despite the variety of workup conditions employed, only rearranged products were isolated. The inability to achieve cleavage of this trisubstituted double bond is a limiting factor in the synthetic utility of this substrate.

A bis-allyl ether derived from (−)-menthone was also prepared. Preliminary data on the rearrangement products of this substrate indicated the presence of two diastereomers in a 2:1 ratio. The stereochemistry of the products was not pursued due to the low selectivity observed.

The stereochemistry of the [2,3]-Wittig rearrangement is often rationalized on the basis of a simple five-membered cyclic transition-state model. For the tertiary bis-allyl ether derived from (+)-camphor, the model predicts (based on the relative energies as calculated by molecular mechanics[18]) that the rearrangement occurs via the endo transition state to yield a product (**4a**) of the *R* configuration. The exo transition state which leads to the product of the *S* configuration at the carbinol center is higher in energy due to an unfavorable 1,3 interaction between the allyl group and the methylene carbon of the bicyclic ring system (Figure 7).

Conversely, the rearrangement of the (−)-fenchone derivative yields only the product from the exo transition state (Figure 8). The simple cyclic transition-state model fails to predict the observed stereochemistry. Examination of models as well as MM2 calculations of the product indicated that the geometry of the newly formed trisubstituted double bond was the more sterically congested of the two possible olefin isomers that could be formed during the rearrangement. This suggested to us that developing steric interactions in the product were unimportant in determining the stereochemical outcome of the reaction. The reasons for this unexpected result are not clear at this

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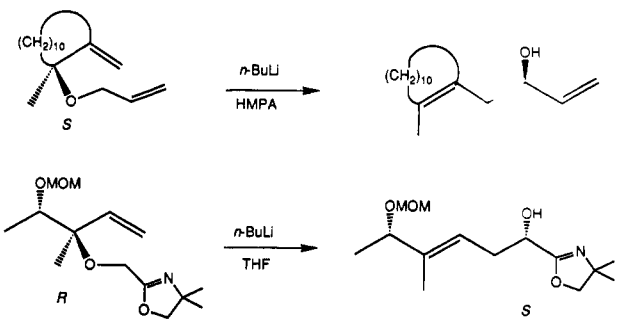

Figure 10. [2,3]-Wittig rearrangements of tertiary bis-allyl ethers.

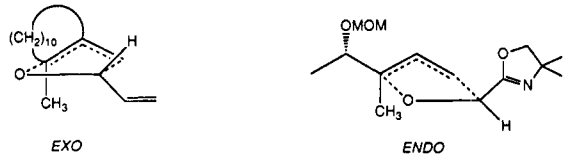

Figure 11. Transition-state models.

time. A more indepth study of the detailed mechanism of the reaction is needed to provide the information necessary for a rational explanation of these observations.

We have examined our transition-state model for a variety of [2,3]-Wittig rearrangements of bis-allyl ether derivatives to determine how well it predicts the observed results. For secondary allyl ether derivatives investigated by Nakai[19] and Midland,[3a] the major products corresponds to the exo transition-state model (Figure 9).

Two other examples of [2,3]-Wittig rearrangements of tertiary allylic ethers are shown in Figure 10. Examination of the transition-state models for the rearrangement of the exocyclic bis-allyl ether reported by Marshall[5] indicates that the major product of the rearrangement is predicted by the exo transition state (Figure 11). The major difference in this substrate is the 10-membered ring appended to the allyl component on which the rearrangement takes place. In this reaction there was a loss of optical activity during the rearrangement. Rearrangement of the alicyclic tertiary ethers reported by Kallmerten[20] occurs through the endo transition state. In this case the alkoxy substituent of the side chain may influence the observed stereochemistry of the products.[20] This complicating factor is not taken into account by the transition-state model.

For secondary allyl ether derivatives the exo transition states predict the major product for a majority of the examples that have been examined. Those derivatives in which the group activating the methylene protons toward deprotonation is an ester or a group that is a good π acceptor tend to rearrange via an endo transition state. While the few examples of tertiary ether derivatives show less uniformity in the preferred transition-state geometry leading to the major products, the reasons for the inconsistent stereochemical outcome of the rearrangements of tertiary bis allyl ether derivatives as well as some secondary allyl ether derivatives, with regard to the simple five-membered cyclic transition-state model are unclear.[21]

In summary, the [2,3]-Wittig rearrangement of the bis-allyl ether derivatives of (+)-camphor and (−)-fenchone have been performed successfully under the influence of the conditions described for each substrate. The (+)-camphor derivative gave two products in a 70/30 ratio, while the (−)-fenchone derivative provided only a single isomer, thus demonstrating the ability of the fenchyl skeleton to impart a high degree of stereochemical control to the [2,3]-Wittig rearrangement.

Simple models of the transition state of this sigmatropic rearrangement fail to completely explain the stereochemical outcome of all the examples investigated. The model does not take into account several factors that may have a strong influence on the course of the rearrangement. It ignores the structure of the base, the nature of the counter ion and effects due to the solvent. Further experiments to better understand the variety of influences that determine the stereochemical outcome of the [2,3]-Wittig rearrangement are currently being pursued in our laboratory.

Experimental Section

General. ^{1}H NMR spectral data were recorded on one of the following instruments: a JOEL FX-200 FT-NMR (200 MHz), a GE QE-300 FT-NMR (300 MHz), or a GE GN-500 FT-NMR (500 MHz) spectrometer. ^{13}C NMR spectra were recorded on the JOEL FX-200 (50 MHz) or the QE-300 (75 MHz) spectrometer. The IR spectra were recorded on a Nicolet 5-DX FT-IR spectrometer. Mass spectral data were obtained on a VG 7070E or a VG ZAB mass spectrometer.

Gas chromatography analysis was performed on a Hewlett-Packard 5880 equipped with a flame ionization detector and a 10-m methylsilicone capillary column or a 3-m Supelcowax 10 capillary column. Nitrogen was used as the carrier gas.

The ketones were purchased commercially from Fluka or Aldrich Chemical Co. Tetrahydrofuran (THF) and dimethoxyethane (DME) were dried by distillation from Na or K benzophenone ketyl under a nitrogen atmosphere.

6-*exo*-Hydroxy-6-*endo*-vinylbornane (2). Cerium(III) chloride heptahydrate was dried in vacuo by heating at 140 °C for 2 h as described in the procedure by Imamoto.[6] The dry cerium(III) chloride (13 mmol) was then stirred at room temperature in 30 mL of THF. The slurry was cooled to −78 °C and vinylmagnesium bromide (13 mmol of a 1 M solution in THF) was added dropwise to the cold stirring solution. After stirring for 1.5 h at −78 °C, solid (+)-camphor was added over 10 min, and the solution was stirred for 2 h before being warmed to room temperature. The reaction was stirred at room temperature for 2 h, quenched with water, extracted with petroleum ether solvent, and dried over $MgSO_4$. After concentrating under reduced pressure, distillation at 50 °C (0.005 mmHg) produced 1.71 g (95% yield) of the allylic alcohol as a colorless liquid: $[\alpha]^{25}_D$ −48.02°, $[\alpha]_{546}$ 57.08° (*c* 3.73, $CHCl_3$); ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.810 (s, 3 H), 0.847 (s, 3 H), 1.0 (s, 3 H), 1–2.2 (m, 8 H), 5.05 (d, J = 10.7 Hz, 1 H), 5.20 (d, J = 17.1 Hz, 1 H), 6.00 (dd, J = 10.7, 17.1 Hz, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 9.8, 20.8, 21.2, 26.6, 31.0, 44.8, 45.2, 49.0, 52.5, 81.5, 112.0, 114.0.

6-*endo*-Vinyl-6-*exo*-bornyl Allyl Ether (3). Allylic alcohol 2 (1.05 g, 5.83 mmol, in 10 mL of DME) was added dropwise to a stirring solution of sodium iodide (1.32 g, 8.8 mmol) and sodium hydride (1.2 g, 30 mmol) in 1,2-dimethoxyethane (DME, 50 mL). Allyl bromide (6.77 g, 56 mmol) was then added dropwise and the resulting slurry stirred at room temperature. Thin layer chromatography indicated the disappearance of all of the starting materials after 2 days. The reaction was quenched with 10 mL of a 1:1 methanol/water mixture. The organic layer was separated and washed with saturated NaCl solution. The combined organic extracts were dried over $MgSO_4$, filtered, and concentrated under reduced pressure. Kugelrohr distillation yielded 1.28 g (5.81 mmol, 99% yield) of ether 2: ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.859 (s, 3 H), 0.884 (s, 3 H), 1.067 (s, 3 H), 1.0–2.0 (m, 7 H), 3.664 (m, 2 H), 5.2 (m, 4 H), 5.8 (m, 2 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 10.16, 21.10, 21.20, 26.60, 31.17, 36.13, 45.6, 49.1, 53.11, 62.11, 86.83, 114.22, (2 C), 136.16, 139.95.

(*E*)- and (*Z*)-5-(6-Bornylidene)-1-penten-3-ol (4a and 5a). The bis-allylic ether 3 (0.23 g, 1.05 mmol) was added to a stirring solution of potassium *tert*-butoxide (0.499 g, 4.0 mmol) in THF (5 mL) at −85 °C (dry ice/ether bath). *tert*-Butyllithium (1.0 equiv of 1.7 M in pentane, 0.59 mL) was added via a syringe pump over 1 h. The dark orange solution was stirred for 6 h and then a second

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equivalent of *tert*-butyllithium was added. After stirring for an additional 6 h, a third and final equivalent was added. The solution was stirred overnight, while the cold bath was slowly warmed to room temperature. The reaction was quenched with methanol, distilled with ether, and washed with water and saturated NaCl solution. The ethereal solution was directed over $MgSO_4$ and evaporated in vacuo to give a yellow oil (0.226 g, 97.8% yield). By capillary GC the product was a mixture of three components, which were determined to be the *E* product (68%), the *Z* product (28%), and the parent allylic alcohol (4%). The [2,3]-Wittig rearrangement products were isolated by flash chromatography (Fluka silica gel (60–200 mesh), 20% ethyl acetate in hexanes) to provide a 92% yield of products.

The geometry of the *E* and *Z* trisubstituted olefin products was determined by NOE (nuclear Overhauser effect) experiments. The experiments involved the selective irradiation of the methyl group resonances of both isomers obtained from the reaction. For the major product there was a large effect on the olefin resonance at 5.04 ppm upon irradiation of the bridghead methyl peak. This isomer was assigned the *E* configuration. The minor component exhibited an effect on the methylene resonance at 2.44 ppm when the bridgehead methyl group was irradiated. Thus, it was assigned the *Z* olefin geometry.

(*E*)-5-(6-Bornylidene)-1-penten-3-ol (4a): ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.718 (s, 3 H), 0.881 (s, 3 H), 0.906 (s, 3 H), 1.0–1.9 (m, 7 H), 1.4 (br, 1 H), 2.18–2.29 (m, 2 H), 4.15 (dt, J = 5.86, 5.88 Hz, 1 H), 5.04 (tt, J = 7.34, 2.5 Hz, 1 H), 5.095 (dt, J = 7.34, 1.5 Hz, 1 H), 5.23 (dt, J = 17.1, 1.5 Hz, 1 H), 5.88 (ddd, J = 17.1, 10.3, 5.9 Hz, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 12.83, 18.87, 19.64, 27.96, 34.92, 35.36, 36.43, 44.60, 47.37, 51.26, 72.67, 110.52, 114.36, 140.73, 153.87; IR (neat, NaCl, cm^{-1}) 3361 (br), 3078, 2900; HRMS (EI, 20 eV) mass calcd for $C_{15}H_{24}O$ 220.1827, found 220.1818.

(*Z*)-5-(6-Bornylidene)-1-penten-3-ol (5a): $[\alpha]^{25}_D$ −68.83° (*c* 4.54, $CDCl_3$); ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.82 (s, 3 H), 0.842 (s, 3 H), 1.153 (s, 3 H), 1.0–2.0 (m, 7 H), 2.30 (br, 1 H), 2.44 (m, 2 H), 4.095 (dt, J = 12.2, 6.3 Hz, 1 H), 5.06 (tt, J = 7.6, 2.0 Hz, 1 H), 5.11 (dt, J = 10.3, 1.4 Hz, 1 H), 5.24 (dt, J = 17.2, 1.4 Hz, 1 H), 5.892 (ddd, J = 17.2, 10.5, 5.8 Hz, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 15.41, 18.72, 19.98, 28.11, 35.06, 35.74, 38.96, 44.45, 48.64, 52.09, 73.16, 114.41, 114.75, 140.73, 150.51; HRMS (EI 20 EV) mass calcd for $C_{15}H_{24}O$ 220.1827, found 220.1818.

1-(6-Bornylidene)-3-(*tert*-butyldimethylsiloxy)-4-pentene (6). The rearrangement products **4a** (0.194 g, 0.881 mmol) were placed in a 10-mL round-bottomed flask purged with nitrogen and equipped with a magnetic stir bar. Solid *tert*-butyldimethylsilyl chloride (0.159 g, 1.06 mmol) and imidazole (0.150 g, 2.20 mmol) were added, followed by DMF (dimethyl formamide, 0.338 mL, 5.0 mmol). The solution was stirred for 16 h at room temperature and then quenched with water. The solution was extracted three times with petroleum ether solvent. The organic layers were combined, dried over $MgSO_4$, and concentrated to provide a clear liquid (0.286 g, 0.855 mmol) in 97% yield: ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.067 (s, 3 H), 0.084 (s, 3 H), 0.737 (s, 3 H), 0.896 (s, 3 H), 0.913 (s, 3 H), 0.928 (s, 9 H), 1.0–2.4 (m, 7 H), 2.15 (dd, J = 7.37 Hz, 2 H), 4.1 (dt, J = 5.86, 6.36 Hz, 1 H), 4.9–5.3 (m, 3 H), 5.82 (m, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ −4.8, −4.5, 12.88, 18.92, 19.64, 25.72, 25.92, (3 C), 28.01, 34.82, 36.16, 37.55, 44.70, 47.37, 50.97, 74.03, 111.98, 113.15, 141.66, 151.14.

5-(6-Bornylidene)-3-(*tert*-butyldimethylsiloxy)pentan-1-ol (7). 1-(6-Bornylidene)-3-(*tert*-butyldimethylsiloxy)-4-pentene (**6**) (0.281 g, 0.84 mmol) and 5 mL of THF were placed in a 25-mL round-bottomed flask equipped with a magnetic stir bar. The solution was cooled to 0 °C and 1.1 equiv of 9-BBN (0.92 mmol, 1.8 mL) was slowly added to the stirred solution. The solution was warmed to room temperature and stirred for 5 h. Thin layer chromatography indicated no reaction at this point. One additional equivalent of 9-BBN was added to give a total of 2.1 equiv. After stirring overnight, 0.583 mL of 3 N NaOH (1.75 mmol) and 0.583 mL of 30% H_2O_2 were added to oxidize the borane. After being stirred for 12 h, the solution was extracted twice with 20-mL portions of petroleum ether solvent and the organic layer washed once with 10 mL of water. The organic layer was dried with $MgSO_4$ and concentrated. The material was purified by flash chromatography (Fluka silica gel 60–200 mesh, 20% ethyl acetate in hexanes) followed by HPLC to give 0.249 g of a yellow liquid (84% yield): $[\alpha]^{25}_D$ −49.27° (*c* 7.59, $CHCl_3$); ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.098 (s, 6 H), 0.690 (s, 3 H), 0.877 (s, 6 H), 0.899 (s, 9 H), 1.0–2.0 (m, 9 H), 2.18 (t, J = 7.34 Hz, 2 H), 2.65 (br, 1 H), 3.6–4.0 (m, 3 H), 4.97 (t, J = 7.34, 2.44 Hz, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ −4.81, −4.37, 12.79, 18.86, 19.59, 25.79 (3 C), 27.98, 31.56, 34.85, 35.07, 36.24, 37.63, 44.64, 47.34, 50.99, 60.34, 72.32, 111.55, 151.58.

1-(6-Bornylidene)-3-(*tert*-butyldimethylsiloxy)-5-(pivaloyloxy)pentane (8). To a 25-mL round-bottomed flask equipped with a reflux condenser and a magnetic stir bar were added alcohol **7** (0.130 g, 0.389 mmol), pyridine (6 mL), pivaloyl chloride (0.0704 g, 0.584 mmol), and 10 mL of THF. The contents were stirred for 2 h at room temperature and then refluxed overnight. Analysis indicated the presence of starting material so an additional equivalent of the acid chloride was added and reflux was continued for 6 h. The reaction was quenched with water and extracted three times with ether. The ether extracts were combined, dried over $MgSO_4$, and concentrated by rotary evaporation to give 0.216 g (0.494 mmol, 70.1% yield) of product: ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.017 (s, 6 H), 0.705 (s, 3 H), 0.879 (s, 6 H), 0.900 (s, 9 H), 1.19 (s, 9 H), 1.0–2.0 (m, 9 H), 2.12 (t, J = 7.34 Hz, 2 H), 3.78 (m, 1 H), 4.0–4.2 (m, 2 H), 5.02 (tt, J = 7.34, 2.44 Hz, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ −4.74, −4.30, 12.79, 18.86, 19.58, 25.87, (3 C), 27.18 (3 C), 27.99, 29.66, 34.85, 35.14, 35.73, 36.82, 38.60, 44.64, 47.34, 50.99, 61.36, 69.48, 111.69, 151.6, 179.0; MS (CI) 437 (MH$^+$), 379, 305, 203, 171, 132, 93, 57.

(*R*)-3-(*tert*-Butyldimethylsiloxy)-5-(pivaloyloxy)-1-pentanol (9). The protected diol **8** (216 mg, 0.495 mmol) was placed in 6 mL of CH_2Cl_2, 2 mL of MeOH, and 1 mL of pyridine. The solution was placed in the ozonolysis apparatus and cooled to −78 °C. The solution was flushed with nitrogen for 8 min before ozone was allowed to bubble through the solution. A blue color appeared after 2 min, signifying excess ozone. The ozone flow was continued for approximately 2 min and then nitrogen was bubbled through for 2 min. Sodium borohydride (2.5 equiv, 46.8 mg, 1.24 mmol) was added and the solution stirred for 2 h before the dry ice/acetone bath was removed. The solution was stirred at room temperature for 2 h, diluted with water, and stirred for an additional 2 h. The solution was extracted three times with ether. The combined ether layers were dried with $MgSO_4$ and concentrated. The material was first purified by flash chromatography (Fluka silica gel 60–200 mesh, 30% ethyl acetate in hexanes) and then HPLC to give 0.0373 g (0.116 mmol, 23.5% yield) of product: $[\alpha]^{25}_D$ −4.55 (*c* 3.73, $CHCl_3$) (lit.[9] $[\alpha]_D$ = −4.4°); $[\alpha]_{546}$ = 5.094°; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.086 (s, 3 H), 0.108 (s, 3 H), 0.903 (s, 9 H), 1.20 (s, 9 H), 1.60 (br, 1 H), 1.68 (m, 1 H), 1.85 (m, 3 H), 3.73 (dt, J = 5.5, 10.9 Hz, 1 H), 3.83 (ddd, J = 4.7, 8.2, 11.0 Hz, 1 H), 4.06 (m, 2 H), 4.165 (dt, J = 6.3, 11.2 Hz, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ −4.66 (2 C), 17.92, 25.76 (3 C), 27.15, (3 C), 35.69, 38.41, 38.66, 59.73, 61.06, 68.21, 178.4; IR (CCl_4, NaCl cell, cm^{-1}) 3529, 2960, 2932, 2895, 2859, 1729, 1158; MS (CI) *m/e* 319 (MH$^+$), 261, 187; (EI) *m/e* 261, 231, 159, 131, 105, 75.

(*E*)- and (*Z*)-1-(6-Bornylidene)-4-penten-3-one (18). Dess–Martin periodinane reagent[13] (1.1 equiv, 85 mg) was added to a mixture of *E* and *Z* alcohols **4** and **5** (40 mg, 0.18 mmol) in deuteriochloroform in an NMR tube. The tube was shaken intermittently over a half-hour period. The appearance of the methylene resonance at 3.2 ppm and the disappearance of the carbinol proton resonance in the ^{1}H NMR were used to monitor the progress of the reaction. Upon completion, the reaction was quenched by addition of the contents of the NMR tube to methylene chloride (10 mL), and the solution was washed with 1.3 M NaOH (2 × 2 mL). The organic layer was washed with water, dried, and concentrated under reduced pressure to give 35 mg (0.16 mmol, 88.9% yield) of ketone. *E* isomer: ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.717, (s, 3 H), 0.886 (s, 3 H), 0.906 (s, 3 H), 1.0–2.5 (m, 7 H), 3.2 (d, 2 H), 5.2 (m, 1 H), 5.8 (dd, 1 H), 6.3 (m, 2 H). *Z* isomer: ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 0.820, (s, 3 H), 0.842 (s, 3 H), 1.153 (s, 3 H), 1.0–2.5 (m, 7 H), 3.2 (d, 2 H), 5.2 (m, 1 H), 5.8 (dd, 1 H), 6.3 (m, 2 H). Coupling constants were not measured.

(*E* and *Z*),(*R* and *S*)-5-(6-Bornylidene)-1-penten-3-ol (4a/4b:5a/5b, 70:30). Sodium borohydride (6.1 mg, 0.16 mmol) was added to a stirring solution of cerium(III) chloride heptahydrate (0.4 mL of a 0.4 M solution in methanol) and ketone **18** (0.16 mmol) in a 5-mL round-bottomed flask. After 10 min, the reaction was quenched with water and extracted with ether. The

ether layer was dried over $MgSO_4$ and concentrated under reduced pressure. All material was recovered as the alcohol. The product was a 70:30 mixture of *E* and *Z* isomers, and a 1:1 epimeric mixture at the carbinol center. *E,R* isomer **4a**: ^1H NMR (500 MHz, $CDCl_3$) δ 0.713 (s, 3 H), 0.880 (s, 3 H), 0.902 (s, 3 H), 1.0–1.9 (m, 5 H), 1.4 (br, 1 H), 2.18–2.29 (m, 2 H), 2.25–2.40 (m, 2 H), 4.15 (dt, J = 5.86, 5.88 Hz, 1 H), 5.04 (tt, J = 7.34, 2.5 Hz, 1 H), 5.095 (dt, J = 7.34, 1.5 Hz, 1 H), 5.23 (dt, J = 17.1, 1.5 Hz, 1 H), 5.88 (ddd, J = 17.1, 10.3, 5.9 Hz, 1 H). *E,S* isomer **4b**: ^1H NMR (500 MHz, $CDCl_3$) δ 0.722 (s, 3 H), 0.880 (s, 3 H), 0.902 (s, 3 H), 1.0–1.9 (m, 5 H), 1.4 (br, 1 H), 2.18–2.229 (m, 2 H), 2.25–2.40 (m, 2 H), 4.15 (dt, J = 5.86, 5.88 Hz, 1 H), 5.04 (tt, J = 7.34, 2.5 Hz, 1 H), 5.095 (dt, J = 7.34, 1.5 Hz, 1 H), 5.23 (dt, J = 17.1, 1.5 Hz, 1 H), 5.88 (ddd, J = 17.1, 10.3, 5.9 Hz, 1 H). *Z,S* isomer **5a**: ^1H NMR (500 MHz, $CDCl_3$) δ 0.818 (s, 3 H), 0.837 (s, 3 H), 1.08 (s, 3 H), 1.0–2.0 (m, 6 H), 2.3 (br, 2 H), 2.44 (m, 2 H), 4.095 (dt, J = 12.2, 6.3 Hz, 1 H), 5.06 (tt, J = 7.6, 2.0 Hz, 1 H), 5.11 (dt, J = 10.3, 1.4 Hz, 1 H), 5.24 (dt, J = 17.2, 1.4 Hz, 1 H), 5.89 (ddd, J = 17.1, 10.3, 5.9 Hz, 1 H). *Z,R* isomer **5b**: ^1H NMR (500 MHz, $CDCl_3$) δ 0.814 (s, 3 H), 0.837 (s, 3 H), 1.08 (s, 3 H), 1.0–2.0 (m, 6 H), 2.3 (br, 2 H), 2.44 (m, 2 H), 4.095 (dt, J = 12.2, 6.3 Hz, 1 H), 5.06 (tt, J = 7.6, 2.0 Hz, 1 H), 5.11 (dt, J = 10.3, 1.4 Hz, 1 H), 5.24 (dt, J = 17.2, 1.4 Hz, 1 H), 5.89 (ddd, J = 17.1, 10.3, 5.9 Hz, 1 H).

1-(6-Bornylidene)-4,5-epoxypentan-3-ol (10 and 11). A 70:30 *E* to *Z* ratio of epimeric allylic alcohols **4** and **5** (0.100 g, 0.454 mmol), titanium(IV) isopropoxide (0.129 g, 0.454 mmol), diisopropyl L-(+)-tartrate (0.128 g, 0.546 mmol), and 5 mL of dry dichloromethane (distilled from calcium hydride) was stirred at −20 °C. After 10 min 0.8 equiv of anhydrous *tert*-butyl hydroperoxide (TBHP, 0.363 mmol, 0.0874 mL of a 4.155 M solution) was added dropwise. The resulting solution was placed in a freezer at −18 °C. The reaction was monitored by GC. After 7 days, two more equivalents of TBHP (at −18 °C) were added. A new longer retention peak slowly grew. After 3 weeks, the reaction was stopped by pouring the solution into a precooled (−20 °C) solution consisting of 10 mL of reagent grade acetone and 0.135 mL of water. The mixture was stirred and allowed to warm to room temperature. The solution was filtered, concentrated, and extracted with water. The organic layer was dried over $MgSO_4$ and concentrated. The remaining oil was purified by HPLC. Capillary GC analysis indicated the epoxide peak to be 46% of the product mixture and a 70:30 *E* to *Z* olefin mixture. *E* isomer **10**: ^1H NMR (199.5 MHz, $CDCl_3$) δ 0.73 (s, 3 H), 0.89 (s, 3 H), 0.92 (s, 3 H), 0.75–2.0 (m, 8 H), 2.3 (dd, J = 8.3 Hz, 2 H), 2.7–2.9 (m, 2 H), 3.0–3.1 (m, 1 H), 3.8 (br, 1 H), 5.1 (m, 1 H). *Z* isomer **11**: ^1H NMR (199.5 MHz, $CDCl_3$) δ 0.82 (s, 3 H), 0.85 (s, 3 H), 1.2 (s, 3 H), 0.75–2.0 (m, 8 H), 2.3 (dd, J = 8.3 Hz, 2 H), 2.7–2.9 (m, 2 H), 3.0–3.1 (m, 1 H), 3.8 (br, 1 H), 5.1 (m, 1 H).

Synthesis of 2-*exo*-Ethynyl-1,3,3-trimethyl-2-*endo*-norbornanol (13). An oven-dried, 500-mL, septum-capped, round-bottomed flask was flushed with nitrogen, charged with 70 mL of THF, and cooled to −78 °C. After the apparatus cooled, 157 mL of a 2.1 M solution of *n*-butyllithium (0.330 mol) was added by using a 50-mL syringe. The contents were mixed by swirling the flask and kept at −78 °C until needed. An oven-dried, 2-L, round-bottomed flask equipped with a magnetic stir bar and capped with a septum was cooled under a nitrogen purge. The flask was charged with 500 mL of THF and cooled to −78 °C. A 100-mL graduated cylinder was fitted with a septum in which an 8-mm hole was bored. A 9-mm glass tube that could be connected to either a nitrogen or acetylene line through a three-way valve was inserted through the septum of the graduated cylinder. A double-ended needle was used to connect the cylinder to the 2-L reaction flask. After the cylinder and reaction flask were thoroughly purged with nitrogen, 70 mL of THF was introduced into the cylinder, and the cylinder cooled to −78 °C. Acetylene was introduced through the 9-mm tube into the bottom of the graduated cylinder at such a rate that 30 mL was added in 20 min. Excess acetylene that did not dissolve in the THF was directed through a double-ended needle into the 2-L reaction flask. The cold acetylene solution was transferred by the double-ended needle to the 2-L reaction flask. While the solution was cooling in the −78 °C bath, nitrogen was blown over the surface to completely purge the system of acetylene gas. The precooled *n*-butyllithium/THF solution was slowly added by double-ended needle over a period of 1 h. The clear solution of lithium acetylide was stirred for an additional 15 min at −78 °C before 48.4 mL of (−)-fenchone (0.3 mol) was slowly added via syringe. The solution immediately became yellow. After addition, the cold bath was removed and the mixture was stirred for 3 h while warming to room temperature. The flask was opened to the atmosphere and 400 mL of 1.0 M HCl was added. The quenched reaction was stirred for 20 min and transferred to a 2-L separatory funnel. The aqueous material was separated and 200 mL of pentane added. The organic layer was sequentially washed with 100 mL of 1.0 M HCl, 300 mL of water, and finally, 100 mL of brine. The combined aqueous materials were extracted with 200 mL of ether. The organic extracts were combined, dried over magnesium sulfate, and filtered. Concentration (rotary evaporation, 40 °C under aspirator pressure) provided a thick yellow oil, which was distilled to obtain 48.2 g (90%) of the alcohol as a pale yellow oil (bp 51–50 °C/0.05 mmHg): $[\alpha]^{25}_D$ +20.4° (*c* 9.0, $CHCl_3$); IR (neat film/NaCl plates, cm^{-1}) 3490, 2110, 1460, 1060; ^1H NMR (199.5 MHz, $CDCl_3$) δ 0.93 (s, 3 H), 1.11 (s, 3 H), 1.17 (s, 3 H), 1.0–1.15 (m, 2 H), 1.20–1.95 (m, 5 H), 1.99 (br, 1 H), 2.53 (s, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 17.84, 21.54, 25.77, 27.08, 29.81, 40.95, 42.90, 48.40, 53.06, 74.86, 80.45, 85.61; HRMS (EI, −70 eV) mass calcd for $C_{12}H_{18}O$ 178.1357, found 178.1355. The product is a 97:3 mixture of endo/exo addition products based upon capillary GC analysis.

Synthesis of 2-*exo*-Vinyl-1,3,3-trimethyl-2-*endo*-norbornanol (14). A suspension of catalyst (1 g of 5% Pd on $BaSO_4$) in methanol (50 mL) was stirred rapidly under an atmosphere of hydrogen gas in a 250-mL, round-bottomed flask equipped with a septum-capped side arm. A solution of 1-methyl-2-ethynyl-*endo*-3,3-dimethyl-2-norbornanol (**13**) (5 g, 28 mmol) in methanol (10 mL) containing 10 drops of quinoline was added rapidly by syringe to the stirred suspension. Hydrogen uptake was monitored with a gas measuring buret. The reaction mixture was removed from the hydrogen atmosphere when the rate of reaction abruptly slowed down (636 mL of H_2 uptake observed, theoretical H_2 uptake 702 mL). The catalyst was removed by filtration and the methanol solution of product was diluted with 150 mL of ether. The ether solution was washed twice with 3 M HCl (20 mL) and saturated NaCl solution (20 mL). Drying ($MgSO_4$) and evaporation of solvent provided 4.62 g (91.3% yield) of product as a colorless oil: $[\alpha]^{25}_D$ −19.47° (*c* 8.7, $CDCl_3$); ^1H NMR (199.5 MHz, $CHCl_3$) δ 0.85 (s, 3 H), 0.89 (s, 3 H), 0.92 (s, 3 H), 0.90–2.1 (m, 8 H), 5.05 (d, J = 10.3 Hz, 1 H), 5.21 (d, J = 17.1 Hz, 1 H), 6.0 (dd, J = 17.1, 10.3 Hz, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 17.21, 21.88, 25.52, 28.64, 29.22, 40.66, 44.40, 48.44, 52.14, 82.45, 110.08, 142.82; IR (thin film/NaCl plates cm^{-1}) 3502, 2959, 2933, 2871, 1457; HRMS (EI, −70 eV) mass calcd for $C_{12}H_{20}O$ 180.1514, found 180.1511.

2-*exo*-Vinyl-1,3,3-trimethyl-2-*endo*-norbornyl Allyl Ether (15). A suspension of NaH (100 mmol) and NaI (26.5 mmol) in 100 mL of DME was stirred rapidly at room temperature. A solution of 1-methyl-2-vinyl-*endo*-3,3-dimethyl-2-norbornanol (**14**) (4.39 g, 24.4 mmol) in DME (10 mL) was added dropwise to the reaction mixture. Then, allyl bromide (15 mL, 173 mmol) was added and the reaction was stirred overnight (12 h). The reaction was quenched by the slow addition of water (3 mL). The two-phase mixture was diluted with ether (100 mL) and the aqueous layer was removed. The ether solution was washed with dilute HCl, sodium sulfite solution, and saturated NaCl solution. Drying and evaporation of excess solvent gave 4.5 g (84% yield) of crude product. The product was purified by flash vacuum chromatography (silica gel 60–230 mesh, Fluka, eluted with hexanes). A 4.1-g (77% yield) quantity of product was recovered as a colorless oil: $[\alpha]^{25}_D$ −23.88° (*c* 10.2, $CHCl_3$); ^1H NMR (199.5 MHz, $CDCl_3$) δ 0.85 (s, 3 H), 0.98 (s, 3 H), 1.15 (s, 3 H), 0.80–2.0 (m, 7 H), 3.83 (dddd, J = 13.7, 3.8, 1.6, 1.6 Hz, 1 H), 3.95 (dddd, J = 13.7, 3.8, 1.6, 1.6 Hz, 1 H), 5.05 (dd, J = 11.2, 1.6 Hz, 1 H), 5.07 (dq, J = 17.5, 2.5 Hz, 1 H), 5.16 (dd, J = 10.8, 2.5 Hz, 1 H), 5.35 (dq, J = 16.7, 1.6 Hz, 1 H), 5.64 (dd, J = 17.5, 10.8 Hz, 1 H), 5.89 (m, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 19.69, 22.22, 26.06, 28.93, 29.81, 43.38, 47.47, 47.91, 51.85, 65.47, 87.27, 112.98, 113.68, 136.86, 137.88; HRMS (EI, −70 eV) mass calcd for $C_{15}H_{24}O$ 220.1827, found 220.1820.

(−)-1-(1,3,3-Trimethyl-2-norbornylidene)-5-penten-3-ol (16a). 1-Methyl-2-vinyl-*endo*-3,3-dimethyl-2-norbornyl allyl ether (**15**) (1.79 g, 8.14 mmol) was dissolved in 10 mL of THF and added

by syringe to a THF (15 mL) solution of *t*-BuOK (3.70 g, 32.5 mmol) at −78 °C. A 5.8-mL quantity of HMPA (32.5 mmol) was added to the reaction mixture followed by the sequential addition of 3 equiv of 1.82 M *t*-BuLi in pentane (24.4 mmol). The reaction was quenched at −78 °C with methanol (8 mL) and diluted with ether (100 mL). The ether solution was washed with water, 1 M HCl, and saturated NaCl solution. Drying and evaporation in vacuo yielded 1.76 g of crude product, which still contained some HMPA. Purification of the crude product by flash chromatography (Fluka silica gel, solvent gradient from 0 to 15% ethyl acetate in hexanes) yielded 1.32 g (74% yield) of product as a colorless oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.136 (s, 3 H), 1.139 (s, 3 H), 1.19 (s, 3 H), 1.3–1.8 (m, 8 H), 2.35 (t, J = 8 Hz, 2 H), 4.1 (m, 1 H), 4.9 (t, J = 8 Hz, 1 H), 5.20 (d, J = 11 Hz, 1 H), 5.30 (d, J = 15 Hz, 1 H), 5.89 (m, 1 H); ^{13}C NMR (49 MHz, $CDCl_3$) δ 19.20, 25.57 (2 C), 27.42, 36.03, 36.13, 42.45, 44.01, 49.65, 50.68, 73.20, 109.95, 114.46, 140.78, 160.63; HRMS (EI, −70 eV) mass calcd for $C_{15}H_{24}O$ 220.1827, found 220.1821.

Synthesis of (*E*)-1-(1,3,3-Trimethyl-2-norbornylidene)-5-penten-3-one (19). To a rapidly stirring solution of allyl alcohol **16a** (0.676 g, 3.07 mmol) in $CHCl_3$ (10 mL) was added 1.63 g (3.83 mmol) of the Dess–Martin periodinane. The reaction was monitored by TLC. The reaction was complete in 1.5 h. The reaction mixture was quenched with 10 mL of 1 N NaOH solution for 10 min. The organic layer was removed and the aqueous layer was extracted twice with hexanes (10 mL). The combined organic extracts were washed with water (10 mL), dried over magnesium sulfate, filtered, and evaporated to yield 0.478 g (71%) of ketone **19**: ^{1}H NMR (199.5 MHz, $CDCl_3$) δ 1.05 (s, 3 H), 1.10 (s, 3 H), 1.15 (s, 3 H), 1.2–1.8 (m, 7 H), 3.4 (d, J = 7.3 Hz, 2 H), 5.15 (t, J = 7.3 Hz, 1 H), 5.8 (dd, J = 10.3, 1.95 Hz, 1 H), 6.3 (m, 2 H).

Synthesis of the C-3 Epimers of (−)-1-(1,3,3-Trimethyl-2-norbornylidene)-5-penten-3-ol (16a and 16b). Ketone **19** (4.78 g, 2.2 mmol) was dissolved in 5.5 mL of 0.4 M $CeCl_3.7H_2O$ in methanol. Sodium borohydride (0.083 g, 2.2 mmol) was added slowly (2 min) with rapid stirring of the reaction mixture. The mixture was stirred for 10 min after addition of $NaBH_4$ was complete. The reaction was then quenched with water and extracted with ether. The ether extracts were dried over magnesium sulfate, filtered, and evaporated under reduced pressure to yield 0.346 g (72%) of product as a colorless oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.121 (s, 3 H, **16b**), 1.138 (s, 3 H), 1.140 (s, 3 H), 1.191 (s, 3 H), 1.207 (s, 3 H, **16b**), 1.3–1.8 (m, 8 H), 2.35 (t, J = 8 Hz, 2 H), 4.1 (m, 1 H), 4.9 (t, J = 8 Hz, 2 H), 5.10 (d, J = 11 Hz, 1 H), 5.30 (d, J = 15 Hz, 1 H), 5.89 (m, 1 H).

Kinetic Resolution by Sharpless Epoxidation of the Epimeric Allylic Alcohol (16a and 16b). Activated 4-Å molecular sieves (30 mg, powdered) and titanium(IV) isopropoxide (13.4 μL, 0.045 mmol) were added to a cooled (−20 °C) solution of epimeric (50/50) allylic alcohol **16a**/**16b** (100 mg, 0.45 mmol) and (+)-diisopropyl tartrate (15.9 mg, 0.068 mmol) in methylene chloride (1.8 mL) containing 8 μL of *n*-decane as an internal standard. The solution was stirred for 30 min at −20 °C. Then, a 2.79 M solution of *tert*-butyl hydroperoxide in isooctane (113 μL, 0.315 mmol) was added, and the temperature was maintained at −20 °C for 7 h (25% conversion). The reaction was quenched by the addition of a solution of citric acid at −20 °C. The solution was warmed to room temperature while being stirred rapidly for 20 min. The two-phase mixture was separated and the aqueous layer was extracted with methylene chloride. The combined extracts were dried over sodium sulfate, filtered, and concentrated to provide 67 mg of crude product mixture. The mixture of products obtained was separated by HPLC (Whatman M-9 column, 10% ethyl acetate in hexanes). Analysis of the ^{1}H NMR (300 MHz) spectra of the recovered starting material indicated that the methyl resonances corresponding to the isomer obtained from the [2,3]-Wittig rearrangement (δ 1.191, 1.140, and 1.37) were diminished with respect to the methyl resonances corresponding to the isomer formed from the Dess–Martin oxidation/Luche reduction of the [2,3]-Wittig product (δ 1.207, 1.138, and 1.121). Epoxide product **20**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.14 (s, 6 H), 1.19 (s, 3 H), 1.25–1.90 (m, 8 H), 2.43 (t, J = 6 Hz, 2 H), 2.74 (m, 1 H), 2.82 (m, J, 1 H), 3.04 (m, 1 H), 3.81 (m, 1 H), 4.97 (t, J = 6 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.16, 25.48 (2 C), 27.30, 32.58, 35.85, 42.37, 43.66, 43.88, 49.54, 50.62, 54.16, 69.04, 109.16, 160.34.

3-[(α-Methoxy-α-(trifluoromethyl)phenylacetyl)oxy]-5-(1,3,3-trimethyl-2-norbornylidene)-1-pentene (17a and 17b). To a solution of (−)-(*S*)-MTPA chloride (26 mL, 0.14 mmol) and dry pyridine (300 μL) in carbon tetrachloride (300 μL) was added the allylic alcohol **16** (22 mg, 0.10 mmol). The reaction vial was shaken for a few minutes and left standing overnight. The excess acid chloride was quenched by addition of 3-(dimethylamino)-1-propylamine (24 μL, 20 mmol). The reaction mixture was shaken periodically for 5 min and then diluted with ether. The ether solution was washed with cold dilute HCl, cold saturated Na_2CO_3 solution, and saturated NaCl solution. Drying with $MgSO_4$ and evaporation of the excess solvent gave an oil, which was purified by HPLC (Whatman M-9 column, 10% ethyl acetate in hexanes). Both the allylic alcohol **17a** and the diastereomeric mixture of allylic alcohols (**17a** and **17b**) were converted to the corresponding (−)-MTPA esters in the manner described above. Inspection of the ^{1}H NMR spectra of these derivatives revealed that the resonance for the vinyl proton of the trisubstituted double bond of each of the diastereomers was a distinct triplet. The spectrum of the ester derived from the diastereomeric mixture of allylic alcohols (**17a** and **17b**) contains two triplet resonances at δ 4.79 and 4.89, whereas the spectrum of the ester derived from the allylic alcohol product of the [2,3]-Wittig rearrangement contains predominantly the resonance at δ 4.79. This upfield shift in this resonance for the major isomer implies that the configuration of the carbinol center is *S* according to the correlation model proposed by Mosher.[17] (C-3 mixture of diastereomers (**17a** and **17b**): ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.040 (s, 3 H), 1.064 (s, 3 H), 1.107 (s, 3 H, **17b**), 1.113 (s, 3 H), 1.155 (s, 3 H, **17b**), 1.179 (s, 3 H, **17b**), 1.1–1.8 (m, 7 H), 2.48 (m, 2 H), 3.55 (s, 3 H), 4.79 (t, J = 7.3 Hz, 1 H), 4.89 (t, J = 7.3 Hz, 1 H, **17b**), 5.355 (m, 3 H), 5.87 (m, 1 H), 7.41 (m, 3 H), 7.53 (m, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 18.99, 19.04, 25.48 (2 C), 25.55 (2 C), 26.94, 27.01, 29.65, 32.85, 35.77, 35.95, 42.33, 42.36, 43.75, 43.86, 49.63, 55.37, 55.41, 78.16, 108.65, 108.87, 117.96, 118.95, 127.41 (2 C), 128.32 (2 C), 129.42, 132.36, 134.94, 135.26, 159.97, 160.07, 165.79.

[2,3]-Wittig rearrangement product ester 17a: ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.040 (s, 3 H), 1.062 (s, 3 H), 1.155 (s, 3 H), 1.1–1.8 (m, 7 H), 2.48 (m, 2 H), 3.55 (s, 3 H), 4.79 (t, J = 7.3 Hz, 1 H), 5.355 (m, 3 H), 5.87 (m, 1 H), 7.41 (m, 3 H), 7.53 (m, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 18.98, 25.55 (2 C), 27.01, 29.65, 32.85, 35.95, 42.35, 43.85, 49.63, 50.56, 55.41, 78.15, 108.85, 118.53, 127.41 (2 C), 128.32 (2 C), 129.48, 132.39, 134.94, 160.07, 165.79. The carbon spectrum is missing one peak, which could possibly be hidden under the $CDCl_3$ peak at 77.0 ppm. HRMS (CI, CH_4^+): mass of (M − 1) calcd for $C_{35}H_{31}O_3F_3$ 435.2147, found 435.2146.

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Supplementary Material Available: ^{1}H and ^{13}C NMR spectra of new compounds (57 pages). Ordering information is given on any current masthead page.