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Rearrangement of 4,5-Epoxy-9-trimethylsilyldecalines. Application to the Synthesis of the Natural Eremophilane (−)-Aristolochene

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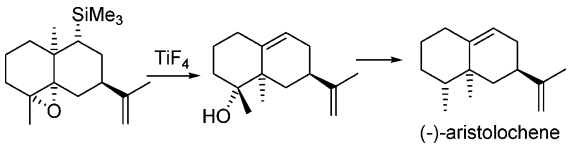

Several 4,5-epoxy-9-trimethylsilyl-eudesmanes and 15-*nor*-eudesmanes, having different relative stereochemistry and substitution at the oxirane ring, have been prepared starting from (−)-carvone and subjected to acid-promoted rearrangement. The presence of the silicon at C9 favors two different main reaction pathways involving C14-methyl or C1-methylene migration through the stabilization of a C10 carbocation intermediate. Selective 1,2-migration of the bridgehead methyl group takes place with trisubstituted β-epoxide and tetrasubstituted α-epoxide, yielding 4-hydroxy-eremophilane and 15-*nor*-eremophilane compounds, while the trisubstituted α-epoxide suffers successive rearrangements to give a 1-hydroxy-15-*nor*-eremophilane through a pathway involving the initial migration of the C1 methylene. The synthetic utility of these rearrangements is shown by the synthesis of natural (−)-aristolochene.

Introduction

Skeletal rearrangements via carbocations are involved in many biogenetic pathways leading to natural products. In the early past century, Robinson suggested that eremophilanes were formed in nature from C5 cationic eudesmane precursors via a route involving methyl migration.[1] Similar rearrangements involving C1- or C9-methylene migrations with concomitant contractions of the A or B rings, respectively, have been proposed for the biosynthesis of sesquiterpenes bearing the spiro[4,5]decane framework, that is, spiroaxanes and spirovetivanes (Figure 1).[2] The hypothesis of a common biogenetic pathway for these kind of compounds is supported by the simultaneous presence of eudesmane, eremophilane, and spirovetivane sesquiterpenes in some plant species.[3]

Because of the extensive synthetic work carried out on eudesmane sesquiterpenes,[4] there is a considerable interest in carrying out this kind of rearrangement in the laboratory to obtain eremophilane or spiranic sesquiterpenes.[5] This task, however, has been shown to be difficult, and only very few successful examples have been described in the literature. Among them, we can mention the photochemical rearrangement of dienones leading to 1,2-methylene or 1,2-methyl migration products,[6] the thermal or acid-catalyzed rearrangements of eudesmanes with special structural features such as hydroxy enones to spirovetivanes[3] and α,β-epoxy ketones to spirovetivanes or eremophilanes,[7] and the rearrangement of an epoxy eudesmanolide to an eremophilanolide.[8] In particular, the rearrangement of 4,5- or 5,6-epoxy eudesmanes or related compounds would be of great interest because their rearrangements lead to compounds functionalized at C4 or C6, which will allow further synthetic modifications at these positions. The acid-catalyzed rearrangements of simple 4,5-epoxy eudesmanes have been studied by different authors who have reported noncoincidental results. However, no products with eremophilane or spiranic structures resulting from these reactions have been reported in any case (Scheme 1).[9,10]

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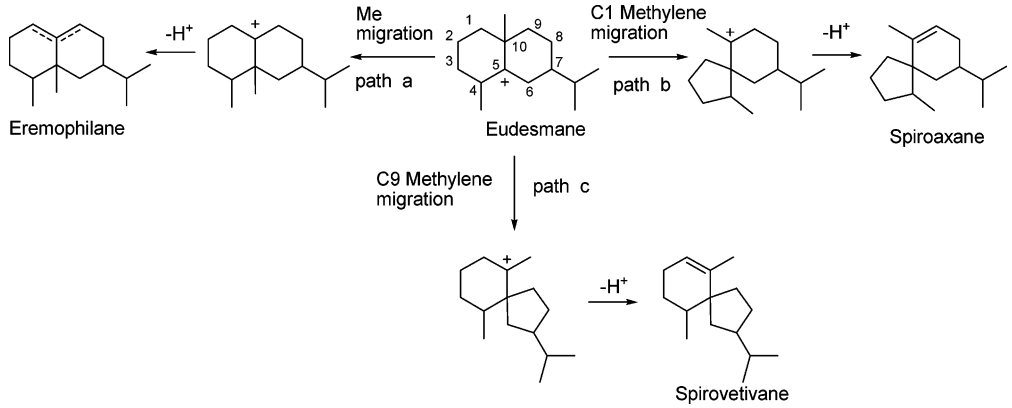
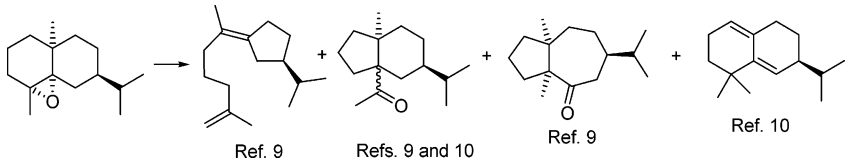


FIGURE 1. Proposed biogenetic pathways from eudesmane to eremophilane, spiroaxane, and spirovetivane sesquiterpenes.

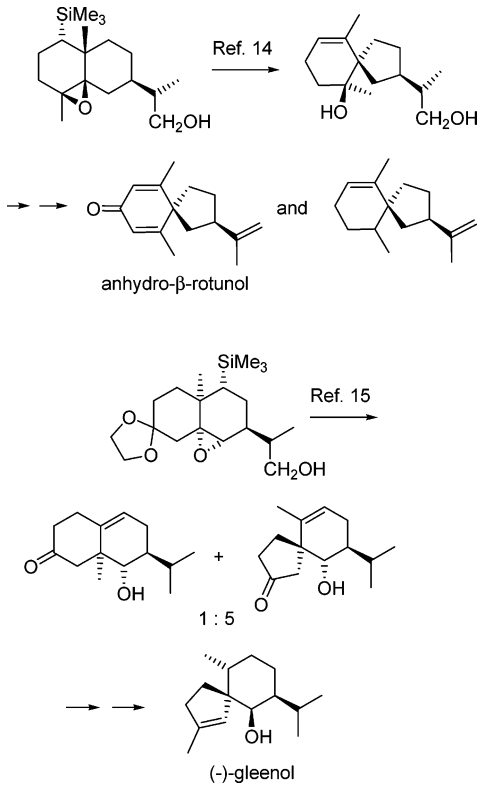
SCHEME 1. Acid-Promoted Rearrangements of Simple 4,5-Epoxyeudesmanes



Three main concerns may be encountered during the acid-catalyzed rearrangement of this kind of epoxides: (a) lack of selectivity of the migrating group, (b) 1,2-elimination of the hydroxyl group before rearrangement,[11] and (c) a Grob-type rearrangement of the 1,3-hydroxycarbocations that result after the initial rearrangement in the case of epoxides.[9,10] In previous work, we have shown that some of these problems can be overcome and selectivity during migration can be gained by introducing a TMS group in the vicinity of the migrating group. In the case of simple decalines, we found that methylene migration was preferred if the epoxide and the TMS group were on the same ring, while methyl migration was the main pathway if both groups were on different rings of the decalin system.[12] It is believed that the TMS group promotes migration of the methyl or methylene groups in β to the TMS group by stabilizing the resulting carbocation at C10 (β-effect), and at the same time, it prevents further rearrangements in the resulting carbocation by rapidly eliminating the TMS group to form a double bond (super proton behavior).[13] The success of this approach has been shown by the synthesis of different spirocyclic sesquiterpenes with spirovetivane[14] or spiroaxane[15] skeleton (Scheme 2).

As a continuation of our research on silicon-guided rearrangements of epoxy decalines, we report here the synthesis and acid-promoted rearrangement of several 4,5-epoxy-9-trimethylsilyl-eudesmanes and 15-*nor*-eudesmanes and the application of such rearrangements in a total synthesis of (−)-aristolochene, an eremophilane sesquiterpene that has been isolated from *Aristolochia indica*,[16] *Bixa orellana*,[17] and *Dumortiera* hirsuta[18] and which is a component of the defensive secretion of some termites.[19] (−)-Aristolochene has been

SCHEME 2. Rearrangement of Epoxytrimethylsilyldecalines



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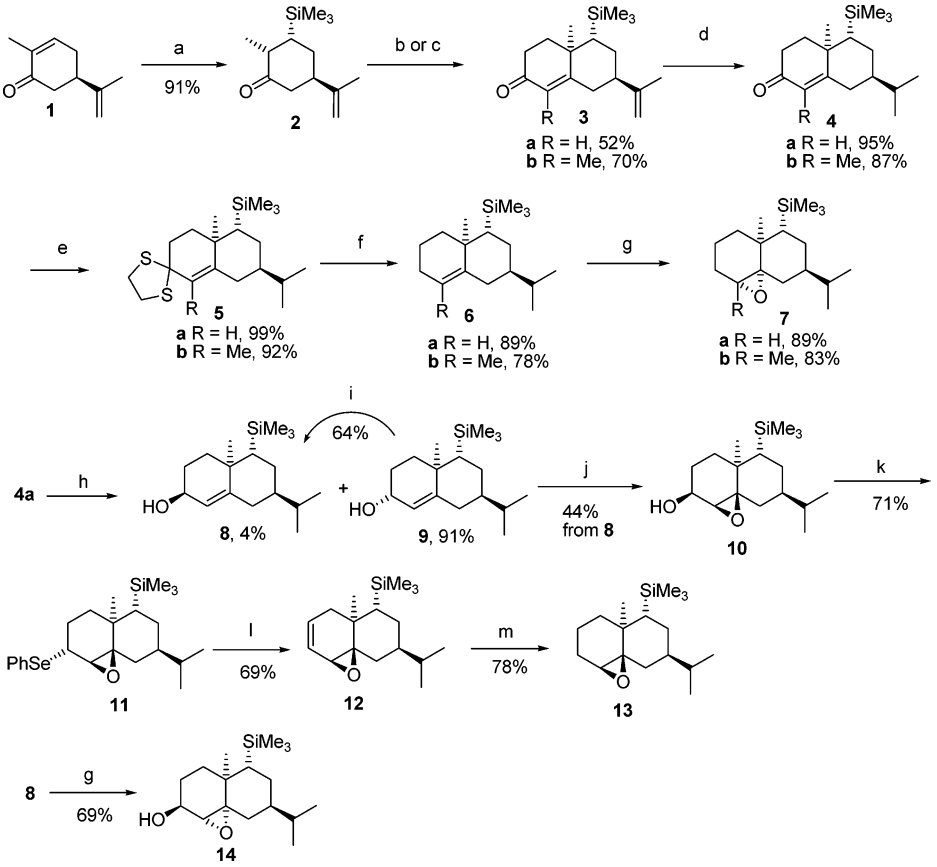
SCHEME 3. Synthesis of Compounds 7a, 7b, 13, and 14[a]



[a] (a) $(Me_3Si)_2$ (2.5 equiv), MeLi (2 equiv), THF−HMPA; ref 15. (b) (1) MVK (2 equiv), Ph_3CSbCl_3 (0.05 equiv), 0 °C; (2) 1 M KOH/MeOH; ref 15. (c) (1) EVK (1.5 equiv), KOH (0.25 equiv), MeOH, reflux. (2) Pyrrolidine (0.12 equiv), Bz, reflux. (d) Wilkinson's catalyst, Bz, H_2. (e) $(CH_2SH)_2$ (4 equiv), $BF_3{\cdot}Et_2O$ (cat), AcOH. (f) Ca, NH_3. (g) *m*-CPBA (1.5 equiv), NaOAc (2.5 equiv), $CHCl_3$, 0 °C. (h) $NaBH_4$ (4 equiv), MeOH, 0 °C. (i) (1) Ph_3P (3 equiv), $PhCO_2H$ (3 equiv), DEAD (2 equiv), THF, 0 °C; (2) $LiAlH_4$ (1 equiv), THF, 0 °C. (j) Ti(*i*-PrO)$_4$ (5 equiv), *t*-BuOOH (2 equiv), Bz. (k) (1) MsCl (4.5 equiv), Et_3N (6 equiv), CH_2Cl_2, −10 °C; (2) $NaBH_4$ (4 equiv), $(PhSe)_2$ (4 equiv), AcOH (1.8 equiv), DMF; then mesylate. (l) 30% aq H_2O_2 (2 equiv), THF, 0 °C to room temperature. (m) $N_2H_4{\cdot}H_2O$ (22 equiv), 30% aq H_2O_2 (11 equiv), EtOH, 0 °C.

synthesized in racemic form[20] and also in enantiomerically pure form starting from (+)-valencene.[21]

Results and Discussion

1. Synthesis of 4,5-Epoxy-9-trimethylsilyldecalines. The starting point for the synthesis of epoxides **7a** and **13** was enone **4a**, which can be readily prepared in three steps from *R*-(−)-carvone (**1**; Scheme 3).[15] To prepare epoxide **7a**, deoxygenation of the carbonyl group at C3 was achieved in two steps involving formation of a thioketal **5a** by treatment with ethanedithiol in acetic acid containing $BF_3{\cdot}Et_2O$ followed by reductive desulfurization with calcium in liquid ammonia[22] to give alkene **6a** in 88% yield for the two steps. Epoxidation of the double bond was carried out by treatment with *m*-CPBA to afford exclusively epoxide **7a** in 89% yield, which resulted from the attack of the epoxidating reagent from the less sterically congested side of the double bond opposite to the C7-isopropyl chain. All attempts to prepare the diastereomeric epoxide **13** directly from alkene **6a** by using different indirect epoxidation approaches[23] were unsuccessful, as they resulted in decomposition mixtures.

To prepare epoxide **13**, we used a modification of the Sharpless epoxidation of allylic alcohols. It is known that allylic and homoallylic hydroxyl groups have a cis directing effect in the metal-catalyzed epoxidation of alkenes.[24] Therefore, we thought that it could be possible to direct the epoxidation of the C4−C5 double bond by a hydroxyl group at C3. Reduction of enone **4a** with $NaBH_4$ gave two epimeric alcohols **8** and **9** in 4 and 91% yields, respectively. The stereochemistry of the new stereogenic center in compounds **8** and **9** was initially assigned according to the shape of the H3 signal in the corresponding ^{1}H NMR spectra. Thus, in the ^{1}H NMR of the minor alcohol **8**, H3 appeared as a broad singlet ($\delta\nu_{1/2} \approx 9.6$ Hz), characteristic for an equatorial proton, while in the ^{1}H NMR of compound **9**, the signal for H3 appeared as a multiplet ($\delta\nu_{1/2} \approx 20$ Hz), characteristic for an axial proton. The

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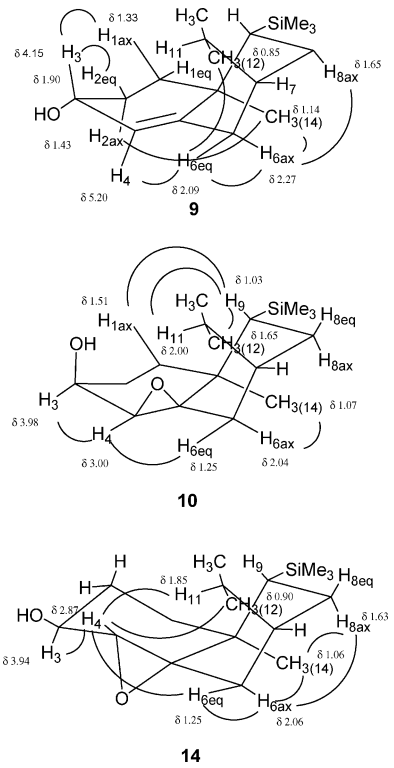


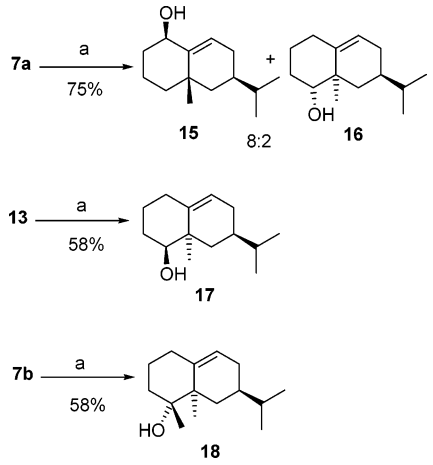
FIGURE 2. Some significant NOEs in compounds **9**, **10**, and **14**.

stereochemistry of H3 in compound **9** was further corroborated by NOE experiments (Figure 2), which were carried out after the assignment of the key peaks in the ^{1}H NMR of compound **9** by homodecoupling experiments. The most significant NOEs were found between the signals of H3 (δ 4.15, m) and the signals of $H2_{eq}$ (δ 1.90, m) and $H1_{ax}$ (1.33, br t, J = 12.5 Hz), which indicates the axial disposition of H3. The stereochemical outcome of the reaction is also in good agreement with the expected preferential attack of the hydride from the less-hindered side of the carbonyl group in compound **4a**, opposite to the C14 methyl group.

Unfortunately, the major alcohol **9** did not have the proper stereochemistry at C3 to induce epoxidation of the double bond from the β-side of the molecule, therefore, it was epimerized at C3 following a Mitsunobu protocol.[25] Treatment of compound **9** with benzoic acid, triphenylphosphine, and diethyl azodicarboxylate (DEAD) gave a benzoate that was reduced with $LiAlH_4$ to yield alcohol **8** in 64% yield in two steps. With this allyl alcohol available, we carried out the epoxidation of the double bond. The reaction of compound **8** with *tert*-butyl hydroperoxide in the presence of Ti(*i*-PrO)$_4$ afforded only the *cis*-epoxy alcohol **10** in 44% yield,[26] part of the allyl alcohol being reoxidized to enone **4a**. For comparative purposes, we also carried out the epoxidation of compound **8** with *m*-CPBA, which afforded a corresponding diastereomeric epoxy alcohol that was given structure **14** with a trans disposition between the hydroxyl group and the epoxide. Both epoxy alcohols were studied by NOE experiments to confirm the expected stereochemistry of the oxirane ring (Figure 2).

To prepare epoxide **13**, removal of the hydroxyl group at C3 in compound **10** was required. Several attempts to cleave the C−O bond by radical procedures via thiocarbonates, mesylates, and related derivatives were unsuccessful because they gave rise to mixtures of rearranged products.[27] Therefore, we planned a sequence involving elimination of the hydroxyl group and hydrogenation of the resulting double bond. Elimination of the hydroxyl group was achieved by its transformation into a phenylselenide: treatment of compound **10** with mesyl chloride gave the corresponding mesylate, which was treated with sodium phenylselenolate to afford phenylselenide **11**. Oxidation of the selenide with aqueous H_2O_2, followed by elimination of the resulting selenoxide gave alkene **12** in 69% yield. Finally, hydrogenation of the double bond with diimine[28] afforded epoxide **13** in 78% yield.[29]

SCHEME 4. Acid-Promoted Rearrangement of 4,5-Epoxy-9-trimethylsilyldecalines 7a, 7b, and 13[a]



[a] (a) $BF_3{\cdot}Et_2O$ (1.25 equiv), CH_3CN, −25 °C.

Epoxide **7b**[30] was synthesized following a similar sequence to that used in the synthesis of epoxide **7a** but starting from enone **4b**, which also can be readily prepared in three steps from *R*-(−)-carvone (**1**), using ethyl vinyl ketone (EVK) in the Robinson annulation step.

2. Acid-Promoted Rearrangement of 4,5-Epoxy-9-trimethylsilyldecalines. With the above epoxides available, we studied their rearrangement in the presence of a Lewis acid. From the different systems tested, the best results were obtained with $BF_3{\cdot}Et_2O$ in acetonitrile at low temperature. The results are summarized in Scheme 4.

Treatment of compound **7a** with $BF_3{\cdot}Et_2O$ in acetonitrile at −25 °C afforded 75% yield of an about 8:2 mixture of two products that could be separated by HPLC. The minor product was assigned structure **16** on the basis of its NMR spectra. The ^{1}H NMR of this compound did not show any signal corresponding to a TMS group. A signal corresponding to an olefinic proton appeared at δ 5.38 (m), indicating the existence of a trisubstituted double bond. A signal corresponding to a singlet methyl group attached to an aliphatic quaternary carbon appeared at δ

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(30) The stereochemistry of epoxide **7b** was assigned on the assumption of a preferential attack of the epoxidating reagent from the α side of the molecule, opposite to the isopropyl chain, as it was proved in compounds **7a** and **20**. See also a discussion on the stereochemistry of compound **20** in the text.

1.00, which was assigned to C14. This indicated that, during rearrangement, the angular methyl group migrated from C10 to C5. The new quaternary bridgehead carbon C5 appeared at δ 41.3 (C), while a signal at δ 80.4 (CH) was assigned to the carbon bearing the secondary alcohol, which results after the opening of the epoxide moiety. The stereochemistry of this carbon was assigned according to the coupling constants for the H4 proton in the ^{1}H NMR (δ 3.24) that appeared as a double doublet with J = 4.2 Hz (ax−eq) and 11.5 Hz (ax−ax), indicating that the OH group was in equatorial disposition and α-oriented, as expected from the stereochemistry of the epoxide in compound **7a**. The major product **15** showed similar NMR spectra to compounds **16** and was also assigned a decalin-derived structure. Most significantly, the CH−O proton appeared at a lower field (δ 4.03) than in compounds **16** (and **17**) as a triplet (J = 7.2 Hz), indicating the possible presence of an allyl alcohol in axial disposition. This fact was confirmed by NOE between the CH−O (δ 4.03) and the olefinic protons (δ 5.36).

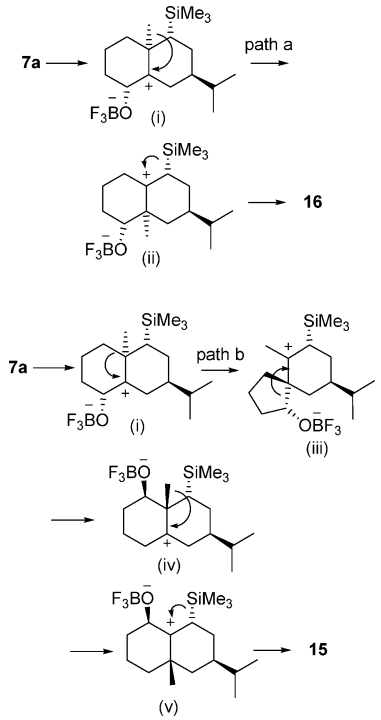
Treatment of compound **13** with $BF_3{\cdot}Et_2O$ in acetonitrile at −25 °C afforded only a major product **17**, which only differed from **16** in the stereochemistry of carbon C4 bearing the secondary alcohol. The stereochemistry of this carbon was confirmed by the shape of the H4 signal in the ^{1}H NMR, which appeared as a broad unresolved dd ($\delta\nu_{1/2} \approx 9.0$ Hz), indicating the α-equatorial orientation of this proton.

Finally, rearrangement of the tetrasubstituted epoxide **7b** was achieved under similar conditions to afford compound **18** in 58% yield. The structure of compound **18** was assigned in a similar way as described above for compounds **16** and **17**. The stereochemistry of C4 was assigned on the assumption of a similar behavior between epoxides **7b** and **20**; see below.

The formation of compounds **16**, **17**, and **18** can be explained in terms of a 1,2-shift of the angular methyl from C10 to C5 in the carbocation (i) that results after the acid-promoted cleavage of the epoxide to give a C10 carbocation (ii), followed by elimination of the TMS group with concomitant formation of a double bond between C9 and C10 (Scheme 5, path a). The formation of compound **15** is more difficult to explain. A possible mechanism would involve successive methylene and methyl migrations, as outlined in Scheme 5 (path b).

Independently of their fate, all these rearrangements start with the formation of a carbocation at C5, followed by methyl or methylene migration to form a carbocation at C10. The formation of the C10 carbocation would be favorable because of the stabilization of the incipient positive charge at C10 by the silicon atom at C9 (β effect), which is accounted for by two different contributions: an inductive effect and hyperconjugation.[31] While the inductive effect does not depend on the migrating group, the hyperconjugative interaction between the silicon atom and the developing positive charge has a cosine-square dependence with the Si−C−C−C (migrating) dihedral angle.[31,32] An examination of the models of epoxides **7a**, **7b**, and **13** indicates that the dihedral angles for the Si−C−C−C1 (methylene) and Si−C−C−C14 (methyl) arrays are similar within each one of the compounds, and they are far from the anti-coplanar arrangement, which would be the most favorable scenario for the hyperconjugative stabilization. Therefore, hyperconjugation must have little differentiating effect to favor

SCHEME 5. Rearrangement of 4,5-Epoxy-9-trimethylsilyldecalines. Mechanistic Pathways



a mechanistic pathway (path a or path b) in respect to the other, and the selectivity observed during the rearrangements of compounds **7a**, **7b**, and **13** most probably is obedient to other causes, probably steric. Thus, in the case of compound **7a**, migration of the methylene C1 anti to the epoxide breaking C−O bond would be preferred with respect to the migration of the C14 methyl syn to the epoxide ring; therefore, path b is the major pathway in this reaction. For some reason, elimination of the TMS group in the resulting spiranic carbocation (iii) is not fast enough, and this allows further rearrangements until the final quenching of the carbocation (v) to give compound **15**.[33] In the case of the rearrangement of epoxide **13**, migration of the C14 methyl anti to the epoxide (path a) would be the most favorable process leading to compound **17**. Finally, in the case of the tetrasubstituted epoxide **7b** migration of the C1 methylene would be hindered by the C15 methyl group, and, therefore, the reaction would follow path a, with methyl migration to give compound **18**. The influence of the TMS group in these rearrangements should be remarked (compare with Scheme 1); and although it is not the only determining factor in the selectivity of methyl versus methylene migration, it plays an important role by stabilizing the C10 carbocation, hence, favoring the reaction pathways (a and b) that occur through this carbocation with respect to other possible mechanistic pathways. It also determines the regioselectivity in the formation of the double bond in the final step of the rearrangements.

3. Synthesis of (−)-Aristolochene. To show a synthetic application of these rearrangements, we report here the synthesis of the eremophilane sesquiterpene (−)-aristolochene (**24**; Scheme

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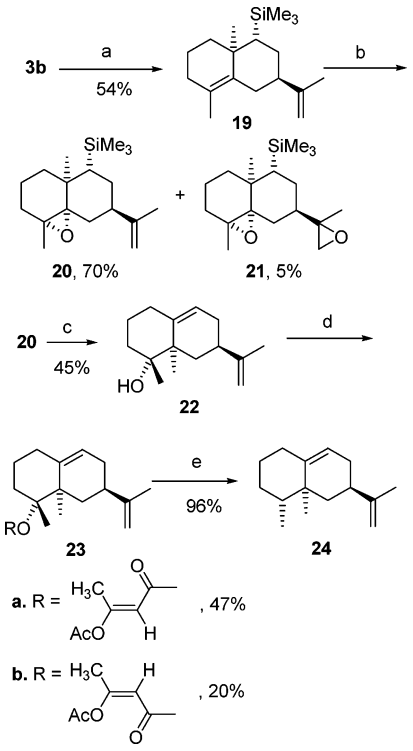
(33) The reasons for the slow elimination of the TMS group in (iii) are not clear at the moment, but it may be due to a lack of coplanarity between the involved orbitals of the C−Si bond and the carbocation. This would permit successive rearrangements from (iii) to (v) that would relieve the angular strain associated with the spiranic carbon and would lead to a final carbocation (v) stabilized by the TMS and also by the neighboring alkoxide.

SCHEME 6. Synthesis of (−)-Aristolochene[a]



[a] (a) $LiAlH_4$ (4.3 equiv), $AlCl_3$ (12.8 equiv), Et_2O, 0 °C, 5 min, then **3b**, 0 °C. (b) *m*-CPBA (1.5 equiv), NaOAc (2.5 equiv), $CHCl_3$, 0 °C. (c) TiF_4 (1.5 equiv), CH_3CN, −20 °C. (d) 4-DMAP (0.46 equiv), Ac_2O−Pyr (1:1); 15% starting material recovered. (e) K (2.5 equiv), 18-crown-6 (cat), *t*-$BuNH_2$.

6), using the rearrangement of epoxide **20** as the key step in this synthesis. The synthesis started with compound **3b**. To remove the oxygen at C3 in this compound, we attempted the same thioketalization−desulfurization procedure that we have described previously for the preparation of **7b**. However, during formation of the thioketal in the presence of $BF_3{\cdot}Et_2O$−acetic acid, migration of the double bond from the isopropylidene chain toward the cyclohexane ring took place. Therefore, deoxygenation was achieved in one step by reduction with $LiAlH_4$−$AlCl_3$ to give diene **19** in 54% yield.[34] Epoxidation of **19** with MCPA at 0 °C afforded epoxide **20** in 70% yield together with 5% of diepoxide **21**. We assumed that epoxidation of the C4−C5 double bond with MCPA took place from the α side of the molecule, as in compounds **6a** and **6b**. This assumption was confirmed by NOE experiments carried out with alcohol **22**, which results after acid rearrangement of compound **20**. Rearrangement of epoxide **20** was carried out with TiF_4 instead of $BF_3{\cdot}Et_2O$ to avoid migration of the isopropylidene double bond. In this way, compound **22** was obtained in 45% yield. The stereochemistry of the carbon bearing the hydroxyl group and, hence, that of epoxide **20**, was confirmed by NOE experiments carried out in DMSO-d_6.[35] Using this solvent, it was possible to induce the selective irradiation of the OH proton, which caused NOEs with two signals at δ 0.80 and δ 1.05, corresponding to the geminal C15 methyl and the C14 angular methyl in axial position, indicating the α orientation of the hydroxyl group. Finally, the synthesis of (−)-aristolochene required the deoxygenation of the tertiary alcohol. The procedure chosen was the reduction of its acetate ester with K in *tert*-butylamine. However, treatment of compound **22** with acetic anhydride/pyridine did not yield the corresponding acetate, but an about 1:2.4 mixture of diastereomeric 3-acetoxy-2-butenoyl esters. This moiety presumably results from a Claisen acylation of the initial acetate, followed by *O*-acetylation of the intermediate dicarbonyl enolate, as we have already reported in a similar transformation.[14a]

The stereochemistry about the double bond was assigned in accord with the chemical shifts for the allylic methyl group in the ^1H NMR spectra which appeared at δ 2.15 in the major *E*-isomer **23a** and at δ 1.97 in the minor *Z*-isomer **23b**.[36] Although the formation of these compounds could not be prevented even by using equivalent amounts of acetic anhydride, treatment of mixtures of **23a** and **23b** with K in *tert*-butylamine brought about the reduction of the ester to give an almost quantitative yield of a product that showed spectral data coincident with those described in the literature for (−)-aristolochene (**24**). During the last reaction, inversion of C4 is produced as a consequence of the preferential protonation from the less-hindered side of the molecule opposite to the angular methyl C14.

In summary, we report the acid rearrangement of several 4,5-epoxy-9-trimethylsilyl eudesmane and 15-*nor*-eudesmanes having different relative stereochemistry and substitution at the oxirane ring. The presence of the silicon at C9 favors two different main reaction pathways involving C14-methyl or C1-methylene migration through the stabilization of a C10 carbocation intermediate. Selective 1,2-migration of the bridgehead methyl group takes place with trisubstituted β-epoxide and tetrasubstituted α-epoxide, yielding 4-hydroxy- eremophilane and 15-*nor*-eremophilane compounds, while the trisubstituted α-epoxide suffers successive rearrangements to give a 1-hydroxy-*nor*-eremophilane through a pathway inolving the initial migration of the C1 methylene. The synthetic utility of these rearrangements is shown by the synthesis of natural (−)-aristolochene.

Experimental Section[37]

(6*R*,7*R*,9*S*)-(−)-3,3-(1,2-Ethanediyldithio)-9-isopropyl-6-methyl-7-trimethylsilylbicyclo[4.4.0]dec-1-ene (5a). A solution containing compound **4a**[15] (1.28 g, 4.59 mmol), ethanedithiol (1.6 mL, 19.1 mmol), and $BF_3{\cdot}Et_2O$ (0.33 mL) in acetic acid (17 mL) was stirred under argon at room temperature for 2 h. After this time, the mixture was diluted with EtOAc, washed with saturated aqueous $NaHCO_3$ and brine, and dried over Na_2SO_4. Evaporation of the solvent under reduced pressure and chromatography, eluting with hexanes−EtOAc (from 100:0 to 95:5), gave 1.62 g (99%) of compound **5a**: white solid; mp 106−107 °C (hexanes−EtOAc); $[\alpha]^{20}_D$ −123 (*c* 1.3, $CHCl_3$); EM *m*/*z* 354 (M^+, 84), 311 (65), 294 (26), 293 (53), 279 (29), 189 (22), 73 (100); HRMS calcd for $C_{19}H_{34}S_2Si$, 354.1871; found, 354.1862 (M^+); IR (KBr) 1458, 1247, 829 cm^{-1}; ^1H NMR δ 5.38 (1H, s), 3.39−3.18 (4H, m, SCH_2CH_2S), 2.27−2.08 (3H, m), 1.83 (1H, dt, J = 13.5, 3.6 Hz), 1.69−1.57

(34) (a) Brewster, J. H.; Bayer, H. O. *J. Org. Chem.* **1964**, *29*, 116−121. (b) Broome, J.; Brown, B. R.; Roberts, A.; White, A. M. S. *J. Chem. Soc.* **1960**, 1406−1408.

(35) DMSO-d_6 slows down the exchange of the hydroxyl proton so it gives a defined signal that can be irradiated in NOE experiments: Sanders, J. K. M.; Hunter, B. K. *Modern NMR Spectroscopy*; Oxford University: Oxford, 1989.

(36) Pretsch, E.; Clerc, T.; Seibl, J.; Simon, W. *Tables of Spectral Data for Structure Determination of Organic Compounds*, 2nd edition; Springer-Verlag: Berlin, Heidelberg, New York, 1989.

(37) For a description of the general experimental methods, see Supporting Information.

(5H, m), 1.28 (1H, m), 1.11 (3H, s), 0.88 (3H, d, $J = 6.6$ Hz), 0.79 (3H, d, $J = 6.6$ Hz), 0.77 (1H, dd, $J = 11.4$, 6.0 Hz, overlapped), 0.03 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 144.9 (C), 124.9 (CH_2), 65.8 (C), 43.1 (CH), 40.0 (CH2), 39.7, 39.4 ($2CH_2$, SCH_2CH_2S), 38.1 (CH_2), 37.2 (C), 35.6 (CH_2), 33.6 (CH), 26.8 (CH_2), 25.1 (CH), 22.0 (CH_3), 21.0 (CH_3), 20.6 (CH_3), 0.3 ($3CH_3$, $(CH_3)_3Si$).

(6*R*,7*R*,9*S*)-(−)-9-Isopropyl-6-methyl-7-trimethylsilylbicyclo-[4.4.0]dec-1-ene (6a). In a flask equipped with a dry ice−acetone condenser, calcium metal (0.92 g, 23.0 mmol) was dissolved in liquid ammonia (ca. 110 mL) at −78 °C under argon. To the resulting blue solution was added dry diethyl ether (30 mL) and a solution of compound **5a** (1.62 g, 4.57 mmol) in dry diethyl ether (19 mL). The cooling bath was removed, and the solution was kept at reflux for 6 h. After this time, solid NH_4Cl was cautiously added, followed by diethyl ether (40 mL), and ammonia was allowed to evaporate overnight. Saturated aqueous NH_4Cl was added, and the aqueous phase was extracted with ether. The organic layer was washed with aqueous NH_4Cl, 10% aqueous NaOH, and brine, dried, filtered, and concentrated under reduced pressure. Column chromatography (hexanes) gave 1.08 g (89%) of compound **6a**: oil; $[\alpha]^{22}_D$ −88 (*c* 1.2, $CHCl_3$); EM *m*/*z* 264 (M^+, 46), 191 (19), 190 (94), 175 (53), 147 (84), 91 (20), 73 (100); HRMS calcd for $C_{17}H_{32}Si$, 264.2273; found, 264.2282 (M^+); IR (NaCl) 1458, 1248, 858, 833 cm^{-1}; ^1H NMR δ 5.19 (1H, m), 2.29 (1H, m), 2.08 (1H, dt, $J = 13.5$, 2.1 Hz), 1.95−1.86 (2H, m), 1.79 (1H, dt, $J = 12.9$, 3.5 Hz), 1.71−1.62 (2H, m), 1.61−1.51 (2H, m), 1.34−1.19 (2H, m), 1.12 (3H, s), 0.88 (3H, d, $J = 6.3$ Hz), 0.82 (3H, d, $J = 6.6$ Hz), 0.05 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 142.7 (C), 120.2 (CH), 43.1 (CH), 40.2 (CH_2), 37.9 (C), 36.0 (CH_2), 33.7 (CH), 26.9 (CH_2), 25.7 (CH_2), 25.1 (CH), 23.0 (CH_3), 21.1 (CH_3), 20.6 (CH_3), 19.3 (CH_2), 0.5 ($3CH_3$, $(CH_3)_3Si$).

(1*S*,2*R*,6*R*,7*R*,9*S*)-(+)-1,2-Epoxy-9-isopropyl-6-methyl-7-trimethylsilylbicyclo[4.4.0]decane (7a). To a solution of compound **6a** (215 mg, 0.81 mmol) and NaOAc (167 mg, 2.04 mmol) in chloroform (17 mL) at 0 °C was added *m*-CPBA (210 mg, 1.22 mmol). After 20 min, saturated aqueous $NaHCO_3$ was added, and the solution was extracted with EtOAc and dried. After filtration and removal of the solvent under reduced pressure, column chromatography afforded 203 mg (89%) of epoxide **7a**: oil; $[\alpha]^{24}_D$ +2 (*c* 1.0, $CHCl_3$); EM *m*/*z* 280 (16), 237 (19), 207 (28), 147 (24), 145 (22), 129 (21), 105 (22), 73 (100); HRMS calcd for $C_{17}H_{32}OSi$, 280.2222; found, 280.2233 (M^+); IR (NaCl) 1460, 1246, 860, 831 cm^{-1}; ^1H NMR δ 2.93 (1H, br t, $J = 2.6$ Hz), 2.05 (1H, dd, $J = 13.5$, 4.8 Hz), 1.87−1.83 (2H, m), 1.75−1.62 (3H, m), 1.45−1.16 (6H, m), 1.08 (3H, s), 0.89 (3H, d, $J = 6.6$ Hz), 0.86 (3H, d, $J = 6.6$ Hz), 0.05 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 63.0 (C), 62.2 (CH), 42.5 (CH), 36.5 (C), 34.4 (CH_2), 34.1 (CH2), 27.2 (CH), 26.6 (CH), 26.0 (CH_2), 24.2 (CH_2), 21.6 ($2CH_3$), 20.7 (CH_3), 16.1 (CH_2), 0.4 ($3CH_3$, $(CH_3)_3Si$).

(3*S*,6*R*,7*R*,9*S*)-(−)-9-Isopropyl-6-methyl-7-trimethylsilylbicyclo-[4.4.0]dec-1-en-3-ol (8) and (3*R*,6*R*,7*R*,9*S*)-(−)-9-Isopropyl-6-methyl-7-trimethylsilylbicyclo[4.4.0]dec-1-en-3-ol (9). To a solution of compound **4a** (739 mg, 2.66 mmol) in MeOH was added $NaBH_4$ in four portions at intervals of 15 min (4 × 100 mg, 2.66 mmol) at 0 °C. After 1 h, the reaction was quenched with saturated aqueous NH_4Cl and extracted with EtOAc. The organic layer was washed with brine until neutrality and dried. Column chromatography eluting with hexanes−EtOAc (from 95:5 to 80:20) gave 27 mg (4%) of alcohol **8** and 675 mg (91%) of alcohol **9**.

8: oil, $[\alpha]^{25}_D$ −128 (*c* 1.2, $CHCl_3$); EM *m*/*z* 280 (M^+, 2), 262 (25), 219 (30), 131 (12), 145 (100), 73 (99); HRMS calcd for $C_{17}H_{32}OSi$, 280.2222; found, 280.2229 (M^+); IR (NaCl) 3520−3300, 1250, 830 cm^{-1}; ^1H NMR (400 MHz) δ 5.36 (1H, d, $J = 5.2$ Hz), 3.98 (1H, br m, $\delta\nu_{1/2} \approx 10.8$ Hz), 2.28 (1H, dd, $J = 13.6$, 3.6 Hz), 2.10 (1H, t, $J = 12.0$ Hz), 1.8−1.5 (8H, m), 1.28 (1H, m), 1.06 (3H, s), 0.86 (3H, d, $J = 6.4$ Hz), 0.78 (3H, d, $J = 6.8$ Hz, overlapped with 1H, dd), 0.03 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 148.4 (C), 121.9 (CH), 64.0 (CH), 42.8 (CH), 38.2 (C), 35.7 (CH_2), 34.0 (CH_2), 33.4 (CH), 27.7 (CH_2), 26.7 (CH_2), 25.1 (CH), 21.4 (CH_3), 21.0 (CH_3), 20.5 (CH_3), 0.4 ($3CH_3$, $(CH_3)_3Si$).

9: white solid, mp 123−124 °C (hexanes−EtOAc); $[\alpha]^{23}_D$ −58 (*c* 1.3, $CHCl_3$); EM *m*/*z* 263 (M^+ − OH, 10), 262 (38), 219 (38), 146 (12), 145 (100), 73 (12); HRMS calcd for $C_{17}H_{31}Si$, 263.2195; found, 263.2119 (M^+ − OH); IR (KBr) 3154, 1461, 1381, 1248, 870 cm^{-1}; ^1H NMR (400 MHz) δ 5.16 (1H, d, $J = 1.2$ Hz), 4.15 (1H, br m, $\delta\nu_{1/2} \approx 20$ Hz), 2.27 (1H, m), 2.09 (1H, m), 1.90 (1H, m), 1.80−1.57 (4H, m), 1.50−1.40 (1H, m), 1.34 (1H, t, $J = 12.5$ Hz), 1.25 (1H, m), 1.14 (3H, s), 0.86 (3H, d, $J = 6.4$ Hz), 0.79 (3H, d, $J = 6.8$ Hz), 0.73 (1H, dd, $J = 4.0$, 12.8 Hz), 0,02 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 145.5 (C), 124.5 (CH), 67.8 (CH), 43.1 (CH), 38.0 (C), 37.9 (CH_2), 35.6 (CH_2), 33.9 (CH), 29.4 (CH2), 26.8 (CH_2), 25.0 (CH), 22.3 (CH_3), 20.9 (CH_3), 20.5 (CH_3), 0.3 ($3CH_3$, $(CH_3)_3Si$).

Compound 8 from 9. A solution of **9** (309 mg, 1.11 mmol), triphenylphosphine (870 mg, 3.32 mmol), and benzoic acid (405 mg, 3.32 mmol) in dry THF (13 mL) at 0 °C under argon was treated with a solution of DEAD (430 μL, 1.95 mmol) in THF (13 mL). After 30 min, the solvent was removed under reduced pressure. The crude was then dissolved in dry THF (20 mL) and cooled at 0 °C, and $LiAlH_4$ was added in portions at intervals of 20 min (4 × 42 mg, 1.11 mmol). After 1.5 h, the excess reagent was destroyed by the addition of water. The mixture was diluted with EtOAc, washed with brine, and dried over Na_2SO_4. After filtration, the solvent was removed under reduced pressure, and the residue was chromatographed on silica gel (hexanes−EtOAc, 90:10) to give 198 mg (64%) of alcohol **8**.

(1*R*,2*S*,3*S*,6*R*,7*R*,9*S*)-(−)-1,2-Epoxy-9-isopropyl-6-methyl-7-(trimethylsilyl)bicyclo[4.4.0]decan-3-ol (10). Alcohol **8** (141 mg, 0.50 mmol) and Ti(*i*-PrO)$_4$ (0.75 mL, 2.51 mmol) were dissolved in benzene (2 mL) and stirred under argon for 5 min. Then, an 80% solution of *t*-BuOOH in di-*tert*-butylperoxide (100 μL, 1.0 mmol) was added. Additional Ti(*i*-PrO)$_4$ and *t*-BuOOH were added after 1 h (0.3 mL and 50 μL, respectively) and after 2 h (0.5 mL and 100 μL, respectively). After an overall reaction time of 3 h, saturated aqueous $NaHCO_3$ was added, and the solution was extracted with EtOAc. After drying and removal of the solvent under reduced pressure, column chromatography, eluting with hexanes−EtOAc (95:5 to 80:20), gave 39.4 mg (14%) of enone **4a** and 64.8 mg (44%) of epoxy alcohol **10**: white solid; mp 61−62 °C (hexanes−EtOAc); $[\alpha]^{29}_D$ −114 (*c* 1.1, $CHCl_3$); EM *m*/*z* 296 (M^+, 3), 226 (80), 145 (39), 119 (18), 107 (39), 105 (28), 95 (17), 94 (42), 93 (26), 73 (100); HRMS calcd for $C_{17}H_{32}O_2Si$, 296.2172; found, 296.2167 (M^+); IR (KBr) 3375, 1249, 861, 832 cm^{-1}; ^1H NMR (400 MHz) δ 3.98 (1H, br s), 3.00 (1H, d, $J = 4.0$ Hz), 2.04 (1H, dd, $J = 14.0$, 6.4 Hz), 2.00 (1H, m), 1.82 (1H, ddd, $J = 14.8$, 13.4, 2.4 Hz), 1.71 (1H, td, $J = 23.6$, 5.2 Hz), 1.51 (1H, td, $J = 14.5$, 4.0 Hz), 1.49 (1H, m), 1.35 (1H, m), 1.25 (1H, d, $J = 14.5$ Hz), 1.17 (1H, m), 1.07 (3H, s), 1.02 (1H, dd, $J = 2.8$, 13.6 Hz), 0.86 (3H, d, $J = 6.4$ Hz), 0.84 (3H, d, $J = 6.4$ Hz), 0.02 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 68.9 (C), 63.4 (CH), 61.6 (CH), 42.2 (CH), 36.2 (C), 31.2 (CH_2), 30.6 (CH_2), 29.4 (CH), 27.1 (CH2), 26.9 (CH), 25.5 (CH_2), 21.7 (CH_3), 21.5 (CH_3), 20.0 (CH_3), 0.4 ($3CH_3$, $(CH_3)_3Si$).

(1*R*,2*R*,3*R*,6*R*,7*R*,9*S*)-1,2-Epoxy-3-phenylselenenyl-9-isopropyl-6-methyl-7-trimethylsilylbicyclo[4.4.0]decane (11). Mesyl chloride (70 μL, 0.90 mmol) was added to a solution of epoxy alcohol **10** (58 mg, 0.20 mmol) and triethylamine (165 μL, 1.2 mmol) in CH_2Cl_2 (1.2 mL) at −10 °C under argon. After 30 min, the reaction mixture was diluted with EtOAc, washed with 1 M HCl, saturated aqueous $NaHCO_3$, and brine, and dried over Na_2SO_4. After filtration, the solvent was removed under reduced pressure. A solution of sodium phenylselenolate was prepared by adding $NaBH_4$ (31 mg, 0.82 mmol) to a solution of PhSeSePh (204 mg, 0.65 mmol) in DMF (2 mL) under argon, followed by the addition of acetic acid (22 μL) after 5 min. To the resulting solution was added via syringe a solution of the crude mesylate in DMF (2.7 mL). The mixture was stirred under argon for 24 h, quenched

with water, extracted with EtOAc, washed with brine, and dried. Evaporation of the solvent and column chromatography (hexanes−EtOAc, 95:5) gave 60.4 mg (71%) of phenylselenide **11**: ^{1}H NMR (300 MHz) δ 7.55 (2H, m), 7.25 (3H, m), 3.50 (1H, t, J = 9.5 Hz), 3.05 (1H, s), 1.99 (1H, dd, J = 14.3, 5.5 Hz), 1.70 (1H, dd, J = 13.0, 4.3 Hz), 1.01 (1H, dd, J = 13.0, 3.3 Hz), 0.92 (3H, s), 0.83 (3H, d, J = 6.8 Hz), 0.81 (3H, d, J = 6.8 Hz), 0.00 (9H, s, $(CH_3)_3$-Si).

(1*R*,2*S*,6*R*,7*R*,9*S*)-(−)-1,2-Epoxy-9-isopropyl-6-methyl-7-trimethylsilylbicyclo[4.4.0]dec-3-ene (12). A solution of phenylselenide **11** (49 mg, 0.11 mmol) in CH_2Cl_2 (1.2 mL) at 0 °C was treated with 30% aq H_2O_2 (27 μL, 0.24 mmol). The mixture was stirred at room temperature for 30 min. After this time, the mixture was diluted with EtOAc, washed with brine, and dried. After removal of the solvent under reduced pressure, the residue was chromatographed (hexanes−EtOAc, 98:2) to give 22 mg (69%) of compound **12**: white solid; mp 50−51 °C (hexanes−EtOAc); $[\alpha]^{29}_D$ −132 (*c* 1.1, $CHCl_3$); EM *m*/*z* 278 (M^+, 5), 145 (36), 143 (20), 135 (31), 129 (23), 93 (30), 73 (100), 57 (28); HRMS calcd for $C_{17}H_{30}OSi$, 278.2066; found, 278.2077 (M^+); IR (KBr) 1461, 1249, 833 cm^{-1}; ^{1}H NMR δ 5.85 (1H, ddd, J = 10.0, 4.0, 3.5 Hz), 5.72 (1H, m), 2.85 (1H, dd, J = 4.0, 1.9 Hz), 2.17 (1H, dd, J = 14.3, 4.9 Hz), 1.67 (1H, td, J = 14.0, 4.1 Hz), 1.07 (1H, dd, J = 13.6, 2.6 Hz), 0.98 (3H, s), 0.88 (3H, d, J = 6.4 Hz), 0.83 (3H, d, J = 6.6 Hz), 0.04 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 131.3 (CH), 123.3 (CH), 67.0 (C), 54.1 (CH), 41.8 (CH), 38.4 (CH_2), 35.7 (C), 31.7 (CH_2), 29.6 (CH), 26.4 (CH), 26.1 (CH_2), 21.8 (CH_3), 21.3 (C), 19.5 (CH_3), 0.4 (3CH_3, $(CH_3)_3Si$).

(1*R*,2*S*,6*R*,7*R*,9*S*)-(−)-1,2-Epoxy-9-isopropyl-6-methyl-7-trimethylsilylbicyclo[4.4.0]decane (13). A solution of compound **12** (12 mg, 0.04 mmol) and N_2H_4·H_2O (42 μL, 0.86 mmol) in absolute EtOH (0.2 mL) at 0 °C was treated with 30% aq H_2O_2 (48 μL, 0.42 mmol) under argon, and the reaction mixture was stirred at room temperature for 21 h. The reaction mixture was diluted with EtOAc and washed with brine. Chromatography, eluting with hexanes−EtOAc (99:1), gave 9.1 mg (78%) of epoxide **13** and 2.0 mg (17%) of unreacted starting material **12**.

13: white solid; mp 70−71 °C (hexanes−EtOAc); $[\alpha]^{28}_D$ −90 (*c* 1.1, $CHCl_3$); EM *m*/*z* 280 (M^+, 21), 237 (17), 207 (30), 145 (17), 105 (18), 73 (100); HRMS calcd for $C_{17}H_{32}OSi$, 280.2222; found, 280.2224 (M^+); IR (KBr) 1462, 1248, 832 cm^{-1}; ^{1}H NMR δ 2.72 (1H, unresolved dd), 1.46 (1H, d, J = 8.5 Hz), 1.11 (3H, s), 1.06 (1H, dd, J = 3.6, 12.8 Hz), 0.85 (3H, d, J = 6.6 Hz), 0.83 (3H, d, J = 7.0 Hz), 0.01 (9H, s, $(CH_3)_3Si$); ^{13}C NMR δ 65.6 (C), 58.9 (CH), 42.5 (CH), 36.5 (C), 33.5 (CH_2), 31.7 (CH_2), 29.3 (CH), 26.9 (CH), 25.6 (CH_2), 21.7 (CH_2), 21.8 (CH_3), 21.5 (CH_3), 20.0 (CH_3), 15.6 (CH2), 0.5 (3CH_3, $(CH_3)_3Si$).

Rearrangement of Compound 13: (1*R*,2*S*,9*R*)-(−)-9-Isopropyl-1-methylbicyclo[4.4.0]dec-6-en-2-ol (17). A solution of BF_3·Et_2O (6.0 μL, 0.045 mmol) in dry CH_3CN (0.6 mL) was added dropwise to a solution of epoxide **13** (10 mg, 0.036 mmol) in dry CH_3CN (0.6 mL) cooled at −25 °C under argon. After 15 min, the reaction was quenched with saturated aqueous $NaHCO_3$ and extracted with EtOAc, washed with brine, and dried. Column chromatography (hexanes−EtOAc, 98:2) gave 4.3 mg (58%) of compound **17**: oil; $[\alpha]^{25}_D$ −42 (*c* 0.7, $CHCl_3$); EM *m*/*z* 208 (M^+, 13), 190 (32), 147 (100), 105 (17), 95 (32); HRMS calcd for $C_{14}H_{24}O$, 208.1827; found, 208.1823 (M^+); IR (NaCl) 3401, 1249, 1041, 832 cm^{-1}; ^{1}H NMR (300 MHz) δ 5.55 (1H, m), 3.45 (1H, unresolved m, $\delta\nu_{1/2} \approx$ 9.0 Hz), 2.18 (1H, m), 2.01−1.84 (3H, m), 1.72−1.63 (3H, m), 1.59−1.52 (4H, m), 1.07 (3H, s), 0.87 (3H, d, J = 6.6 Hz), 0.86 (3H, d, J = 6.6 Hz); ^{13}C NMR δ 139.0 (C), 124.2 (CH), 75.3 (CH), 41.2 (C), 36.4 (CH), 36.2 (CH_2), 32.4 (CH), 30.9 (CH_2), 29.5 (CH_2), 28.4 (CH_2), 24.1 (CH_3), 20.8 (CH_2), 20.0 (CH_3), 19.6 (CH_3).

(−)-Aristolochene (24). To a solution of compound **22** (343 mg, 1.6 mmol) in pyridine (4 mL) was added acetic anhydride (4 mL) and 4-(dimethylamino)pyridine (4-DMAP; 90 mg, 0.75 mmol), and the mixture was stirred at room temperature. Additional loads of pyridine (4 × 2 mL) and acetic anhydride (4 × 2 mL) were added at intervals of 1.5 h. After a total of 8 h, the reaction mixture was diluted with EtOAc, washed with 2 M HCl, saturated aqueous $NaHCO_3$, and brine, and dried. Filtration and solvent evaporation under reduced pressure, followed by column chromatography (hexanes−EtOAc 100:0 to 90:10), afforded 252 mg (47%) of **23a**, 105 mg (20%) of **23b**, and 52.4 mg (15%) of unreacted starting material **22**.

23a: oil; $[\alpha]^{18}_D$ −63 (*c* 1.3, $CHCl_3$); EM *m*/*z* 346 (M^+, 5), 202 (62), 201 (16), 161 (23), 159 (35), 147 (43), 145 (15), 119 (18), 105 (18), 85 (100); HRMS calcd for $C_{21}H_{30}O_4$, 346.2144; found, 346.2131 (M^+); IR (NaCl) 2937, 1766, 1717, 1667, 1439, 1372, 1343, 1206, 1117, 1022, 899 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.60 (1H, d, J = 1.2 Hz), 5.45 (1H, dt, J = 6.3, 2.0 Hz), 4.71, (1H, d, J = 1.8 Hz), 4.69 (1H, br s), 2.59 (1H, br d, J = 12.6 Hz), 2.30 (3H, s), 2.15 (3H, s), 1.72 (3H, s), 1.54 (3H, s), 1.23 (3H, s); ^{13}C NMR δ 168.4 (C), 165.2 (C), 162.8 (C), 150.0 (C), 140.4 (C), 122.4 (CH), 111.7 (CH), 108.5 (CH_2), 87.3 (C), 45.2 (C), 37.8 (CH), 35.8 (CH_2), 31.7 (CH_2), 30.9 (CH_2), 30.6 (CH_2), 22.7 (CH_2), 22.2 (CH_3), 21.1 (CH_3), 21.0 (CH_3), 20.9 (CH_3), 17.8 (CH_3).

23b: oil; $[\alpha]^{18}_D$ −35 (*c* 1.2, $CHCl_3$); EM *m*/*z* 346 (M^+, 5), 203 (34), 202 (53), 201 (15), 161 (28), 159 (33), 147 (42), 145 (15), 119 (23), 105 (29), 85 (100); HRMS calcd for $C_{21}H_{30}O_4$, 346.2144; found, 346.2129 (M^+); IR (NaCl) 2927, 1763, 1715, 1672, 1644, 885, 830 cm^{-1}; ^{1}H NMR δ 5.53 (1H, t, J = 1.5 Hz), 5.44 (1H, br d), 4.71 (1H, d, J = 1.5 Hz), 4.70 (1H, br s), 2.55 (1H, br d, J = 13.0 Hz), 2.22 (3H, s), 1.97 (3H, s), 1.73 (3H, s), 1.50 (3H, s), 1.22 (3H, s); ^{13}C NMR δ 168.1 (C), 162.9 (C), 158.8 (C), 150.0 (C), 140.5 (C), 122.4 (CH), 109.6 (CH), 108.5 (CH_2), 87.1 (C), 45.2 (C), 37.8 (CH), 35.8 (CH2), 31.7 (CH_2), 31.0 (CH_2), 30.6 (CH_2), 22.7 (CH_2), 22.1 (CH_3), 21.5 (CH_3), 21.1 (CH_3), 21.0 (CH_3), 20.9 (CH_3).

A blue solution of potassium was generated by stirring potassium metal (ca. 50 mg, 1.3 mmol) and 18-crown-6 (10 mg) in dry *tert*-butylamine (2 mL) under argon. To this solution was added a mixture of compounds **23a** and **23b** (170 mg, 0.49 mmol) dissolved in *tert*-butylamine (8 mL), and the reaction mixture was stirred at room temperature for 30 min. The excess of potassium was destroyed by the careful addition of *tert*-butyl alcohol. Water was added, and the mixture was extracted with pentane and washed with brine. After careful evaporation of the solvent, the resulting oil was chromatographed, eluting with pentane to give compound **24** (96 mg, 96%): volatile oil; $[\alpha]^{20}_D$ −79 (*c* 1.1, $CHCl_3$) [lit.[16] $[\alpha]_D$ −76.47°]; EM *m*/*z* 204 (M^+, 9), 189 (56), 121 (21), 107 (25), 105 (57), 91 (36), 80 (39), 55 (100), 53 (50); HRMS calcd for $C_{15}H_{24}$, 204.1878; found, 204.1869 (M^+); IR (NaCl) 2922, 1644, 1445, 1373, 887 cm^{-1}; ^{1}H NMR (400 MHz) δ 5.30 (1H, m), 4.69 (2H, s), 2.3−2.1 (2H, m), 1.72 (3H, s), 2.1−1.6 (6H, m), 1.5−1.2 (3H, m), 1.15 (1H, t, J = 12.4 Hz), 0.95 (3H, s), 0.83 (3H, d, J = 6.8 Hz); ^{13}C NMR δ 150.7 (C), 144.5 (C), 118.7 (CH), 108.3 (CH_2), 44.1 (CH), 43.2 (CH_2), 38.7 (C), 37.7 (CH), 32.5 (CH_2), 31.6 (CH_2), 31.3 (CH_2), 27.8 (CH_2), 20.9 (CH_3), 18.1 (CH_3), 15.7 (CH_3).

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Supporting Information Available: Experimental procedures and characterization data for compounds **3b**−**7b**, **14**−**16**, and **18**−**22**. ^{1}H and ^{13}C NMR spectra of compounds **5a**−**7a**, **3b**−**7b**, **8**−**10**, and **12**−**24**. This material is available free of charge via the Internet at http://pubs.acs.org.

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