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Comparison of the electronic effect and the steric influence between the 1,1,2,2,2-pentamethyldisilanyl and the trimethylsilyl groups

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Abstract

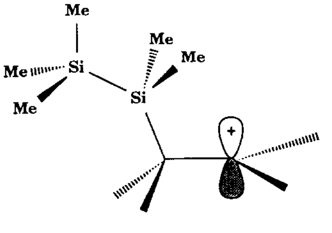
A comparison of the electronic effects expressed by the Me_3SiMe_2Si– and Me_3Si– groups towards carbocationic intermediates was made by study of acid-catalyzed rearrangements of decalin epoxides **3** and **4**. Reaction of the Me_3SiMe_2Si-epoxide **3** with $BF_3 \cdot Et_2O$ in CH_2Cl_2 at −50°C gave four products: B-ring contracted spirocyclic alcohol **9** (21%), methyl-migrated decanol **12** (23%), A-ring contracted aldehyde **15** (21%), and fluorohydrin **17** (14%). Under the same conditions, Me_3Si-epoxide **4** afforded alcohol **9** (24%), decanol **12** (18%), aldehyde **16** (23%; *cf.* **15**), and fluorohydrin **18** (13%; *cf.* **17**). These results show that the Me_3SiMe_2Si– and Me_3Si– groups exerted electronic influence to the same extents on carbocations.

In HMPA and THF at −78°C, reagent Me_3SiMe_2SiLi reacted with cross-conjugated dienone **19** in a 1,4 fashion from the less hindered side to give enone **20** (63%) as the only adduct. In comparison with Me_3SiLi, reagent Me_3SiMe_2SiLi possessed better stereoselectivity. In addition, the Me_3SiMe_2Si– moiety with α configuration in **24** was able to prevent *m*-chloroperbenzoic acid (*m*-CPBA) from attacking from the same face during epoxidation, such that β-epoxide **3** was obtained in 59% yield exclusively.

1. Introduction

The 1,1,2,2,2-pentamethyldisilanyl (Me_3SiMe_2Si–) group can play various roles in organic reactions [1]. Recently we investigated its electronic and steric effects in comparison with those resulting from the commonly used Me_3Si– group [2].

Silyl groups can stabilize a carbocation at either the β- [3–7] or the γ-position [8–16]. We considered a special disilanyl carbocation **1**, in which the positive charge is β to one silicon atom and γ to the other. Therefore, both silicon atoms might contribute stabilization to this positive charge and thus make it more stable than the corresponding β-$SiMe_3$ carbocation **2**. On the other hand, d-orbital overlap [17] between the two silicon atoms of **1**, or geometrical constraints, might limit the capacity of the Me_3SiMe_2Si– group to stabilize carbocation **1**. We report here a study showing that, in comparison with the Me_3Si– group, the Me_3SiMe_2Si– group showed a similar electronic effect towards carbocations and exerted greater steric influence on certain chemical reactions.



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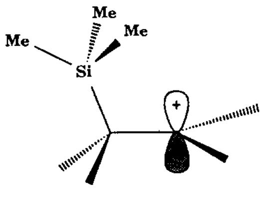

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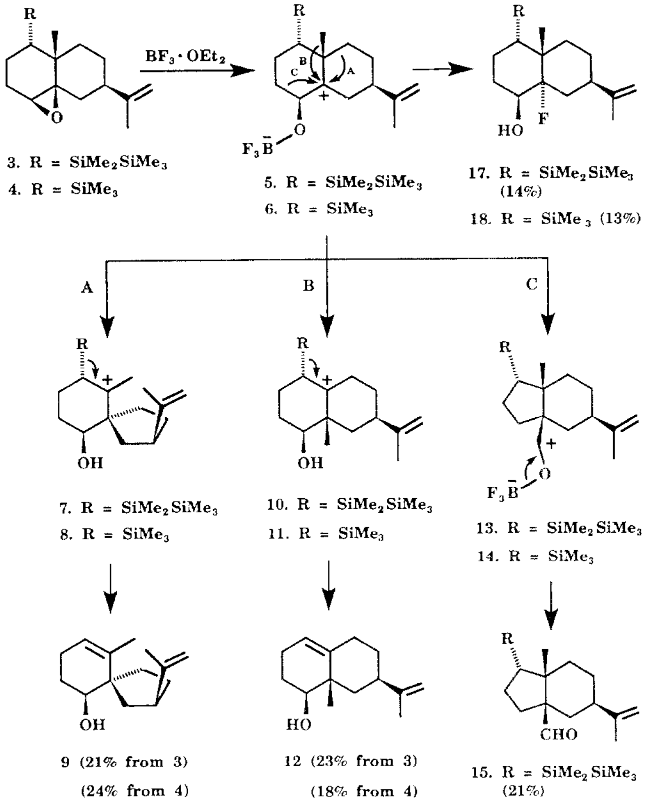
2. Results

2.1. Acid-catalyzed rearrangement of decalin epoxides

Upon treatment with Lewis acid, decalin epoxides **3** and **4** would give tertiary carbocations **5** and **6**, respectively (Scheme 1). Because the R group in **5** and **6** can stabilize a β carbocation, the B-ring residue (pathway A) or the angular methyl group (pathway B) could undergo a 1,2 migration to give thermodynamically more stable carbocations, such as **7**, **8**, **10**, and **11**. Then elimination of the R group would occur to lead to alcohols **9** and **12**. Alternatively, A-ring contraction [18,19] may take place in **5** and **6** to give aldehydes **15** and **16**, respectively, via intermediates **13** and **14** (pathway C). It is also possible that nucleophile F^- attacks carbocations **5** or **6** to give fluorohydrins **17** and **18**, respectively [20].

To investigate the similarities and differences between the Me_3SiMe_2Si– and the Me_3Si– groups, we need conditions that could convert epoxides **3** and **4** to several products in reasonable yields for each, instead of one major product in a high yield. We therefore treated disilanyl epoxide **3** with 1.3 equivalents of $BF_3 \cdot Et_2O$ in CH_2Cl_2 at −50°C (Scheme 1). The mixture was worked up and separated by silica gel chromatography to give four products: spirocyclic dienol **9** in 21% yield, decalinol **12** in 23% yield, aldehyde **15** in 21% yield, and fluorohydrin **17** in 14% yield.



Scheme 1.

Spirocyclic dienol **9** displayed in its ^{13}C NMR spectrum a characteristic singlet at δ 50.620 ppm, which indicates the quaternary carbon of a spiro ring system. In its ^1H NMR spectrum, a broad peak at δ 1.73 ppm integrated for 6 protons reveals the presence of two allylic methyl groups. Decalinol **12** showed in its ^1H NMR spectrum a singlet at δ 1.06 ppm for the angular methyl group.

Aldehyde **15** exhibited in its ^1H NMR spectrum a singlet at δ 9.66 ppm for the angular formyl proton, a singlet at δ 1.13 ppm for the angular methyl group, a singlet at δ 0.07 ppm with 9 protons for the $Si(CH_3)_3$ group, and two singlets at δ 0.08 ppm and 0.10 ppm with 3 protons each for the two CH_3 groups of the $Si(CH_3)_2$ moiety. The IR spectrum of **15** showed an absorption at 2720 cm^{-1} for an aldehydic C–H stretching and an absorption at 1720 cm^{-1} for a C=O stretching.

Fluorohydrin **17** displayed in its ^1H NMR spectrum a doublet (J(H–C–C–F) = 24 Hz) of multiplets at δ 3.28–4.30 ppm for the HC(OH)CF methine proton. The angular methyl group showed a doublet (J = 2.0 Hz) at δ 1.16 ppm; the splitting was attributed to a fluorine atom four bonds away. The ^{19}F NMR spectrum of **17** contained a broad doublet (J = 24 Hz) at δ −175.16 ppm relative to $CFCl_3$. This observation supports our assignment of **17** as a tertiary fluoride with hydrogens vicinal to the fluorine atom.

We subjected trimethylsilyl epoxide **4** to the same acidic conditions (*i.e.*, $BF_3 \cdot Et_2O$) used for the disilanyl epoxide **3** (Scheme 1). Four compounds were isolated: spirocyclic dienol **9** in 24% yield, decalinol **12** in 18% yield, aldehyde **16** in 23% yield, and fluorohydrin **18** in 13% yield.

Aldehyde **16** exhibited similar spectroscopic characteristics as those for aldehyde **15** except that the ^1H NMR spectrum of **16** showed a singlet at δ 0.03 ppm for the $Si(CH_3)_3$ protons. Fluorohydrin **18**, similar to **17**, displayed in its ^1H NMR spectrum a doublet (J(H–C–C–F) = 26 Hz) of multiplets at δ 3.33–4.29 ppm for the HC(OH)CF methine proton. The angular methyl group was also split by the fluorine atom four bonds away to give a doublet (J = 2.1 Hz) at δ 1.16 ppm. In addition, a singlet at δ 0.05 ppm belonged to the protons of the $Si(CH_3)_3$ group. The ^{19}F NMR spectrum of **18** contained a broad doublet (J = 26 Hz) at δ −175.38 pm relative to $CFCl_3$.

2.2. Reaction of Me_3SiMe_2SiLi and Me_3SiLi with a cross-conjugated dienone

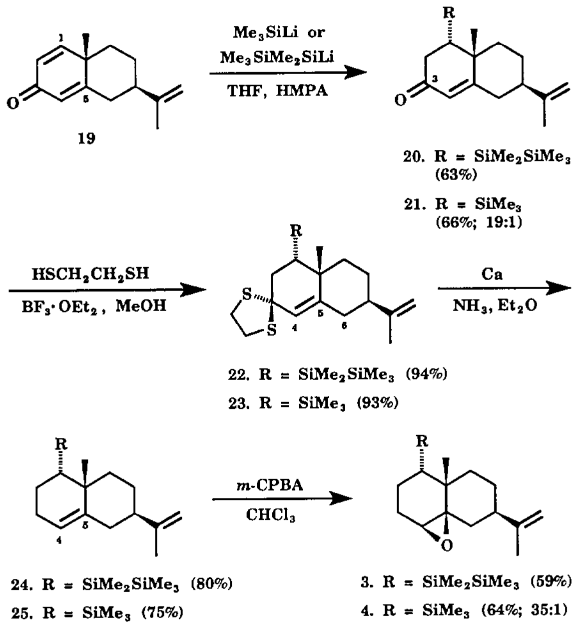
1,4-Addition of a silyl anion to an α,β-unsaturated enone moiety is an efficient way to introduce the Me_3SiMe_2Si– and Me_3Si– groups into a molecule. To the best of our knowledge, few reports are related to reactions of $Me_3SiMe_2Si^-$ with an enone and Me_3Si^- with a cross-conjugated dienone [21].

To explore the difference between the Me_3SiMe_2Si– and Me_3Si– groups towards steric influence, we reacted Me_3SiMe_2SiLi and Me_3SiLi separately with cross-conjugated dienone **19** [22,23]. Treatment of Me_3SiMe_2SiLi, generated from $Me_3SiSiMe_3$ and MeLi in HMPA [24] with **19** in THF at −78°C afforded enone **20** in 63% yield as the only 1,4 adduct (Scheme 2).

On the other hand, reaction of Me_3SiLi with **19** under the same conditions gave a mixture of 1,4 adducts. The GC chromatogram of the crude product mixture showed two peaks with a 19:1 ratio. The major component with t_R 6.82 min was separated in 66% yield by medium pressure liquid column chromatography and identified as the α-$SiMe_3$ enone **21**. The small peak with t_R 7.39 min from a unisolable component was assigned to the β-epimer of **21**, in which all three ring substituents were *cis*.

2.3. Epoxidation of Me_3SiMe_2Si- and Me_3Si-containing cyclohexenes

Epoxidation of dienes **24** and **25** with *m*-CPBA should occur preferentially at the more electron-rich



Scheme 2.

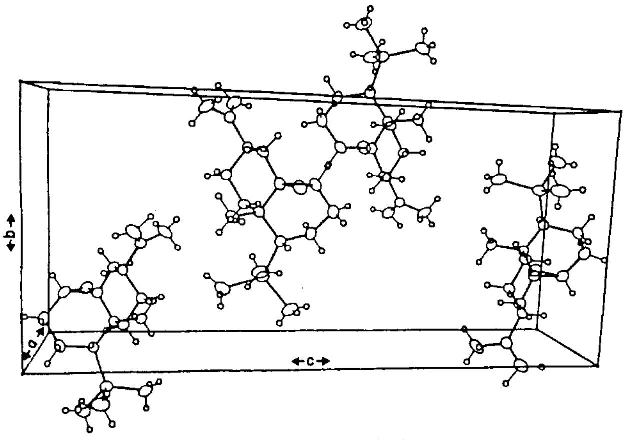


Fig. 1. Unit cell of the crystal lattice of (−)-**4**.

trisubstituted C–C double bond [25] instead of at the isopropenyl unit. Furthermore, we considered that the bulky R group with α configuration in dienes **24** and **25** may prevail over the angular methyl group located on the opposite side in directing epoxidation to give the corresponding β-epoxides as the major products.

By reacting diene **24** with *m*-CPBA in $CHCl_3$ at −10°C [25], we obtained β-monoepoxide **3** (59%) exclusively. Its ^1H NMR spectrum showed a broad doublet ($J = 5.1$ Hz) at δ 2.98 ppm for the oxirane C–H proton.

Under similar epoxidation conditions, diene **25** gave a mixture of α- (t_R 8.86 min) and β-4,5-monoepoxides (t_R 9.17 min) in a ratio of $\leq 1:35$, as determined by GC (Scheme 2). The β-4,5-monoepoxide **4** was isolated in 64% yield [26]. We confirmed its structural assignment by using single crystal X-ray diffraction analysis of a white crystal of (–)-**4** (mp 76.5–77.0°C). The results showed that the angular methyl group in (–)-**4** was *trans* to the Me_3Si– group and *cis* to the epoxy oxygen. Crystals of this epoxide, grown from a THF solution, belonged to the orthorhombic space group $P2_12_12_1$. Four molecules composed the unit cell, which had lattice constants $a = 6.2510$ Å, $b = 11.5720$ Å, and $c = 24.1960$ Å. Figure 1 illustrates the unit cell of the crystal lattice.

2.4. Preparation of substrates for the key reactions

We outline our methods in Scheme 2 for the syntheses of compounds used for the key transformations. After trienone **19** [22,23] was converted to disilanyl enone **20**, it was reacted with 1,2-ethanedithiol and $BF_3 \cdot OEt_2$ in methanol [27] to give **22** in 94% yield. The C_4–C_5 double bond in **22** did not shift to the C_5–C_6 position, as indicated by the ^1H NMR spectrum which contained a broad singlet at δ 5.65 ppm for a vinylic proton. Lack of splitting larger than 2 Hz for this signal showed that the vinylic proton did not have a vicinal hydrogen.

Reaction of **22** with 6.0 equivalents of calcium [28] in liquid ammonia with ether as co-solvent gave the desired diene **24** in 80% yield after purification (Scheme 2). In contrast, reduction of **22** with sodium in liquid ammonia produced **24** in 7% yield only. The major product of the latter reaction gave a peak at δ 0.21 ppm with 6 protons in the ^1H NMR spectrum. We attributed this signal to the methyl protons of an $Si(CH_3)_2$ group. Nevertheless, this spectrum contained no signal assignable to an $Si(CH_3)_3$ group. We believe that this major product arose from cleavage of the Si–Si bond in **22**. Thus, calcium is superior to sodium for the chemoselective reduction of the ethylene thioacetal moiety in the presence of the Me_3SiMe_2Si–group.

For the preparation of Me_3Si-containing diene **25** from dienone **19**, the procedure is similar to that for the Me_3SiMe_2Si-containing diene **24**. This is described in a previous paper [26].

3. Discussion

We found that, under the same conditions, both Me_3SiMe_2Si-epoxide **3** and Me_3Si-epoxide **4** reacted with $BF_3 \cdot OEt_2$ to give four products each: two of them are identical (*i.e.*, spirocyclic dienol **9** and decalinol **12**) and the other two are closely related (**15** *versus* **16** and **17** *versus* **18**). Formation of these products involves various steps as shown in Scheme 1. They included epoxide ring-opening, contraction of cyclohexane ring B (pathway A), elimination of a β-$SiMe_2SiMe_3$ or $SiMe_3$ group from a carbocation, 1,2 migration of the angular methyl group (pathway B), contraction of the cyclohexane ring A (pathway C), and trapping of carbocationic intermediates with F^-. The yields differed, however, by $\leq 5\%$ when the same products (*i.e.*, **9** and **12**) or closely related pairs (**15** *versus* **16** and **17** *versus* **18**) generated from these two reactions are compared. Thus, we conclude that the Me_3SiMe_2Si– and Me_3Si– groups have very similar electronic effects on carbocationic intermediates generated by acid-catalyzed rearrangement of decalin epoxides.

Cross-conjugated dienone **19** may react with a silyl anion at C_1 or C_5 position. The disubstituted C_5 sp^2 center is sterically more hindered than the monosubstituted C_1 sp^2 center, which offers both the α and β faces for the silyl anion to attack. The angular methyl group, however, creates steric congestion to prevent Me_3SiLi approaching from the β face. Our experimental results showed that Me_3SiLi reacted with dienone **19** at the C_1 position exclusively, but this reaction gave an epimeric mixture of α- and β-Me_3Si enones in a ratio of 19:1 (Scheme 2, **19** → **21**). Reagent Me_3SiMe_2SiLi is sterically more hindered than Me_3SiLi and thus provided only one (*i.e.*, α-disilanyl epoxide **20** in 63% yield) of the four possible adducts.

We successfully converted enones **20** and **21** to the corresponding thioacetals **22** and **23**, respectively, in excellent yields. These results indicate that the bulky Me_3SiMe_2Si– and Me_3Si– groups at the C_1 position of decenones (see **20** and **21**) did not hinder the C=O group at the C_3 position from being bisthiolated. On the other hand, we were able to utilize these bulky groups in decenes **24** and **25** to direct epoxidation. Silyl groups residing at the α face forced oxidizing agent *m*-CPBA to react with the C_4–C_5 double bond from the β face, which is blocked to some extent by the angular methyl group. The bulkier Me_3SiMe_2Si-moiety exhibited a potent directing effect and allowed decene **24** to be converted to epoxide **3** exclusively. The less bulky Me_3Si– group also gave the β-epoxide **4** as the major product in 64% yield, along with a small amount of α-epimer (α-epoxide : β-epoxide = 1 : 35).

4. Conclusions

In an acid-catalyzed rearrangement of silicon-containing epoxides, the Me_3SiMe_2Si– group was found to influence carbocationic intermediates electronically to the same extent as the Me_3Si– group. On the other hand, reagent Me_3SiMe_2SiLi exerted greater steric effect than reagent Me_3SiLi in 1,4-addition to a cross-conjugated dienone. The bulky Me_3SiMe_2Si-moiety on a cyclohexene ring can also fully direct oxidizing agent *m*-CPBA to react with the C=C double bond from the opposite side.

5. Experimental section

5.1. General

All reactions were carried out under a static atmosphere of nitrogen and stirred magnetically unless otherwise noted. For anhydrous reactions, glassware was dried overnight in an oven at 120°C and cooled in a desiccator over anhydrous $CaSO_{4(s)}$ or silica gel. Unless otherwise stated, reagents were purchased from Aldrich or prepared as noted. Dry ether and tetrahydrofuran (THF) were obtained by distillation from the sodium ketyl of benzophenone under nitrogen. Other solvents, including chloroform, dichloromethane, ethyl acetate and hexanes, were distilled over CaH_2 under nitrogen. Absolute methanol was purchased from Baker and used as received.

Melting points were obtained with a Büchi 510 melting point apparatus. Infrared (IR) spectra were recorded on either a Perkin-Elmer Model 599B spectrophotometer or a Perkin-Elmer Model 1600 Fourier transform spectrophotometer. The wavenumbers reported are referenced to the 1601 cm^{-1} absorption of polystyrene. Infrared absorption intensities are designated by use of the following abbreviations: s, strong; m, medium; w, weak. Proton NMR spectra were obtained on either a Varian CFT-20 (80 MHz) or a Varian XL-400 (400 MHz) spectrometer. Chloroform-*d* was used as solvent; either Me_4Si (δ 0.00 ppm) or $CHCl_3$ (δ 7.26 ppm) was used as an internal standard. Carbon-13 NMR spectra were recorded on a Varian XL-400 spectrometer at 101 MHz. Chloroform-*d* was used as solvent. Carbon-13 chemical shifts are referenced to the center of the $CDCl_3$ triplet (δ 77.0 ppm). Fluorine-19 NMR spectra were obtained on a Varian XL-400 spectrometer at 376 MHz. Chloroform-*d* was used as solvent and $CFCl_3$ (δ 0.00 ppm) was used as an internal standard. All NMR chemical shifts are reported as δ values in parts per million (ppm) and coupling constants (J) are given in Hertz. The splitting pattern abbreviations are as follows: s, singlet; d, doublet; t, triplet; q, quartet; br, broad; m, unresolved multiplet; dd, doublet of doublets; dm, doublet of multiplets. Mass spectral analyses were recorded on an AEI MS-30 spectrometer at the University of Minnesota Mass Spectral Service Laboratory or a VG-70S spectrometer at The Johns Hopkins University Mass Spectrometry Facility. Gas chromatographic analyses were performed on a Hewlett-Packard 5794A instrument equipped with a 12.5 m cross-linked methylsilicone gum capillary column (0.2 mm i.d.). The injector and detector temperatures were set at 260°C and 270°C, respectively. Medium pressure liquid chromatography (MPLC) separations were performed at a flow rate of 60 ml/h by use of an ISCO Model 312 Metering Pump [29]. The columns were packed with EM Reagents Silica Gel 60 (particle size 0.040–0.063 mm, 230–400 mesh ASTM). Purification on silica gel refers to gravity column chromatography on EM Reagents Silica Gel 60 (particle size 0.063–0.200 mm, 70–230 mesh ASTM). Column dimensions for gravity and MPLC columns are listed as diameter × height. Analytical TLC was performed on Silica Gel GHLF precoated plates (Analtech). Compounds were visualized by use of UV light, I_2 vapor and/or 2.5% phosphomolybdic acid in ethanol with heating. Mixtures of ethyl acetate and hexanes were used as eluants, except where noted.

5.2. (5S,6R,9R)-9-Isopropenyl-6-methyl-5-(1,1,2,2,2-pentamethyldisilanyl)bicyclo[4.4.0]dec-1-en-3-one (20)

A solution of hexamethyldisilane (95% pure, 3.72 ml, 17.3 mmol, 3.8 equiv) in hexamethylphosphoramide (1.6 ml) was cooled to 0°C under argon. Low-halide methyllithium (1.8 M in ether, 7.7 ml, 13.8 mmol, 3.0 equiv) and THF (8.0 ml) was injected dropwise into the reaction flask and the resultant red solution was stirred for 30 min at 0°C. Ice-cold THF (70 ml) was added to the reaction mixture via cannula, and the solution was cooled to −78°C. To this yellow-green solution was added a solution of trienone **19** [22] (930.8 mg, 4.601 mmol, 1.0 equiv) in THF (7.0 ml). The resultant dark blue-green solution was stirred at −78°C for 1.8 h. Water was added to the reaction flask and the mixture was warmed to room temperature. The mixture was concentrated, and ether was added to the residue. The ether solution was washed with water and brine, dried over $MgSO_{4(s)}$, filtered, and concentrated. Purification of the residue by MPLC (2.2 × 30 cm column, 4% EtOAc in hexanes as eluant) provided **20** as a yellow oil in 63% yield (963.6 mg, 2.88 mmol): TLC R_f 0.53 (20% EtOAc in hexanes); GC t_R 10.46 min (column temperature program: initial temperature 170°C, duration 3.0 min; increment rate 10°C/min; final temperature 210°C); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.10 (s, 9H, $Si(CH_3)_3$), 0.13 (s, 3H, $CHSiCH_3$), 0.14 (s, 3H, $CHSiCH_3$), 1.18–2.57 (m, 10H, $4 \times CH_2 + 2 \times CH$), 1.29 (s, 3H, CH_3), 1.75 (br s, 3H, $CH_3C{=}C$), 4.76 (br s, 2H, $C{=}CH_2$), 5.79 (br s, 1H, C=CH–C=O); IR (neat) 3080w (=C–H), 2925s, 1670s (conjugated C=O), 1620m (conjugated C=C), 1440m, 1375m, 1255s ($SiMe_3$), 890m (=CH_2), 845s ($SiMe_3$), 810m cm^{-1}; exact mass calcd. for $C_{19}H_{34}OSi_2$ 334.2148, found 334.2149.

5.3. (5S,6R,9R)-9-Isopropenyl-6-methyl-5-(1,1,2,2,2-pentamethyldisilanyl)bicyclo[4.4.0]dec-1-en-3-one 3-ethylene thioacetal (22)

Dienone **20** (104 mg, 0.310 mmol, 1.0 equiv) and 1,2-ethanedithiol (96% pure, 34 μl, 0.39 mmol, 1.3 equiv) were dissolved in MeOH (3.0 ml) in a flask equipped with a KOH drying tube. Boron trifluoride etherate (49 μl, 57 mg, 0.40 mmol, 1.3 equiv) was added dropwise into the reaction flask and the mixture was stirred at room temperature for 4 h. The reaction was quenched by addition of saturated aqueous $NaHCO_3$. The mixture was concentrated and ether was added to the residue. The ether solution was washed with saturated aqueous $NaHCO_3$ and brine, dried over $MgSO_{4(s)}$, filtered and concentrated. The residual cloudy yellow oil (127 mg) was chromatographed on silica gel (10 × 60 mm column) with 1% EtOAc in hexanes as eluant to provide **22** as a colorless oil in 94% yield (120 mg, 0.292 mmol): TLC R_f 0.65 (10% EtOAc in hexanes); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.12 (s, 12H, $Si(CH_3)_3 + CHSiCH_3$), 0.18 (s, 3H, $CHSiCH_3$), 0.97–2.48 (m, 10H, $4 \times CH_2 + 2 \times CH$), 1.13 (s, 3H, CH_3), 1.72 (t, $J = 1.0$ Hz, 3H, $CH_3C{=}C$), 3.17–3.53 (m, 4H, SCH_2CH_2S), 4.70 (br s, 2H, $C{=}CH_2$), 5.65 (br s, 1H, HC=C); IR (neat) 3070w(=C–H), 2910s, 2850s, 1670w (C=C), 1645m (C=C), 1440m, 1375m, 1250s ($SiMe_3$), 890m (=CH_2), 840s ($SiMe_3$), 805s, 765m, 745m, 730m, 695m cm^{-1}; exact mass calcd. for $C_{20}H_{35}S_2Si_2$ ($M^{+\cdot} - CH_3$) 395.1719, found 395.1724.

*5.4. (5S,6R,9R)-9-Isopropenyl-6-methyl-5-(1,1,2,2,2-pentamethyldisilanyl)bicyclo[4.4.0]dec-1-ene (**24**)*

Calcium metal (99.5% pure, 1.02 g, 25.2 mmol, 6.0 equiv) was dissolved in liquid ammonia (125 ml) at −78°C under an argon atmosphere in a three-necked flask equipped with a dry ice-acetone cooled Dewar condenser [28]. To this blue solution was added ether (38 ml) and a solution of ethylene thioacetal **10** (1.73 g, 4.21 mmol, 1.0 equiv) in ether (12 ml). The cooling bath was removed and the deep blue solution was refluxed for 1 h. Solid NH_4Cl was added cautiously to the reaction flask, followed by ether (50 ml), and the ammonia was allowed to evaporate overnight. Saturated aqueous NH_4Cl was added to the residue, and the aqueous phase was extracted with three portions of ether. The combined ether solutions were washed with saturated aqueous NH_4Cl, 10% aqueous NaOH, and brine, dried over $MgSO_{4(s)}$, filtered through Celite, and concentrated. The residue was purified by chromatography on silica gel (19 × 95 mm column) with hexanes as eluant to afford **24** as a colorless oil in 80% yield (1.08 g, 3.37 mmol): TLC R_f 0.58 (hexanes); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.08 (s, 9H, $Si(CH_3)_3$), 0.11 (s, 3H, $CHSiCH_3$), 0.13 (s, 3H, $CHSiCH_3$), 0.73–2.26 (m, 12H, $5 \times CH_2 + 2 \times CH$), 1.14 (s, 3H, CH_3), 1.73 (t, J = 1.0 Hz, 3H, CH_3C=C), 4.69 (br s, 2H, C=CH_2), 5.41 (m, 1H, HC=C); IR (neat) 2920s, 2855s, 1640w, (C=C), 1460m, 1375m, 1250s ($SiMe_3$), 890m (=CH_2), 835s ($SiMe_3$), 805s, 725m, 690m cm^{-1}; exact mass calcd. for $C_{19}H_{32}Si_2$ 320.2356, found 320.2360.

*5.5. (1R,2S,5S,6R,8R)-5,6-Epoxy-8-isopropenyl-1-methyl-2-(1,1,2,2,2-pentamethyldisilanyl)bicyclo[4.4.0]decane (**3**)*

A solution of *m*-CPBA (80–85% pure, 64.3 mg, ~ 0.31 mmol, 1.3 equiv) in $CHCl_3$ (1.5 ml) was added dropwise to a solution of **24** (77 mg, 0.24 mmol, 1.0 equiv) in $CHCl_3$ (2.0 ml) at −10°C. The resultant white slurry was stirred at the same temperature for 3 h. Aqueous NaOH (10%) and ether were added and the mixture was warmed to room temperature. The organic layer was washed with 5% aqueous Na_2CO_3 and brine, dried over $MgSO_{4(s)}$, filtered, and concentrated. The residual yellow oil (77 mg) was purified by MPLC (1.5 × 30 cm column) with 2% EtOAc in hexanes as eluant to afford **3** as a colorless oil in 59% yield (48 mg, 0.14 mmol): TLC R_f 0.59 (10% EtOAc in hexanes); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.07 (s, 12H, $Si(CH_3)_3$ + $CHSiCH_3$), 0.09 (s, 3H, $CHSiCH_3$) 0.62–2.16 (m, 12H, $5 \times CH_2 + 2 \times CH$), 1.16 (s, 3H, CH_3), 1.72 (t, J = 1.1 Hz, 3H, CH_3C=C), 2.98 (br d, J = 5.1 Hz, 1H, HCO), 4.70 (br s, 2H, C=CH_2); IR (CCl_4) 2945s, 2860m, 1640w (C=C), 1440m, 1380w, 1250s (epoxide), 940m (epoxide), 915m, 900m (=CH_2), 840s ($SiMe_3$) cm^{-1}; MS m/e (relative intensity) 336 (M^+, 15), 263 (22), 247 (10), 187 (18), 147 (30), 145 (19), 133 (17), 132 (13), 131 (69), 119 (13), 117 (13), 107 (12), 105 (14), 91 (11), 75 (100), 73 (71), 59 (16); exact mass calcd. for $C_{19}H_{36}OSi_2$ 336.2305, found 336.2314.

*5.6. Reaction of (1R,2S,5S,6R,8R)-5,6-epoxy-8-isopropenyl-1-methyl-2-(1,1,2,2,2-pentamethyldisilanyl)bicyclo[4.4.0]decane (**3**) with $BF_3 \cdot Et_2O$*

Boron trifluoride etherate (222 μl, 257 mg, 1.81 mmol, 1.3 equiv) was added dropwise to a solution of epoxide **3** (479.7 mg, 1.425 mmol, 1.0 equiv) in CH_2Cl_2 (36 ml) at −50°C. The mixture was stirred at the same temperature for 20 h. Saturated aqueous $NaHCO_3$ (1.0 ml) was added to the reaction flask and the mixture was poured into ether. The organic layer was washed with saturated aqueous $NaHCO_3$ and brine, dried over anhydrous $MgSO_{4(s)}$, filtered, and concentrated to give a yellow oil (403.9 mg). This oil was purified by MPLC (1.5 × 30 cm column) with 5% EtOAc in hexanes as eluant to afford (2*R*,5*R*,10*S*)-2-isopropenyl-6-methylspiro[4.5]dec-6-en-10-ol (**9**) as a white solid in 21% yield (61.8 mg, 0.299 mmol), (5*S*,6*S*,8*R*)-8-isopropenyl-6-methylbicyclo[4.4.0]dec-1-en-5-ol (**12**) as a white solid in 23% yield (68.3 mg, 0.331 mmol), (1*R*,3*R*,6*R*,7*S*)-3-isopropenyl-6-methyl-7-(1,1,2,2,2-pentamethyldi-silanyl) bicyclo[4.3.0]nonane-1-carbaldehyde (**15**) as a white solid in 21% yield (101.1 mg, 0.300 mmol), and (1*R*,2*S*,5*S*,6*S*,8*R*)-6-fluoro-8-isopropenyl-1-methyl-2-(1,1,2,2,2-pentamethyldisilanyl)bicyclo[4.4.0]decan-5-ol (**17**) as a white solid in 14% yield (72.8 mg, 0.204 mmol).

For **9**: mp 43.0–45.0°C; TLC R_f 0.24 (20% ether in hexanes); GC t_R 4.30 min (column temperature program: initial temperature 150°C, duration 5.0 min; increment rate 10°C/min; final temperature 170°C); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.65–2.80 (m, 11H, $5 \times CH_2$ + $1 \times CH$), 1.73 (m, 6H, $2 \times CH_3C$=C), 3.63 (m, 1H, HCO), 4.72 (br s, 2H, C=CH_2), 5.31 (m, 1H, HC=C); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 19.565 (q), 21.376 (q), 22.960 (t), 27.598 (t), 32.425 (t), 35.725 (t), 36.810 (t), 47.478 (d, C_2), 50.620 (s, C_5), 74.239 (d, C_{10}), 108.199 (t, C_{12}), 120.969 (d, C_7), 138.758 (s, C_6), 148.329 (s, C_{11}); IR (melt) 3540–3120m (O–H), 3076w (=C–H), 2930s, 2860s, 1642m (C=C), 1445m, 1376m, 1048m (C–O), 888m (=CH_2), 801w cm^{-1}; exact mass calcd. for $C_{14}H_{22}O$ 206.1671, found 206. 1672.

For **12**: mp 76.0–79.0°C; TLC R_f 0.19 (20% ether in hexanes); GC t_R 4.30 min (column temperature program: initial temperature 150°C, duration 5.0 min; increment rate 10°C/min; final temperature 170°C); ^1H NMR ($CDCl_3$, 80 MHz) δ 1.06 (s, 3H, CH_3), 1.20–2.61 (m, 11H, 5 × CH_2 + 1 × CH), 1.73 (br s, 3H, CH_3C=C), 3.40–3.78 (m, 1H, HC–O), 4.72 (br s, 2H, C=CH_2), 5.29 (m, 1H, HC=C); IR (CCl_4) 3615w (free O–H), 3590–3365w (H-bonded O–H), 3080w (=C–H), 3043w (=C–H), 2940s, 2865m, 1644m (C=C), 1441m, 1376m, 1047m (C–O), 958w, 895s (=CH_2) cm^{-1}; exact mass calcd. for $C_{14}H_{22}O$ 206.1671, found 206.1674.

For **15**: mp 39.5–41.0°C; TLC R_f 0.64 (10% EtOAc in hexanes); GC t_R 13.73 min (column temperature program: initial temperature 150°C, duration 7.0 min; increment rate 10°C/min; final temperature 210°C); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.07 (s, 9H, $Si(CH_3)_3$), 0.08 (s, 3H, $CHSiCH_3$), 0.10 (s, 3H, $CHSiCH_3$), 0.63–2.21 (m, 11H, 5 × CH_2 + 1 × CH), 1.13 (s, 3H, CH_3), 1.74 (br s, 3H, CH_3C=C), 4.74 (br s, 2H, C=CH_2), 9.66 (s, 1H, CHO); IR (melt) 3070w (=C–H), 2940s, 2870m, 2720w (H–C=O), 1720s (C=O), 1645w (C=C), 1440m, 1370m, 1250s ($SiMe_3$), 895m (=CH_2), 870m, 840s ($SiMe_3$), 800s, 730w, 690m, 660w cm^{-1}; exact mass calcd. for $C_{19}H_{36}OSi_2$ 336.2305, found 336.2306.

For **17**: mp 80.5–81.0°C; TLC R_f 0.22 (10% EtOAc in hexanes); GC t_R 15.40 min (column temperature program: initial temperature 150°C, duration 7.0 min; increment rate 10°C/min; final temperature 210°C); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.08 (s, 12H, $Si(CH_3)_3$ + $CHSiCH_3$), 0.11 (s, 3H, $CHSiCH_3$), 1.00–2.56 (m, 11H, 5 × CH_2 + 1 × CH), 1.16 (d, $J = 2.0$ Hz, 3H, CH_3), 1.74 (br s, 3H, CH_3C=C), 3.28–4.30 (dm, $J = 24$ Hz, 1H, HCO), 4.74 (br s, 2H, C=CH_2); ^{19}F NMR ($CDCl_3$, 376 MHz) δ −175.16 (br d, $J = 24$ Hz); IR (neat) 3400–3000m (O–H), 3070w (=C–H), 2940s, 2870m, 1645w (C=C), 1455m, 1250s ($SiMe_3$), 1070s, 1000w, 975w, 935w, 915m, 895m (=CH_2), 870m, 840s ($SiMe_3$), 805s, 730m, 690m, 625m cm^{-1}; exact mass calcd. for $C_{19}H_{37}FOSi_2$ 356.2367, found 356.2373.

5.7. Reaction of (1R,2S,5S,6R,8R)-5,6-epoxy-8-isopropenyl-1-methyl-2-(trimethylsilyl)bicyclo[4.4.0]decane (4) with $BF_3 \cdot Et_2O$

Boron trifluoride etherate (18.4 μl, 21.2 mg, 0.150 mmol, 1.3 equiv) was added dropwise to a solution of epoxide **4** [26] (32.8 mg, 0.118 mmol, 1.0 equiv) in CH_2Cl_2 (2.9 ml) at −50°C. The mixture was stirred at the same temperature for 22 h. Saturated aqueous $NaHCO_3$ (1.0 ml) was added into the reaction flask and the mixture was poured into ether. The organic layer was washed with saturated aqueous $NaHCO_3$ and brine, dried over anhydrous $MgSO_{4(s)}$, filtered, and concentrated to give a colorless oil (27.5 mg). This oil was purified by chromatography on silica gel (7 × 200 mm column) with 5% ether in hexanes as eluant to afford **9** as a white solid in 24% yield (5.8 mg, 0.028 mmol), **12** as a white solid in 18% yield (4.4 mg, 0.021 mmol), (1*R*,3*R*,6*R*,7*S*)-3-isopropenyl-6-methyl-7-(trimethylsilyl)bicyclo[4.3.0]nonane-1-carbaldehyde (**16**) as a white amorphous solid in 23% yield (7.5 mg, 0.027 mmol), and (1*R*,2*S*,5*S*,6*S*,8*R*)-6-fluoro-8-isopropenyl-1-methyl-2-(trimethylsilyl)bicyclo[4.4.0]decan-5-ol (**18**) as a white solid in 13% yield (4.4 mg, 0.015 mmol). The physical and spectroscopic characteristics of compounds **9** and **12** were identical with those obtained from the reaction of **3** with $BF_3 \cdot Et_2O$ in CH_2Cl_2.

For **16**: mp 35.0–37.0°C; TLC R_f 0.70 (20% ether in hexanes); GC t_R 8.89 min (column temperature program: initial temperature 150°C, duration 5.0 min; increment rate 10°C/min; final temperature 170°C); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.03 (s, 9H, $Si(CH_3)_3$), 0.70–2.30 (m, 11H, 5 × CH_2 + 1 × CH), 1.14 (s, 3H, CH_3), 1.74 (t, $J = 1.0$ Hz, 3H, CH_3C=C), 4.74 (br s, 2H, C=CH_2), 9.65 (s, 1H, CHO); IR (melt) 3078w (=C–H), 2940s, 2866m, 2722w (H–C=O), 1719s (C=O), 1645m (C=C), 1441m, 1381m 1253s ($SiMe_3$), 1202w, 1174w, 961w, 918m, 893m (=CH_2), 856s, 839s ($SiMe_3$), 758m, 692m cm^{-1}; exact mass calcd. for $C_{17}H_{30}OSi$ 278.2066, found 278.2068.

For **18**: mp 151.0–153.0°C; TLC R_f 0.27 (20% ether in hexanes); GC t_R 11.57 min (column temperature program: initial temperature 150°C, duration 5.0 min; increment rate 10°C/min; final temperature 170°C); ^1H NMR ($CDCl_3$, 80 MHz) δ 0.05 (s, 9H, $Si(CH_3)_3$), 0.71–2.62 (m, 11H, 5 × CH_2 + 1 × CH), 1.16 (d, $J = 2.1$ Hz, 3H, CH_3), 1.74 (t, $J = 0.9$ Hz, 3H, CH_3C=C), 3.33–4.29 (dm, $J = 26$ Hz, 1H, HCO), 4.74 (br s, 2H, C=CH_2); ^{19}F NMR ($CDCl_3$, 376 MHz) δ −175.38 (br d, $J = 26$ Hz); IR (melt) 3400–3100m (OH), 3080w (=C–H), 2935s, 2870m, 1645w (C=C), 1457m, 1379w, 1254s ($SiMe_3$), 1159w, 1070s, 998w, 939w, 918s, 892m (=CH_2), 858s, 839s ($SiMe_3$), 762w, 742m, 682w cm^{-1};

TABLE 1. Crystallographic data for (−)-**4**

chem formula	$C_{17}H_{30}OSi$	Z	4
fw	279.51	T, °C	23
space group	$P2_12_12_1$	λ(Mo Kα), Å	0.71069
a, Å	6.251(2)	ρ_{calc}, $g.cm^{-3}$	1.33
b, Å	11.572(4)	μ(Mo Kα), cm^{-1}	1.402
c, Å	24.196(6)	V, $Å^3$	1750.3(16)
No. refl collected	2362	No. obs > 3σ(I)	1107
No. variables	274	refinement	full matrix l.s.
R [a]	0.0420	R_w [b]	0.0427

[a] $R = \Sigma \| F_o | - | F_c \| / \Sigma | F_o |$.

[b] $R_w = [\Sigma w(|F_o| - |F_c|)^2 / \Sigma w |F_o|^2]^{1/2}$, $w = 1/\sigma^2 (|F_o|)$.

MS *m/e* (relative intensity) 298.3 (M^+, 4), 283 (12), 188 (18), 145 (27), 107 (61), 73 (100).

5.8. (−)-(1R,2S,5S,6R,8R)-5,6-Epoxy-8-isopropenyl-1-methyl-2-(trimethylsilyl)bicyclo[4.4.0]decane ((−)-4) [26].

The crystal was mounted on a Nicolet P3m microprocessor controlled diffractometer in a random orientation. Cell constants, space group, and reflection data were obtained and processed by normal methods [30] (see Table 1). The structure was solved by direct methods and refined by full matrix least squares. All non-hydrogen atoms were refined anisotropically, while the hydrogen atoms, which were located from difference Fourier maps, were refined isotropically.

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