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Synthesis of 3-Methylenecyclohexan-1-ols by Lewis Acid Catalyzed Cyclization of (Epoxy–allyl)silanes

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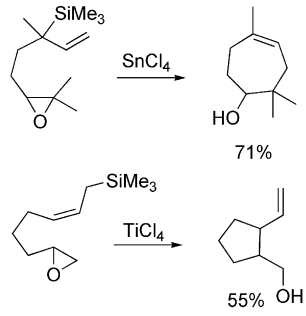
A new route for the synthesis of (epoxy–allyl)silanes bearing the $PhMe_2Si$ group has been developed and their acid-catalyzed cyclization studied. The so-called normal products derived from 5-*exo* or 6-*endo* attack were never obtained. On the contrary, an interesting tandem rearrangement/cyclization process was observed, which selectively led to 3-methylenecyclohexan-1-ols. A mechanism is proposed to explain this tandem reaction. The stereoselectivity of the cyclization process depends on the nature of the catalyst.

Introduction

Most biologically active molecules contain quite complex ring skeletons. Among them, polycyclic natural products containing cyclopentanoid, cyclohexanoid and cycloheptanoid systems are abundant in nature, for example, himachalane and perforenone sesquiterpenes. The structural diversity of these compounds has provided many challenges for synthetic chemists and has inspired many creative procedures for the stereoselective synthesis of medium-sized carbocyclic rings.[1] Cyclization strategies to give medium-sized rings are often inhibited by entropic factors and transannular interactions.[2] Moreover, a flexible route using simple reagents and mild conditions that allows the synthesis of different-sized carbocycles is a valuable alternative.

During the past few decades, the importance of silicon-containing compounds has increased tremendously due to their use as versatile building blocks in a variety of synthetic transformations.[3] Moreover, organosilanes have often been used in the synthesis of natural products to control the stereochemistry of reactions taking place in their neighbourhood.[4] In particular, allylsilanes have proved to be one of the most useful reagents in the construction of carbo- and heterocyclic compounds. Our contribution to this active field has focused on developing new procedures for five-, six- or seven-membered ring annulations using allylsilane chemistry.[5]

However, the corresponding acid-catalyzed cyclization of allylsilanes containing an epoxide group has attracted less attention. It has been observed, as a general trend, that the reaction involves nucleophilic ring-opening of the epoxide group, activated by the Lewis acid, proceeding through the most stable carbocation[6,7] (Scheme 1).



Scheme 1. Lewis acid catalyzed cyclization of (epoxy–allyl)silanes.

In a preliminary communication, we showed that (epoxy–allyl)silanes bearing a dimethyl(phenyl)silyl group undergo Lewis acid catalyzed cyclization reactions to give 3-methylenecyclohexan-1-ols.[8] We now present in full the results of this methodology, together with a discussion of the factors governing the stereocontrol of the process, and report new examples reflecting the influence of the silyl group ($PhMe_2Si$ vs. Me_3Si) and the substitution of the epoxide on the course of the reaction.

Results and Discussion

The synthesis of allylsilanes[9] and -stannanes[10] by the metallocupration of allenes and their synthetic applications have been the subject of intense study in our group for the last decade. In particular, the reaction of allene with the lower order cyano(silyl)cuprate $PhMe_2SiCu(CN)Li$ involves addition of copper to the central carbon atom and a silicon

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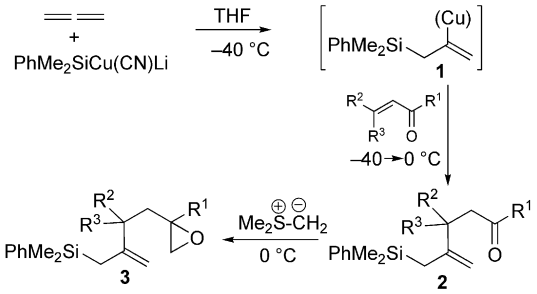
atom to the terminal carbon atom of the allenic system to form intermediates of type **1**, which, in the presence of α,β-unsaturated oxo compounds undergo Michael addition reactions to yield (oxo–allyl)silanes **2a**–**g** (Table 1). All the reactions were carried out in the presence of $BF_3{\cdot}OEt_2$ or TMSCl, which considerably increased the yield (Table 1). Subsequent reaction of compounds **2a**–**g** with dimethylsulfonium methylide gave (epoxy–allyl)silanes **3a**–**g** as mixtures of diastereomers (Table 1).

Table 1. Synthesis of (epoxy–allyl)silanes **3a**–**g** by silylcupration of allene.



Entry	R^1	R^2	R^3	Yield [%] **2**	**3**
a	Me	Ph	H	90[a]	72
b	Me	Me	Me	87[a]	78
c	Et	Me	H	82[a]	65
d	Et	H	H	80[b]	76
e	*i*Pr	H	H	70[b]	68
f	H	H	H	91[b]	75
g	H	Me	H	83[b]	67

[a] $BF_3{\cdot}Et_2O$ was used as catalyst. [b] TMSCl was used as catalyst.

For the acid-mediated cyclization of (epoxy–allyl)silanes **3** we used 1 equiv. of the appropriate Lewis acid and dichloromethane as solvent, which is the most commonly employed solvent for allylation reactions with allylsilanes. In most cases the cyclization process was complete almost as soon as the sample could be analysed. The use of aluminium-based Lewis acids resulted in the formation of complex mixtures and low yields of the cyclic products. The results of this Lewis acid catalyzed cyclization reactions are shown in Table 2.[8]

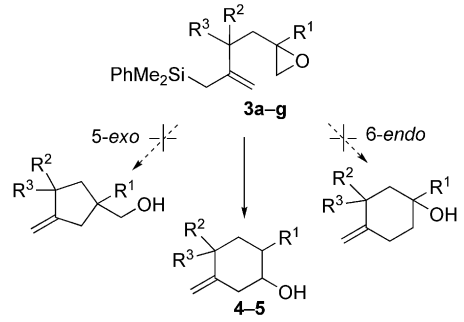
The relative stereochemistries of the products **4** and **5** were determined by extensive NMR experiments and in particular by COSY and NOESY. For example, in compound **4a** the coupling pattern for 4-H (t, J = 5.0 Hz) clearly indicates that it is equatorial (Ph axial), whereas the coupling pattern for 1-H (td, J = 9.0 and 4.2 Hz) indicates that 1-H and 2-H are axial (OH and Me, *trans*-diequatorial). The NOE correlations between 1-H and Me show strong cross-peaks at the coordinates with no cross-peaks being found for the correlation between 1-H and 2-H, which supports the *trans* OH/Me relationship. At the same time, 4-Ph shows a cross-peak with 2-H with no cross-peak with Me observed, which confirms the *anti* relationship of 4-Ph and 2-Me.

Table 2. Lewis acid catalyzed cyclization of (epoxy–allyl)silanes **3**.

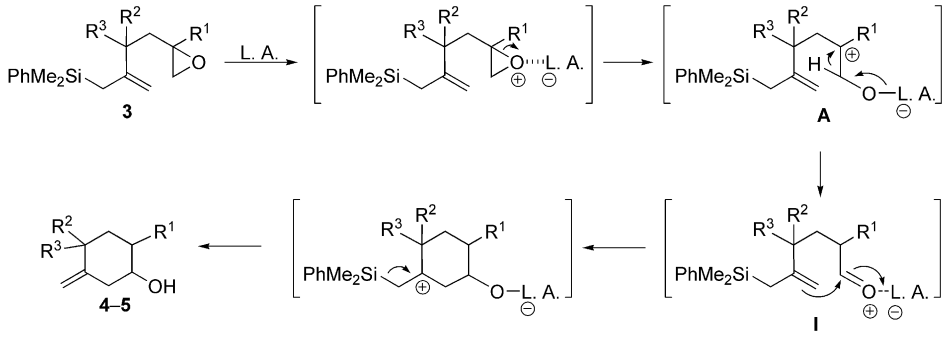
Entry	Silane	Lewis acid	Products	Yield (%)
1	**3a**	$BF_3{\cdot}Et_2O$[a]	**4a** 4:1 **5a**	75
2	**3b**	$BF_3{\cdot}Et_2O$[a]	**4b** 2:1 **5b**	87
3	**3b**	$TiCl_4$[b]	**4b** 1:10 **5b**	80
4	**3c**	$BF_3{\cdot}Et_2O$[a]	**4c** 3:1 **5c**	68
5	**3d**	$BF_3{\cdot}Et_2O$[a]	**4d** 3:1 **5d**	82
6	**3d**	$TiCl_4$[b]	**4d** 1:5 **5d**	79
7	**3e**	$BF_3{\cdot}Et_2O$[a]	**4e** 2:1 **5e**	80
8	**3e**	$TiCl_4$[b]	**4e** 1:17 **5e**	84
9	**3f**	$BF_3{\cdot}Et_2O$[a]	**4f**	80
10	**3g**	$BF_3{\cdot}Et_2O$[a]	**4g** 2:1 **5g**	70

[a] Reactions with $BF_3{\cdot}Et_2O$ were performed in CH_2Cl_2 at 0 °C. [b] Reactions with $TiCl_4$ were performed in CH_2Cl_2 at –78 °C.

The first thing to note is that the Lewis acid mediated cyclization of (epoxy–allyl)silanes **3** is mechanistically quite different to the classic intramolecular S_N2 opening of the oxirane ring. In effect, compounds **4** and **5** thus obtained are the reaction products of neither a 5-*exo* nor 6-*endo* cyclization. Instead, the cyclization of **3** unexpectedly afforded 3-methylenecyclohexan-1-ols in good yields (Scheme 2).



Scheme 2. Possible pathways for the cyclization of (epoxy–allyl)-silanes **3**.

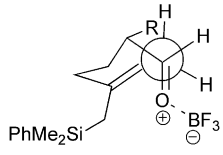


Scheme 3. Plausible mechanism for the formation of 3-methylenecyclohexanols.

A plausible mechanism for the formation of 3-methylenecyclohexanols can be rationalized as shown in Scheme 3. Thus, the reaction pathway would involve two steps: an initial Lewis acid catalyzed rearrangement of the epoxide group to the corresponding aldehyde (via the most stable carbocation to give intermediate **I**) followed by reaction with the allylsilane unit to provide an intermediate carbocation (stabilized by strong hyperconjugative donation or hyperconjugation[11] from the adjacent carbon–silicon bond), finally losing its silyl group to a nucleophile (e.g., a halide ion) to complete the process. The degree of concertedness between the two steps is still uncertain.[12]

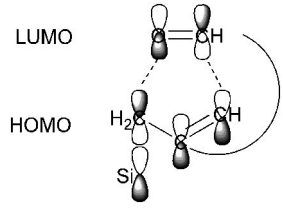
The fact that the observed epoxide rearrangement takes place prior to the cyclization is probably a consequence of an unfavourable orbital alignment of the allylsilane/epoxide pair in the reactive conformation, as we will discuss later. It is also likely that both steric and electronic factors play an important role in governing the stereochemical outcome of the reaction.

Examination of the results for the Lewis acid mediated cyclization of (epoxy–allyl)silanes **3**, summarized in Table 2, indicates two different types of behaviour depending on the nature of the Lewis acid used. Thus, with a small Lewis acid such as $BF_3{\cdot}OEt_2$, the predominant methylenecyclohexanol in every case (except for **3a**) is the *syn* adduct **4** (Table 2, Entries 2, 4, 5, 7 and 10). To rationalize this result we propose that the reaction proceeds through a chair-like transition state in which the R substituent at C-2 adopts a pseudoequatorial orientation and the aldehyde functionality adopts a pseudoaxial orientation (Scheme 4).



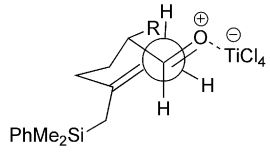
Scheme 4. Synclinal transition state.

The predominance of the *syn* products **4** can be rationalized by using a frontier molecular orbital (FMO) argument. In related work by Keck[13] and Cox[14] and their coworkers, good stereoselectivities were obtained in the intramolecular acid-catalyzed cyclization of aldehydes containing in the alkyl side-chain an allylstannane or -silane when a small Lewis acid was used. To rationalize the observed stereoselectivity, Keck et al. invoked a transition-state conformation in which the aldehyde and allylstannane assume a synclinal orientation that favors secondary orbital overlap (bonding and energy-lowering) between the π* LUMO of the aldehyde and the HOMO of the allylstannane nucleophile. In the absence of steric and other interactions, this frontier orbital effect could account for the observed *syn* stereoselectivity (Scheme 5).



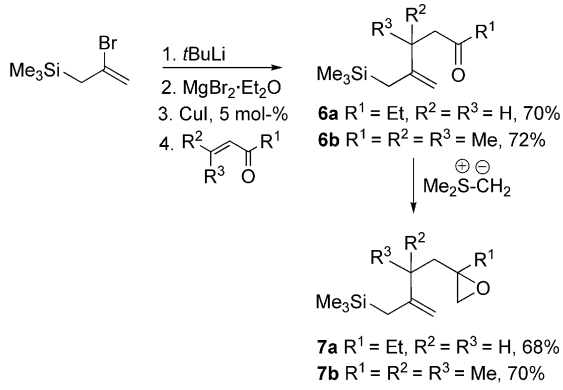
Scheme 5. Favorable secondary orbital interaction between the oxygen atom of the carbonyl group and the silylmethylene carbon atom.

Note, it is interesting that when $TiCl_4$ is used for the cyclization process the stereoselectivity observed is noticeably higher, but in the opposite sense. The main products are methylenecyclohexanols **5**, which have an *anti* relationship between the hydroxy group and the C-2 substituent and must result from an antiperiplanar transition state (Scheme 6). The product ratio observed is the result of simple thermodynamic control via a Zimmerman–Traxler-type transition state in which the bulky Lewis acid complexed to the carbonyl group shows a steric preference to be equatorial and *anti* to the pseudoequatorial substituent on C-2. This hypothesis is reinforced by the fact that the greater the bulkiness of the C-2 substituent, the higher the stereoselectivity of the cyclization (Table 2, Entries 3, 6 and 8).



Scheme 6. Antiperiplanar transition state.

Unfortunately, cyclization of (epoxy–allyl)silanes **3a**, **3c** and **3f** with $TiCl_4$ did not give the desired methylenecyclohexanols as a result of competitive chlorohydrin formation or a protodesilylation process. Nevertheless, whatever the factors that influence the stereochemical outcome of this cyclization, it is important to note that we are able to access both 1,6-*syn*- and 1,6-*anti*-cyclohexanol diastereoisomers in a selective fashion through the appropriate choice of Lewis acid. This attractive feature of the reported strategy provides a route for the synthesis of both diastereomers of menthol from methylenecyclohexanols **4e** and **5e** (i.e., neomenthol and isomenthol) according to the procedure described by Braddock and Brown.[15]



Scheme 7. Synthesis of (epoxy–allyl)trimethylsilanes **7a**,**b**.

Mechanistic Insights

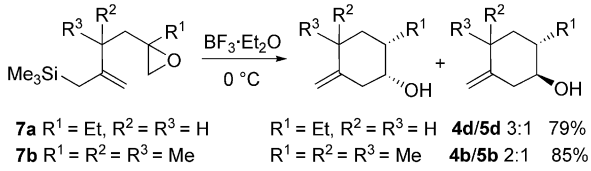
The acid-catalyzed rearrangement of epoxides to aldehydes or ketones is a well-known synthetic transformation.[16,17] Moreover, the strong anionic nature of the oxygen–Lewis acid bond in intermediate **A** (Scheme 3) would favour the rearrangement.[18] However, this is the first time that this sequential type of process (rearrangement/cyclization) has been observed[19] in the acid-catalyzed cyclization of (epoxy–allyl)silanes. The former observation seems to indicate that in the case of (epoxy–allyl)silanes **3**, rearrangement of the epoxide occurs much faster than nucleophilic substitution on the epoxy group. In this sense, the fact that cyclization of both diastereoisomers of **3a** gives the same result when treated with Lewis acids indicates that the reaction proceeds through common intermediates, and it could be considered as evidence that rearrangement takes place prior to cyclization.

The question to be analysed is why substrates **3** show preference to undergo acid-promoted epoxide rearrangement instead of the expected oxirane-cleavage/allylsilane-terminated cyclization process leading to 5-*exo* or 6-*endo* adducts.

The fact that the previously reported[6,7] cyclization of (epoxy–allyl)trimethylsilanes is perceptibly different from that observed for our dimethyl(phenyl)silyl derivatives (Scheme 1) led us to think that the nature of such a group may be the cause of the different behaviour shown. To study such an influence we synthesized (epoxy–allyl)trimethylsilanes **7a** and **7b**, which are structurally analogous to the dimethyl(phenyl)silyl substrates **3d** and **3b** (Scheme 7). The silanes **7a** and **7b** were synthesized by using the Trost methodology.[20]

The magnesium derivative of 2-bromo-3-(trimethylsilyl)-propene was generated by metal/halogen exchange with *t*BuLi followed by the addition of anhydrous magnesium bromide. Transmetallation with CuI followed by Michael addition to the corresponding enone gave the desired allyltrimethylsilanes **6a** and **6b** in satisfactory yields. The (epoxy–allyl)silane derivatives were obtained by standard reaction with dimethylsulfonium methylide (Scheme 7).

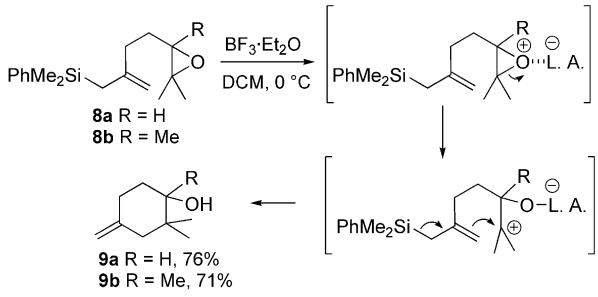
We then subjected (epoxy–allyl)silanes **7a** and **7b** to the standard cyclization conditions with boron trifluoride–diethyl ether at 0 °C. Surprisingly, the reaction again afforded compounds **4** and **5** in similar ratios,[21] which means that the nature of the silyl group is not the cause of this unusual tandem process (Scheme 8).



Scheme 8. Lewis acid catalyzed cyclization of (epoxy–allyl)trimethylsilanes **7a** and **7b**.

To give some support to this hypothesis, we performed a simple semi-empirical analysis of a model of (epoxy–allyl)-silane by using Gaussian 98,[22] and the preliminary results seem to indicate that the geometry, symmetry and orientation of the HOMO orbital of the allylsilane and the LUMO of the epoxide are not favourable for a good overlap in (epoxy–allyl)silanes of type **3**. However, a good electronic interaction could be observed in the regioisomeric (oxo–allyl)silane **I** between the LUMO of the aldehyde and the HOMO of the allylsilane nucleophile. However, more theoretical work is probably needed before a definitive picture can be provided, and this is not the aim of this work.

Another factor to be considered in these cyclization reactions is the influence of the substitution of the epoxide on the course of the reaction. For this purpose we prepared 1,1-disubstituted (epoxy–allyl)silanes **8a** and **8b** and tested them under the standard Lewis acid cyclization conditions. As is shown in Scheme 9, we obtained the normal 6-*endo* products **9a** and **9b**, which corresponds to a direct opening of the epoxide. This result reinforces our hypothesis because in substrates **8a** and **8b** the poorer intrinsic migratory aptitude of the methyl group (compared with hydrogen) prevents the migration from being much faster than further attack of the nucleophilic allylsilane on the stable tertiary carbocation intermediate.



Scheme 9. Cyclization of substituted (epoxy–allyl)silanes **8a**,**b**.

Conclusions

A new synthesis of (γ,δ-epoxy–allyl)silanes by silylcupration of allene and capture of the intermediate cuprate with enones has been developed. Surprisingly, the Lewis acid catalyzed cyclization of these substrates leads to 3-methylenecyclohexanols through an interesting tandem process of an epoxide/aldehyde rearrangement and an allylsilane-terminated cyclization.

The factors governing this tandem reaction have been studied, and a mechanism is proposed. Moreover, a study of the influence of the Lewis acid used on the stereoselectivity of the cyclization shows two different types of behaviour. Thus, the major diastereomeric *syn*-cyclohexanol obtained when a small Lewis acid (e.g., BF_3) is used indicates a synclinal transition state. However, when the size of the Lewis acid used is larger, for example, $TiCl_4$, excellent diastereoselectivities are observed in favor of the *anti*-cyclohexanol, which is the result of simple thermodynamic control via an antiperiplanar transition state.

Experimental Section

Synthesis of (Epoxy–allyl)silanes: BuLi (0.6 mL, 1 mmol, 1.6 M in hexanes) was added dropwise to a solution of trimethylsulfonium iodide (220 mg, 1 mmol) in dry THF (5 mL) and the mixture stirred at 0 °C for 5 min. Then a solution of the (oxo–allyl)silane (0.8 mmol) in THF (1 mL) was added. After stirring at 0 °C for an additional 30 min and at room temp. for 1 h, brine (10 mL) was added and the mixture extracted with diethyl ether, dried and concentrated to dryness. The residue was purified by chromatography to give (epoxy–allyl)silanes **3a**–**g** and **7a**,**b**. Compounds **3a**,[8] **3b**[8] and **3g**[8] have been described previously.

2-Ethyl-5-(dimethylphenylsilylmethyl)-4-methyl-1,2-epoxy-5-hexene (3c): Colourless liquid of a 1:1 mixture of diastereoisomers A + B (150 mg, 65%).

A: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.33 (s, 6 H, $SiMe_2$), 0.87 (t, J = 7.5 Hz, 3 H, CH_3CH_2), 1.02 (d, J = 6.8 Hz, 3 H, Me), 1.30 (dd, J = 14.5, 8.6 Hz, 1 H, CHHCO), 1.41 (dd, J = 14.5, 7.5 Hz, 1 H, CHHCO), 1.67–1.53 (m, 1 H), 1.78 (s, 2 H, CH_2Si), 1.85–1.74 (m, 2 H), 2.44 (d, J = 4.6 Hz, 1 H, CHHO), 2.52 (d, J = 4.6 Hz, 1 H, CHHO), 4.56 (s, 1 H, =CHH), 4.66 (s, 1 H, =CHH), 7.55–7.35 (m, 5 H, Ph) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –2.8, 9.1, 19.8, 24.7, 26.4, 37.1, 40.3, 51.6, 59.2, 106.7, 127.7, 128.9, 133.5, 139.0, 151.7 ppm.

B: ^{1}H NMR (300 MHz, $CDCl_3$, recognizable signals): δ = 0.97 (d, J = 6.8 Hz, 3 H, Me), 2.54 (d, J = 4.8 Hz, 1 H, CHHO), 2.60 (d, J = 4.8 Hz, 1 H, CHHO), 4.56 (s, 1 H, =CHH), 4.64 (s, 1 H, =CHH) ppm. ^{13}C NMR (75 MHz, $CDCl_3$, recognizable signals): δ = 8.5, 19.2, 24.9, 26.3, 40.1, 53.1, 59.0, 106.4 ppm. IR (neat): $\tilde{\nu}$ = 1632, 1248, 1100, 836 cm^{-1}. MS (EI): m/z = 289 [M + 1]$^+$, 273 [M – Me]$^+$, 203, 135.

2-Ethyl-5-{[dimethyl(phenyl)silyl]methyl}-1,2-epoxy-5-hexene (3d): Colourless liquid (167 mg, 76%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.35 (s, 6 H, $SiMe_2$), 0.90 (t, J = 7.5 Hz, 3 H, Me), 1.78–1.50 (m, 4 H), 1.79 (s, 2 H, CH_2Si), 1.89 (t, J = 8.1 Hz, 2 H, CH_2C=), 2.48 (d, J = 4.7 Hz, 1 H, CHHO), 2.55 (d, J = 4.7 Hz, 1 H, CHHO), 4.57 (s, 1 H, =CHH), 4.64 (s, 1 H, =CHH), 7.57–7.37 (m, 5 H, Ph) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –3.0, 8.8, 26.2, 26.8, 32.1, 33.0, 52.0, 59.8, 107.7, 127.7, 129.0, 133.5, 138.9, 146.3 ppm. IR (neat): $\tilde{\nu}$ = 1650, 1225, 1100, 910 cm^{-1}. MS (EI): m/z = 275 [M + 1]$^+$, 259 [M – Me]$^+$, 197, 135. $C_{17}H_{26}OSi$ (274.18): calcd. C 74.39, H 9.55; found C 74.78, H 9.84.

2-Isopropyl-5-{[dimethyl(phenyl)silyl]methyl}-1,2-epoxy-5-hexene (3e): Colourless liquid (157 mg, 68%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.34 (s, 6 H, $SiMe_2$), 0.90 (d, J = 6.8 Hz, 3 H, Me), 0.99–0.87 (m, 1 H, CHMe_2), 0.93 (d, J = 6.8 Hz, 3 H, Me), 1.79 (s, 2 H, CH_2Si), 1.83–1.62 (m, 4 H, CH_2CH_2), 2.43 (d, J = 4.6 Hz, 1 H, CHHO), 2.53 (d, J = 4.6 Hz, 1 H, CHHO), 4.56 (s, 1 H, =CHH), 4.62 (s, 1 H, =CHH), 7.56–7.35 (m, 5 H, Ph) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –3.0, 17.8, 18.1, 26.3, 29.2, 32.0, 32.4, 50.3, 62.1, 107.5, 127.7, 128.9, 133.5, 138.9, 146.6 ppm. $C_{18}H_{28}OSi$ (288.19): calcd. C 74.94, H 9.78; found C 75.26, H 10.07.

5-{[Dimethyl(phenyl)silyl]methyl}-1,2-epoxy-5-hexene (3f): Colourless liquid (148 mg, 75%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.35 (s, 6 H, $SiMe_2$), 1.66–1.59 (m, 2 H), 1.81 (s, 2 H, CH_2Si), 2.11–1.94 (m, 2 H), 2.42 (dd, J = 5.0, 2.7 Hz, 1 H, CHHO), 2.72 (dd, J = 5.0, 4.1 Hz, 1 H, CHHO), 2.88–2.82 (m, 1 H, CHO), 4.60 (s, 1 H, =CHH), 4.67 (s, 1 H, =CHH), 7.60–7.34 (m, 5 H, Ph) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –3.0, –2.9, 26.0, 30.6, 34.1, 47.0, 51.9, 108.1, 127.7, 129.0, 133.5, 138.8, 145.8 ppm. IR (neat): $\tilde{\nu}$ = 1634, 1249, 1100, 837 cm^{-1}. MS (EI): m/z = 246 [M]$^+$, 231 [M – Me]$^+$, 135. HRMS (ESI): calcd. for $C_{15}H_{22}OSi$ 246.1440 [M]$^+$; found 246.1473.

2-Ethyl-5-[(trimethylsilyl)methyl]-1,2-epoxy-5-hexene (7a): Colourless liquid (115 mg, 68%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.03 (s, 9 H, $SiMe_3$), 1.22 (t, J = 7.5 Hz, 3 H, Me), 1.53 (s, 2 H, CH_2Si), 1.78–1.55 (m, 4 H, CH_2CH_2), 1.89 (t, J = 8.3 Hz, 2 H, CH_2Me), 2.61–2.58 (m, 2 H, CH_2O), 4.53 (s, 1 H, =CHH), 4.60 (s, 1 H, =CHH) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –1.4, 8.8, 26.9, 27.0, 32.2, 33.1, 52.1, 59.9, 106.9, 146.9 ppm. IR (neat): $\tilde{\nu}$ = 1630, 1463, 1248, 854 cm^{-1}. $C_{12}H_{24}OSi$ (212.16): calcd. C 67.86, H 11.39; found C 68.19, H 11.62.

2,4,4-Trimethyl-5-[(trimethylsilyl)methyl]-1,2-epoxy-5-hexene (7b): Colourless liquid (127 mg, 70%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.04 (s, 9 H, $SiMe_3$), 1.19 (s, 3 H, Me), 1.20 (s, 3 H, Me), 1.30 (s, 3 H, Me), 1.39 (d, J = 14.3 Hz, 1 H, CHHSi), 1.57 (s, 2 H, CH_2CO), 1.98 (d, J = 14.3 Hz, 1 H, CHHSi), 2.54 (d, J = 4.9 Hz, 1 H, CHHO), 2.63 (d, J = 4.9 Hz, 1 H, CHHO), 4.65 (s, 1 H, =CHH), 4.82 (s, 1 H, =CHH) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –0.50, 21.1, 22.1, 27.6, 28.5, 39.4, 47.7, 54.7, 55.9, 108.2, 153.4 ppm. $C_{13}H_{26}OSi$ (226.18): calcd. C 68.96, H 11.57; found C 69.27, H 11.80.

Synthesis of (1,1-Dimethylepoxy–allyl)silanes: *tert*-Butyllithium (0.6 mL, 1.7 M in pentane, 1 mmol) was added dropwise to a solution of isopropyldiphenylsulfonium fluoroborate (1 mmol) in dry THF at –40 °C, and the resulting mixture was stirred at this temperature for 1 h. A solution of the (oxo–allyl)silane (0.85 mmol) in

dry THF (4 mL) was added; after 1 h at –40 °C, the mixture was warmed to 0 °C and quenched with brine (10 mL). After standard workup, the residue was purified by chromatography to give (epoxy–allyl)silanes **8a**,**b**.

5-{[Dimethyl(phenyl)silyl]methyl}-1,1-dimethyl-1,2-epoxy-5-hexene (8a): Colourless liquid (121 mg, 52%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.34 (s, 6 H, $SiMe_2$), 1.24 (s, 3 H, Me), 1.30 (s, 3 H, Me), 1.71–1.57 (m, 2 H), 1.80 (s, 2 H, CH_2Si), 2.04–1.93 (m, 2 H), 2.65 (t, J = 6.2 Hz, 1 H, CHO), 4.59 (s, 1 H, =C*H*H), 4.69 (s, 1 H, =CH*H*), 7.56–7.31 (m, 5 H, Ph) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –3.0, 18.7, 24.8, 26.0, 27.1, 34.7, 58.2, 64.0, 108.1, 127.7, 129.0, 133.5, 138.8, 145.9 ppm. $C_{17}H_{26}OSi$ (274.18): calcd. C 74.39, H 9.55; found C 74.72, H 9.89.

5-{[Dimethyl(phenyl)silyl]methyl}-1,1,2-trimethyl-1,2-epoxy-5-hexene (8b): Colourless liquid (135 mg, 55%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.33 (s, 6 H, $SiMe_2$), 1.18 (s, 3 H, Me), 1.26 (s, 3 H, Me), 1.28 (s, 3 H, Me), 1.54–1.50 (m, 1 H), 1.77–1.69 (m, 1 H), 1.78 (s, 2 H, CH_2Si), 1.94–1.79 (m, 2 H), 4.55 (s, 1 H, =C*H*H), 4.62 (s, 1 H, =CH*H*), 7.56–7.31 (m, 5 H, Ph) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = –3.0, 19.5, 20.8, 21.3, 26.2, 33.7, 33.8, 62.1, 64.4, 107.5, 127.7, 129.0, 133.5, 138.8, 146.5 ppm. $C_{18}H_{28}OSi$ (288.19): calcd. C 74.94, H 9.78; found C 75.31, H 10.11.

Cyclization of (Epoxy–allyl)silanes: $BF_3{\cdot}OEt_2$ (0.15 mL, 1.2 mmol) or $TiCl_4$ (0.13, 1.2 mmol) was slowly added to a solution of the (epoxy–allyl)silane (1 mmol) in DCM (10 mL) under nitrogen. After stirring at the appropriate temperature (0 or –78 °C) for 30 min, MeOH (2 mL) was added and the mixture warmed to room temperature. The organic layer was washed with brine and dried with $MgSO_4$. The solvent was evaporated and the residue purified by chromatography to give methylenecyclohexanols **4a**–**g**, **5a**–**g** and **9a**,**b**. Compounds **4a**,**b**,[8] **4d**,**e**,[23] **5a**,**b**,[8] **5d**,**e**,[23] **4g**[8] and **5g**[8] have been described previously. The relative stereochemistries of the cyclic products were determined by extensive NMR experiments and in particular by COSY and NOESY data.

(1*R,2*S**,4*S**)-2-Ethyl-4-methyl-5-methylenecyclohexanol (4c):** Colourless liquid (79 mg, 51%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.92 (t, J = 7.2 Hz, 3 H, *Me*CH_2), 1.06 (d, J = 6.5 Hz, 3 H, Me), 1.37–1.21 (m, 3 H), 1.51–1.39 (m, 2 H), 1.64 (dt, J = 13.0, 3.7 Hz, 1 H), 2.10–2.01 (m, 1 H), 2.31 (dd, J = 13.5, 2.9 Hz, 1 H, C*H*HC=), 2.44 (dd, J = 13.5, 3.4 Hz, 1 H, CH*H*C=), 3.92 (br. s, 1 H, C*H*OH), 4.80 (s, 2 H, =CH_2) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 11.7, 18.0, 25.1, 36.8, 37.1, 43.5, 43.9, 69.2, 108.7, 149.0 ppm. IR (neat): $\tilde{\nu}$ = 3450, 3083, 1648, 1013, 890 cm^{-1}. $C_{10}H_{18}O$ (154.14): calcd. C 77.87, H 11.76; found C 78.19, H 11.95.

(1*R,2*S**,4*R**)-2-Ethyl-4-methyl-5-methylenecyclohexanol (5c):** Colourless liquid (26 mg, 17%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.94 (t, J = 7.4 Hz, 3 H, *Me*CH_2), 1.10 (d, J = 7.0 Hz, 3 H, Me), 1.63–1.22 (m, 6 H), 2.24 (dd, J = 13.7, 5.0 Hz, 1 H), 2.54–2.48 (m, 2 H), 3.89 (br. s, 1 H, C*H*OH), 4.71 (s, 1 H, =C*H*H), 4.83 (s, 1 H, =CH*H*) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 11.8, 18.9, 23.6, 34.3, 35.9, 38.1, 38.8, 70.1, 110.1, 149.2 ppm. IR (neat): $\tilde{\nu}$ = 3580, 3072, 1648, 1038, 803 cm^{-1}.

3-Methylenecyclohexanol (4f): Colourless liquid (90 mg, 80%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.52–1.39 (m, 2 H), 1.66 (br. s, 1 H, OH), 1.97–1.89 (m, 2 H), 2.12–2.02 (m, 2 H), 2.38–2.30 (m, 2 H), 3.82 (tt, J = 9.0, 3.8 Hz, 1 H, C*H*OH), 4.65 (s, 2 H, =CH_2) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 31.6, 35.9, 69.2, 107.8, 147.6 ppm. IR (neat): $\tilde{\nu}$ = 3350, 1650, 1061, 894 cm^{-1}. MS (EI): *m*/*z* = 112 $[M]^+$, 94, 79. $C_7H_{12}O$ (112.09): calcd. C 74.95, H 10.78; found C 75.29, H 11.06.

2,2-Dimethyl-4-methylenecyclohexanol (9a): Colourless liquid (106 mg, 76%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.86 (s, 3 H, Me), 0.98 (s, 3 H, Me), 1.61–1.46 (m, 2 H), 1.84–1.76 (m, 1 H), 1.88 (d, J = 13.4 Hz, 1 H, C*H*HC=), 2.06 (d, J = 13.4 Hz, 1 H, CH*H*C=), 2.12–2.02 (m, 1 H), 2.31 (dt, J = 13.6, 5.1 Hz, 1 H), 3.46 (dd, J = 9.1, 3.9 Hz, 1 H, C*H*OH), 4.60 (s, 1 H, =C*H*H), 4.70 (s, 1 H, =CH*H*) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 20.1, 27.4, 31.0, 31.9, 36.7, 46.1, 76.4, 109.2, 145.9 ppm. $C_9H_{16}O$ (140.12): calcd. C 77.09, H 11.50; found C 77.43, H 11.76.

1,2,2-Trimethyl-4-methylenecyclohexanol (9b): Colourless liquid (109 mg, 71%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.89 (s, 3 H, Me), 0.97 (s, 3 H, Me), 1.19 (s, 3 H, Me), 1.74–1.55 (m, 4 H, CH_2CH_2), 2.08 (d, J = 13.2 Hz, 1 H, C*H*HC=), 2.18–2.03 (m, 1 H), 2.32 (d, J = 13.2 Hz, 1 H, CH*H*C=), 4.59 (s, 1 H, =C*H*H), 4.68 (s, 1 H, =CH*H*) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 23.4, 24.2, 24.3, 31.1, 37.1, 39.1, 45.5, 73.7, 108.4, 146.6 ppm. $C_{10}H_{18}O$ (154.14): calcd. C 77.87, H 11.76; found C 78.11, H 12.02.

Supporting Information (see footnote on the first page of this article): General experimental methods, details of the synthesis of oxoallylsilanes, characterization of compounds **2c**–**f** and **6a**,**b** and ^{1}H and ^{13}C NMR spectra for all new compounds.

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