Comparison Between the Epoxide Ring-opening of 1-Trimethylsilylcyclohexene Oxide and Some Electrophilic Additions to 1-Trimethylsilylcyclohexene

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The reactions of 1,2-epoxy-1-trimethylsilylcyclohexane (**1**) with several nucleophilic reagents under acidic conditions have been studied and the ring-opened products identified. In all cases ring-opening occurs in a *trans* fashion with attack by the nucleophile on the carbon α to silicon, the only exception being the reaction with hydrogen chloride in which the regioisomeric *trans*-chlorohydrin, 2-chloro-1-trimethylsilylcyclohexanol is also formed as a minor product in amounts that depend on the solvent. These reactions were compared with those of 1-trimethylsilylcyclohexene with chlorine, bromine, and mercury-based electrophiles in water and in methanol. Whereas the reactions with *N*-bromoacetamide in water and methoxymercuriation yielded exclusively anti-Markovnikov adducts, reactions with hypochlorous acid in water and in methanol and with *N*-bromosuccinimide in methanol were less specific, yielding mixtures of regioisomers. The mechanism of these reactions is discussed and it is proposed that the main factor in determining the regioselectivity is the stability of the intermediate mercurinium, halonium, or epoxonium ion and that assistance by a silicon empty d orbital on the attacking nucleophile plays a role only in the reactions involving less-stable three-membered ring intermediates (epoxonium, chloronium, and to a lesser extent bromonium). ^{1}H N.m.r. data for the prepared adducts point to the existence of those in which a hydrogen bond can form between the two substituents prevalently in chair conformations with an axial trimethylsilyl substituent, in chloroform solutions.

α,β-Epoxysilanes have attracted much attention in recent years, owing to their easy availability and usefulness as intermediates in synthesis.[1] In the course of our extensive investigation on oxirane ring-opening reactions, we started some time ago a study[2] of the attack by various reagents on 1-trimethylsilyl-7-oxabicyclo[4.1.0]heptane (**1**), in order to see how a silyl substituent, when compared with others, affected the regio- and stereo-selectivity of the opening of the cyclohexene oxide ring. When we started this work it was already known that epoxides of acyclic vinylsilanes exhibited a preference for nucleophilic attack α to silicon by hydrides or organometallic reagents[3] but, in the case of the reaction of (triphenylsilyl)oxirane with hydrogen chloride, β attack by the chlorine anion had been observed.[4] While our work was in progress, preliminary reports appeared,[5,6] showing that in acid-catalysed reactions of (**1**) the nucleophile attacks exclusively the position α to silicon, in spite of the fact that a β-silyl carbocation is known to be more stable than an α-silyl one.[7a] Only in the case of the reaction of (**1**) with methanol over alumina, was 2-methoxy-1-trimethylsilylcyclohexanol (**6**) reported[8] to be the main product; when a protic acid was used as the catalyst, the regioisomer (**3**) was the only product. The recent publication of a full paper[9] on the reactions of (**1**) and many other α,β-epoxysilanes, confirming a constant regiospecificity for α-attack, induces us to publish our results, some of which deviate from the usual pattern of behaviour. We are also reporting on the related reaction of 1-trimethylsilylcyclohexene (**11**) with electrophilic brominating reagents and on the conformation of some of the products.

We confirmed the previously reported complete regiospecificity involving nucleophilic attack α to silicon for the acid-catalysed reactions of (**1**) with water, with methanol and with HBr, both in water and in benzene, to give the adducts (**2**), (**3**), and (**5**). Ethanol behaved similarly to give (**4**). We found, however, that in the previously unreported reaction of (**1**) with HCl the main adduct was always accompanied by a minor product (g.l.c. analysis) in amounts ranging between 2 and 11% depending on the solvent (see Table). The main product was identified as (**8**) by its conversion into a *p*-nitrobenzoate ester, oxidation to the ketone (**9**), and reconversion into (**1**) with base. Also the minor product gave (**1**) with base showing a *trans* disposition of OH and Cl, so that it was evidently the regioisomer (**7**). No apparent relation between polarity of the solvent and amount of (**7**) formed was observed, although the

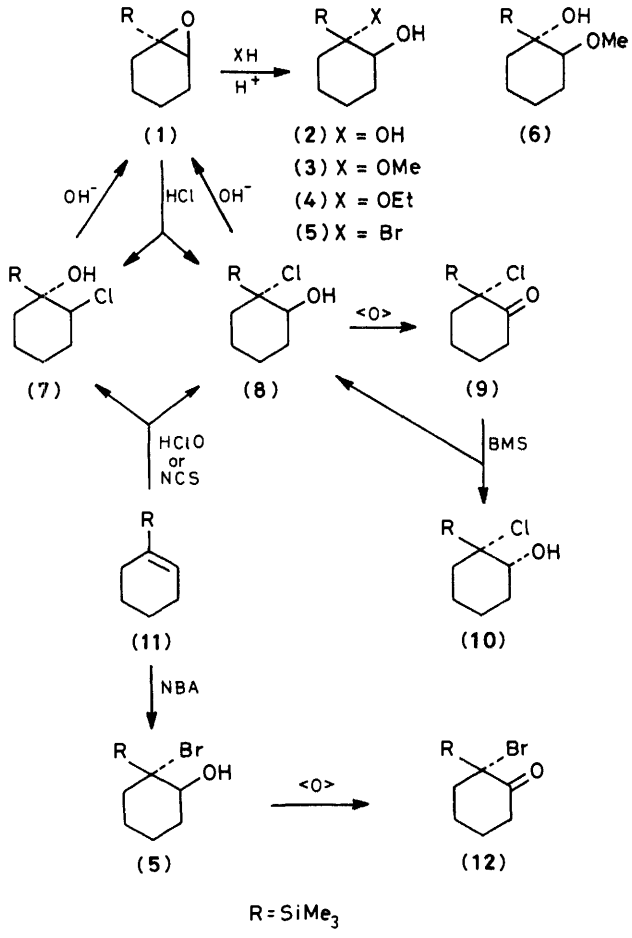
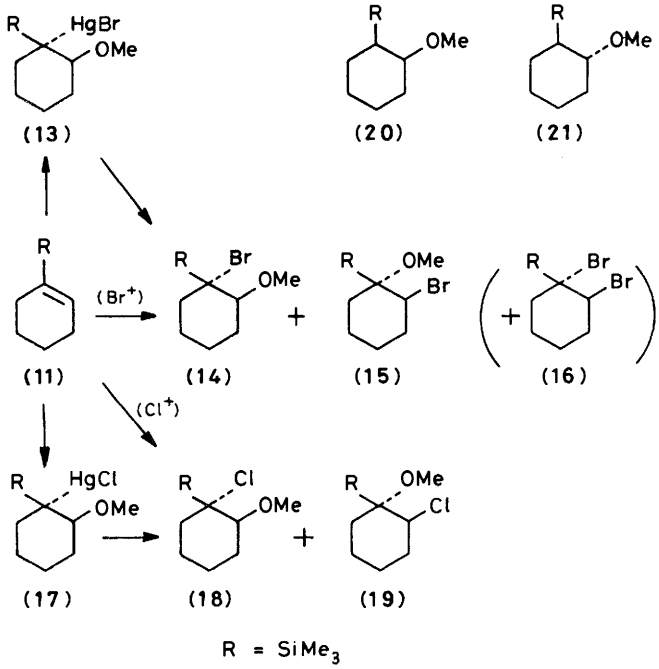


Table. Regioselectivity of the ring-opening of epoxide (1) with HCl

Solvent	HCl:(1) ratio	% (8)	% (7)
Benzene	Large excess	98.0	2.0
Benzene	Stoicheiometric	95.5	4.5
Water	Large excess	95.0	5.0
CH_2Cl_2	Excess	95.0	5.0
Et_2O	Excess	93.0	7.0
CH_2Cl_2	Stoicheiometric	92.5	7.5
CCl_4	Large excess	90.0	10.0
Et_2O	Stoicheiometric	90.0	10.0
Cyclohexane	Large excess	89.0	11.0

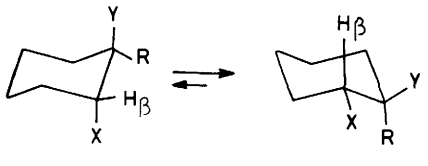
percentage of β-attack is higher when HCl is used in equimolar amount than when the reaction is conducted with an excess of the acid. The *cis*-chlorohydrin (**10**) was obtained as a 28:72 mixture with (**8**) by reduction of the ketone (**9**) with borane–dimethyl sulphide (BMS). Since the chlorohydrins (**7**), (**8**), and (**10**) gave well separated g.l.c. peaks and also separate signals for the protons α to OH or Cl, it was possible to establish that the *cis*-chlorohydrin (**10**) was entirely absent in the reaction products of (**1**) with HCl. A primary formation of some (**10**), followed by its epimerization to (**8**), or destruction through a 1,2-elimination in the acidic reaction medium were also ruled out by the finding that the (**8**) + (**10**) mixture was recovered with its composition unchanged after protracted treatment with HCl. The stability of (**10**) to acidic conditions is somewhat surprising in view of the behaviour of the 1-methoxy-2-trimethylsilylcyclohexanes (**20**) and (**21**). Whereas the *cis*-isomer (**20**) was reported to be stable to acids, the *trans*-isomer (**21**) was rapidly converted by toluene-*p*-sulphonic acid at room temperature into cyclohexene and $MeOSiMe_3$;[10] this agrees with the requirement of acid-catalysed 1,2-elimination for an anticoplanar disposition of the silyl and alkoxy groups. Evidently the presence of an electron-withdrawing group α to silicon prevents the postulated nucleophilic displacement of the trimethylsilyl group.[7b] These results confirmed that the ring-opening of (**1**) takes an entirely *anti* course, but may, at least in the case of HCl, not be completely regiospecific.



There often exists a parallel pattern of behaviour between oxirane ring-opening reactions with hydrogen halides and the formation of halohydrins from the corresponding alkenes with hypohalogenous acids or their equivalents, the intermediate halonium ions formed in the latter reactions being equivalent to epoxonium ions. Since this approach usually gives rise to regioisomeric halohydrins, we also investigated the reactions of 1-trimethylsilylcyclohexene (**11**) with HClO and with *N*-chlorosuccinimide–$HClO_4$ in dioxane–water. Both reactions yielded a roughly 56:44 mixture of (**8**) and (**7**); this indicates the almost complete absence of regioselectivity, in contrast with the reported behaviour of several iodine-based electrophiles[11] in which attack by iodine was reported to take place α to the silicon atom of (**11**). We then established that the reaction of (**11**) with *N*-bromoacetamide formed exclusively (**5**), the bromohydrin also obtained in the ring-opening of (**1**) with HBr. Its structure was confirmed by oxidation to the ketone (**12**), formation of a *p*-nitrobenzoate and cyclization to (**1**).

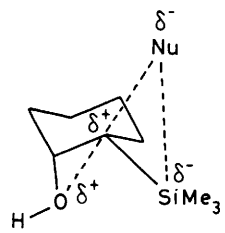
The reaction of (**11**) with several brominating agents in methanol was also investigated. NBS gave a 67:33 mixture of methoxy bromides and Br_2–$CaCO_3$ a similar mixture in a ratio of 81:19. The main product was identified as (**14**) by independent synthesis, *via* methoxymercuriation followed by exchange with bromide to give (**13**); this was converted into (**14**) with Br_2–pyridine complex, a reaction which is known to proceed with complete retention of configuration.[12] The methoxymercuriation of (**11**) has previously been described to be regio- but not stereo-specific, on the basis of the formation, in 20% yield, of a 65:35 mixture of *cis*- and *trans*-1-methoxy-2-trimethylsilylcyclohexane, (**20**) and (**21**) respectively, after reduction with borohydride of the unisolated product of the reaction with mercury acetate in methanol.[13] We found that the mercury derivative (**13**) can be isolated pure as the sole product. No evidence was found for the presence of a stereoisomer but, because of the low yield (30%), its formation cannot be ruled out completely. We think, however, that the previously reported[13] formation of (**20**) and (**21**) is due to a lack of stereoselectivity in the reduction of the mercuric derivative, rather than an unlikely partial *syn* addition in the methoxymercuriation step. The minor product of the reaction of (**11**) with NBS or Br_2 in MeOH was not isolated, but on the basis of the n.m.r. spectrum of the mixture (two methoxy and two CHX signals) it is thought to be the regioisomer (**15**). When the pyridine–bromine complex or pyridinium tribromide were used to brominate (**11**) this product was absent, a mixture (*ca.* 1:1) of (**14**) and the dibromide (**16**) being formed. The latter was prepared for comparison from (**11**) and Br_2. The reaction of (**11**) with *N*-chlorosuccinimide (NCS) in methanol–dioxane also gave a mixture which on g.l.c. analysis showed two main peaks (45 and 31% of total areas) and three minor components. The most abundant peak corresponded to compound (**18**). The latter was prepared by an independent synthesis *via* the chloromercuric derivative (**17**) which was converted into (**18**) with pyridine–chlorine complex. The second most abundant component of the reaction mixture of (**11**) with NCS was not isolated, but probably corresponded to the regioisomer (**19**) on the basis of the identification of a second methoxy singlet and a second narrow CHX multiplet.

In the n.m.r. spectra in $CDCl_3$ of *trans* products obtained during the present work the signal for the CHX protons β to silicon (H_β) are easily identified as multiplets at medium field. Their half-band widths are in the range 6.0—14.3 Hz, a fact that clearly indicates that in this series of structurally very similar compounds some exhibit a high preference for conformation (**22e**) with an equatorial Me_3Si group and H_β ($W_{\frac{1}{2}}$ 6—7.5 Hz), while in others the conformation (**22a**) with axial Me_3Si and H_β ($W_{\frac{1}{2}}$ 9—14 Hz) is significantly populated. Preference for one or other conformation is evidently connected with the ability to



(22e) (22a) (23)

R = $SiMe_3$



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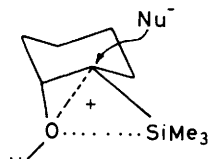

(25)

form an intramolecular hydrogen bond, since compounds (**2**), (**3**), (**4**), (**5**), (**7**), and (**8**), all having at least one OH group, exhibit broad signals for the H_β proton [conformation (**22a**)], whereas for those in which OH is absent, (5-PNB), (8-PNB), (**13**), (**14**), (**15**), (**16**), (**17**), and (**18**) the same signals are narrow. The preference for the conformation with the bulky Me_3Si group in an axial position, though surprising, can be explained on the basis of the recently reported relatively low *A* value for this substituent (2.4—2.6).[14] We shall discuss this conformational problem in greater detail in a separate paper which will also report on an *X*-ray diffraction study of compound (**3**).[15]

The results of the ring-opening reactions of (**1**) once again stress the fact that a high preference for attack by the nucleophile α to silicon and *anti* to the oxirane oxygen is exhibited in the cleavage of α-silyl epoxides. We found for the first time incomplete regiospecificity only in the case of the reaction with HCl, but no evidence at all for the formation of regioisomers in the other investigated reactions. Furthermore, we were also able to rule out completely, in the case of the reactions with HCl, the formation of measurable amounts of the *syn* adduct (**10**). No clear-cut explanation has been proposed so far for the unexpected course of reactions of this type, that is in apparent contrast with the higher stability of β- with respect to α-silylcarbonium ions.[7,16] A tentative explanation for the absence of β-attack has been proposed on the basis of a deviation of the relative orientation of the C–Si and β-C–O bonds from the coplanarity necessary for the stabilization of an incipient positive charge on the β-carbon.[17] From the point of view of regioselectivity, the behaviour is similar to that of epoxides substituted with highly carbocation-stabilizing groups, such as aryl, which induce complete α-opening of the oxirane ring. For instance the analogue of (**1**), 1,2-epoxy-1-phenylcyclohexane opens, in acid-catalysed reactions, entirely at the benzylic carbon.[18] However, from the point of view of stereoselectivity the two types of epoxides differ sharply, the phenyl substituted ones giving rise, in variable amounts, in some cases exclusively, to the *cis* adducts[18] which are completely absent in the reactions of (**1**). From this point of view, therefore, (**1**) behaves more like an alkyl substituted epoxide, since in these compounds *anti*-opening is the normal course, even if in the case of 1,2-epoxy-1-methylcyclohexane a low percentage of *syn* opening has been observed.[19] The effect of a trimethylsilyl group on oxirane ring-openings differs from that of all other substituents so far studied. In our opinion the known data could be reconciled with a transition state having a limited amount of carbocationic character in which a silicon empty d orbital could assist in the attack by the nucleophile on the α-carbon (**24**), similar to the one proposed by Eisch and Trainor[3] for the reduction of epoxysilanes with lithium alanate. This could also explain the incomplete regioselectivity observed in the reaction with HCl since the more electronegative chlorine anion would be expected to be less prone to donate electrons to silicon in transition state (**24**) than the bromine anion or neutral oxygen nucleophiles. An alternative transition state involving a stabilizing interaction between the developing OH group and the silicon atom, (**25**), similar to the dipolar one proposed by Hudrlik to explain the pyrolytic rearrangement of α,β-epoxysilanes to silyl enol ethers,[20] appears less likely owing to the distance between these two atoms, at least 3 Å, as roughly estimated on Dreiding models.

The results of the additions of electrophilic chlorine and bromine derivatives to 1-trimethylsilylcyclohexene (**11**) are not easily correlated with the epoxide ring-openings of (**1**); this contrasts with the often observed similarity between these two reaction types which was mentioned above. It is known that the β-effect usually predominates in the former reactions,[21] so that electrophiles (H^+, ^+HgOAc, I^+, diborane, *etc.*) normally attack the double bond α to silicon to give β-carbocations. These processes correspond to anti-Markovnikov *anti* additions, but several exceptions are known, such as Markovnikov additions due to steric[22] or electronic[23] effects, or *syn* additions when a phenyl group β to silicon is present.[24] It must further be stressed that although additions of hypohalogenous acids or equivalent reagents to alkenes without silyl substituents gives rise to regioselectivity which usually favours Markovnikov opening, this can be partly, or totally, inverted in the presence of bulky substituents,[25] or on passing from HClO to HBrO.[26] It is also known that the regiochemistry of addition to 3-alkylcyclohexenes can change considerably on changing the type of halogenating reagent.[27] It is, therefore, not surprising that for electrophilic additions to (**11**) both Markovnikov and anti-Markovnikov type adducts are obtained. Thus, while iodine and mercury based electrophiles attack exclusively α to silicon, some bromine based ones behave similarly (NBA in dioxane–H_2O, Br_2–Py–MeOH, pyridinium tribromide), others are less regioselective (NBS–MeOH, Br_2–MeOH), and chlorinating reagents are the least regioselective. These data indicate that the bulk of the electrophile is unimportant in determining the site of attack, since the larger reagents have a higher preference for the more hindered carbon than the smaller ones. On the other hand, if a β carbocation were supposed to be the intermediate, no apparent reason can be seen for its being formed more easily with iodine than with chlorine. It rather appears that the choice between Markovnikov and anti-Markovnikov course could be dictated by the stability of three-membered ring intermediates. Mercury, iodine, and to a lesser extent bromine, which should form the more stable epimercurinium and epihalonium ions, would lead exclusively, or predominantly, to anti-Markovnikov adducts, as observed, by a normal S_N2-type cleavage on the less hindered carbon. With electrophilic chlorine the epichloronium ion would be less stable and the situation would become more closely similar to that observed with the even less stable epoxonium ion. A mechanism different from purely a S_N2 one, but more like a borderline one, involving a higher degree of C–O bond breaking in the transition state and assisted by an interaction between nucleophile and silicon, similar to the one depicted in (**24**) for the epoxide cleavage, but with Cl in place of OH, could well compete with the one involving normal S_N2 attack on an epichloronium ion and justify the large amount of Markovnikov adduct that is observed.

Experimental

M.p.s were determined on a Kofler apparatus and are uncorrected. I.r. spectra for comparison between compounds were taken on a Perkin-Elmer 137 instrument. ^{1}H N.m.r. spectra were determined in deuteriochloroform on a Jeol C 60 HL spectrometer; $CHCl_3$ was used as internal standard due to the presence of the Me_3Si group in all compounds. G.l.c. analyses were carried out on a Carlo Erba Fractovap GV apparatus with a flame ionization detector and glass columns (1.5 m × 2.5 mm) packed with 3% neopentylglycol succinate on 80—100 mesh silanized Chromosorb W, using the following conditions. Conditions A: low isotherm 90 °C (10 min), high isotherm 180 °C (increase 2.5 °C/min), evaporator and detector 180 °C, nitrogen flow 30 ml/min. Conditions B: column 80 °C, evaporator and detector 220 °C, nitrogen flow 30 ml/min. Conditions C: low isotherm 75 °C (10 min), high isotherm 160 °C (increase 4 °C/min), evaporator and detector 180 °C, nitrogen flow 30 ml/min. Conditions D: column 85 °C, evaporator and detector 200 °C, nitrogen flow 30 ml/min. Some g.l.c. analyses were carried out on a Perkin-Elmer model 11 apparatus with a flame ionization detector with glass columns (2 m × 2.5 mm) packed with 10% Carbowax 20 M on 80—100 mesh silanized Chromosorb W [column 165 °C, evaporator and detector 220 °C, nitrogen flow 30 ml/min (Conditions E)]. Preparative t.l.c. was performed on 2-mm layer silica gel plates (Merck F_{254}) containing a fluorescent indicator; t.l.c. plates were visualized by spraying with 1N-$K_2Cr_2O_7$ in 40% aqueous sulphuric acid followed by gentle heating. All comparison between compounds were made on the basis of i.r. and ^{1}H n.m.r. spectra and g.l.c. Magnesium sulphate was always used as drying agent. Evaporations were under reduced pressure (rotating evaporator). Light petroleum refers to the fraction with b.p. 30—50 °C.

1-*Trimethylsilylcyclohexene* (**11**).—This compound, b.p. 170—173 °C (lit.,[28] 171.5 °C), was prepared according to a previously described method.[28]

1,2-*Epoxy*-1-*trimethylsilylcyclohexane* (**1**).—A solution of (**11**) (29.0 g, 0.188 mol) in chloroform (30 ml) was added with stirring to a 0.38M-solution of peroxybenzoic acid in chloroform (591 ml, 0.224 mol) while the temperature was kept at 0 °C. The resulting solution was left for 3 h at 0 °C and then washed (10% aqueous sodium carbonate and water), dried, and evaporated to give crude (**1**) which was distilled to yield pure (**1**) (23.0 g), b.p. 85—87 °C at 20 mmHg (lit.,[29] b.p. 106—107 °C/55 mmHg). The ^{1}H n.m.r. data are in accordance with the previously reported ones.[29]

1-*Trimethylsilylcyclohexane*-r-1,c-2-*diol* (**2**).—The epoxide (**1**) (1.0 g, 5.87 mmol) was treated at room temperature with a 0.1M-solution of sulphuric acid in 1:1 (v/v) water–dioxane (100 ml) for 10 min, then saturated with sodium chloride and extracted with ether. Evaporation of the washed (water) ether extracts yielded practically pure (**2**) (0.99 g) (g.l.c., conditions B); after crystallization from light petroleum, m.p. 81.0—81.5 °C (lit.,[9] m.p. 81—82 °C); δ 3.63 (1 H, m, $W_{\frac{1}{2}}$ 14.0 Hz, C*H*OH).

t-2-*Methoxy*-2-*trimethylsilylcyclohexan*-r-1-*ol* (**3**).—A solution of (**1**) (0.50 g, 2.94 mmol) in 0.1M-sulphuric acid in anhydrous methanol (50 ml) was left for 10 min at room temperature and then diluted with water and extracted with ether. Evaporation of the washed (water) and dried ether extracts gave a solid product (0.515 g) consisting of (**3**) (g.l.c., conditions B and E), which was crystallized from light petroleum to yield pure (**3**) (0.360 g), m.p. 85—86 °C (lit.,[9] m.p. 82—83 °C); δ 3.97 (1 H, m, $W_{\frac{1}{2}}$ 14.3 Hz, C*H*OH).

t-2-*Ethoxy*-2-*trimethylsilylcyclohexan*-r-1-*ol* (**4**).—Similar treatment of (**1**) (0.20 g, 1.17 mmol) with 0.1M-sulphuric acid in anhydrous ethanol gave a crude product (0.162 g) consisting of (**4**) (g.l.c., conditions B and E), m.p. 61—62 °C (from light petroleum); δ 3.85 (1 H, m, $W_{\frac{1}{2}}$ 14.0 Hz, C*H*OH) (Found: C, 61.15; H, 11.25. $C_{11}H_{24}O_2Si$ requires C, 61.05; H, 11.18%).

t-2-*Bromo*-2-*trimethylsilylcyclohexan*-r-1-*ol* (**5**).—(a) *From the epoxide* (**1**) *and dry hydrogen bromide.* Hydrogen bromide was bubbled through a solution of (**1**) (2.0 g, 11.7 mmol) in anhydrous benzene until the latter was saturated. After 10 min at room temperature the solution was washed (water) and evaporated to give pure (**5**) (2.60 g) (g.l.c., conditions B) (lit.,[9] m.p. 23—28 °C), δ 4.10 (1 H, m, $W_{\frac{1}{2}}$ 9.7 Hz, C*H*OH). Compound (**5**) was converted into the *p*-nitrobenzoate with *p*-nitrobenzoyl chloride in dry pyridine 4 h at room temperature. Work-up yielded the *p*-nitrobenzoate of (**5**), m.p. 116—117 °C (from methanol), $\nu_{max.}$(Nujol) 1 725 cm^{-1}; δ 5.63 (1 H, m, $W_{\frac{1}{2}}$ 6.2 Hz, CHOCO) (Found: C, 48.15; H, 5.65; N, 3.35. $C_{16}H_{22}BrNO_4Si$ requires C, 48.00; H, 5.54; N, 3.50%).

(b) *From the epoxide* (**1**) *and hydrobromic acid.* A suspension of (**1**) (0.250 g, 14.7 mmol) in 48% aqueous hydrobromic acid (3 ml) was stirred for 20 min at room temperature; the mixture was then diluted with water and extracted with ether. Evaporation of the washed (water) ether extracts yielded pure (**5**) (0.223 g) (g.l.c., conditions B, n.m.r.).

(c) *From* 1-*trimethylsilylcyclohexene* (**11**) *and* NBA. A solution of (**11**) (1.98 g, 12.8 mmol) in 75:25 (v/v) dioxane–water (50 ml) was added to a solution of NBA (2.03 g, 14.7 mmol) in 50% aqueous dioxane (v/v) (20 ml), and the mixture then warmed on a steam-bath for 5 min, cooled, diluted with water, and extracted with ether. Evaporation of the washed (water) ether extracts gave a product (2.40 g) consisting essentially of (**5**) (g.l.c., conditions B; ^{1}H n.m.r.).

Ring-opening Reactions of the Epoxide (**1**) *with* HCl.—(a) *With hydrogen chloride in benzene.* A solution of (**1**) (0.516 g, 3.03 mmol) in anhydrous benzene (30 ml) was saturated with dry hydrogen chloride and the mixture then washed (water) and evaporated to dryness to yield a product (0.512 g) consisting of t-2-*chloro*-2-*trimethylsilylcyclohexan*-r-1-*ol* (**8**) containing 2% of its regioisomer 1-*trimethylsilyl*-t-2-*chlorocyclohexan*-r-1-*ol* (**7**) [see Table; g.l.c., conditions A, retention times (**8**) > (**7**)]. The pure *p*-nitrobenzoate of (**8**) was obtained from the crude product with *p*-nitrobenzoyl chloride in pyridine. After crystallization from methanol it had m.p. 112—113 °C; $\nu_{max.}$ 1 700 cm^{-1}; δ 5.47 (1 H, m, $W_{\frac{1}{2}}$ 6.0 Hz, CHOCO) (Found: C, 54.05; H, 6.15; N, 4.05. $C_{16}H_{22}ClNO_4Si$ requires C, 53.99; H, 6.23; N, 3.93%).

A similar reaction of (**1**) (0.335 g, 1.97 mmol) in anhydrous benzene (15 ml) with a 1.9M-solution of dry hydrogen chloride in the same solvent (1.06 ml, 2.01 mmol) for 7 h at room temperature, gave a product (0.231 g) consisting of a mixture of (**8**) and (**7**) in a ratio of 95.5:4.5, accompanied by some of the starting epoxide (**1**) (g.l.c.).

(b) *With hydrogen chloride in cyclohexane.* Dry hydrogen chloride was bubbled through a solution of (**1**) (0.30 g, 1.76 mmol) in anhydrous cyclohexane for 20 min at room temperature. Work-up as under (a) afforded a mixture of (**8**) and (**7**) (0.237 g) in a ratio of 89:11.

(c) *With hydrogen chloride in carbon tetrachloride.* Similar treatment of (**1**) (0.300 g, 1.81 mmol) in dry carbon tetrachloride yielded a mixture of (**8**) and (**7**) (0.328 g) in a ratio of 90:10.

(d) *With hydrogen chloride in ether.* A solution of (**1**) (0.52 g, 3.05 mmol) in anhydrous ether (20 ml) was treated with a 2.7M-solution of dry hydrogen chloride in anhydrous ether (15 ml, 40.5 mmol); the mixture was stirred for 24 h at room temperature and then washed (saturated aqueous sodium

hydrogen carbonate and water). Evaporation of the dried organic phase gave a product (0.519 g) consisting of a mixture of (**8**) and (**7**) in a ratio of 93:7.

When the reaction of (**1**) with hydrogen chloride in ether was carried out as described above, but with stoicheiometric amounts of acid, the ratio between (**8**) and (**7**) was found to be 90:10; a small amount (*ca.* 6%) of the starting epoxide (**1**) was still present (g.l.c.).

(e) *With hydrogen chloride in dichloromethane.* A solution of (**1**) (0.201 g, 1.18 mmol) in anhydrous dichloromethane (15 ml) was treated with a 0.14M-solution of dry hydrogen chloride in the same solvent (84 ml, 11.76 mol equiv.); the mixture was stirred at room temperature for 7 h and then worked up as above to give a mixture of (**8**) and (**7**) (0.227 g) in a ratio of 95:5.

When the same reaction was carried out using a stoicheiometric amount of acid, (**8**) and (**7**) were obtained in a ratio of 92.5:7.5.

(f) *With aqueous hydrochloric acid.* Compound (**1**) (0.320 g, 1.88 mmol) was added to 36% aqueous hydrochloric acid (10 ml). The mixture was stirred at room temperature for 40 min, and then diluted with water and extracted with ether. Evaporation of the washed (water) and dried ether extracts yielded a product (0.318 g) consisting of a mixture of (**8**) and (**7**) in a ratio of 95:5.

Reaction of 1-*Trimethylsilylcyclohexene* (**11**) *with Hypochlorous Acid.*—(a) A solution of (**11**) (6.00 g, 38.9 mmol) in 50% aqueous dioxane (v/v) was treated with 70% perchloric acid (0.50 ml) and *N*-chlorosuccinimide (10.05 g, 76.7 mmol) and then stirred at room temperature for 48 h. The reaction mixture was diluted with water, extracted with ether, and the washed (water) and dried ether extracts were evaporated. The residue obtained was taken up with light petroleum and the succinimide eliminated by filtration. Evaporation of the solvent gave an oily residue (6.15 g) consisting of a mixture of (**8**) and (**7**) in a ratio of 56.5:43.5 (g.l.c.). This mixture was separated into its pure components by preparative t.l.c. [eluant: light petroleum–diethyl ether (4:1)]: (**8**) δ 3.90 (1 H, m, $W_{\frac{1}{2}}$ 9.0 Hz, CHOH) (Found: C, 52.4; H, 9.1. $C_9H_{19}ClOSi$ requires C, 52.27; H, 9.26%); (**7**) δ 4.03 (1 H, m, $W_{\frac{1}{2}}$ 11.8 Hz, CHCl) (Found: C, 52.4; H, 9.15. $C_9H_{19}ClOSi$ requires C, 52.27; H, 9.26%).

(b) To a stirred solution of (**11**) (0.25 g, 1.62 mmol) in dioxane (80 ml) was added at room temperature portionwise (20 ml every 15 min) a freshly distilled 0.025M-aqueous solution of hypochlorous acid (80 ml).[30] When the addition was finished, the reaction mixture was stirred at room temperature for 1 h and then diluted with water and extracted with ether. Evaporation of the washed (10% aqueous potassium iodide, 10% aqueous potassium carbonate, and water) ether extracts gave a residue (0.224 g) consisting of a mixture of (**8**) and (**7**) in a ratio of 56:44 (g.l.c.).

Conversion of Halohydrins (**5**), (**7**), *and* (**8**) *into the Epoxide* (**1**).—A solution of (**5**) (0.251 g, 1.0 mmol) in propan-2-ol (5 ml) was treated with potassium hydroxide (0.1 g, 1.8 mmol), stirred 15 min at room temperature, diluted with water, and extracted with ether. Evaporation of the washed (water) and dried ether extracts gave pure (**1**) (0.160 g).

Similar treatments of (**7**) and (**8**) produced pure (**1**).

2-*Bromo*-2-*trimethylsilylcyclohexanone* (**12**).—To a stirred suspension of Corey's reagent[31] (1.39 g, 6.45 mmol) in dry dichloromethane (30 ml) was added a solution of (**5**) (1.0 g, 3.98 mmol) in the same solvent. The resulting mixture was stirred at room temperature for 2.5 h, then refluxed for 1 h, diluted with ether, and filtered. Evaporation of the washed (water) organic phase yielded an oily residue consisting of pure (**12**) (0.828 g); $\nu_{max.}$ 1 700 cm^{-1} (Found: C, 43.15; H, 6.8. $C_9H_{17}BrOSi$ requires C, 43.37; H, 6.88%).

2-*Chloro*-2-*trimethylsilylcyclohexanone* (**9**).—Oxidation of (**8**) (1.0 g, 4.84 mmol) as described above for the oxidation of the corresponding bromohydrin (**5**), gave an oily residue of (**9**) (0.813 g); $\nu_{max.}$ 1 700 cm^{-1} (Found: C, 52.35; H, 8.25. $C_9H_{17}ClOSi$ requires C, 52.79; H, 8.37%).

Reduction of (**9**) *with Borane–Dimethyl Sulphide* (BMS).—A solution of (**9**) (0.690 g, 3.37 mmol) in anhydrous ether (60 ml) was treated with BMS (0.8 ml) under nitrogen, and the resulting mixture was left at room temperature for 3 h. Methanol (25 ml) was added at 0 °C and after 3 h at room temperature evaporation under reduced pressure gave a product (0.626 g), in which the C=O stretching band was completely absent, consisting of a 72:28 mixture of (**8**) and of its *cis*-diastereoisomer (**10**) [g.l.c., conditions A, retention times (**8**) > (**7**) > (**10**)]; (**10**), δ 3.68 (1 H, m, $W_{\frac{1}{2}}$ 16.5 Hz, C*H*OH).

A solution of the crude mixture of (**8**) and (**10**) in anhydrous benzene was saturated with dry hydrogen chloride and left for 1 h at room temperature; it was then washed (water) and evaporated to give unchanged starting mixture. No new peaks appeared in the gas chromatogram.

r-1-*Bromomercurio*-t-2-*methoxy*-1-*trimethylsilylcyclohexane* (**13**).—To a stirred suspension of mercuric acetate (4.96 g, 15.57 mmol) in methanol (75 ml) was added (**11**) (2.0 g, 12.96 mmol) and the mixture was stirred for a further 24 h at room temperature. After evaporation of the solvent the residue was treated with saturated aqueous potassium bromide (75 ml) and chloroform (75 ml) and the two-phase mixture was stirred for 30 min. After filtration to remove the insoluble inorganic salts, the chloroform layer was evaporated to give crude (**13**) (1.69 g), which on crystallization from benzene–light petroleum had m.p. 174—175 °C. The ^1H n.m.r. spectra of the crude and of crystallized (**13**) were identical: δ 3.36 (3 H, s, CH_3O) and 3.97 (1 H, m, $W_{\frac{1}{2}}$ 5.9 Hz, CHO) (Found: C, 26.0; H, 4.65. $C_{10}H_{21}BrHgOSi$ requires C, 25.78; H, 4.54%).

t-2-*Methoxy*-r-1-*bromo*-1-*trimethylsilylcyclohexane* (**14**).—A solution of (**13**) (1.5 g, 3.22 mmol) in anhydrous pyridine (15 ml), cooled at −10 °C, was treated with pyridine–bromine complex[32] (1.80 g, 7.53 mmol) stirred for 4 h at the same temperature and 12 h at room temperature, and then diluted with water and extracted with light petroleum. Evaporation of the organic extracts after washing with 2M-aqueous hydrochloric acid, water, and saturated aqueous sodium hydrogen carbonate gave pure (**14**) (0.552 g) (g.l.c., conditions B); δ 3.32 (3 H, s, CH_3O) and 3.55 (1 H, m, $W_{\frac{1}{2}}$ 7.2 Hz, CHO) (Found: C, 45.55; H, 8.15. $C_{10}H_{21}BrOSi$ requires C, 45.28; H, 7.98%).

Addition Reactions to (**11**) *initiated by Electrophilic Bromine in Methanol.*—(a) *With* N-*bromoacetamide.* A solution of (**11**) (1.98 g, 12.83 mmol) in 1:1 (v/v) methanol–dioxane (100 ml) was treated with NBA (2.02 g, 14.64 mmol) and warmed on a steam-bath for 5 min. After cooling the reaction mixture was diluted with water and extracted with ether. Evaporation of the washed (water) and dried ether extracts gave a residue (2.80 g) consisting essentially of a mixture of (**14**) and (**15**) in a ratio of 67:33 [g.l.c., conditions B, retention times (**15**) > (**14**)]. The minor component (**15**) was not isolated. Its structure has been tentatively assigned on the basis of the ^1H n.m.r. spectrum of the mixture: two methoxy and two CHX signals in a 2:1 ratio; the signals of the major component correspond to (**14**) and the others have been assigned to (**15**). Compound (**15**) δ 4.85 (1 H, m, $W_{\frac{1}{2}}$ 7.3 Hz, CHBr).

(b) *With bromine in the presence of* $CaCO_3$. To a stirred solution of (**11**) (0.50 g, 3.24 mmol) in methanol (50 ml) was added calcium carbonate (0.40 g) and the resulting suspension was treated dropwise at 0 °C with a solution of bromine (0.52 g,

3.25 mmol) in methanol (25 ml). Stirring at 0 °C was continued for 15 min, after which the suspension was filtered and the solvent evaporated to give a mixture of (**14**) and (**15**) in a ratio of 81:19; two other peaks of unidentified products were also present in the gas chromatogram (5.4% of the total area).

(c) *With pyridine perbromide.* A solution of (**11**) (0.307 g, 1.99 mmol) in anhydrous methanol was treated with pyridine–bromine complex[32] (0.52 g, 2.18 mmol) at 0 °C and then left at the same temperature for 15 min; it was then diluted with water and extracted with ether. Evaporation of the washed (aqueous sodium hydrogen sulphite, dilute hydrochloric acid, and water) and dried ether extracts yielded an oily residue (0.462 g) consisting of a mixture of (**14**) and of the dibromide (**16**) in a ratio of 52:48 (g.l.c., conditions B).

(d) *With pyridinium tribromide.* Compound (**11**) (0.414 g, 2.68 mmol) was treated with pyridinium tribromide[33] (0.944 g, 2.95 mmol) as described above in (c) for the analogous reaction with pyridine perbromide to afford a mixture (0.597 g) of (**14**) and (**16**) in a ratio of 42:58.

r-1,t-2-*Dibromo*-1-*trimethylsilylcyclohexane* (**16**).—A solution of bromine (0.907 g, 5.68 mmol) in dry carbon tetrachloride (20 ml) was added dropwise to a solution of (**11**) (0.796 g, 5.16 mmol) in the same solvent (25 ml). When the addition was finished, the solution was left for 20 min at room temperature, washed (aqueous sodium hydrogen sulphite and water), dried, and evaporated to give (**16**); δ 4.68 (1 H, m, $W_{\frac{1}{2}}$ 7.3 Hz, CHBr) (Found: C, 34.5; H, 5.7. $C_9H_{18}Br_2Si$ requires C, 34.38; H, 5.79%).

r-1-*Chloromercurio*-t-2-*methoxy*-1-*trimethylsilylcyclohexane* (**17**).—Mercuric acetate (4.98 g, 15.63 mmol) was added to a solution of (**11**) (2.01 g, 13.02 mmol) and the resulting suspension was stirred for 24 h. After evaporation of the solvent the residue was treated with saturated aqueous sodium chloride (75 ml) and chloroform (75 ml). The two-phase system was stirred for 30 min after which the organic phase was filtered and evaporated to yield (**17**) (1.73 g), m.p. 177—180 °C; δ 3.32 (3 H, s, CH_3O) and 3.88 (1 H, m, $W_{\frac{1}{2}}$ 6.8 Hz, CHO) (Found: C, 28.26; H, 4.82. $C_{10}H_{21}ClHgOSi$ requires C, 28.50; H, 5.02%).

r-1-*Chloro*-t-2-*methoxy*-1-*trimethylsilylcyclohexane* (**18**).—Compound (**17**) (0.30 g, 0.71 mmol) was added to pyridine perchloride (1.66 mmol) in carbon tetrachloride [prepared by mixing at 0 °C a 0.165M-solution of chlorine in anhydrous carbon tetrachloride (10.1 ml) and a solution of dry pyridine (0.131 g, 0.166 mmol) in the same solvent (10 ml), and used immediately] and the mixture then stirred for 4 h at −10 °C and 12 h at room temperature. After this it was diluted with light petroleum, washed (water, dilute hydrochloric acid, aqueous $NaHCO_3$, water), dried, and evaporated to give an oily residue consisting of (**18**) (0.095 g) (g.l.c., conditions C); δ 3.44 (3 H, s, CH_3O) and 3.57 (1 H, m, $W_{\frac{1}{2}}$ 7.5 Hz, CHO) (Found: C, 54.2; H, 9.35. $C_{10}H_{21}ClOSi$ requires C, 54.39; H, 9.59%).

Reaction of (**11**) *with* N-*Chlorosuccinimide in Methanol.*—A solution of (**11**) (0.307 g, 1.99 mmol) in 1:1 (v/v) methanol–dioxane (10 ml) was treated with NCS (0.50 g, 3.74 mmol) and stirred for 48 h at room temperature. The reaction mixture was diluted with water and extracted with ether. After evaporation of the organic layer, the residue was taken up with light petroleum, filtered, and the organic solvent evaporated to dryness to yield a residue that on g.l.c. analysis (conditions C) showed two main peaks (45% and 31% of the total areas) and three minor components. The most abundant peak corresponded to (**18**). The second most abundant component was not isolated, but probably corresponded to (**19**) on the basis of the presence of a second methoxy singlet (δ 3.71) and a second narrow CHX multiplet (δ 4.55) in the ^1H n.m.r. spectrum.

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