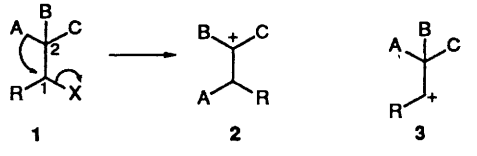
# Alkyl Migration in Competition with Phenylthio Migration in the Acid-catalysed Rearrangement of Alcohols

**Malcolm Hannaby and Stuart Warren** *
*University Chemical Laboratory, Lensfield Road, Cambridge CB2 1EW, UK*

Sulfonate derivatives of conformationally rigid *syn*-2-phenylthiocyclohexanols, which are prevented from phenylthio migration by stereochemistry, rearrange slowly by alkyl migration or ring contraction. In contrast to other electronegative groups, phenylthio slows the reaction down but allows migration of other groups.

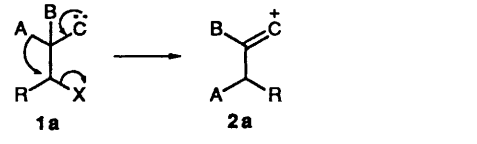
Solvolysis of compounds of type **1** usually gives products derived from the rearranged cation **2** rather than from the unrearranged cation **3** formed by simple loss of the leaving group X. It is usually claimed that rearrangement occurs because the cation **2** is more stable than the cation **3**. This is true if the substituents A, B, C, at the migration origin (C-2 in **1**), or R, at the migration terminus (C-1 in **1**), are simple alkyl groups, that is none of them has lone pair or π electrons. It is then also true that the migrating group (A in **1**) is chosen by two simple rules: that group migrates which is (i) best able to share the positive charge in the transition state and (ii) occupies an



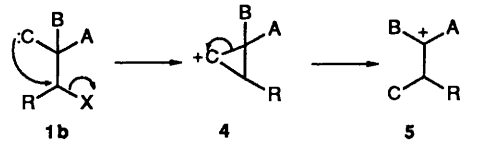
**1** **2** **3**

*anti-peri*-planar position relative to the C–X bond. Even when substituents at the migration origin do have lone pair or π electrons, the same rules often apply. The Baeyer–Villiger[1] and dienone–phenol[2] rearrangements are excellent examples.

In other cases, particularly where an electron-donating group C can help another group (A in **1a**) to migrate, or can itself participate **1b** to form a cyclic intermediate **4** and hence become the migrating group, giving **5**, these simple rules no longer

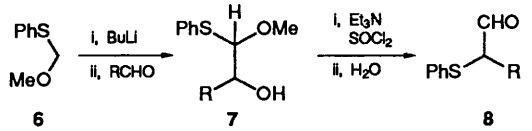


**1a** **2a**

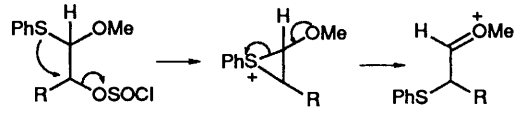


**1b** **4** **5**

apply. The OR group is good at helping another group to migrate, as in the pinacol rearrangement,[3] while the SR group is particularly good at participating, as in our series of synthetic methods based on stereospecific PhS migration.[4] The best illustration of their preferred roles is in the rearrangement of the adducts[5] **7** when PhS migrates because it participates (see **9**) while MeO stays behind because it prefers to form a π-bond and help PhS to migrate (see **10**). Electron-withdrawing groups[6] (*e.g.* RCO, $NO_2$, $R_2PO$ or $RSO_2$) also fail to conform to the simple rules, but this is because they reject the apparently passive role of group B in **1**, **1a**, or **1b** and are therefore obliged to migrate (A in **1**).

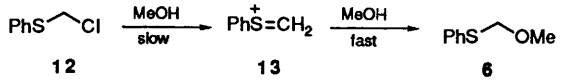


**6** **7** **8**

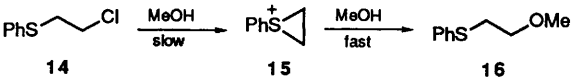


**9** **10** **11**

This paper[7] explores the conflict between the roles assigned to the electron-rich group C in **1a** and **1c** when C is PhS. There is no doubt that PhS is one of the best migrating groups, but, if the stability of the rearranged cation is all that matters, it ought to be even better at helping other groups to migrate since the solvolysis of **12** is about 600 times faster[8] than the solvolysis of **14** and the cations formed in the slow step, **13** and **15**, should have similar relative stabilities to those of **2a** and **4**. The abilities of RO and RS in stabilising cations such as **2a** and **4** have been compared by rate and product studies on reactions such as the hydrolysis of mixed acetals[9] **17** and the protonation of enol



**12** **13** **6**

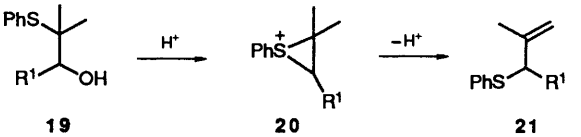


**14** **15** **16**

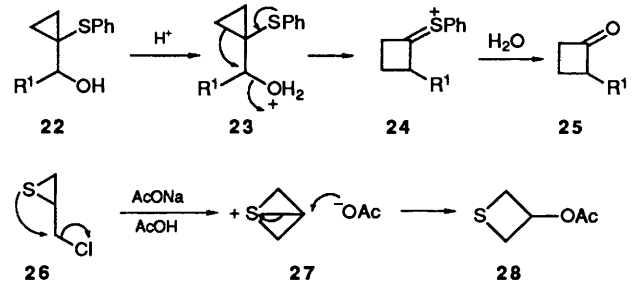
ethers[10] **18** and by calculations.[11] The results are inconclusive: both groups stabilise such cations but changing the reaction or the substituents often affects which of the two (RO or RS) is

**17** **18**

more effective. Nevertheless, in spite of all these factors, the results of acid-catalysed rearrangements of alcohols **19**, (*i.e.* **1**; A = PhS, B = C = Me) are clear: PhS migration always occurs and never methyl migration.[12]

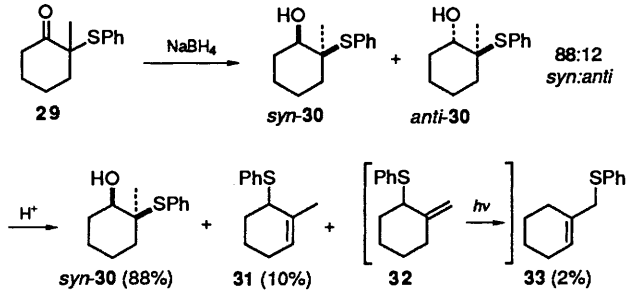


**19** **20** **21**



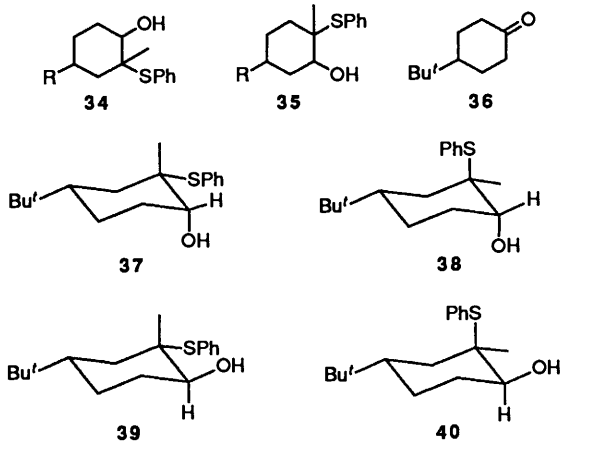

The well known rearrangements[13] of adducts **22**, in which a PhS group does appear to help an alkyl shift, confuse the issue: they are the only such migrations. In all other cases the PhS group migrates and the product is an allyl sulfide. This cannot be because cation **24** is particularly stable, rather it is a kinetic effect of the instability of the three-membered ring. Given a choice, even a three membered ring prefers to use sulfur participation **26** rather than alkyl migration.[14]

We already knew that the PhS group was unwilling to assist alkyl migration because acid-catalysed rearrangement of the mixture of *syn*- and *anti*-alcohols **30** from the reduction of the 2-PhS ketone **29** gave allyl sulfides **31** and **33** from rapid




rearrangement of *anti*-**30**, but left *syn*-**30** unchanged even after very long reflux times.[15] Only when the ring size was 12 or more did *syn*-alcohols such as **30** rearrange, and then PhS migration occurred. We decided to attempt to force an alkyl shift by making all four diastereoisomers of an alcohol such as **34** or **35** where R is large so that at least one diastereoisomer would have Me and OH related in a *trans*-diaxial fashion.

We began by attempting to make **37**–**40** by sulfenylation, methylation, and reduction of the ketone **36**, hoping that the

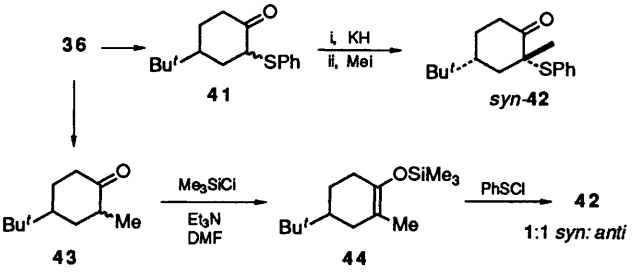



order of the first two reactions and the choice of reducing agent would allow full stereochemical control. Sulfenylation of the lithium enolate of **36** gives about a 2:1 mixture[16,17] favouring *anti*-**41**, the product of axial sulfenylation, while reaction of the silyl enol ether gave a 78:22 mixture[18] with $PhSSO_2Ph$ or a 1:1 mixture with PhSCl. There was no point in separating this

**Table 1** Stereoselectivity of reduction of 4-*tert*-butylcyclohexanones

| Ketone | Product ratios from axial:equatorial attack by reagents | | |
|---|---|---|---|
| | $LiAlH_4$ | $Li(Bu^s_3BH)$ | $Zn(BH_4)_2$ |
| **36** | 91:9[a] | 3.5:96.5[b] | — |
| *syn*-**42** | 86:14 | 5:95 | — |
| *anti*-**42** | 100:0 | 93:7 | 99:1 |

[a] See ref. 21. [b] See ref. 22.




mixture as both give the same enolate. Alkylation (KH, MeI) gave a moderate yield (51%) of a mixture of diastereoisomers of **42** which could be separated by HPLC. The ketone *syn*-**42**, the product of axial alkylation, was favoured by 6:1. Attempts to improve the yield with different bases or conditions were unsuccessful.

Reversing the order of the first two reactions was achieved by methylation of the lithium enolate or magnesium aza-enolate[19] of **36** to give a mixture of diastereoisomers of **43** followed by formation of the silyl enol ether **44** under equilibrating conditions in DMF.[20] Sulfenylation with PhSCl then gave a 1:1 mixture of the diastereoisomers of **42**, separated by HPLC. This disappointing lack of stereoselectivity presumably arises because the electrophile approaches the potassium enolate of **41** at the enolate carbon but approaches **44** towards the centre of the double bond. These methods nevertheless gave enough material for reduction.

The reduction of ketone **36** can be controlled[21] to give almost entirely equatorial alcohol with small reducing agents and almost entirely axial alcohol with $Bu^s_3BHLi$ and other large reducing agents.[21,22] The same methods were applied to the two ketones *syn*- and *anti*-**42** (Table 1). It proved possible to control the reduction of *syn*-**42**, with its equatorial PhS group, to give the equatorial alcohol **39** with $LiAlH_4$, and the axial alcohol **37** with $Bu^s_3BHLi$. Selectivities were very similar to those obtained with the simple ketone **36** (Table 1). In contrast, the *anti*-ketone gave predominantly axial attack with either reagent, the equatorial alcohol **40** being almost the only product. This must be because of interaction between the C–S bond and the C=O p-orbitals, as analysed by Cieplak.[23] Chelation control, *e.g.* with $Zn(BH_4)_2$, can deliver hydride from the same side as the RS group in α-RS ketones,[24] but this method also gave only the equatorial alcohol in this case. We were unable to make the last alcohol **38** in high yield by reduction, but, as it has axial PhS and OH groups, it is the least interesting as it can rearrange only by PhS migration.

The stereochemistry of alcohol **37** was determined by X-ray crystal structure analysis,[25] which revealed the configuration and conformation shown in Fig. 1. This also confirms the configuration of both ketones and the configuration of the other alcohol **39** formed by reduction of *syn*-**42**. The two remaining alcohols were distinguished by a typical axial C*H*OH at δ 3.34 (dd, $J_{AA}$ 11.5, $J_{AE}$ 4.3) in the proton NMR spectrum of the

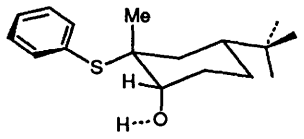
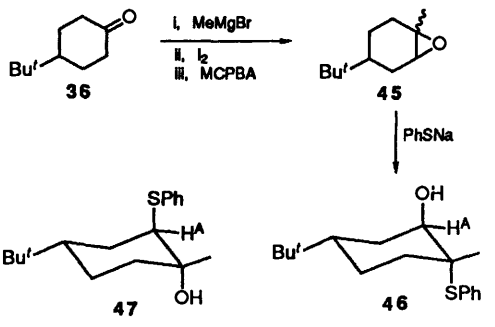


Fig. 1 X-Ray structure of the alcohol **37**

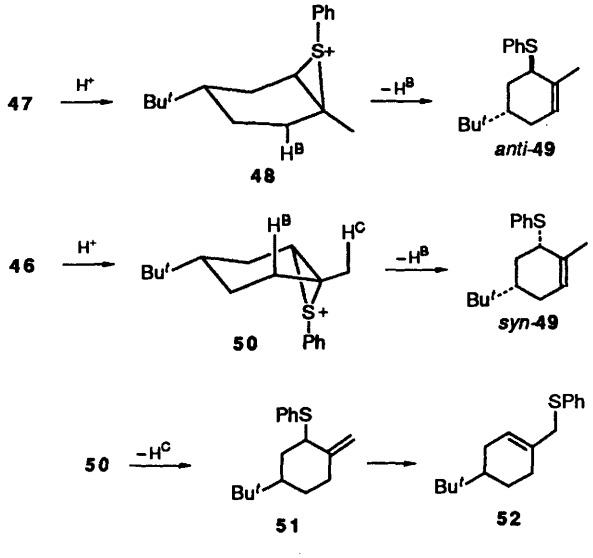
equatorial alcohol **40**, and a typical equatorial C*H*OH at $\delta$ 3.40 (dd, $J_{EA}$ 3.5, $J_{EE}$ 1.6) in that of the axial alcohol **38**.

A regioisomeric alcohol **46** having the missing stereochemical pattern was prepared from the epoxides **45** with PhSNa. Two alcohols were the major products (separated by HPLC), the



secondary alcohol **46** formed by diaxial opening of the *syn*-epoxide **45** and the tertiary alcohol **47** from diaxial opening of the *anti*-epoxide **45**. The protons marked $H^A$ in **46** and **47** had characteristic shifts and splitting patterns.

These two alcohols **46** and **47** did indeed rearrange only with PhS migration. The tertiary alcohol **47** gave only the *endo*cyclic allyl sulfide *anti*-**49** *via* the episulfonium ion **48**, while the



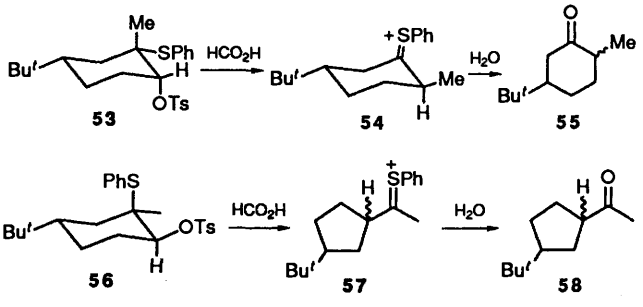
secondary alcohol **46** gave a 4:1 mixture of *endo*- and *exo*-allyl sulfides *syn*-**49** and **52**. The tertiary alcohol **47** behaves much as other related tertiary alcohols,[15] while the behaviour of the secondary alcohol **46** is very similar to the rearrangement[15] of *anti*-**30** which gave a 5:1 ratio of *endo*-and *exo*-cyclic allyl sulfides **31** and **33**.

Though these compounds rearranged in a similar way to all the others we have studied, the isomeric alcohols **37**, **39** and **40** gave no recognisable products of PhS or alkyl migration when treated with TsOH, NaOAc–HOAc, concentrated sulfuric acid in HOAc, thionyl chloride in pyridine, or zinc chloride. Either no reaction occurred or mixtures of decomposition products were found. We therefore converted alcohols **37** and **40** into their toluene-*p*-sulfonates (i, BuLi; ii, TsCl) **53** and **56** without change in stereochemistry (NMR). Alcohol **39**, with equatorial PhS and OH groups, would not form a toluene- or methanesulfonate under a variety of conditions.

**Table 2** Rates of solvolysis of cyclohexyl toluene-*p*-sulfonates

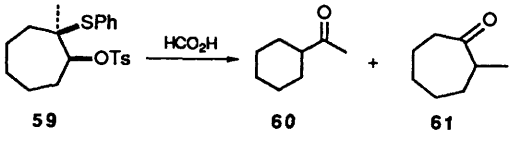
| Compound | Estimated half life (min) | Ref. |
|---|---|---|
| **62** | 0.42 | 27 |
| **65** | 15.2 | 29 |
| **66** | 25.8 | 29 |
| **53** | 36 ± 8 | — |
| **56** | 56 ± 16 | — |

Rearrangement of the sulfonates **53** and **56** in formic acid at 90 °C finally gave alkyl migration. The solutions turned deep violet: addition of water (ammonium chloride solution) after 30

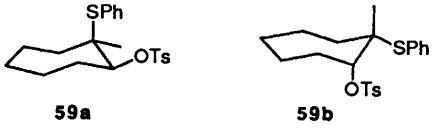


min quenched the violet colour and gave the ketones **55** and **58**, the products of methyl migration and ring contraction respectively. In each case, the group *anti-peri*-planar to the OTs group has migrated. Both compounds are formed as mixtures of diastereoisomers. The intermediate ions **54** and **57** (which may be responsible for the violet colour) are presumably acidic enough for epimerisation to occur *via* the vinyl sulfide.

Other ring sizes offer more flexible conformations and we rearranged the sulfonate **59** derived from the *syn* isomer of an alcohol which would not rearrange even after 80 h with TsOH



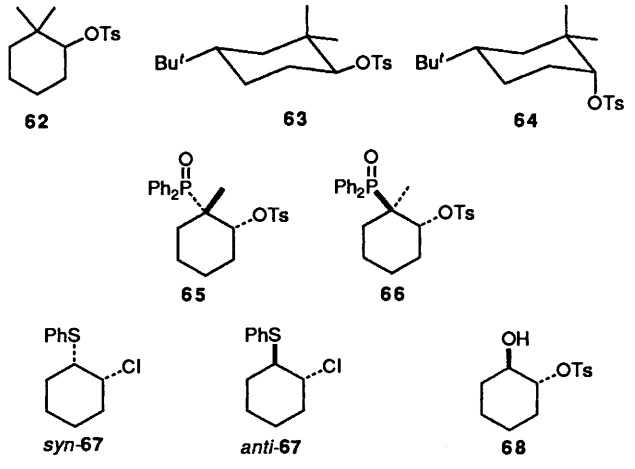
in benzene under reflux.[15] Rearrangement was quantitative after 1 h in formic acid at 90 °C giving ring contraction **60** and methyl migration **61** products in a 4:1 ratio. The conformation **59a** leading to ring contraction has a pseudo-equatorial OTs



group and may be more stable than **59b**. Though these reactions are formally 1,2-carbonyl transpositions,[26] there are more efficient ways to carry out such reactions using sulfur chemistry[26] and we believe they are more valuable for the insight they offer into the details of the rearrangement process.

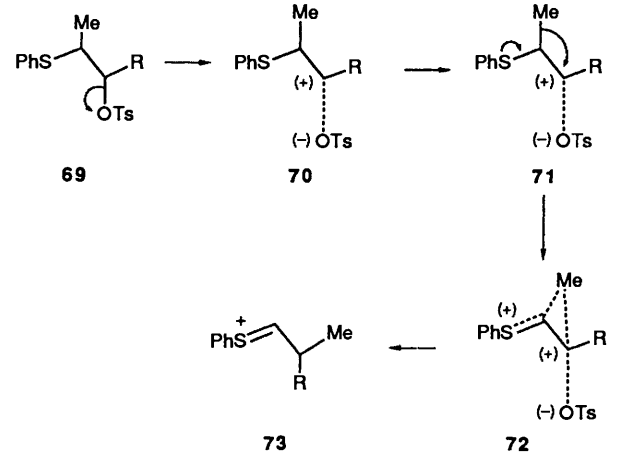
We must now attempt to decide whether these successful alkyl migrations are actively encouraged or reluctantly permitted by the PhS group. Crude rate measurements (half-life determinations by TLC) on the rearrangements of **53** and **56**

show that they are much slower (Table 2) than those of the simple model **62**, which gives a mixture of ring contraction and methyl migration,[27] or of the conformationally fixed analogues




**63** and **64**, which react at about the same rate as each other and as **62**, giving mostly ring contraction and methyl migration respectively.[28] They are even slightly slower than the reactions of the $Ph_2PO$ analogues **65** and **66** which give unrearranged alkenes.[29] The PhS group is evidently slowing down the rearrangement but still allowing it to happen in contrast to the $Ph_2PO$ group which slows the reaction down by about the same amount but will not allow alkyl shifts to occur. Another related observation is that *syn*-**67** solvolyses in aqueous ethanol about six times more slowly than cyclohexyl chloride while *anti*-**67** solvolyses about $10^6$ more rapidly,[30] evidently with PhS participation.

A recent study[31] by X-ray crystallography on the change in C–O bond length in analogues of **68** with leaving group ability as an approach to the transition state for the pinacol rearrangement found that as the leaving group (OTs in **68**) got better, the C–O bond joining it to the rest of the molecule lengthened but there was almost no change at the CHOH centre. All these observations can be reconciled in a transition state **70** for rearrangement in which the leaving group has nearly




gone before alkyl shift **71** occurs. The rate is reduced by the inductive effect of the C–S bond destabilising **70** but the product is controlled by the assistance of the lone pair of electrons on the sulfur atom in **72**. This destabilisation is related to the high and irreversible stereoselectivity in the reduction of the axial 2-phenylthio ketone *anti*-**42**. A similar effect destabilises the cationic transition state for the solvolysis of *syn*-**67**, while the transition states for the dehydration of **65** and **66** must resemble **70** without any assistance to alkyl shift after the transition state is passed.

A thorough understanding of rearrangement reactions requires consideration not only of the migrating group but also of the groups which remain behind. These apparently passive groups may control the reaction to a remarkable degree depending on stereochemistry, electronegativity, availability of lone pair electrons, and inherent ability to migrate or fragment. This complete picture can emerge only by the study of potential migrating groups covering a wide range of such properties.[6,29]

## Experimental

4-tert-*Butyl*-1-*trimethylsiloxycyclohexene*.—4-*tert*-butylcyclohexanone **36** (1.54 g, 10 mmol) was stirred with hexamethyldisilazine (2.53 $cm^3$, 12 mmol) in dry pentane (150 $cm^3$) under nitrogen. The mixture was cooled to −20 °C, freshly distilled trimethylsilyl iodide (12.5 $cm^3$, 11 mmol) added and the solution stirred for 10 min at −20 °C then for a further 3 h at room temperature. The resulting slurry was centrifuged and the supernatant washed with cold sodium hydrogen carbonate solution (100 $cm^3$) and solvent removed under reduced pressure. The residue was distilled to give the silyl enol ether (1.99 g, 88%) as an oil, b.p. 76–78 °C/1.4 mmHg (lit.,[32] 98 °C/4.2 mmHg), $R_f$ ($CH_2Cl_2$) 0.75.

4-tert-*Butyl*-2-*phenylthiocyclohexanone* **41**.—Phenylsulfenyl chloride (49.0 $cm^3$, 1.0 molar in dichloromethane, 49 mmol) was added slowly to a solution of 4-*tert*-butyl-1-trimethylsiloxycyclohexene (9.0 g, 40 mmol) in dry dichloromethane (200 $cm^3$) under nitrogen at −78 °C. The mixture was allowed to warm to room temperature and solvent removed under reduced pressure. Purification by column chromatography on silica gel eluting with dichloromethane gave the diastereoisomeric ketones[16] **41** (7.22 g, 69%) as an oil, $R_f$ ($CH_2Cl_2$) 0.31 and 0.41, $\nu_{max}$(liquid film)/$cm^{-1}$ 1710 (C=O) and 1580 (SPh); $\delta_H$($CDCl_3$) 7.5–7.2 (5 H, m, SPh), 4.05(*cis*) (1 H, dd, $J_{cis}$ 6, 12, CHSPh), 3.80(*trans*) (1 H, dd, $J_{trans}$ 3, 4, CHSPh), 3.15 (1 H, dt, *J* 6, 14, 14, $CH_AH_EC$=O), 2.6–1.3 (6 H, m, $CHCH_2CHCH_2$) and 0.86 and 0.93 (9 H, each s, Bu$^t$) (Found: $M^+$, 262.1412. $C_{16}H_{22}OS$ requires *M*, 262.1391); *m*/*z* 262 (11%, $M^+$), 128 (52), 110 (100, PhSH) and 57 (59).

2-*Bromo*-4-tert-*butylcyclohexanone*.—Bromine (14.9 g, 0.1 mol) was added dropwise to a solution of 4-*tert*-butylcyclohexanone (15.4 g, 0.1 mol) and aluminium trichloride (0.15 g) in dry ether (50 $cm^3$) under nitrogen at 0 °C. Hydrogen bromide was removed by bubbling dry nitrogen through the ethereal solution which was poured into water (10 $cm^3$) and ether (20 $cm^3$), the organic fraction was separated, dried ($MgSO_4$) and solvent removed under reduced pressure. The residue was distilled to give the 2-bromo ketones[33] (14.7 g, 63%) as an orange oil, b.p. 86–94 °C/16 mmHg, $R_f$ ($CH_2Cl_2$) 0.52 and 0.59; $\nu_{max}$(thin film)/$cm^{-1}$ 1710 (C=O) and 1580 (SPh); $\delta_H$($CDCl_3$) 4.6(*cis*) (1 H, dd, $J_{cis}$ 6, 12, CHBr), 4.3(*trans*) (1 H, dd, $J_{trans}$ 3, 5, CHBr), 3.2–1.4 (7 H, m, $CH_2CH_2CHCH_2$) and 0.9 (9 H, s, Bu$^t$) (Found: $M^+$, 232.0455. $C_{10}H_{17}BrO$ requires *M*, 232.0463); *m*/*z* 232 and 234 (7%, $M^+$), 176 and 178 (8), 153 (2, $M^+$ − Br), 97 (29) and 57 (100).

4-tert-*Butylcyclo*-2-*phenylthiohexanone* **41** *from the Bromo Ketone*.—A solution of 2-bromo-4-*tert*-butylcyclohexanone (13.56 g, 58 mmol) in ethanol (10 $cm^3$) was added slowly to a stirred solution of thiophenol (6.38 g, 58 mmol) and sodium hydroxide (2.32 g, 58 mmol) in ethanol (50 $cm^3$) under nitrogen at room temperature. After 24 h the solvent was removed under reduced pressure, the residue diluted with water (100 $cm^3$) and extracted with dichloromethane (4 × 25 $cm^3$), the combined

organic layers were washed with sodium hydroxide solution (2 × 25 $cm^3$), water (25 $cm^3$), brine (25 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure. Reduced pressure distillation gave the above 2-phenylthio ketones[33] **41** (12.73 g, 83%) as an oil, $R_f$ ($CH_2Cl_2$) 0.31 and 0.41.

4-tert-*Butyl-2-methyl-2-phenylthiocyclohexanone* **42**.—A solution of 4-*tert*-butyl-2-phenylthiocyclohexanone **41** (5.52 g, 21.1 mmol) in dry THF (10 $cm^3$) was added dropwise to a suspension of light petroleum-washed potassium hydride (1.20 g, 30.0 mmol) in dry THF (50 $cm^3$) under nitrogen at room temperature. The yellow anion was allowed to form, indicated by the evolution of hydrogen (approximately 30 min), and quenched with methyl iodide (2.63 $cm^3$, 42.2 mmol) at 0 °C. After 2 h the mixture was cautiously poured into ammonium chloride solution (50 $cm^3$), extracted with ether (3 × 25 $cm^3$), and the combined organic fractions washed with sodium carbonate solution (2 × 25 $cm^3$), brine (10 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure. Purification by column chromatography on silica gel eluting with dichloromethane gave the diastereoisomeric ketones (*syn*- and *anti*-**42**) (2.96 g, 51%) as an oil, $R_f$ ($CH_2Cl_2$) 0.45. HPLC separation eluting with 5% ethyl acetate in light petroleum (b.p. 60–80 °C) on a Zorbax sil column with flow rate 14.3 $cm^3$ $min^{-1}$ gave the (2RS,4SR)-*ketone anti*-**42** (81 mg) as an oil, $R_f$ 9.5 min; $\nu_{max}$ (thin film)/$cm^{-1}$ 1710 (C=O) and 1580 (SPh); $\delta_H$($CDCl_3$) 7.35–7.25 (5 H, m, PhS), 3.40 (1 H, dt, *J* 15, 15, 5, $CH_AH_ECO$), 2.35 (1 H, ddd, *J* 15, 4, 2.5, $CH_AH_ECO$), 2.25–1.10 (5 H, m, $CH_2CHCH_2$), 1.20 (3 H, s, Me) and 0.92 (9 H, s, Bu$^t$) (Found: $M^+$, 276.1549. $C_{17}H_{24}OS$ requires *M*, 276.1548); *m*/*z* 276 (12%, $M^+$), 219 (18), 110 (37, PhSH), 109 (27, PhS) and 57 (100) and the (2RS,4RS)-*ketone syn*-**42** (479 mg) as a solid, $R_f$ 11.5 min, m.p. 44–45 °C; $\nu_{max}$(Nujol)/$cm^{-1}$ 1710 (C=O) and 1580 (SPh), $\delta_H$($CDCl_3$) 7.46–7.25 (5 H, m, PhS), 2.77 (1 H, ddd, *J* 15, 7, 5, $CH_AH_ECO$), 2.35 (1 H, ddd, *J* 15, 9, 7, $CH_AH_ECO$), 2.0–1.3 (5 H, m, $CH_2CHCH_2$), 1.34 (3 H, s, Me) and 0.86 (9 H, s, Bu$^t$); $\delta_C$($CDCl_3$) 209.6 (C=O), 136.9, 129.0 and 128.5 (aromatic), 57.1 (*C*SPh), 42.8 ($CH_2C$=O), 40.3 (*C*Bu$^t$), 36.6 (Me), 32.5 ($CMe_3$), 27.2 ($CMe_3$), 25.3 and 23.7 ($CH_2CHCH_2$) (Found: $M^+$, 276.1564. $C_{17}H_{24}OS$ requires *M*, 276.1548); *m*/*z* 276 (31%, $M^+$), 219 (30), 110 (51, PhSH) and 57 (100).

4-tert-*Butyl-2-methylcyclohexanone* **43**.—4-*tert*-Butylcyclohexanone **36** (6.16 g, 40 mmol) was refluxed with cyclohexylamine (9.1 $cm^3$, 80 mmol) in benzene (50 $cm^3$) for 24 h using a Dean–Stark apparatus. Solvent was removed under reduced pressure and distillation gave *N*-(4-*tert*-butylcyclohexylidene)-cyclohexylamine (7.35 g, 79%) as an oil b.p. 120–124 °C/1.5 mmHg. The freshly distilled imine (1.17 g, 5 mmol) in dry ether (5 $cm^3$) was added to a stirred solution of isopropylmagnesium bromide (6 $cm^3$, 2.0 molar in ether, 12 mmol) in dry ether (25 $cm^3$) under nitrogen at 0 °C. The mixture was refluxed for 45 min, cooled to 0 °C and methyl iodide (0.75 $cm^3$, 12 mmol) added. After 1 h the mixture was warmed to room temperature, stirred for a further 20 min and poured into ammonium chloride solution (25 $cm^3$). The organic phase was shaken with a buffered acetic acid solution (20 $cm^3$ glacial acetic acid, 10 g sodium acetate, 20 $cm^3$ water) for 5 min, washed with brine (2 × 25 $cm^3$), sodium hydrogen carbonate solution (4 × 25 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure to give the ketones[34] **43** (0.79 g, 94%), $R_f$ ($CH_2Cl_2$) 0.31 and 0.36, $\nu_{max}$(thin film)/$cm^{-1}$ 1710 (C=O); $\delta_H$($CDCl_3$) 2.6–1.3 (8 H, m, $CH_2CH_2CHCH_2CH$), 1.15 and 1.0 (3 H, each d, *J* 6, CH*Me*) and 0.9 (9 H, s, Bu$^t$) (Found: $M^+$, 168.1523. $C_{11}H_{20}O$ requires *M*, 168.1514); *m*/*z* 168 (20%, $M^+$), 153 (5, M − Me), 143 (10), 112 (60), 97 (20), 69 (30) and 57 (100).

4-tert-*Butyl-2-methylcyclohexanone* **43** *by Methylation of the Lithium Enolate*.—4-*tert*-Butylcyclohexanone **36** (1.54 g, 10 mmol) in dry THF (10 $cm^3$) was added dropwise to a stirred solution of LDA (10 mmol) in dry THF (50 $cm^3$) under argon at −78 °C. After 1 h methyl iodide (1.24 $cm^3$, 20 mmol) was added and the solution allowed to warm to room temperature, poured into ammonium chloride solution (50 $cm^3$) and extracted with ether (3 × 25 $cm^3$). The combined organic fractions were washed with sodium hydrogen carbonate solution (2 × 50 $cm^3$), brine (20 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure. Column chromatography on silica gel eluting with dichloromethane gave the ketones **43** (1.23 g, 73%) as an oil, $R_f$ ($CH_2Cl_2$) 0.31 and 0.36.

4-tert-*Butyl-2-methyl-1-trimethylsiloxycyclohex-1-ene* **44**.—Trimethylsilyl chloride (0.62 $cm^3$, 4.8 mmol) was added dropwise to a stirred solution of 4-*tert*-butyl-2-methylcyclohexanone **43** (5.67 mg, 4 mmol) and dry triethylamine (1.12 $cm^3$, 8 mmol) in dry THF (10 $cm^3$). The mixture was heated for 90 h at 130 °C under nitrogen. The solution was cooled, diluted with ether (50 $cm^3$) and poured into sodium hydrogen carbonate solution (50 $cm^3$). The aqueous phase was extracted with ether (3 × 25 $cm^3$) and the combined organic fractions were washed with 0.5 mol $dm^{-3}$ hydrochloric acid (50 $cm^3$), saturated sodium hydrogen carbonate solution (2 × 50 $cm^3$), and water (50 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure to give the silyl enol ether **44** (580 mg, 71%) as an oil, b.p. 92–95 °C/1.4 mmHg, $R_f$ ($CH_2Cl_2$) 0.69; $\delta_H$($CDCl_3$) 2.1–1.0 (7 H, m, $CH_2CH_2CHCH_2$), 1.55 (3 H, br s, C=CMe), 0.85 (9 H, s, Bu$^t$) and 0.06 (9 H, s, $SiMe_3$). Formation of the silyl enol ether with trimethylsilyl iodide and hexamethyldisilazane gave a 9:1 mixture of silyl enol ether **44** and 4-*tert*-butyl-6-methyl-1-trimethylsiloxycyclohex-1-ene, $R_f$ ($CH_2Cl_2$) 0.69; $\delta_H$($CDCl_3$) 4.85 (1 H, m, CH=C), 2.3–1.2 (6 H, m, $CH_2CHCH_2CH$), 1.0 (3 H, d, *J* 6, CH*Me*), 0.9 (9 H, s, Bu$^t$) and 0.1 (9 H, s, $SiMe_3$).

4-tert-*Butyl-2-methyl-2-phenylthiocyclohexanone* **42** *by Sulfenylation of the Silyl Enol Ether* **44**.—Phenylsulfenyl chloride (2.4 $cm^3$, 1.0 mol $dm^{-3}$ in dichloromethane, 2.4 mmol) was added slowly to a solution of 4-*tert*-butyl-2-methyl-1-trimethylsiloxycyclohex-1-ene **44** (580 mg, 24 mmol) in dry dichloromethane (10 $cm^3$) under argon at −78 °C. The mixture was allowed to warm to room temperature and solvent removed under reduced pressure. Purification by column chromatography on silica gel eluting with dichloromethane gave the diastereoisomeric ketones (*syn* and *anti*-**42**) (320 mg, 67% based on recovered starting material) as an oil. HPLC separation eluting with 5% ethyl acetate in light petroleum (b.p. 60–80 °C) flow rate 14.3 $cm^3$ $min^{-1}$ gave the two ketones in a 1:1 ratio.

*Preparation of Alcohol* **40**.—Lithium aluminium hydride (40 mg, 1.05 mmol) was added to a solution of (2*RS*,4*SR*)-4-*tert*-butyl-2-methyl-2-phenylthio-cyclohexanone *anti*-**42** (25 mg, 0.09 mmol) in dry ether (10 $cm^3$) at 0 °C. The mixture was stirred for 30 min and quenched with ethyl acetate (5 $cm^3$) and methanol (2 $cm^3$) and poured into sodium hydroxide solution (20 $cm^3$), and extracted with ether (3 × 10 $cm^3$). The organic layers were combined and shaken with brine (10 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure to give (1SR,2RS,4SR)-4-tert-*butyl-2-methyl-2-phenylthiocyclohexanol* **40** (22 mg, 88%) as prisms; $\nu_{max}$(Nujol)/$cm^{-1}$ 3450 (OH) and 1580 (SPh); $\delta_H$($CDCl_3$) 7.54–7.25 (5 H, m, SPh), 3.37 (1 H, dd, *J* 4.3, 11.5, C*H*OH), 1.8–1.0 (7 H, m, $CH_2CH_2CHCH_2$), 1.16 (3 H, s, Me) and 0.86 (9 H, s, Bu$^t$) (Found: C, 73.3; H, 9.45; S, 11.7%; $M^+$, 278.1711. $C_{17}H_{26}OS$ requires C, 73.3; H, 9.4; S, 11.5%; *M*, 278.1704); *m*/*z* 278 (95%, $M^+$), 169 (100) and 151 (85).

Similarly reduction of ketone *anti*-**42** (52 mg, 0.19 mmol) with zinc borohydride (0.63 $cm^3$, 0.15 molar in ether, 0.09 mmol) in dry ether (10 $cm^3$) gave only alcohol **40** (51 mg, 96.5%).

Prepared in the same manner were:

*Alcohols* **37** *and* **39**. (2*SR*,4*SR*)-4-*tert*-Butyl-2-methyl-2-phenylthiocyclohexanone *syn*-**42** (50 mg, 0.18 mmol) gave a 14:86 mixture (by HPLC) of alcohols **37** and **39** (50 mg, 100%) as an oil. HPLC separation, eluting with 10% ethyl acetate in light petroleum (b.p. 60–80 °C) with flow rate 14.3 $cm^3$ $min^{-1}$ gave (1RS,2SR,4SR)-4-tert-*butyl*-2-*methyl*-2-*phenylthiocyclohexanol* **37** (25 mg) as prisms, m.p. 115–116 °C, $R_f$ ($CH_2Cl_2$) 0.33; $\nu_{max}$(Nujol)/$cm^{-1}$ 3450 (OH) and 1580 (SPh); $\delta_H$($CDCl_3$) 7.53–7.25 (5 H, m, SPh), 3.36 (1 H, dd, *J* 1.6, 3.4, C*H*OH), 2.0–1.3 (7 H, m, $CH_2CH_2CHCH_2$), 1.19 (3 H, s, Me) and 0.86 (9 H, s, Bu$^t$) (Found: $M^+$, 278.1697. $C_{17}H_{26}OS$ requires *M*, 278.1704); *m*/*z* 278 (2%, $M^+$), 183 (24), 169 (7, M − PhS) and 110 (100, PhSH); and (1SR,2SR,4SR)-4-tert-*butyl*-2-*methyl*-2-*phenylthiocyclohexanol* **39** (31 mg) as an oil, $R_f$ ($CH_2Cl_2$) 0.40, $\nu_{max}$(thin film)/$cm^{-1}$ 3450 (OH) and 1580 (SPh); $\delta_H$($CDCl_3$) 7.52–7.25 (5 H, m, SPh), 3.27 (1 H, dd, *J* 4.7, 11.4, C*H*OH), 2.0–1.3 (7 H, m, $CH_2CH_2CHCH_2$), 1.24 (3 H, s, Me) and 0.76 (9 H, s, Bu$^t$) (Found: $M^+$, 278.1691. $C_{17}H_{26}OS$ requires *M*, 278.1704); *m*/*z* 178 (8%, $M^+$), 169 (32), 151 (19) and 110 (100, PhSH).

L-*Selectride Reduction of Ketones* **42**.—L-Selectride® (Aldrich) (1 $cm^3$, 1.0 mol $dm^{-3}$ in THF, 1 mmol) was added dropwise to a stirred solution of (2*SR*,4*SR*)-4-*tert*-butyl-2-methyl-2-phenylthiocyclohexanone *syn*-**42** (138 mg, 0.5 mmol) in dry THF (2 $cm^3$) under argon at −78 °C. The mixture was quenched after 20 min with acetic acid (2 $cm^3$), poured into water (5 $cm^3$), washed with sodium hydrogen carbonate solution (4 × 25 $cm^3$), and extracted with ether (3 × 15 $cm^3$). The combined organic fractions were washed with brine (10 $cm^3$), dried ($MgSO_4$), and solvent removed under reduced pressure to give the boronate ester (224 mg) as a solid. This was redissolved in ether (5 $cm^3$) and lithium aluminium hydride (120 mg, 3 mmol) added at 0 °C. After 30 min the mixture was poured into sodium hydroxide solution (30 $cm^3$), and extracted with ether (3 × 15 $cm^3$), the combined organic fractions were washed with brine (10 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure to give a 94:6 mixture of alcohols (128 mg, 92%) which were separated by HPLC to give (1*RS*,2*SR*,4*SR*)-4-*tert*-butyl-2-methyl-2-phenylthiocyclohexanol **37** (44 mg) and (1*SR*,2*SR*,4*SR*)-4-*tert*-butyl-2-methyl-2-phenylthiocyclohexanol **39** (3 mg), $R_f$ ($CH_2Cl_2$) 0.4.

L-Selectride® (Aldrich) reduction of ketone *anti*-**42** gave a 9:92 mixture of alcohols **38** and **40** by HPLC.

(1SR,2RS,4SR)-(4-tert-*Butyl*-2-*methyl*-2-*phenylthiocyclohexyl*) *Toluene*-p-*sulfonate* **56**.—Butyllithium (0.16 $cm^3$, 1.3 molar in hexane, 0.21 mmol) was added dropwise to a stirred solution of alcohol **40** (43 mg, 0.16 mmol) in dry THF (2 $cm^3$). After 30 min toluene-*p*-sulfonyl chloride (6.1 mg, 0.32 mmol) in dry THF (1 $cm^3$) was added and stirring continued overnight. The mixture was poured into ammonium chloride solution (10 $cm^3$), extracted with ether (3 × 10 $cm^3$), and the combined organic fractions were washed with sodium hydrogen carbonate solution (2 × 10 $cm^3$), brine (5 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure. Purification by preparative TLC on silica gel eluting with dichloromethane gave the *sulfonate ester* **56** (67 mg, 100%) as prisms, m.p. 139–139.5 °C, $R_f$ ($CH_2Cl_2$) 0.71; $\nu_{max}$(Nujol)/$cm^{-1}$ 1360, 1180 ($OSO_2Tol$) and 1585 (SPh); $\delta_H$($CDCl_3$) 7.8–7.6 (4 H, two d, *J* 9, Ar), 7.6–7.2 (5 H, m, SPh), 4.50 (1 H, dd, *J* 4, 12, C*H*OTs), 2.4 (3 H, s, Ar*Me*), 2.2–1.5 (7 H, m, $CH_2CH_2CHCH_2$), 1.1 (3 H, s, Me) and 0.8 (9 H, s, Bu$^t$) (Found: $M^+$, 432.1788. $C_{24}H_{32}O_3S_2$ requires *M*, 432.1793); *m*/*z* 432 (12%, $M^+$), 323 (16, M − SPh), 155 (86, $SO_2Tol$), 151 (100), 110 (26, PhSH) and 109 (16, PhS).

Also prepared by the same method were:

(1RS,2SR,4SR)-(4-tert-*Butyl*-2-*methyl*-2-*phenylthiocyclohexyl*) *toluene*-p-*sulfonate* **53**. The alcohol **37** gave the *sulfonate ester* **53** (500 mg, 52%) as prisms m.p. 115–117 °C [from light petroleum (b.p. 40–60 °C)], $R_f$ (5% EtOAc–light petroleum) 0.22, $R_f$ ($CH_2Cl_2$) 0.56; $\nu_{max}$(Nujol)/$cm^{-1}$ 1360, 1180 ($OSO_2Tol$) and 1580 (SPh); $\delta_H$($CDCl_3$) 7.8–7.6 (4 H, two d, *J* 9, Ar), 7.6–7.2 (5 H, m, SPh), 4.7 (1 H, m, *J* 7, C*H*OTS), 2.3 (3 H, s, Ar*Me*), 2.2–1.2 (7 H, m, $CH_2CH_2CHCH_2$), 1.1 (3 H, s, Me) and 0.8 (9 H, s, Bu$^t$) (Found: $M^+$, 432.1785. $C_{24}H_{32}O_3S$ requires *M*, 432.1793); *m*/*z* 432 (14%, $M^+$) 323 (16, M − SPh), 155 (80, M − $SO_2Tol$), 151 (100), 110 (25, PhSH) and 109 (10, PhS).

(1RS,2SR)-(4-tert-*Butyl*-2-*methyl*-2-*phenylthiocycloheptyl*) *toluene*-p-*sulfonate* **59**. *Syn*-2-Methyl-2-phenylthiocycloheptanol[15] (500 mg, 2.12 mmol) gave the *sulfonate ester* **59** (760 mg, 92%) as an oil, $R_f$ ($CH_2Cl_2$) 0.68; $\nu_{max}$(thin film)/$cm^{-1}$ 1585 (SPh), 1375 and 1170 ($OSO_2Tol$); $\delta_H$ ($CDCl_3$) 7.7–7.3 (4 H, two d, *J* 8.4, Ar), 7.6–7.2 (5 H, m, SPh), 4.55 (1 H, dd, *J* 2, 9, C*H*OTs), 2.4 (3 H, s, Ar*Me*), 1.9–1.2 [10 H, m, $(CH_2)_5$] and 1.10 (3 H, s, C*Me*SPh) (Found: $M^+$, 390.1341. $C_{21}H_{26}O_3S_2$ requires *M*, 390.1323); *m*/*z* 390 (4%, $M^+$), 281 (3, M − SPh), 218 (15, M − TsOH), 172 (11, TsOH) and 155 (100).

*Formolysis of Tosylate* **53**.—The sulfonate ester **53** (30 mg, 0.07 mmol) in formic acid (5 $cm^3$) was stirred at 90 °C for 1 h, poured into ammonium chloride solution (10 $cm^3$) diluted with ether (15 $cm^3$), washed with sodium hydrogen carbonate solution, brine (10 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure. Purification by preparative TLC eluting with dichloromethane gave a 2:1 mixture of (2*RS*,5*SR*)- and (2*SR*,5*SR*)-5-*tert*-butyl-2-methylcyclohexanone[35] **55** (7 mg, 60%) as an oil, $R_f$ ($CH_2Cl_2$) 0.53; $\nu_{max}$(thin film)/$cm^{-1}$ 1710 (C=O); $\delta_H$($CDCl_3$) 2.4–1.0 (8 H, m, methylene envelope), 0.99(*equatorial*) and 1.01(*axial*) (3 H, each d, *J* 6.4, CH*Me*), 0.87(*equatorial*) and 0.90(*axial*) (9 H, each s, Bu$^t$) (Found: $M^+$, 168.1516. $C_{11}H_{20}O$ requires *M*, 168.1514); *m*/*z* 168 (5%, $M^+$), 131 (19), 112 (38), 84 (42), 65 (80) and 57 (100).

*Formolysis of Tosylate* **56**.—In a similar manner the sulfonate ester **56** (50 mg, 0.12 mmol) gave 1-(3-*tert*-butylcyclopentyl)-ethanone[36] **58** (8 mg, 41%) as an oil, $R_f$ ($CH_2Cl_2$) 0.51; $\nu_{max}$(thin film)/$cm^{-1}$ 1705 (C=O); $\delta_H$($CDCl_3$) 2.7 (1 H, m, CHCO), 2.15 (3 H, s, COMe), 2.1–1.0 (7 H, m, $CH_2CH_2CHCH_2$) and 0.9 (9 H, s, Bu$^t$) (Found: $M^+$, 168.1514. $C_{11}H_{20}O$ requires *M* 168.1514); *m*/*z* 168 (10%, M), 112 (32) and 57 (100).

*Formolysis of Tosylate* **59**.—The sulfonate ester **59** (328 mg, 0.84 mmol) gave a mixture of ketones **60** and **61** (105 mg, 100%) as an oil, $R_f$ ($CH_2Cl_2$) 0.51, $\nu_{max}$(thin film)/$cm^{-1}$ 1710 (C=O). 2-Methylcycloheptanone[37] **61** had $\delta_H$($CDCl_3$) 2.0–1.2 [11 H, m, $CH_2)_5CH$] and 1.05 (3 H, d, *J* 6.9, CH*Me*CO). 1-Cyclohexylethanone[38] **60**, had $\delta_H$($CDCl_3$) 2.30 (1 H, m, C*H*COMe), 2.12 (3 H, s, COMe), 2.0–1.2 [10 H, m, $(CH_2)_5$] (Found: $M^+$, 126.1057. $C_8H_{14}O$ requires *M*, 126.1045); *m*/*z* 126 (11%, M), 198 (54) and 55 (100).

*Sodium Thiophenate Opening of Epoxide* **45**.—A mixture of 4-*tert*-butyl-1-methylcyclohex-1-ene (1.52 g, 10 mmol), MCPBA (1.94 g, 11.2 mmol) and sodium carbonate (1.18 g) in dry dichloromethane (150 $cm^3$) was stirred at room temperature under argon for 24 h. The resulting suspension was filtered through Celite and the solid residue washed with dichloromethane (100 $cm^3$). The fractions were combined and solvent removed under reduced pressure to give epoxides **45** (1.43 g, 85%) as an oil, $R_f$ ($CH_2Cl_2$) 0.52; $\delta_H$($CDCl_3$) 3.05(*trans*) (1 H, br s, $J_{trans}$ 3, CHO), 3.0(*cis*) (1 H, d, $J_{cis}$ 6, CHO), 2.2–1.2 (7 H, m, $CH_2CH_2CHCH_2$), 1.3 (3 H, s, Me) and 0.85 (9 H, s, Bu$^t$). The crude epoxides (840 mg, 5 mmol) were added dropwise to a stirred solution of thiophenol (1.10 g, 10 mmol) and sodium hydroxide (0.40 g, 10 mmol) in ethanol (25 $cm^3$). After 1 h the mixture was poured into ammonium chloride solution (25 $cm^3$),

extracted with ether (3 × 25 $cm^3$), the combined organic fractions were washed with sodium hydroxide (3 × 20 $cm^3$), water (20 $cm^3$), brine (10 $cm^3$), dried ($MgSO_4$) and solvent removed under reduced pressure to give a mixture of alcohols (1.00 g, 72%) as an oil. HPLC eluting with 10% ethyl acetate in light petroleum (b.p. 60–80 °C) flow rate 14.3 $cm^3$ $min^{-1}$ gave (1*SR*,2*SR*,5*SR*)-5-tert-*butyl*-2-*methyl*-2-*phenylthiocyclohexanol* **47** (114 mg) as an oil, $R_f$ 11.7 min; $\nu_{max}$(thin film)/$cm^{-1}$ 3350 (OH) and 1575 (SPh); $\delta_H$($CDCl_3$) 7.6–7.2 (5 H, m, SPh), 3.75 (1 H, t, *J* 5, C*H*OH), 2.2–1.4 (7 H, m, $CH_2CH_2CHCH_2$), 1.2 (3 H, s, Me) and 0.8 (9 H, s, $Bu^t$) (Found: $M^+$, 278.1679. $C_{17}H_{26}OS$ requires *M*, 278.1704); *m*/*z* 278 (37%, $M^+$), 221 (10), 169 (12, M − SPh), 110 (100, PhSH) and 57 (92); and (1SR,2SR,4SR)-4-tert-*butyl*-1-*methyl*-2-*phenylthiocyclohexanol* **46** (305 mg) as an oil, $R_f$ 15.0 min., $\nu_{max}$(thin film)/$cm^{-1}$ 3350 (OH) and 1575 (SPh); $\delta_H$($CDCl_3$) 7.6–7.2 (5 H, m, SPh), 3.3 (1 H, br s, *J* 9, C*H*SPh), 2.2–1.4 (7 H, m, $CH_2CH_2CHCH_2$), 1.3 (3 H, s, Me) and 0.8 (9 H, s, $Bu^t$) (Found: $M^+$, 278.1681. $C_{17}H_{26}OS$ requires *M*, 278.1704); *m*/*z* 278 (38%, $M^+$), 221 (9), 169 (12, M − SPh), 110 (100, PhSH) and 57 (92), and an alcohol (50 mg) as an oil, $R_f$ 12.9 min, tentatively assigned by NMR as (1*RS*,2*RS*,5*SR*)-5-*tert*-butyl-2-methyl-2-phenylthiocyclohexanol; $\delta_H$($CDCl_3$) 7.6–7.2 (5 H, m, SPh), 3.15 (1 H, dd, *J* 5, 12, C*H*SPh), 2.2–1.4 (7 H, m, $CH_2CH_2CHCH_2$), 1.25 (3 H, s, Me) and 0.8 (9 H, s, $Bu^t$).

*Rearrangement of Alcohol* **47**.—The alcohol **47** (110 mg, 0.39 mmol) was refluxed in benzene (10 $cm^3$) with a catalytic amount of toluene-*p*-sulfonic acid (8 mg, 0.04 mmol). After 4 min the mixture was poured into sodium hydrogen carbonate solution (10 $cm^3$), extracted with dichloromethane (3 × 10 $cm^3$), the combined organic fractions were dried ($MgSO_4$) and solvent removed under reduced pressure. Purification by preparative TLC on silica eluting with dichloromethane gave 4-tert-*butyl*-1-*methyl*-6-*phenylthiocyclohex*-1-*ene* (*anti*-**49**) (98 mg, 95%) as an oil, $R_f$ ($CH_2Cl_2$) 0.79; $\nu_{max}$(thin film)/$cm^{-1}$ 1575 (SPh); $\delta_H$($CDCl_3$) 7.6–7.2 (5 H, m, SPh), 5.6 (1 H, m, CH=C), 3.65 (1 H, d, *J* 3, C=C-C*H*SPh), 2.2–1.2 (5 H, m, $CH_2CHCH_2$), 1.85 (3 H, br s, C=CMe) and 0.85 (9 H, s, $Bu^t$) (Found: $M^+$, 260.1609. $C_{17}H_{24}S$ requires *M*, 260.1599); *m*/*z* 260 (4%, $M^+$), 151 (20, M − SPh), 110 (31, PhSH) and 57 (100, $Bu^t$).

Similarly (1*SR*,2*SR*,5*SR*)-5-*tert*-butyl-2-methyl-2-phenylthiocyclohexanol **46** (114 mg, 0.41 mmol) gave a 4:1 mixture of allyl sulfide **49** and 4-*tert*-butyl-1-(phenylthiomethyl)cyclohex-1-ene **52** (98 mg, 92%) as an oil, $R_f$ ($CH_2Cl_2$) 0.79; $\delta_H$($CDCl_3$) 7.6–7.2 (5 H, m, SPh), 5.6 (1 H, m, CH=C), 3.45 (2 H, s, $CH_2$SPh), 2.2–1.2 (7 H, m, $CH_2CH_2CHCH_2$) and 0.90 (9 H, s, $Bu^t$).

## References


1 G. R. Krow, *Comprehensive Organic Synthesis*, eds. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991, vol. 7, p. 671–686.
2 D. A. Whiting, in, *Comprehensive Organic Synthesis*, eds. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991, vol. 3, pp. 803–820.
3 B. Rickborn, in, *Comprehensive Organic Synthesis*, eds. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991, vol. 3, pp. 721–732.
4 V. K. Aggarwal, I. Coldham, S. McIntyre and S. Warren, *J. Chem. Soc., Perkin Trans. 1*, 1991, 451; I. Coldham and S. Warren, *Tetrahedron Lett.*, 1989, **30**, 5937; K. Chibale and S. Warren, *Tetrahedron Lett.*, 1991, **32**, 6645; 1992, **33**, 4369.
5 A. de Groot and B. J. M. Jansen, *Tetrahedron Lett.*, 1981, **22**, 887; *Synthesis*, 1985, 434; J. Otera, *Synthesis*, 1988, 95.
6 D. Howells and S. Warren, *J. Chem. Soc., Perkin Trans. 2*, 1973, 1645; P. Brownbridge, P. K. G. Hodgson, R. Shepherd and S. Warren, *J. Chem. Soc., Perkin Trans. 1*, 1976, 2024.
7 Preliminary communication: M. P. Hannaby and S. Warren, *Tetrahedron Lett.*, 1986, **27**, 1069.
8 E. Eliel, W. H. Pearson, L. M. Jewel and A. C. Abatjoglou, *Tetrahedron Lett.*, 1980, **21**, 331.
9 J. L. Jensen and W. P. Jencks, *J. Am. Chem. Soc.*, 1979, **101**, 1476; R. A. Cox and K. Yates, *J. Org. Chem.*, 1986, **51**, 3619; D. P. N. Satchell and R. S. Satchell, *Chem. Soc. Rev.*, 1990, **19**, 55.
10 R. A. McClelland, *Can. J. Chem.*, 1977, **55**, 548; T. Okuyama, *Acc. Chem. Res.*, 1986, **19**, 370; N. Banait, M. Hojatti, P. Findlay and A. J. Kresge, *Can. J. Chem.*, 1987, **65**, 441.
11 Y. Apeloig and M. Karni, *J. Chem. Soc., Perkin Trans. 2*, 1988, 625.
12 P. Brownbridge and S. Warren, *J. Chem. Soc., Perkin Trans. 1*, 1977, 1131, 2272.
13 B. M. Trost, *Acc. Chem. Res.*, 1974, **7**, 85.
14 H. Morita and S. Oae, *Tetrahedron Lett.*, 1969, 1347; I, Tabushi, Y. Tamaru and Z-i. Yoshida, *Bull. Chem. Soc. Jpn.*, 1974, **47**, 1455.
15 M. P. Hannaby and S. Warren, *Tetrahedron Lett.*, 1986, **27**, 765; *J. Chem. Soc., Perkin Trans. 1*, 1989, 303; M. P. Hannaby, P. Judson and S. Warren, *J. Chem. Soc., Perkin Trans. 1*, 1992, 2609.
16 B. M. Trost, T. N. Salzmann and K. Hiroi, *J. Am. Chem. Soc.*, 1976, **98**, 4887.
17 J. W. Huffman, M.-J. Wu and H. H. Joyner, *J. Org. Chem.*, 1991, **56**, 5224.
18 R. Caputo, C. Ferreri and G. Palumbo, *Synthesis*, 1989, 464.
19 J. K. Whitesell and M. A. Whitesell, *Synthesis*, 1983, 517.
20 I. Fleming and I. Paterson, *Synthesis*, 1979, 736.
21 B. Caro, B. Boyer, G. Lamaty and G. Jaouen, *Bull Soc. Chim. Fr.*, 1983, II-281; N. Greeves, in, *Comprehensive Organic Chemistry*, eds. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991, vol. 8, pp. 1–24, see Table on p. 14.
22 H. C. Brown and S. Krishnamurthy, *J. Am. Chem. Soc.*, 1972, **94**, 7159; C. A. Brown and S. Krishnamurthy, *J. Org. Chem.*, 1986, **51**, 238.
23 A. S. Cieplak, *J. Am. Chem. Soc.*, 1981, **103**, 4540.
24 M. Shimagaki, T. Maeda, Y. Matsuzaki, I. Hori, T. Nakata and T. Oishi, *Tetrahedron Lett.*, 1984, **25**, 4775.
25 P. R. Raithby, unpublished work.
26 D. G. Morris, *Chem. Soc. Rev., Chem. Soc. Rev.*, 1982, **11**, 397; 27. V. V. Kane, V. Singh, A Martin and D. L. Doyle, *Tetrahedron*, 1983, **39**, 345.
27 A. P. Krapcho, J. E. McCullough and K. V. Nahabedian, *J. Org. Chem.*, 1965, **30**, 139.
28 J.-C. Richer and P. Belanger, *Can. J. Chem.*, 1969, **47**, 3281.
29 D. Howells and S. Warren, *J. Chem. Soc., Perkin Trans. 2*, 1974, 992.
30 H. L. Goering and K. L. Howe, *J. Am. Chem. Soc.*, 1957, **79**, 6542.
31 P. G. Jones, M. R. Edwards and A. J. Kirby, *Acta Cryst. Sect. C*, 1989, **45**, 252.
32 H. O. House, L. J. Czuba, M. Gall and H. D. Olmstead, *J. Org. Chem.*, 1969, **34**, 2324.
33 N. L. Allinger and J. Allinger, *J. Am. Chem. Soc.*, 1958, **80**, 5476.
34 J. M. Conia and P. Briet, *Bull. Soc. Chim. Fr.*, 1966, 3881.
35 H. O. House and M. J. Umen, *J. Org. Chem.*, 1973, **38**, 1000.
36 R. Granger, J. Boussinesq, J. P. Girard, J. C. Rossi and J. P. Vidal, *Bull. Soc. Chim. Fr.*, 1969, 2806.
37 W. L. Mock and M. E. Hartman, *J. Org. Chem.*, 1977, **42**, 459.
38 L. Cottier and G. Descottes, *Bull. Soc. Chim. Fr.*, 1972, 1072.


*Paper* 2/04305J
*Received* 10*th August* 1992
*Accepted* 25*th August* 1992