Homochiral 2,3-epoxy sulfides—powerful new synthetic building blocks providing stereoselective access to 2,3-epoxy sulfoxides, 2,3-dihydroxy sulfoxides and (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides and sulfones. X-Ray molecular structure of *rac*-(2*R**,3*R**)-1-[(*S**)-phenylsulfinyl]hexane-2,3-diol

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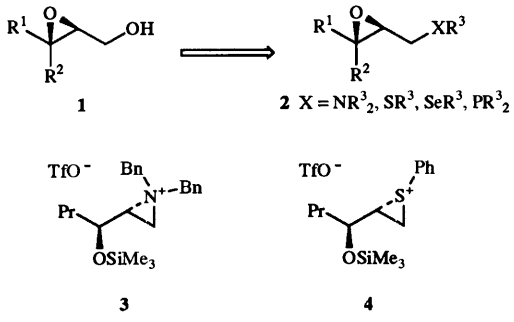
The stereoselective transformation of homochiral 2,3-epoxy sulfoxides into 2,3-epoxy sulfoxides is described. These intermediates undergo elimination under basic reaction conditions to give (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides, and under Lewis acidic conditions form novel cyclic sulfoxonium salts which on hydrolysis give 2,3-dihydroxy sulfoxides with excellent stereochemical control. 2,3-Dihydroxy sulfoxides can also be converted into (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides by elimination *via* a cyclic sulfite. The synthesis of (*E*)-γ-hydroxy-α,β-unsaturated sulfones by base-catalysed elimination of a 2,3-epoxy sulfone is also described.

The Sharpless asymmetric epoxidation is one of the most useful asymmetric reactions available to the synthetic chemist.[1] In particular, the generality of the reaction allows for the preparation of a wide variety of homochiral 2,3-epoxy alcohols which are extremely useful synthetic intermediates.[2] Some time ago, we initiated a research programme to investigate the chemistry of derivatives of 2,3-epoxy alcohols **1** where the oxygen atom of the alcohol group is replaced by a different heteroatom, *i.e.*, compounds **2**. We have recently reported that 2,3-epoxy amines, *e.g.* **2**, X = NBn_2, undergo a highly efficient conversion into the corresponding 3-trimethylsiloxy-1,2-aziridinium salts **3** which can be trapped regiospecifically with nucleophiles at C-1 to form homochiral amino alcohols.[3] We have also reported that 2,3-epoxy sulfides undergo an analogous conversion into the corresponding thiiranium ion **4** which can also be trapped regiospecifically by suitable nucleophiles to form homochiral β-hydroxy sulfides.[4] This paper describes, in detail, our work on oxidised 2,3-epoxy sulfides,[5] namely the derived sulfoxides and sulfones, and how these useful synthetic intermediates can be transformed into 2,3-dihydroxy sulfoxides[6] and (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides and sulfones[7] which are themselves useful and interesting synthetic intermediates (*vide infra*).



Synthesis of 2,3-epoxy sulfoxides

The 2,3-epoxy sulfoxide substrates were synthesized as shown in Scheme 1. Both racemic and homochiral 2,3-epoxy alcohols were prepared by oxidation using *tert*-butyl hydroperoxide (TBHP), catalysed by either $VO(acac)_2$ or the standard Sharpless asymmetric epoxidation (SAE) conditions, respectively.[8] Conversion into the sulfide was then readily carried out by using the corresponding disulfide and tributylphosphine as previously reported.[9] For our initial studies we concentrated on the 2,3-epoxy phenyl sulfoxides as these proved easier to work with than the *S*-methyl analogues as a result of their lower polarity. A 1:1 mixture of racemic diastereoisomeric 2,3-epoxy phenyl sulfoxides **8** and **9** was easily prepared by oxidation of the sulfide by using TBHP/$VO(acac)_2$. Despite considerable experimentation, no diastereoselectivity could be induced in this oxidation reaction from a wide range of other standard achiral oxidants, including oxaziridines,[10] and a Lewis acidic aluminium-based reagent which is reported to give high diastereoselectivity for oxidations directed by suitable adjacent ether substituents.[11]

The 2,3-epoxy phenyl sulfoxides **8** and **9** could be separated by careful column chromatography. In order to get some idea of the relative configuration of the epoxide and sulfoxide chiral centres, we used ^1H NMR spectroscopy. Of particular use in this case were the protons on C-2. A sulfoxide group is known to deshield protons in which the S=O bond and the C–H bond are in a 1,3-parallel orientation.[12] Approximate energy-minimised conformations (MM2 force field using Chem3D Plus™) of these compounds ‡ are shown in Fig. 1. In the case of isomer **8**, although the molecule would be rather flexible, on average, the proton on C-2 would occupy such a position, whilst for isomer **9** the C–H bond is almost orthogonal to the sulfoxide. The observed chemical shifts were δ 2.83 and 3.12; thus significant relative deshielding is observed in the latter case, and this was assigned as diastereoisomer **8**.

This assignment has since been confirmed by stereoselective synthesis using a double asymmetric oxidation protocol, which provided an alternative route to diastereoisomerically enriched 2,3-epoxy sulfoxides. Although attempts at diastereoselective oxidation had been unsuccessful, the possibility of controlling the epoxide's configuration by asymmetric epoxidation, and

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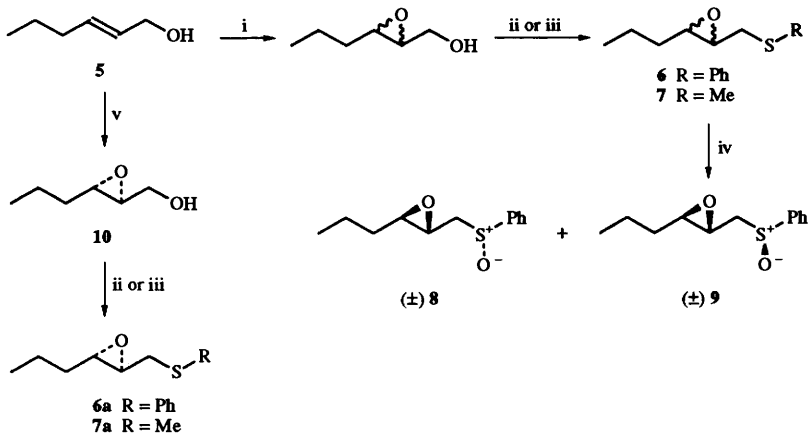
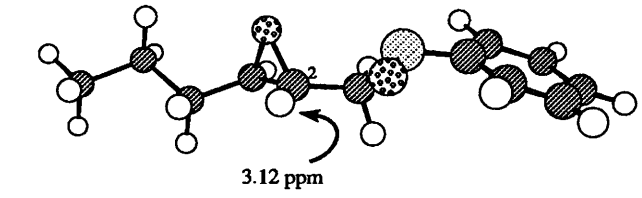
‡ Although the conformations shown are reasonable, it should be appreciated that others of similar energy are also likely.



Scheme 1 *Reagents and conditions:* i, Bu^{t}OOH, $VO(acac)_2$, CH_2Cl_2 (86%); ii, PhSSPh, PBu_3, pyridine or DMF (75–87%); iii, MeSSMe, PBu_3, DMF (65%); iv, Bu^{t}OOH, $VO(acac)_2$, CH_2Cl_2, −40 °C (84%); v, Bu^{t}OOH, $Ti(O^iPr)_4$, L-(+)-DET, CH_2Cl_2, 70%



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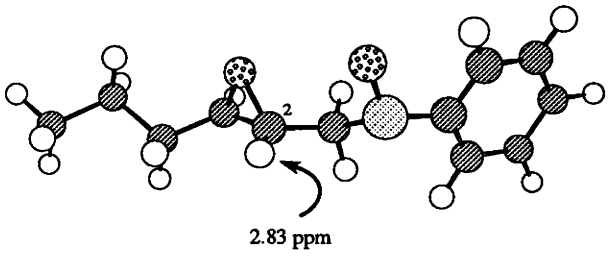

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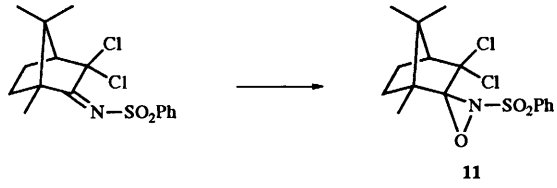
Fig. 1



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Scheme 2 *Reagents and conditions:* MCPBA (>95%) (1 mol equiv. per day), CH_2Cl_2, K_2CO_3 (aq.), 7 days

that of the sulfoxide by asymmetric oxidation, provided an attractive alternative strategy. Obviously, the SAE could be used to control the epoxide's configuration. The situation regarding asymmetric oxidation of sulfur was less clear; however, the methods of Kagan,[13] using a titanium–tartrate system analogous to that of the Sharpless epoxidation, and Davis,[14] using the camphor-derived oxaziridine **11**, have been reported to give moderate to excellent enantioselectivities in some cases, and were thus investigated in this study. Not only would this provide an opportunity to confirm the configurational assignments, but would also allow us to make a direct, independent comparison of the relative efficiencies of the two oxidation systems which are amongst the best available.[15] The results of these oxidations are shown in Table 1. The 2,3-epoxy sulfides used in this case were prepared *via* the homochiral epoxy alcohol **10**§ or its enantiomer (Scheme 1).

There are a number of points which should be noted from Table 1. First, the Davis oxaziridine gives the best stereoselectivities for oxidation of the *S*-phenyl sulfides, with higher selectivities being observed at low temperatures (entries 2 and 5, *cf.* 3 and 6). The Kagan oxidation shows complementary selectivity in that it is most successful with the *S*-methyl sulfides (entries 7 and 9). The configurational assignments are in accord with the known enantioselectivity of the two oxidation systems,¶ and also the relative rates of reaction under Lewis acidic conditions (see below). For both oxidation systems, with substrates showing poor selectivity, they show a weak preference for formation of the product with the epoxide and sulfoxide *anti*,‖ irrespective of the original epoxide stereostructure and the inherent enantioselective bias of the oxidising agent (entries 1, 4, 8, 10 and 11). With substrates showing higher selectivities, this effect is also observed such that when the systems are matched to favour formation of the *anti* isomer, higher selectivities are realised (entries 2 and 5, and 7 and 9). This effect is generally quite weak, but becomes more significant at low temperatures (entry 11). It is interesting that it occurs with both oxidation systems. The exact reason for this bias is not clear, although as it is observed with both the *S*-methyl and *S*-phenyl sulfoxides, simple steric and/or electronic repulsion of the epoxide oxygen with the incoming oxidant would seem likely.

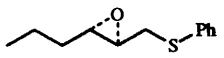
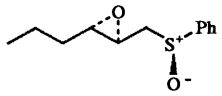
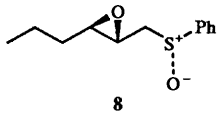
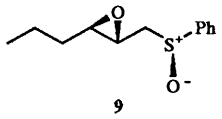
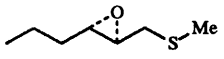
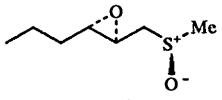
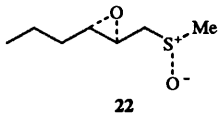
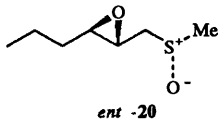
On a more practical level, the two oxidation systems have their own advantages and disadvantages. The Kagan system allows for the preparation of either absolute configuration at sulfur of the sulfoxide simply by switching the chirality of the tartrate ligand. For the Davis system, it would be necessary to

§ Determined as >95% enantiomeric excess (ee) by using $Eu(hfc)_3$ on the acetate derivative.

¶ Oxidation of methyl octyl sulfide under Kagan conditions [(+)-DET] gives the (*R*)-sulfoxide (80% ee), see ref. 13*a*. Oxidation of butyl *p*-tolyl sulfide using oxaziridine **11** gives the (*S*)-sulfoxide (84% ee), see ref. 14*a*.

‖ In this case, *syn* refers to the isomer with the oxygens on sulfur and C-2 pointing either both toward or both away from the viewer when the main chain of the molecule is in an extended form. The *anti* isomer has one substituent pointing away from the viewer and one toward. In all cases when this terminology has been used in this paper, the configuration at C-3 relative to C-2 is fixed and is ignored.[16] The Seebach–Prelog *ul* terminology[17] has been avoided because of possible confusion resulting from a change in priorities of substituents at sulfur between the methyl and phenyl sulfoxides (phenyl > 2,3-epoxyalkyl but 2,3-epoxyalkyl > methyl).

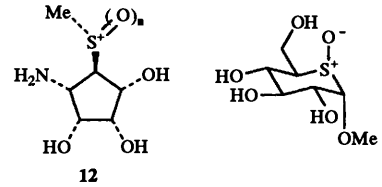
Table 1 Synthesis of 2,3-epoxy sulfoxides by double enantioselective oxidation

Substrate	Entry	Method	Major Product	Ratio [(*T*/°C), yield %])
 **6a**	1	A	 **16**	1.8:1 [−40, 86]
	2	B		13:1 [0, 65]
	3	B		6.3:1 [25, 65]
 **6b**	4	A	 **8**	1.4:1 [−40, 90]
	5	B	 **9**	7.0:1 [0, 59]
	6	B		2.0:1 [25, 61]
 **7a**	7	A	 **20**	5.1:1 [−40, 61]
	8	B		1.5:1 [0, 85]
	9	C	 **22**	4.6:1 [−40, 72]
 **7b**	10	B	 *ent* **-20**	1.3:1 [0, 65]
	11	B		3.3:1 [−40[a], 31]

Reagents and conditions: **A**, $Ti(OPr^i)_4$, water (1 mol equiv.), L-(+)-DET, cumene hydroperoxide, CH_2Cl_2; **B**, oxaziridine **11**, CCl_4; **C**, $Ti(OPr^i)_4$, water (1 mol equiv.), D-(−)-DET, cumene hydroperoxide, CH_2Cl_2. [a] Reaction run in $CHCl_3$.

prepare both enantiomeric oxaziridines. Removal of tartrate was a problem in the case of the Kagan oxidation of the *S*-methyl sulfides **7a** and **7b**. A particularly effective method of removal of tartrate commonly used involves hydrolysis using aqueous base and removal of the resultant carboxylate salt by a water wash during extraction. Under such conditions, our relatively sensitive substrates easily underwent β-elimination to give the γ-hydroxy-α,β-unsaturated sulfoxide, a process we were later able to exploit synthetically (*vide infra*). However, for the preparation of the 2,3-epoxy sulfoxides, it meant that column chromatography was necessary which, because of the sensitivity and high polarity of our products, resulted in variable isolated yields (31–85%). In the case of the *S*-methyl sulfoxides it proved impossible to separate the two diastereoisomeric sulfoxides and so in all subsequent reactions diastereoisomerically enriched mixtures (Table 1, entries 7 and 9) were used.

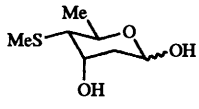
The preparation of oxaziridine **11** is worthy of comment. Preparation of the imine precursor proved relatively straightforward; however, the final oxidation to the oxaziridine was somewhat problematic (Scheme 2). Although full details have recently been reported by Davis *et al.*,[14b] even using this procedure, with >95% *m*-chloroperbenzoic acid (MCPBA), we obtained only low yields of the oxaziridine (~20%), and for our sulfur oxidations would typically use a mixture of oxaziridine and imine.** However, this having been said, we found it to be by far the best reagent for the oxidation of the *S*-phenyl sulfides, and allowed assignment of configuration in accord with the known selectivity of the reagent on a related system.¶



12

Mannostatin A (*n* = 0)
Mannostatin B (*n* = 1)

13



14

Preparation of 2,3-dihydroxy sulfoxides—formation and subsequent hydrolysis of cyclic sulfoxonium salts by Lewis acid-catalysed intramolecular epoxide opening by sulfoxide

With the new stereoselective routes to 2,3-epoxy sulfoxides established, we were interested in the possibility of hydrolysis of the epoxides to form 2,3-dihydroxy sulfoxides. This forms part of an investigation into the preparation of important poly-

** We observed that the crystalline oxaziridine was rather unstable, and so it was generally used immediately after purification (column chromatography). The reason for this instability is unclear as it is known that the pure oxaziridine can be stored at room temperature for prolonged periods of time; however, trace impurities such as *m*-chlorobenzoic acid or bis(*m*-chlorobenzoyl) peroxide, which can be difficult to detect (integration of ^1H NMR spectrum), are known to decrease the stability of the oxaziridine and may be important in this case (F. A. Davis, personal communication to C. M. R.).

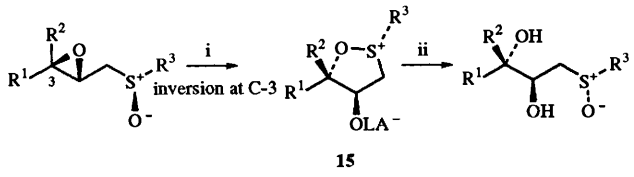
¶ See footnote on page 848.

hydroxylated sulfides and sulfoxides, relevant examples of which are the mannosidase inhibitors mannostatin A and B **12**,[18] the thiosugar **13**, an inhibitor of α-glucosidase,[19] and the thiosugar of the enediyne antitumour antibiotic esperamicin A_1 **14**.[20]

One obvious problem with using the 2,3-epoxy sulfoxides as precursors to these types of molecules is that non-regioselective hydrolysis of the epoxide would lead to diastereoisomeric mixtures of 2,3-dihydroxy sulfoxides. It was thus envisaged as being essential to be able to control such regiochemistry. One approach to solving this kind of problem, which has been exploited extensively since the development of the SAE, is to use the alcohol group of a 2,3-epoxy alcohol to attach a pendant nucleophile, which is then delivered intramolecularly to open the epoxide with a high degree of regiocontrol.[2] In our system, we wanted the sulfoxide group to act as the pendant nucleophile, which would result in formation of novel cyclic sulfoxonium salts **15**, which could then be hydrolysed to give the desired dihydroxy sulfoxide (Scheme 3). Note that we expected this to be a stereoselective process, *i.e.* for formation of the 5-membered sulfoxonium salt overall inversion at C-3 would be observed, along with retention at C-2. In addition, it is known that hydrolysis of sulfoxonium salts proceeds with clean inversion at sulfur, and so overall the configuration at sulfur would be inverted.[21]

Thus the pure 2,3-epoxy sulfoxide diastereoisomers **16** and **18** were treated individually with BF_3·Et_2O and over a period of time a white precipitate was observed, which we believe to be the intermediate sulfoxonium salts. The reaction was monitored by TLC for disappearance of starting material, and then aq. $NaHCO_3$ was added and the reaction mixture was stirred for 1 h. The products obtained from this reaction were pure diastereoisomers in very high yield (Scheme 4). Interestingly, the rate of reaction was very different for the two phenyl sulfoxide diastereoisomers, the *syn* isomer **18** reacting within 40 min, whereas the *anti* isomer **16** requires *ca.* 16 h to go to completion. This could be rationalised by consideration of the necessary reactive conformations (Fig. 2) for formation of sulfoxonium salts, the slower reacting diastereoisomer having the phenyl group in a pseudo-axial orientation for reaction, a pseudo-equatorial arrangement being possible for the faster reacting isomer. The *S*-methyl sulfoxides **20** and **22** underwent similar solvolysis, although it was not possible to use them diastereoisomerically pure, as they were not separable by chromatography. Instead, the enriched mixtures (both ~5:1 in favour of the isomer shown) produced using the double asymmetric oxidation protocol were used, and gave products with the same diastereisomeric ratio, indicative of a stereospecific process (Scheme 5). In this case, the difference in rate of reaction for the *S*-methyl sulfoxides was much less pronounced, indicating that the size of the substituent is important and suggesting that the rate difference is a result of steric interactions.

In the case of the *S*-phenyl sulfides, the rate difference could be exploited to obtain two essentially diastereoisomerically pure products which were readily separable. If a 1:1 mixture of



Scheme 3 *Reagents and reactions:* i, Lewis acid (LA); ii, hydrolysis

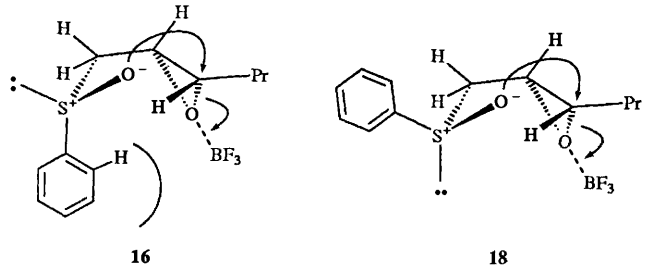
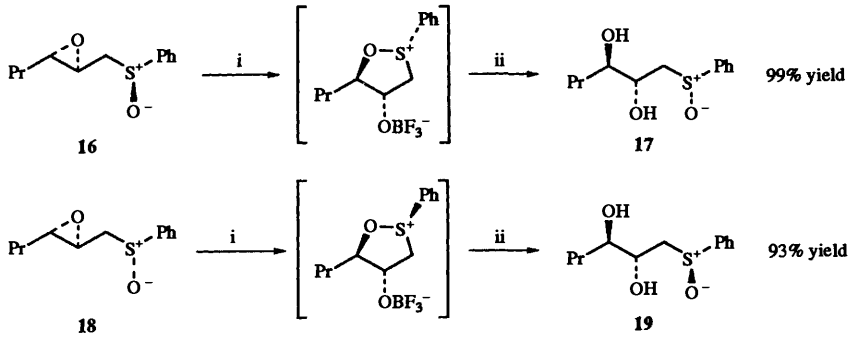
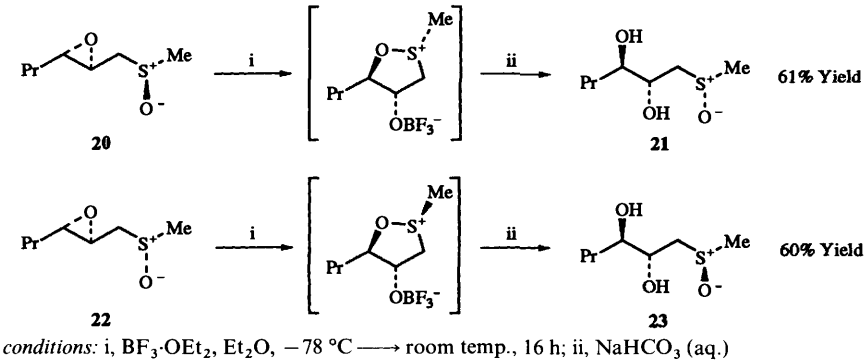


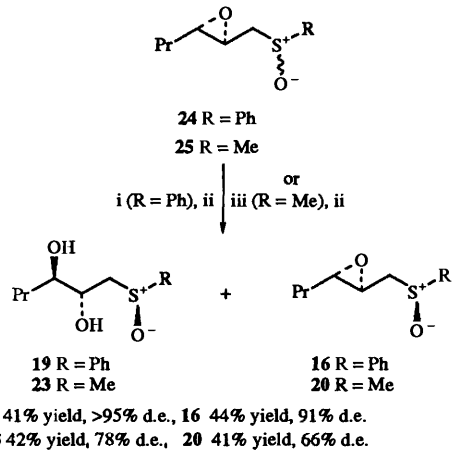
Fig. 2



Scheme 4 *Reagents and conditions:* i, BF_3·OEt_2, Et_2O, −78 °C ⟶ room temp., 16 h (**16**), 40 min (**18**); ii, $NaHCO_3$ (aq.)



Scheme 5 *Reagents and conditions:* i, BF_3·OEt_2, Et_2O, −78 °C ⟶ room temp., 16 h; ii, $NaHCO_3$ (aq.)



Scheme 6 *Reagents and conditions:* i, BF_3·OEt_2, Et_2O, −78 ⟶ 9 °C, 50 min; ii, $NaHCO_3$ (aq.); iii, BF_3·OEt_2, Et_2O, −78 ⟶ 5 °C, 3 h

the two epoxy sulfoxide diastereoisomers **24** was treated with BF_3·OEt_2 under carefully controlled conditions (Scheme 6), then essentially only the faster reacting diastereoisomer was converted into the sulfoxonium salt, which on hydrolysis gave the dihydroxy sulfoxide **19** (41% yield, >95% de), along with unchanged slower reacting diastereoisomer **16** (44% yield, 91% de). At higher temperatures or after prolonged reaction times compound **16** could be isolated with >95% de although the yield, and diastereoisomeric purity, of diol **19** were lower. This method was particularly useful for large-scale work, and for preparation of the diastereoisomeric (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides (*vide infra*), as no chromatography was required, the highly crystalline dihydroxy sulfoxide **19** readily crystallising from a benzene solution of the crude product mixture, the resolved epoxy sulfoxide **16** remaining in solution. Unfortunately, the difference in rate of reaction for the *S*-methyl sulfoxides **25** was not as large as for the *S*-phenyl sulfoxides, and although a similar diastereoisomer-separation process was possible, the diastereoisomeric excesses of the products were considerably reduced, the diol **23** having 78% de (42% yield) and recovered 2,3-epoxy sulfoxide **20** 66% de (41% yield).

At this stage we needed to confirm the stereostructure of the dihydroxy sulfoxide products in order to confirm further our original configurational assignments of the epoxy sulfoxides, and also to check that the stereochemical course of the reaction was consistent with the intermediacy of the cyclic sulfoxonium salts.

Significant information regarding the configuration at C-2 of **17** and **19** can be obtained by consideration of the hydrogen-bonding properties of what is in effect a β-hydroxy sulfoxide. It is known, for such systems, that intramolecular hydrogen bonding can occur between the sulfoxide and the alcohol group, depending on their relative configuration.[22] In spite of the reputation of the sulfoxide as a strong hydrogen-bond donor, in systems such as ours, the hydrogen bond is not of sufficient strength to dominate other conformation-determining factors. Indeed, it has been shown in competition experiments that a hydroxy-group proton would rather bond intramolecularly to a ketone carbonyl group than to a sulfoxide, other things being equal.[23] Although from modelling and X-ray studies (*vide infra*) the O - - - O distance of the hydrogen bond is ~2.8 Å, which is close to the ideal value, the fact that the hydrogen bond is intramolecular adds additional constraints and the usual linear geometry is not favoured.[24] It is thus important to note that the hydrogen bond is relatively weak and while it will have some effect on the conformation, it is not sufficiently strong to control the conformation of the molecule on its own. Thus in the likely

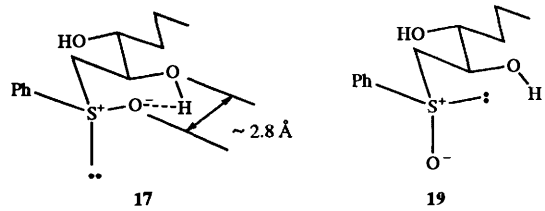


Fig. 3

minimum-energy conformers (Fig. 3),†† diastereoisomer **17** would be expected to form the intramolecular hydrogen bond shown, whereas diastereoisomer **19** would hydrogen bond mainly through intermolecular interactions. As an initial rough guide this is reflected in the observed mps of 66–67.5 °C and 96–97.5 °C, respectively, for stereoisomers **17** and **19**, the higher mp indicating more significant intermolecular interactions, as would be expected if there were no intramolecular hydrogen bonds.[22a,b]

In addition to mps, the coupling constant between the hydroxy-group protons and their adjacent α-hydrogens in the ^1H NMR spectra of β-hydroxy sulfoxides can indicate whether an intramolecular hydrogen bond is present in a molecule.[22a,b] In dry, dilute $CDCl_3$ solution, coupling between the hydroxy-group protons and the α-hydrogens can be easily observed.[25] If there is no hydrogen bonding then the coupling constant is averaged from all the possible conformers, usually giving a value ~5 Hz.[26] Restricted rotation due to hydrogen bonding can lead to significant deviations from this value depending on the angle between the O–H bond and the C–H bond of the α-hydrogen. However, for both dihydroxy sulfoxide diastereoisomers **17** and **19**, values of 2.6 and 2.9 Hz, respectively, would tend to suggest that both have significant intramolecular hydrogen bonding. The analogous values for C(3)H–OH are 5.0 and 3.7 Hz, respectively, much more consistent with relatively free rotation. The unexpectedly low values observed for isomer **19** may be a result of enhanced rigidity due to intermolecular hydrogen bonding, possibly as a symmetrical homodimer similar to that observed in the solid state (*vide infra*).[22] However, these results indicate that great care must be taken in using such measurements to assign configuration, particularly if only one isomer is available. Unfortunately, studies of the hydrogen bonding by using IR spectroscopy at various concentrations were inconclusive, mainly because of the additional absorptions resulting from the C-3 hydroxy group.

A more reliable use of ^1H NMR spectroscopy for assignment of configuration in β-hydroxy sulfoxides is by comparison of coupling constants for the protons directly bonded to carbon in the β-hydroxy sulfoxide moiety.[22c] These are shown in Table 2, along with some typical previously reported values for the related compounds **26** ⟶ **29**.[22a,c] As can be seen from Table 2 there is a good correlation between the two diastereoisomeric series, for both the methyl and phenyl sulfoxides.

All these results helped to confirm the relative configuration between the sulfoxide and the C-2 hydroxy group, while little could be done to assign unambiguously the configuration at C-3. It was thus necessary to resort to X-ray crystallography, and suitable crystals of racemic *S*-phenyl dihydroxy sulfoxide **19** were grown and the X-ray structure was determined (Fig. 4).[27] This confirmed all our original configurational assignments, and was consistent with the intermediacy of the cyclic sulfoxonium salts **15** (Scheme 3). Interestingly, in the solid state, compound **19** exists in a columnar structure, resulting from an intricate hydrogen-bonding network between two rows of

†† These are analogous to those suggested previously for β-hydroxy sulfoxides,[22] and are also consistent with the X-ray crystal structure (Fig. 4).

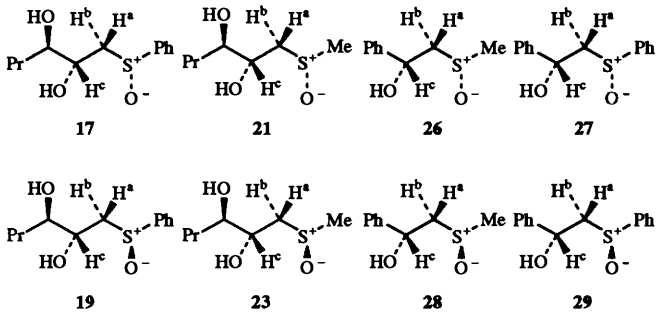
equivalent molecules, shown schematically in Fig. 5.[28] We are currently further investigating the interactions of these molecules in solution and in the solid state, with the aim of designing new sulfoxide-based self-organising molecular systems.[3]

Preparation of (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides from 2,3-epoxy sulfoxides and 2,3-dihydroxy sulfoxides

The use of optically active α,β-unsaturated sulfoxides as dienophiles, dipolarophiles and Michael acceptors has been the subject of considerable recent interest, primarily due to the ability of the sulfoxide to act as a stereocontrolling element.[29] Related reactions have also been reported for the corresponding sulfones,[30] and in addition, for these substrates, it has been shown that substitution in the γ-position can have a strong influence on the facial selectivity for addition to the carbon–carbon double bond.[31] The corresponding γ-hydroxy-α,β-unsaturated sulfoxides have been relatively little investigated,[32] but are intriguing substrates for stereochemical studies due to the presence of two potential stereocontrolling elements, the sulfoxide and the alcohol (or its equivalent). We thus applied our new routes to homochiral 2,3-epoxy sulfoxides and dihydroxy sulfoxides to the synthesis of these interesting intermediates. As mentioned earlier, during attempted hydrolysis of tartrate from the Kagan oxidation of the *S*-methyl sulfide **7**, using aq. NaOH, we had observed a simple β-elimination to give the corresponding (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides. This reaction was investigated for all our diastereoisomeric 2,3-epoxy sulfoxides, and was found to be general (Scheme 7), proceeding with retention of configurational integrity at the chiral centres, and with high *E*-selectivity as determined by ^1H and ^{13}C NMR spectroscopy. This is in contrast to related eliminations recently reported for 2,3-epoxy sulfides, where significant amounts of the *Z*-isomers were formed (up to 1.7:1, *E*:*Z*).[33]

To convert our 2,3-dihydroxy sulfoxides into the corresponding (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides we were able to adapt methodology previously used for the preparation of (*E*)-γ-hydroxy-α,β-unsaturated nitriles,[34] sulfones[35] and amides[36] from the corresponding β,γ-dihydroxy precursors. To the best of our knowledge this procedure has not been reported for sulfoxides. Thus, conversion of the dihydroxy sulfoxides **17** and **19** into the cyclic sulfites (diastereoisomeric mixture) and elimination using 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) (excess) gave the (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides (Scheme 8). In all cases exclusive *E*-selectivity for the new double bond was observed and for the phenyl sulfoxides **17** and **19** complete retention of configurational integrity. Unfortunately, in the case of the methyl sulfoxides **21** and **23**, considerable loss of diastereoisomeric purity was observed, probably by partial inversion of configuration of the sulfoxide under the reaction conditions.

Table 2 Comparison of coupling constants (*J*/Hz) in β-hydroxy sulfoxides



	$J_{a,c}$	$J_{b,c}$	$J_{a,b}$
17	2.5	8.2	13.5
21	2.7	8.2	13.5
26	2.9	9.5	13.2
27	3.3	9.6	13.2
19	1.5	10.0	13.8
23	1.8	9.7	13.4
28	1.9	10.9	13.0
29	2.4	10.1	13.1

Preparation of (*E*)-γ-hydroxy-α,β-unsaturated sulfones from 2,3-epoxy sulfides

In a process closely related to the one above, it was also possible to convert 2,3-epoxy sulfides to (*E*)-γ-hydroxy-α,β-unsaturated sulfones[30,31] *via* the 2,3-epoxy sulfones. Although a related reaction has been reported in the racemic series,[37] our method (Scheme 9) compares very favourably with previously reported routes to homochiral γ-hydroxy-α,β-unsaturated sulfones. Thus, oxidation of the required sulfide with excess of MCPBA

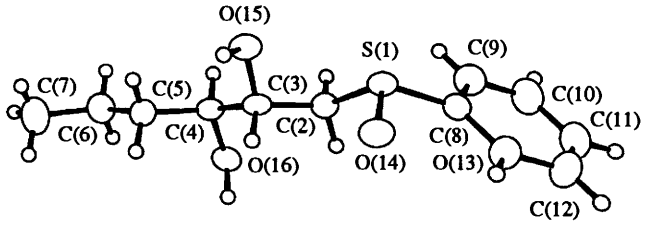


Fig. 4 X-Ray ORTEP crystal structure of compound (±)-**19** with crystallographic numbering scheme

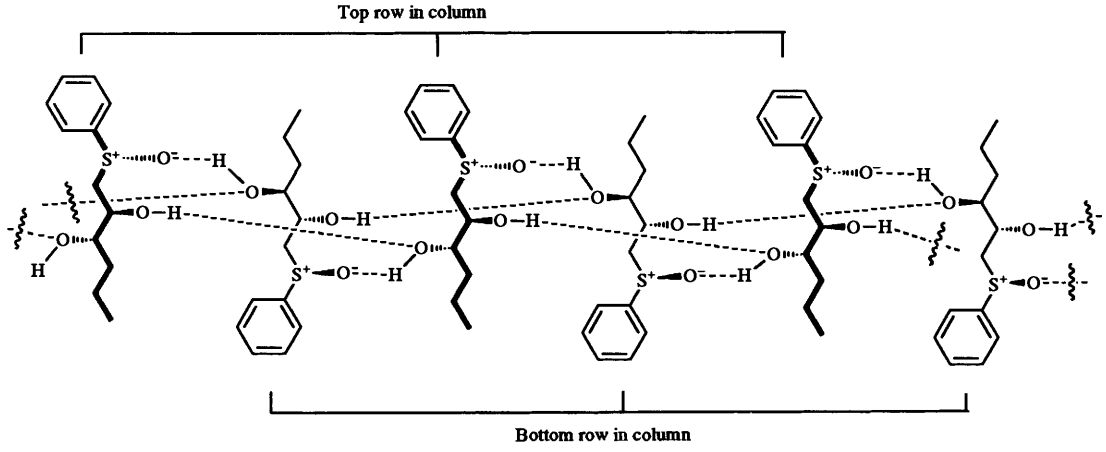
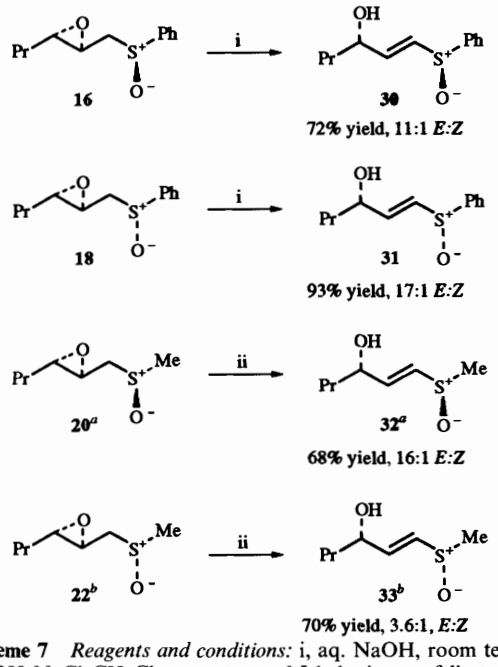
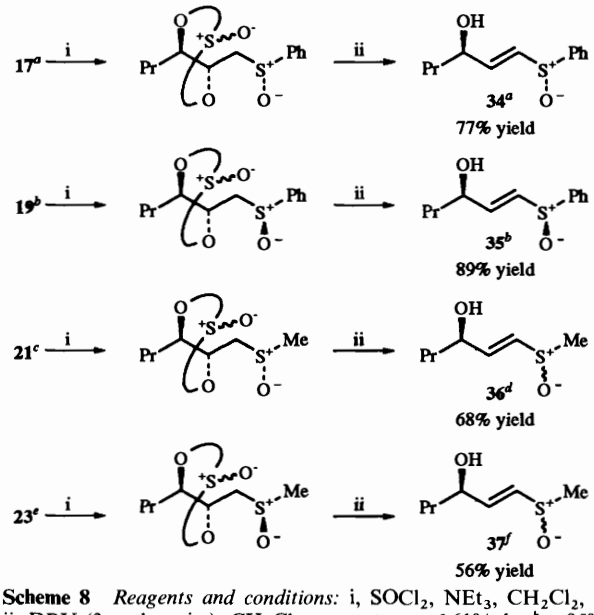


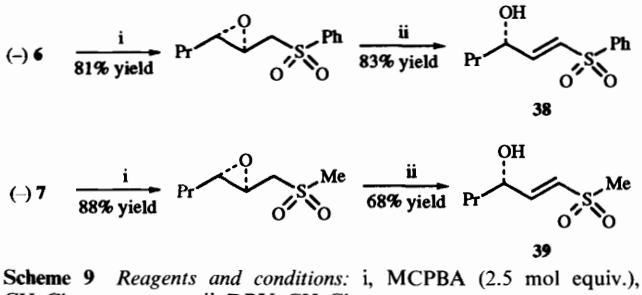
Fig. 5 Network of intermolecular hydrogen bonds of compound (±)-**19** from X-ray crystal structure



Scheme 7 *Reagents and conditions:* i, aq. NaOH, room temp.; ii, aq. NaOH, NaCl, CH_2Cl_2, room temp.; [a] 5.1 : 1 mixture of diastereoisomers; [b] 4.6 : 1 mixture of diastereoisomers



Scheme 8 *Reagents and conditions:* i, $SOCl_2$, NEt_3, CH_2Cl_2, 0 °C; ii, DBU (3 mol equiv.), CH_2Cl_2, room temp.; [a] 61% de; [b] >95% de; [c] 66% de; [d] 12% de; [e] 78% de; [f] 33% de



Scheme 9 *Reagents and conditions:* i, MCPBA (2.5 mol equiv.), CH_2Cl_2, room temp.; ii, DBU, CH_2Cl_2, room temp.

gives the 2,3-epoxy sulfone in high yield, which readily undergoes β-elimination on treatment with DBU to give exclusively the *E*-isomer.

Conclusions

In conclusion, we have shown that homochiral 2,3-epoxy sulfides are useful synthetic intermediates, allowing access to 2,3-epoxy sulfoxides, 2,3-dihydroxy sulfoxides and (*E*)-γ-hydroxy-α,β-unsaturated sulfoxides and sulfones. We are continuing to investigate the chemistry of these interesting substrates, and the results of such studies will be reported in due course.

Experimental

Mps were determined on a Reichert Hot Stage apparatus and are uncorrected. NMR spectra were recorded on a General Electric QE 300 or a Bruker AM 400 spectrometer. Chemical shifts are expressed in parts per million (ppm) downfield of tetramethylsilane (singlet at 0 ppm, TMS) for proton resonances and referenced to the central peak of the triplet for deuteriated chloroform (77.0 ppm) for ^{13}C resonances. Coupling constants are given in Hz.

IR spectra were recorded on a Phillips PU 8706 infrared spectrophotometer and signals were referenced to a peak at 1601 cm^{-1} of polystyrene. Mass spectra were recorded on a VG Autospec mass spectrometer using electron impact (EI) ionisation. Optical rotations were measured on an Optical Activity AA-1000 polarimeter and were calibrated using a solution of camphor in ethanol of known rotation, $[\alpha]_D^{20}$ +44.1 deg cm^2 g^{-1} (*c* 10, EtOH). Microanalyses were carried out at the University of Leeds Microanalytical Laboratory.

TLC was carried out using precoated aluminium-backed silica plates which were visualised using either UV light, permanganate or anisaldehyde stain.

In all cases, except those employing aqueous conditions, reactions were carried out under a positive pressure of dry and oxygen-free nitrogen, and glassware was oven dried before use. Solvents were removed under reduced pressure using a Buchi rotary evaporator at water-aspirator pressure in many cases followed by drying under high vacuum at 0.5 mmHg.

All solvents were dried and distilled before use by usual procedures[38] and other reagents used as received. TBHP was prepared according to literature procedures.[8] Light petroleum refers to the fraction with distillation range 40–60 °C unless otherwise stated. Dimethyl disulfide was purified by passage through a short column of silica gel immediately prior to use.

The homochiral epoxy alcohols **10** were prepared according to the literature[8] and were found to be of >95% ee by using $Eu(hfc)_3$ on the corresponding acetate. (1*S*,2*R*)-(–)-3,3-dichloro-1,7,7-trimethyl-*N*-phenylsulfonylspiro{bicyclo[2.2.1]-heptane-2,3′-oxaziridine} **11** was prepared according to the method of Davis.[14b]

(2*R*,3*S*)-2-[(Phenylsulfanyl)methyl]-3-propyloxirane 6a

Diphenyl disulfide (5.70 g, 26.1 mmol) was added to a stirred solution of (2*S*,3*S*)-(–)-3-propyloxirane-2-methanol **10** (2.00 g, 17.2 mmol) in dimethylformamide (DMF) (15 cm^3) at 0 °C under N_2. Tributylphosphane (6.50 cm^3, 26.1 mmol) was then added dropwise to the solution, which was stirred at room temperature for 18 h. The reaction mixture was diluted with distilled water (500 cm^3), and the crude product was extracted with light petroleum (4 × 200 cm^3), dried ($MgSO_4$), filtered and concentrated. The crude product was purified by column chromatography [silica gel (700 g); eluent 5% ethyl acetate–light petroleum] to give title compound **6a** (2.68 g, 75%) as an oil; δ_H(300 MHz; $CDCl_3$) 0.90 (3 H, t, *J* 6.8, Me), 1.33–1.47 (4 H, m, CH_2CH_2), 2.68 (1 H, dt, *J* 6.0 and 2.4, 3-H), 2.91 (1 H, dd, *J* 16.0 and 6.7, one of CH_2S), 2.92 (1 H, m, 2-H), 3.16 (1 H, dd, *J* 16.0 and 7.3, remaining CH_2S) and 7.22–7.43 (5 H, m, Ph); δ_C(100 MHz; $CDCl_3$) 13.74 (Me), 18.92 ($MeCH_2$), 33.58 ($MeCH_2CH_2$), 36.12 (CH_2S), 56.85 (C-3), 59.03 (C-2), 126.44

(CHAr), 128.77 (CHAr), 130.03 (CHAr) and 135.23 (CAr); ν_{max}(thin film)/cm^{-1} 2970–2850s (C–H), 1585m, 1472m, 1440m, 925m, 740s and 695s; MS (EI) *m/z* 208 (M^+, 100%), 165 (38), 123 (58), 109 (61), 99 (73) and 57 (94); $[\alpha]_D^{20}$ −25.6 (*c* 0.41, EtOH) (Found: C, 69.2; H, 7.75; S, 15.6. Calc. for $C_{12}H_{16}OS$: C, 69.20; H, 7.75; S, 15.40%).

(2*R*,3*S*)-2-[(Methylsulfanyl)methyl]-3-propyloxirane 7a

Dimethyl disulfide (5.86 cm^3, 63.7 mmol) was added to a stirred solution of (2*S*,3*S*)-(−)-3-propyloxirane-2-methanol **10** (3.70 g, 31.9 mmol) in DMF (10 cm^3) at 0 °C under N_2. Tributylphosphane (16.0 cm^3, 63.7 mmol) was then added dropwise to the solution, which was then stirred at room temperature for 18 h. The reaction mixture was diluted with distilled water (300 cm^3) and the product was extracted with light petroleum (4 × 100 cm^3), dried ($MgSO_4$), filtered and concentrated. Purification by column chromatography [silica gel (400 g); eluent 5% ethyl acetate–light petroleum] gave title compound **7a** (3.03 g, 65%) as an oil, bp 102 °C/20 mmHg; δ_H(300 MHz; $CDCl_3$) 0.97 (3 H, t, *J* 7.5, *Me*CH_2), 1.41–1.58 (4 H, m, C*H*$_2$C*H*$_2$), 2.18 (3 H, s, MeS), 2.54 (1 H, dd, *J* 14.0 and 5.9, one of CH_2S), 2.70 (1 H, dd, *J* 14.0 and 5.4, remaining CH_2S), 2.77 (1 H, dt, *J* 3.6 and 1.8, 3-H) and 2.90 (1 H, dt, *J* 5.5 and 1.8, 2-H); δ_C(75 MHz; $CDCl_3$) 13.69 (*Me*CH_2), 15.65 (Me*C*H$_2$), 19.01 (MeS), 33.57 (MeCH_2CH_2), 35.56 (CH_2S), 57.52 (C-3) and 58.18 (C-2); ν_{max}(thin film)/cm^{-1} 2960–2850s (C–H), 1465–1410m and 902m; MS (EI) *m/z* 146 (M^+, 23%), 103 (39), 57 (100) and 55 (99); $[\alpha]_D^{20}$ −28.2 (*c* 2.78, EtOH) (Found: C, 57.25; H, 9.8; S, 21.85. Calc. for $C_7H_{14}OS$: C, 57.5; H, 9.60; S, 21.9%).

Oxidation of 2-[(phenylsulfanyl)methyl]-3-propyloxirane 6a using compound 11. Representative procedure for Table 1, entries 2, 3, 6, 8, 10 and 11

The oxaziridine **11** (71.0 mg, 0.189 mmol) was added to a stirred solution of compound **6** (28.8 mg, 0.138 mmol) in carbon tetrachloride (4 cm^3) at 0 °C under N_2. The reaction mixture was stirred for 5 h, then was concentrated to give a mixture of the crude product and (+)-3,3-dichloro-*N*-(phenylsulfonyl)-camphorimine. Purification by column chromatography [silica gel (2.5 g); eluent 40% ethyl acetate–light petroleum] gave (2*R*,3*S*)-2-[(*S*)-(phenylsulfinyl)methyl]-3-propyloxirane **16** (Table 1, entry 2) (20.0 mg, 65%) as the major diastereoisomer (13:1 ratio) as an oil. The individual diastereoisomers (>95% de) could be isolated by further column chromatography (silica gel; eluent 30% ethyl acetate–light petroleum); δ_H(300 MHz; $CDCl_3$) 0.88 (3 H, t, *J* 7.0, Me), 1.30–1.50 (4 H, m, CH_2CH_2), 2.69 (1 H, dt, *J* 5.0 and 2.1, 3-H), 2.90, 2.93 and 3.12 (3 H, ABX system, *J* 13.9, 4.9 and 6.7, CH_2S and 2-H, respectively), 7.43–7.56 (3 H, m, ArH) and 7.60 (2 H, dd, *J* 7.5 and 1.9, ArH); δ_C(100 MHz; $CDCl_3$) 13.88 (Me), 19.00 (Me*C*H$_2$), 33.58 (MeCH$_2$*C*H$_2$), 51.68 (CH_2S), 59.06 (C-3), 60.62 (C-2), 123.79 (CHAr), 129.40 (CHAr), 131.28 (CHAr) and 143.56 (CAr); ν_{max}(thin film)/cm^{-1} 2980–2870s (C–H), 1448s (C=C), 1255w (C–O) and 1045s (S=O); MS (EI) *m/z* 224 (M^+, 2.5%), 208 (3), 125 (32), 99 (80), 77 (41), 57 (100), 55 (92) and 43 (75); $[\alpha]_D^{20}$ −196.8 (*c* 0.25, EtOH) (Found: C, 64.15; H, 7.15; S, 14.25. Calc. for $C_{12}H_{16}O_2S$: C, 64.25; H, 7.20; S, 14.30%).

Oxidation of (2*S*,3*R*)-2-[(Phenylsulfanyl)methyl]-3- propyloxirane 6b using 11 (Table 1, entry 5)

A similar procedure using (2*S*,3*R*)-2-[(phenylsulfanyl)methyl]-3-propyloxirane **6b** (30.8 mg, 0.148 mmol) and the oxaziridine **11** (123.0 mg, 0.327 mmol) gave (2*S*,3*R*)-2-[(*S*)-(phenylsulfinyl)-methyl]-3-propyloxirane (Table 1, entry 5) (19.7 mg, 59%) as the major diastereoisomer (7.0:1 ratio) as an oil. The individual diastereoisomers (>95% de) could be isolated by further column chromatography (silica gel; eluent 30% ethyl acetate–light petroleum); δ_H(300 MHz; $CDCl_3$) 0.93 (3 H, t, *J* 7.0, Me), 1.35–1.60 (4 H, m, CH_2CH_2), 2.83 (1 H, dt, *J* 5.4 and 2.4, 2-H), 2.87 (1 H, dt, *J* 4.2 and 2.4, 3-H), 3.01 (1 H, dd, *J* 13.5 and 5.1, one of CH_2S), 3.12 (1 H, dd, *J* 13.5 and 5.9, remaining CH_2S), 7.50–7.60 (3 H, m, ArH) and 7.67 (2 H, dd, *J* 2.0 and 7.4, ArH); δ_C(100 MHz; $CDCl_3$) 13.58 (Me), 18.76 (Me*C*H$_2$), 33.32 (MeCH$_2$*C*H$_2$), 50.82 (CH_2S), 57.84 (C-3), 58.36 (C-2), 123.76 (CHAr), 129.03 (CHAr), 131.03 (CHAr) and 142.46 (CAr); ν_{max}(thin film)/cm^{-1} 2980–2870s (C–H), 1448s (C=C), 1255w (C–O) and 1045s (S=O); MS (EI) *m/z* 224 (M^+, 2.3%), 208 (5), 125 (27), 99 (76), 78 (34), 77 (39), 57 (100), 55 (98) and 43 (75); $[\alpha]_D^{20}$ +46.8 (*c* 0.22, EtOH).

(2*R*,3*S*)-2-[(*R*)-(Methylsulfinyl)methyl]-3-propyloxirane (Table 1, entry 7) *via* Kagan oxidation

(+)-Diethyl tartrate (DET) (0.23 cm^3, 1.37 mmol) and titanium(IV) isopropoxide (0.21 cm^3, 0.69 mmol) were dissolved in stirred methylene dichloride at room temperature under N_2. Distilled water (12.4 mm^3, 0.69 mmol) was then added to the stirred solution. Upon complete dissolution of the water (formation of a pale yellow solution after *ca.* 40 min), a solution of (2*R*,3*S*)-2-[(methylsulfanyl)methyl]-3-propyloxirane **7** (0.20 g, 1.37 mmol) in methylene dichloride (3 cm^3) was added to the reaction mixture. The solution was cooled (−40 °C using acetone–solid CO_2-bath) and stirred for 40 min, after which time cumene hydroperoxide (0.25 cm^3, 1.37 mmol) was added dropwise to the stirred mixture. The mixture was kept at −40 °C (deep freeze) for 20 h, then distilled water (0.23 cm^3) was added and the mixture was stirred at room temperature for 90 min. The suspension resulting from hydrolysis was filtered through a Celite pad (55 mm diameter, 15 mm deep) which was then washed thoroughly with methylene dichloride (5 × 100 cm^3), dried ($MgSO_4$), filtered and concentrated. Purification by column chromatography [silica gel (7.5 g); eluent 10% ethanol–ethyl acetate] gave (2*R*,3*S*)-3-[(*R*)-(methylsulfinyl)methyl]-3-propyloxirane **20** (Table 1, entry 7) (0.14 g, 61%) as the major diastereoisomer (5.1:1 ratio); δ_H(300 MHz; $CDCl_3$) 0.95 (3 H, t, *J* 7.1, *Me*CH_2), 1.40–1.65 (4 H, m, CH_2CH_2), 2.66 (3 H, s, MeS), 2.68 (1 H, dd, *J* 13.1 and 8.2, one of CH_2S), 2.87 (1 H, dt, *J* 4.7 and 1.2, 3-H), 3.05 (1 H, ddd, *J* 8.2, 3.6 and 1.2, 2-H) and 3.15 (1 H, dd, *J* 13.1 and 3.6, remaining CH_2S); δ_C(75 MHz; $CDCl_3$) 13.70 (*Me*CH_2), 18.92 (Me*C*H$_2$), 33.42 (MeCH$_2$*C*H$_2$), 39.50 (MeS), 51.38 (CH_2S), 57.93 (C-3) and 58.51 (C-2); ν_{max}(thin film)/cm^{-1} 2980–2860s (C–H), 1465m, 1430m, 1260w (C–O), 1040s (S=O) and 905m; MS (EI) *m/z* 162 (M^+, 8%), 147 ($M - CH_3$, 11), 139 (12), 120 (14), 99 (26), 92 (36), 71 (33), 57 (95), 55 (94) and 43 (100); $[\alpha]_D^{20}$ −129.5 (*c* 1.65, EtOH) (Found: C, 51.6; H, 8.6; S, 19.55. Calc. for $C_7H_{14}O_2S$: C, 51.80; H, 8.70; S, 19.75%).

(2*R*,3*S*)-2-[(*S*)-(Methylsulfinyl)methyl]-3-propyloxirane 22 *via* Kagan oxidation (Table 1, entry 9)

A similar procedure using (2*R*,3*S*)-2-[(methylsulfanyl]-3-propyloxirane **7** (55.8 mg, 0.382 mmol), titanium isopropoxide (58.5 mm^3, 0.191 mmol), (−)-DET (65.3 mm^3, 0.382 mmol), water (3.4 mm^3, 0.191 mmol) and cumene hydroperoxide (70.5 mm^3, 0.382 mmol) gave the (2*R*,3*S*)-2-[(*S*)-(methylsulfinyl)methyl]-3-propyloxirane **22** (Table 1, entry 9) (44.3 mg, 72%) as the major diastereoisomer (4.6:1 ratio); δ_H(300 MHz; $CDCl_3$) 0.97 (3 H, t, *J* 7.2, *Me*CH_2), 1.45–1.65 (4 H, m, CH_2CH_2), 2.70 (3 H, s, MeS), 2.72 (1 H, dd, *J* 14.0 and 6.9, one of CH_2S), 2.91 (1 H, dt, *J* 5.5 and 2.2, 3-H), 3.11 (1 H, dd, *J* 14.0 and 3.7, remaining CH_2S) and 3.26 (1 H, ddd, *J* 6.9, 3.7 and 2, 2-H); δ_C(75 MHz; $CDCl_3$) 13.83 (*Me*CH_2), 19.13 (*C*H$_2$Me), 33.64 (MeCH$_2$*C*H$_2$), 38.25 (MeS), 50.67 (CH_2S), 54.80 (C-3) and 57.25 (C-2); ν_{max}(thin film)/cm^{-1}

2980–2860s (C–H), 1465m, 1430m, 1260w (C–O), 1040s (S=O) and 905m; MS (EI) *m/z* 162 (M^+, 0.3%), 146 (1.2), 131 (1.3), 99 (9), 57 (20), 55 (24) and 40 (100); $[\alpha]_D^{20}$ −20.7 (*c* 0.058, EtOH).

(2*R*,3*S*)-2-[(Methylsulfinyl)methyl]-3-propyloxirane (mixture of diastereoisomers) 25 using $VO(acac)_2$–TBHP

Vanadyl bis(acetoacetonate) (0.813 g, 3.07 mmol) was added to a stirred solution of (2*R*,3*S*)-2-[(methylsulfanyl)methyl]-3-propyloxirane **7** (3.06 g, 20.9 mmol) in methylene dichloride (15 cm^3) at −40 °C (acetone–solid CO_2-bath) under N_2. TBHP (8.62 cm^3 of 2.67 mol dm^{-3} solution in toluene, 23.0 mmol) was then added and the reaction mixture was stirred at −40 °C for 2 days, after which time distilled water (15 cm^3) was added and the crude product was extracted using methylene dichloride (3 × 15 cm^3). The organic fractions were dried ($MgSO_4$), filtered and concentrated. Purification by column chromatography [silica gel (150 g); eluent 10% ethanol–ethyl acetate] gave compound **25** (2.169 g, 64%) as a 1:1 mixture of diastereoisomers **20** and **22**.

(2*R*,3*S*)-2-[(Phenylsulfinyl)methyl]-3-propyloxirane (mixture of diastereoisomers) 24 using $VO(acac)_2$–TBHP

A similar procedure using (2*R*,3*S*)-2-[(phenylsulfanyl)methyl]-3-propyloxirane **6** (5.62 g, 27.0 mmol), vanadyl bis(acetoacetonate) (1.13 g, 4.04 mmol) and TBHP (11.1 cm^3 of 2.67 mol dm^{-3} solution, 29.7 mmol) gave compound **24** (5.08 g, 84% as a 1:1 mixture of diastereoisomers **16** and **18**.

(2*R*,3*R*)-1-[(*R*)-Phenylsulfinyl]hexane-2,3-diol 17

Boron trifluoride–diethyl ether (75.9 mm^3, 0.617 mmol) was added to a stirred solution of (2*R*,3*S*)-2-[(*S*)-(phenylsulfinyl)methyl]-3-propyloxirane **16** (0.126 g, 0.561 mmol, >95% de) in diethyl ether (3 cm^3) at −78 °C under N_2. The reaction mixture was allowed to warm to room temperature, then was stirred for 16 h. Saturated aq. sodium hydrogen carbonate (3 cm^3) was then added and the mixture was stirred for a further 1 h. The crude product was extracted using chloroform (3 × 5 cm^3), dried ($MgSO_4$), filtered and concentrated. Recrystallisation gave diol **17** (0.135 g, 99%) as needles, mp 66–67.5 °C (from ethyl acetate–light petroleum); δ_H(300 MHz; $CDCl_3$) 0.95 (3 H, t, *J* 7.1, Me), 1.20–1.70 (4 H, m, CH_2CH_2), 2.63 (1 H, d, *J* 4.9, 3-OH), 2.90 (1 H, dd, *J* 13.5 and 2.5, one of 1-H), 3.10 (1 H, dd, *J* 13.5 and 8.2, 1-H), 3.73–3.76 (1 H, m, 3-H), 4.03 (1 H, d, *J* 2.6, 2-OH), 4.20–4.26 (1 H, m, 2-H) and 7.50–7.70 (5 H, m, ArH); δ_C(75 MHz; $CDCl_3$) 13.95 (C-6), 18.97 (C-5), 34.65 (C-4), 58.85 (C-1), 71.70 (C-3), 73.56 (C-2), 123.98 (CHAr), 129.42 (CHAr), 131.46 (CHAr) and 143.25 (CAr); ν_{max}(Nujol)/cm^{-1} 3600–3125br (O–H), 2985–2850s (C–H), 1650w, 1088m, 1068m, 1025s (S=O), 750m and 695m; MS (EI) *m/z* 242 (M^+, 0.3%), 226 (4), 208 (6), 169 (13), 135 (14), 126 (49), 110 (100), 78 (54), 55 (55) and 43 (75); $[\alpha]_D^{20}$ +9.3 (*c* 2.07, EtOH) (Found: C, 59.45; H, 7.5; S, 13.35. Calc. for $C_{12}H_{18}O_3S$: C, 59.50: H, 7.50; S, 13.25%).

(2*R*,3*R*)-1-[(*S*)-Phenylsulfinyl]hexane-2,3-diol 19

A similar procedure using (2*R*,3*S*)-2-[(*R*)-phenylsulfinyl]-3-propyloxirane **18** (86.2 mg, 0.384 mmol, >95% de), boron trifluoride–diethyl ether (52.0 mm^3, 0.423 mmol) and saturated aq. sodium hydrogen carbonate (3 cm^3) gave diol **19** (86.6 mg, 93%) as needles, mp 96–97.5 °C (from benzene); δ_H(300 MHz; $CDCl_3$) 0.85 (3 H, t, *J* 7.1, Me), 1.10–1.50 (4 H, m, CH_2CH_2), 2.23 (1 H, d, *J* 3.7, 3-OH), 2.60 (1 H, dd, *J* 13.8 and 1.5, 1-H), 3.30 (1 H, dd, *J* 13.8 and 10.0, 1-H), 3.61–3.72 (1 H, m, 3-H), 3.95–4.05 (1 H, m, 2-H), 4.15 (1 H, d, *J* 2.8, 2-OH) and 7.48–7.72 (5 H, m, ArH); δ_C(75 MHz; $CDCl_3$) 13.94 (C-6), 18.97 (C-5), 34.02 (C-4), 57.40 (C-1), 69.23 (C-3), 73.98 (C-2), 123.94 (CHAr), 129.37 (CHAr), 131.10 (CHAr) and 142.66 (CAr); ν_{max}(Nujol)/cm^{-1} 3380–3160 br (O–H), 2990–2860s (C–H), 1094w (C–O), 1067m (C–O), 1023s (S=O) and 750m; MS (EI) *m/z* 243 ($M^+ + 1$, 1.9%), 225 ($M + 1 - H_2O$, 3.4), 207 ($M + 1 - 2 \times H_2O$, 0.8), 169 (59), 126 (100), 125 (63), 99 (69), 78 (60), 55 (63) and 43 (61); $[\alpha]_D^{20}$ −174.6 (*c* 0.63, EtOH).

(2*R*,3*R*)-1-[(*S*)-Methylsulfinyl]hexane-2,3-diol 21

A similar procedure using (2*R*,3*S*)-2-[(*R*)-methylsulfinyl]-3-propyloxirane **20** (major diastereoisomer, 5:1 mixture of **20** and **22**) (12.5 mg, 0.077 mmol), boron trifluoride–diethyl ether (14.2 mm^3, 0.116 mmol) and saturated aq. sodium hydrogen carbonate (1.5 cm^3) gave diol **21** (5:1 mixture of isomers) (8.5 mg, 61%) as an oil; δ_H(300 MHz; $CDCl_3$) 0.95 (3 H, t, *J* 6.8, *Me*CH_2), 1.32–1.61 (4 H, m, CH_2CH_2), 2.71 (3 H, s, MeS), 2.90 (1 H, dd, *J* 13.5 and 2.7, 1-H), 3.02 (1 H, dd, *J* 13.5 and 8.2, 1-H), 3.30–3.31 (1 H, m, 3-OH), 3.72–3.74 (1 H, m, 3-H), 4.13–4.15 (1 H, m, 2-H) and 4.35–4.36 (1 H, m, 2-OH); δ_C(100 MHz; $CDCl_3$) 14.02 (C-6), 19.06 (C-5), 34.60 (C-4), 39.22 (MeS), 54.58 (C-1), 71.23 (C-3) and 73.67 (C-2); ν_{max}(Nujol)/cm^{-1} 3460–3150br (O–H), 2980–2840s (C–H), 1670–1610br w, 1335m, 1307m, 1100m, 1075s, 1027s (S=O), 958m, 948m and 787w (Found: M^+, 181.090. Calc. for $C_7H_{16}O_3S$: M, 181.090); $[\alpha]_D^{20}$ −26.7 (*c* 1.02, EtOH).

(2*R*,3*R*)-1-[(*R*)-Methylsulfinyl]hexane-2,3-diol 23

A similar procedure using (2*R*,3*S*)-2-[(*S*)-methylsulfinyl]-3-propyloxirane **22** (major diastereoisomer, 5:1 mixture of **22** and **20**) (30.5 mg, 0.188 mmol), boron trifluoride–diethyl ether (27.7 mm^3, 0.225 mmol) and saturated aq. sodium hydrogen carbonate (1.5 cm^3) gave diol **23** (5:1 mixture of diastereoisomers) (20.4 mg, 60%) as a waxy solid, mp 82.0–85.5 °C (from benzene); δ_H(300 MHz; $CDCl_3$) 0.96 (3 H, t, *J* 5.9, *Me*CH_2), 1.37–1.59 (4 H, m, CH_2CH_2), 2.68 (3 H, s, MeS), 2.74 (1 H, dd, *J* 13.4 and 1.8, 1-H), 3.03 (1 H, dd, *J* 13.4 and 9.7, 1-H), 3.53 (1 H, m, 3-OH), 3.77–3.79 (1 H, m, 3-H), 4.20–4.22 (1 H, m, 2-H) and 4.88 (1 H, m, 2-OH); δ_C(100 MHz; $CDCl_3$) 14.00 (C-6), 19.09 (C-5), 34.23 (C-4), 38.49 (MeS), 56.04 (C-1), 68.58 (C-3) and 73.98 (C-2); ν_{max}(Nujol)/cm^{-1} 3460–3150br (O–H), 2980–2840s (C–H), 1670–1610br w, 1335m, 1307m, 1100m, 1075s, 1027s (S=O), 958m, 948m and 787w; MS (EI) [Found: ($M + 1$), 181.090. Calc. for $C_7H_{17}O_3S$: *m/z* 181.090] *m/z* 181 ($M^+ + 1$, 7%), 163 ($M + 1 - H_2O$, 8), 149 (8), 137 (8), 107 (77), 99 (72), 73 (76), 64 (56), 55 (77) and 43 (100); $[\alpha]_D^{20}$ −96.8 (*c* 0.38, EtOH).

Lewis acid-induced diastereoisomer-selective reaction of (2*R*,3*S*)-2-[(phenylsulfinyl)methyl]-3-propyloxiranes 24

Boron trifluoride–diethyl ether (0.67 cm^3, 5.48 mmol) was added to a stirred solution compound of **24** (1:1 mixture of diastereoisomers) (1.025 g, 4.57 mmol) in diethyl ether (10 cm^3) at −78 °C under N_2. The reaction mixture was allowed to warm to −9 °C and was stirred at this temperature for 135 min, after which time saturated aq. sodium hydrogen carbonate (2 cm^3) was added. After being stirred at room temperature for a further 1 h the phases were separated and the aqueous phase was extracted with chloroform (5 × 50 cm^3). The combined organic layers were dried ($MgSO_4$), filtered and concentrated to give a mixture of **19** and **16**. Recrystallisation from benzene gave (2*R*,3*R*)-1-[(*S*)-phenylsulfinyl]hexane-2,3-diol **19** (0.454 g, 41%, >95% de) as needles with spectroscopic data identical with those reported previously. Concentration of the residue gave (2*R*,3*S*)-2-[(*S*)-(phenylsulfinyl)methyl]-3-propyloxirane **16** (0.451 g, 44%, 91% de) as an oil with spectroscopic data identical with those reported previously.

Lewis acid-induced diastereoisomer-selective reaction of (2*R*,3*S*)-2-[(methylsulfinyl)methyl]-3-propyloxiranes 25

Boron trifluoride–diethyl ether (0.144 cm^3, 1.17 mmol) was added to a stirred solution of compound **25** (1:1 mixture of diastereoisomers) (0.158 g, 0.974 mmol) in diethyl ether (5 cm^3) at −78 °C under N_2. The reaction mixture was allowed to warm to +5 °C and was stirred at this temperature for 2 h, after which time saturated aq. sodium hydrogen carbonate (0.7 cm^3) was added. After being stirred at room temperature for a further 1 h the reaction mixture was concentrated under reduced pressure and the residue was washed with chloroform (4 × 25 cm^3), dried ($MgSO_4$), filtered and concentrated to give a mixture of isomers **23** and **20**. Recrystallisation from benzene gave (2*R*,3*R*)-1-[(*R*)-methylsulfinyl]hexane-2,3-diol **23** (73.8 mg, 42%, 78% de) as a solid, mp 82.0–85.5 °C (from benzene), with spectroscopic data identical with those reported previously. Concentration of the mother liquors and column chromatography [silica gel (5 g); eluent 10% ethanol–ethyl acetate] gave (2*R*,3*S*)-2-[(*R*)-(methylsulfinyl)methyl]-3-propyloxirane **20** (64.8 g, 41%, 66% de), as an oil, with spectroscopic data identical with those reported previously.

(3*S*)-(*E*)-1-[(*S*)-Phenylsulfinyl]hex-1-en-3-ol 30

Aq. sodium hydroxide (7.25 cm^3 of 0.05 mol dm^{-3} solution, 0.363 mmol) was added to stirred (2*R*,3*S*)-2-[(*S*)-(phenylsulfinyl)methyl]-3-propyloxirane **16** (34.8 mg, 0.155 mmol, 95% de) at room temp. The reaction mixture was stirred for 1 h, then the product was extracted with methylene dichloride (3 × 10 cm^3), dried ($MgSO_4$), filtered and concentrated to give enol **30** (24.9 mg, 72%, 11:1 *E*:*Z*) as an oil, δ_H(300 MHz; [$^2H_6$]benzene) 0.76 (3 H, t, *J* 6.9, *Me*CH_2), 1.16–1.38 (4 H, m, CH_2CH_2), 2.47 (1 H, m, 3-OH), 3.95 (1 H, m, 3-H), 6.42 (1 H, d, *J* 14.9, 1-H), 6.58 (1 H, dd, *J* 14.9 and 3.8, 2-H), 6.90–7.01 (3 H, m, ArH) and 7.48 (2 H, d, *J* 7.6, ArH); δ_C(100 MHz; $CDCl_3$) 13.87 (C-6), 18.46 (C-5), 38.87 (C-4), 70.59 (C-3), 124.51 (CHAr), 129.35 (CHAr), 131.03 (CHAr), 133.73 (C-2), 141.99 (C-1) and 143.59 (CAr); ν_{max}(thin film)/cm^{-1} 3560–3105s (O–H), 2980–2830s (C–H), 1740w, 1630w, 1590w, 1450s, 1138m, 1088s (C–O), 1033s (S=O), 967m, 753s and 694s; MS (EI) (Found: M^+, 224.086. Calc. for $C_{12}H_{16}O_2S$: M, 224.087) *m*/*z* 224 (M^+, 14%), 208 (M − O, 10), 175 (M − SO, 42), 152 (95), 133 (84), 109 (97), 78 (70), 71 (77), 55 (100) and 43 (94); $[\alpha]_D^{20}$ −71.2 (*c* 0.37, EtOH).

(3*S*)-(*E*)-1-[(*R*)-Phenylsulfinyl]hex-1-en-3-ol 31

A similar procedure using (2*R*,3*S*)-2-[(*R*)-(phenylsulfinyl)methyl]-3-propyloxirane **18** (13.1 mg, 0.058 mmol, >95% de) and aq. sodium hydroxide (3.5 cm^3 of 0.05 mol dm^{-3} solution, 0.088 mmol) gave enol **31** (12.2 mg, 93%, 17:1 *E*:*Z*) as an oil, δ_H(300 MHz; [$^2H_6$]benzene) 0.71 (3 H, t, *J* 6.8, *Me*CH_2), 1.06–1.19 (4 H, m, CH_2CH_2), 3.76–3.79 (1 H, m, 3-H), 6.26 (1 H, d, *J* 14.9, 1-H), 6.53 (1 H, dd, *J* 14.9 and 4.4, 2-H), 6.98–7.10 (3 H, m, ArH) and 7.49 (2 H, d, *J* 7.0, ArH); δ_C(100 MHz; $CDCl_3$) 13.87 (C-6), 18.49 (C-5), 38.88 (C-4), 70.67 (C-3), 124.59 (CHAr), 129.36 (CHAr), 131.08 (CHAr), 133.70 (C-2), 141.97 (C-1) and 143.51 (CAr); ν_{max}(thin film)/cm^{-1} 3530–3110s (O–H), 2980–2820s (C–H), 1740w, 1650w, 1623w, 1448s, 1134m, 1088s (C–O), 1068m, 1033s (S=O), 750s and 692s; MS (EI) (Found: M^+, 224.086. Calc. for $C_{12}H_{16}O_2S$: M, 224.087) *m*/*z* 224 (M^+, 13%), 208 (M − O, 11), 175 (M − SO, 40), 152 (92), 133 (93), 109 (98), 78 (69), 71 (76), 55 (100) and 43 (94); $[\alpha]_D^{20}$ +112.1 (*c* 0.61, EtOH).

(3*S*)-(*E*)-1-[(*R*)-Methylsulfinyl]hex-1-en-3-ol 32

Aq. sodium hydroxide (29.9 cm^3 of 0.05 mol dm^{-3} solution, 1.50 mmol) was added to stirred (2*R*,3*S*)-2-[(*R*)-(methylsulfinyl)-methyl]-3-propyloxirane **20** (0.113 g, 0.695 mmol, 5.1:1 mixture of isomers) contaminated with DET (the crude product resulting from the Kagan oxidation described above) at room temp. After the mixture had been stirred for 5 h, water was removed on a rotary evaporator (bath temp. ~60 °C). The residue was then extracted with chloroform (3 × 10 cm^3), dried ($MgSO_4$), filtered and concentrated to give enol **32** (75.6 mg, 68%, 16:1 *E*:*Z*, 5:1 mixture of isomers) as an oil, δ_H(300 MHz; [$^2H_6$]benzene) 0.83 (3 H, t, *J* 6.8, *Me*CH_2), 1.24–1.44 (4 H, m, CH_2CH_2), 1.90 (3 H, s, MeS), 2.97 (1 H, d, *J* 5.7, 3-OH), 4.05 (1 H, m, 3-H), 6.18 (1 H, d, *J* 14.9, 1-H) and 6.52 (1 H, dd, *J* 14.9 and 4.6, 2-H); δ_C(100 MHz; $CDCl_3$) 13.85 (C-6), 18.44 (C-5), 38.88 (MeS), 40.56 (C-4), 70.45 (C-3), 132.77 (C-2) and 142.02 (C-1); ν_{max}(thin film)/cm^{-1} 3617–3055s (O–H), 2955–2825s (C–H), 1650w (C=C), 1465m, 1421m, 1305m, 1136m, 1030s (S=O), 970s, 745w and 687m; MS (EI) *m*/*z* 162 (M^+, 11%), 145 (M − OH, 20), 119 (47), 103 (29), 91 (74), 73 (47), 71 (58), 55 (74), 43 (100) and 41 (49); $[\alpha]_D^{20}$ +220.9 (*c* 0.39, EtOH) (Found: C, 51.55; H, 8.65; S, 19.65. Calc. for $C_7H_{14}O_2S$: C, 51.80; H, 8.70; S, 19.75%).

(3*S*)-(*E*)-1-[(*S*)-Methylsulfinyl]hex-1-en-3-ol 33

A similar procedure using (2*R*,3*S*)-2-[(*S*)-(methylsulfinyl)-methyl]-3-propyloxirane **22** (0.107 g, 0.659 mmol, 4.6:1 mixture of isomers) and aq. sodium hydroxide (28.6 cm^3 of 0.05 mol dm^{-3} solution, 1.43 mmol) gave enol **33** (75.2 mg, 70%, 3.6:1 *E*:*Z*, 4.6:1 mixture of diastereoisomers) as an oil, δ_H(300 MHz; [$^2H_6$]benzene) 0.82 (3 H, t, *J* 6.8, *Me*CH_2), 1.22–1.42 (4 H, m, CH_2CH_2), 1.90 (3 H, s, MeS), 3.11 (1 H, d, *J* 5.2, 3-OH), 4.05 (1 H, m, 3-H), 6.27 (1 H, d, *J* 14.9, 1-H) and 6.50 (1 H, dd, *J* 14.9 and 4.1, 2-H); δ_C(100 MHz; $CDCl_3$) 13.88 (C-6), 18.48 (C-5), 38.93 (MeS), 40.60 (C-4), 70.56 (C-3), 132.94 (C-2) and 142.05 (C-1); ν_{max}(thin film)/cm^{-1} 3620–3025s (O–H), 2975–2830s (C–H), 1650m (C=C), 1463m, 1419m, 1302m, 1137m, 1027s (S=O), 965s, 748w and 692m; MS (EI) *m*/*z* 162 (M^+, 12%), 145 (M − OH, 38), 119 (58), 103 (37), 91 (74), 73 (50), 71 (58), 55 (76), 43 (100) and 41 (54); $[\alpha]_D^{20}$ +63.0 (*c* 0.33, EtOH).

(3*R*)-(*E*)-1-[(*R*)-Phenylsulfinyl]hex-1-en-3-ol 34

Triethylamine (0.70 cm^3, 4.94 mmol) was added to a stirred solution of (2*R*,3*R*)-1-[(*R*)-phenylsulfinyl]hexane-2,3-diol **17** (0.240 g, 0.988 mmol, 61% de) in methylene dichloride (5 cm^3) at 0 °C under N_2. Thionyl dichloride (86.5 mm^3, 1.19 mmol) was then slowly added and the reaction mixture was stirred for 40 min at 0 °C and then concentrated under reduced pressure for 30 min. The intermediate sulfite was redissolved in stirred methylene dichloride (3 cm^3) under N_2, cooled to 0 °C and DBU (0.74 cm^3, 4.94 mmol) was added. After being stirred for a further 1 h 20 min the reaction mixture was quenched with saturated aq. ammonium chloride (3 cm^3) and the crude product was extracted using chloroform (4 × 10 cm^3), dried ($MgSO_4$), filtered and concentrated. Purification by column chromatography [silica gel (~40 g); eluent 40% ethyl acetate–light petroleum] gave enol **34** (0.171 g, 77%, 60% de) as an oil, with spectroscopic data identical with those of compound **34**.

(3*R*)-(*E*)-1-[(*S*)-Phenylsulfinyl]hex-1-en-3-ol 35

A similar procedure using (2*R*,3*S*)-[(*R*)-phenylsulfinyl]hexane-2,3-diol **19** (0.285 g, 1.18 mmol, >95% de), triethylamine (0.83 cm^3, 5.88 mmol), thionyl dichloride (0.103 cm^3, 1.41 mmol) and DBU (0.88 cm^3, 5.88 mmol) gave enol **35** (0.236 g, 89%, >95% de) as an oil, $[\alpha]_D^{20}$ −111.2 (*c* 1.37, EtOH). Other spectroscopic data were identical with those of compound **35**.

(3*R*)-(*E*)-1-(Methylsulfinyl)hex-1-en-3-ol 36

Triethylamine (41.3 mm^3, 0.296 mmol) was added to a stirred solution of (2*R*,3*R*)-1-[(*S*)-methylsulfinyl]hexane-2,3-diol **21** (17.8 mg, 0.099 mmol, 66% de) in methylene dichloride (1.5 cm^3) at 0 °C under N_2. Thionyl dichloride (8.6 mm^3, 0.119 mmol) was then slowly added and the reaction mixture was

stirred for 40 min at 0 °C, then was concentrated under reduced pressure for 30 min. The intermediate sulfite was redissolved in stirred methylene dichloride (2 cm^3) under N_2, and DBU (44.3 mm^3, 0.296 mmol) was added. After being stirred for a further 6.5 h the reaction mixture was quenched with saturated aq. sodium hydrogen carbonate (1.5 cm^3) and the layers were separated. The aqueous layer was washed with chloroform (3 × 5 cm^3), dried ($MgSO_4$), filtered and concentrated. Purification by column chromatography [silica gel (~5 g); eluent 10% ethanol–ethyl acetate] gave enol **36** (10.9 mg, 68%, 12% de, mixture of **32** and **33**) as an oil.

(3*R*)-(*E*)-1-(Methylsulfinyl)hex-1-en-3-ol 37

A similar procedure using (2*R*,3*R*)-[(*R*)-methylsulfinyl]hexane-2,3-diol **23** (31.0 mg, 0.172 mmol, 78% de), triethylamine (71.9 mm^3, 0.516 mmol), thionyl dichloride (15.1 mm^3, 0.206 mmol) and DBU (77.2 mm^3, 0.516 mmol) gave enol **37** (15.6 mg, 56%, 33% de, mixture of **32** and **33**) as an oil.

(3*S*)-(*E*)-1-(Phenylsulfonyl)hex-1-en-3-ol 38

MCPBA (6.56 g, 20.9 mmol) was added to a solution of (2*R*,3*S*)-2-[(phenylsulfanyl)methyl]-3-propyloxirane **6** (1.74 g, 8.36 mmol) in stirred methylene dichloride (10 cm^3) at 0 °C under N_2. The reaction mixture was stirred for 24 h at room temperature, then further methylene dichloride (20 cm^3) was added and the solution was washed with saturated aq. sodium carbonate (3 × 10 cm^3). The aqueous layer was washed with methylene dichloride (2 × 15 cm^3) and the combined organic extracts were dried ($MgSO_4$), filtered and concentrated. Purification by column chromatography [silica gel, (100 g); eluent 25% ethyl acetate–light petroleum] gave (2*R*,3*S*)-2-[(phenylsulfonyl)methyl]-3-propyloxirane (1.63 g, 81%) as an oil, δ_H(300 MHz; $CDCl_3$) 0.91 (3 H, t, *J* 7.0, Me), 1.36–1.48 (4 H, m, CH_2CH_2), 2.61–2.64 (1 H, m, 3-H), 3.07 (1 H, dt, *J* 5.8 and 1.6, 2-H), 3.26 (1 H, dd, *J* 14.5 and 5.1, one of CH_2S), 3.37 (1 H, dd, *J* 14.5 and 6.6, remaining CH_2S), 7.61 (2 H, t, *J* 7.6, ArH), 7.70 (1 H, t, *J* 7.25, ArH) and 7.96 (2 H, d, *J* 7.6, ArH); δ_C(75 MHz; $CDCl_3$) 13.86 ($MeCH_2$), 19.02 ($MeCH_2$), 33.43 ($MeCH_2CH_2$), 51.33 (CH_2S), 57.82 (C-3), 59.26 (C-2), 128.19 (CHAr), 129.41 (CHAr), 134.13 (CHAr) and 139.31 (CAr); ν_{max}(thin film)/cm^{-1} 2980–2880s (C–H), 1737m, 1455s, 1320s (S=O), 1155s (S=O), 1090s, 922s, 755s and 690s; MS (EI) *m*/*z* 241 (M^+ + 1, 56%), 223 (34), 143 (56), 125 (49), 99 (100), 81 (93), 77 (91), 57 (94) and 55 (94); $[\alpha]_D^{20}$ −21.8 (*c* 0.95, EtOH) (Found: C, 59.8; H, 6.65; S, 13.1. Calc. for $C_{12}H_{16}O_3S$: C, 60.00; H, 6.70; S, 13.30%).

DBU (0.39 cm^3, 2.51 mmol) was added to a stirred solution of (2*R*,3*S*)-2-[(phenylsulfonyl)methyl]-3-propyloxirane (0.604 g, 2.51 mmol) in methylene dichloride (5 cm^3) at room temp. under N_2. After 4 h, chloroform (5 cm^3) was added and the solution was washed with 0.1 mol dm^{-3} sulfuric acid (3 × 4 cm^3). The aqueous phase was extracted with chloroform (3 × 10 cm^3) and the combined organic extracts were dried ($MgSO_4$), filtered and concentrated to give the crude product. Purification by column chromatography [silica gel (50 g); eluent 20% ethanol–light petroleum] gave title compound **38** (0.50 g, 83%) as a solid, mp 56–58 °C; δ_H(300 MHz; $CDCl_3$) 0.94 (3 H, t, *J* 7.2, Me), 1.40–1.62 (4 H, m, CH_2CH_2), 1.82 (1 H, m, 3-OH), 4.39–4.41 (1 H, m, 3-H), 6.60 (1 H, d, *J* 14.9, 1-H), 7.00 (1 H, dd, *J* 14.9 and 3.6, 2-H), 7.52–7.66 (3 H, m, ArH) and 7.89 (2 H, dd, *J* 7.4 and 1.6, ArH); δ_C(75 MHz; $CDCl_3$) 13.76 (C-6), 18.37 (C-5), 38.33 (C-4), 69.97 (C-3), 127.56 (CH), 129.26 (CH), 129.40 (CH), 133.38 (CH), 133.42 (CH) and 148.80 (CAr); ν_{max}(Nujol)/cm^{-1} 3595–3410m (O–H), 2980–2860s (C–H), 1470m, 1385m, 1300m (S=O), 1150m (S=O) and 760w; MS (EI) *m*/*z* 241 (M^+ + 1, 14%), 211 (33), 169 (100), 125 (94), 99 (50), 77 (58) and 57 (47); $[\alpha]_D^{20}$ +31.9 (*c* 0.82, EtOH) (Found: C, 59.75; H, 6.7; S, 13.25. Calc. for $C_{12}H_{16}O_3S$: C, 60.00; H, 6.70; S, 13.34%).

(3*S*)-(*E*)-1-(Methylsulfonyl)hex-1-en-3-ol 39

A similar procedure using (2*R*,3*S*)-2-[(methylsulfanyl)methyl]-3-propyloxirane **7** (0.57 g, 3.93 mmol) and MCPBA (3.08 g, 9.82 mmol) gave, after purification by column chromatography [Fluorosil (60 g); eluent 40% ethyl acetate–light petroleum], (2*R*,3*S*)-2-[(methylsulfonyl)methyl]-3-propyloxirane (0.62 g, 88%) as an oil, δ_H(300 MHz; $CDCl_3$) 0.97 (3 H, t, *J* 7.1, $MeCH_2$), 1.45–1.62 (4 H, m, CH_2CH_2), 2.86–2.90 (1 H, m, 3-H), 2.94–2.98 (1 H, m, 2-H), 3.01 (3 H, s, $MeSO_2$), 3.20 (1 H, dd, *J* 14.4 and 2.2, one of CH_2S) and 3.38 (1 H, d, *J* 14.4, remaining CH_2S); ν_{max}(thin film)/cm^{-1} 3000–2880s (C–H), 1310s (S=O), 1143s (S=O) and 922m; MS (EI) *m*/*z* no M^+ detected, 115 (47%), 86 (38), 73 (32), 57 (94) and 55 (100); $[\alpha]_D^{20}$ −58.4 (*c* 0.15, EtOH) (Found: C, 47.0; H, 7.85; S, 18.05. Calc. for $C_7H_{14}O_3S$: C, 47.15; H, 7.90; S, 18.00%).

A similar procedure using (2*R*,3*S*)-2-[(methylsulfonyl)methyl]-3-propyloxirane (36.3 mg, 0.20 mmol) and DBU (37.7 mm^3, 0.24 mmol) gave compound **39** (24.5 mg, 68%) as a solid, mp 77.5–79.2 °C; δ_H(300 MHz; $CDCl_3$) 0.96 (3 H, t, *J* 7.2, $MeCH_2$), 1.41–1.61 (4 H, m, CH_2CH_2), 2.96 (3 H, s, MeS), 4.43 (1 H, m, 3-H), 6.67 (1 H, d, *J* 14.9, 1-H) and 6.96 (1 H, dd, *J* 14.9 and 3.5, 2-H); ν_{max}(Nujol)/cm^{-1} 3560–3500w (OH), 2980–2850s (C–H), 1380m (S=O), 1134w (S=O) and 980w (C=C); MS (EI) *m*/*z* 179 (M^+ + 1, 0.4%), 161 (M + 1 − H_2O, 1.4), 149 (69), 107 (100), 81 (68), 73 (71) and 57 (69); $[\alpha]_D^{20}$ −4.8 (*c* 0.13, EtOH) (Found: C, 47.25; H, 7.75; S, 18.15. Calc. for $C_7H_{14}O_3S$: C, 47.15; H, 7.90; S, 18.00%).

Single-crystal X-ray diffraction analysis of compound (±)-19

All crystallographic measurements were carried out at 200 K on a Stoe STAD14 diffractometer operating in the ω–θ scan mode with graphite-monochromated copper-Kα X-radiation (λ = 1.541 84 Å). The data-set was corrected for absorption empirically using azimuthal Ψ-scans (max. and min. transmission factors 0.6374 and 0.8039, respectively).

The structure was determined by direct methods using SHELXS-86[27a] and was refined by full-matrix least-squares (based on F^2) using SHELXL-93.[27b] All data were used for refinement. All non-hydrogen atoms were refined with anisotropic thermal parameters. Restraints were applied to the phenol ring such that it was flat with overall C_{2v} symmetry. Phenyl, methine, methylene and methyl hydrogen atoms were constrained to calculated positions (C–H = 0.95, 1.00, 0.99 and 0.98 Å, respectively). The hydroxy-group hydrogen atoms were located on a difference synthesis. All hydrogen atoms were assigned fixed isotropic thermal parameters of $n(U_{eq})$ of the parent carbon atom, where *n* was 1.5 for methyl and hydroxy hydrogens and 1.2 for the rest. The weighting scheme $w = [\sigma^2(F_o^2) + (0.0578P)^2 + 0.2328P]^{-1}$ [where $P = (F_o^2 + 2F_c^2)/3$] was used. The final Fourier difference synthesis was flat and showed no features of chemical significance (max. and min. densities 0.146 and −0.315 e $Å^{-3}$ respectively). Final atomic coordinates are given in a supplementary publication available from the Cambridge Crystallographic Data Centre.‡‡ An ORTEP[27c] diagram of compound **19** is given in Fig. 4.

Crystal data. Formula $C_{12}H_{18}O_3S$, crystal dimensions 0.90 × 0.08 × 0.08 mm, M = 242.32, monoclinic, space group $P2_1/c$, a = 14.5898(7), b = 5.2669(3), c = 17.2425(9) Å, β = 105.259(4)°, V = 1278.3(2) $Å^3$, Z = 4, D_x = 1.259 Mg m^{-3}, μ = 2.182 mm^{-1}, $F(000)$ = 520.

Data collection. 4.0 < 2Θ < 120.0°, scan widths = 1.05 + α-doublet splitting, scan speeds, 1.0–8.0° min^{-1}. Number of data collected = 2134; number of unique data, n = 1862;

‡‡ *Supplementary Publication:* see Instructions for Authors, in the January issue.

number with $F_o > 4.0$ $\sigma(F_o) = 1386$; $R_{sig}\{= \Sigma[\sigma F_o^2]/\Sigma[F_o^2]\} = 0.0293$.

Structure refinement. Number of parameters, $p = 148$; $R_1 = \{\Sigma||F_o| - |F_c||/\Sigma|F_o|\} = 0.0340$; wR_2 $\{= (\Sigma[w(F_o^2 - F_c^2)^2]/\Sigma[w(F_o^2)^2])^{1/2}\} = 0.0943$; goodness of fit s $(= \Sigma[w(F_o^2 - F_c^2)^2]/(n - p)]^{1/2}\} = 1.020$; max. $\Delta/\sigma = 0.001$, mean $\Delta/\sigma + 0.000$.

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References

1 T. Katsuki and K. B. Sharpless, *J. Am. Chem. Soc.*, 1980, **102**, 5974; J. G. Hill, M. G. Finn and K. B. Sharpless, *Asymmetric Synthesis*, ed. J. D. Morrison, Academic Press, New York, 1985, vol. 5.

2 A. Pfenninger, *Synthesis*, 1986, 89; B. E. Rossiter, *Asymmetric Synthesis*, ed. J. D. Morrison, Academic Press, New York, 1985, vol. 5. See also P. C. B. Page, C. M. Rayner and I. O. Sutherland, *J. Chem. Soc., Perkin Trans. 1*, 1990, 1375 and references cited therein; R. A. Johnson and K. B. Sharpless, in *Comprehensive Organic Synthesis*, ed. B. M. Trost, Pergamon Press, Oxford, 1991, vol. 7, ch. 3.2, pp. 389–436.

3 Q. Liu, M. J. Simms, N. Boden and C. M. Rayner, *J. Chem. Soc., Perkin Trans. 1*, 1994, 1363.

4 D. M. Gill, N. A. Pegg and C. M. Rayner, *J. Chem. Soc., Perkin Trans 1*, 1993, 1371.

5 C. M. Rayner, M. S. Sin and A. D. Westwell, *Tetrahedron Lett.*, 1992, **33**, 7237.

6 C. M. Rayner and A. D. Westwell, *Tetrahedron Lett.*, 1992, **33**, 2409.

7 A. D. Westwell and C. M. Rayner, *Tetrahedron Asymm.*, 1994, **5**, 355.

8 K. B. Sharpless, C. M. Exon and R. Regenye, *Org. Synth.*, 1984, **63**, 66.

9 I. Nakagawa and T. Hata, *Tetrahedron Lett.*, 1975, 1409.

10 F. A. Davis and A. C. Sheppard, *Tetrahedron*, 1989, **45**, 5703; F. A. Davis, J. Lamendola Jnr., U. Nadir, E. W. Kluger, T. C. Sedergran, T. W. Panunto, R. Billmers, R. Jenkins Jnr., I. J. Turchi, W. H. Watson, J. S. Chen and M. Kimura, *J. Am. Chem. Soc.*, 1980, **102**, 2000; F. A. Davis and O. D. Stringer, *J. Org. Chem.*, 1982, **47**, 1170.

11 Y. Honda, A. Ori and G. Tsuchihashi, *Chem. Lett.*, 1986, 6257. Non-regioselective epoxide-ring opening by chloride was the dominant reaction under these conditions.

12 (*a*) P. Sohar, in *Nuclear Magnetic Resonance Spectroscopy*, CRC Press Inc., Florida, 1983, vol. 1, p. 34; (*b*) A. B. Foster, T. D. Inch, M. H. Qadir and J. M. Webber, *J. Chem. Soc., Chem. Commun.*, 1968, 1086; (*c*) M. C. Carreno, J. L. Garcia Ruano, A. M. Martin, C. Pedregal, J. H. Rodriguez, A. Rubio, J. Sanchez and G. Solladie, *J. Org. Chem.*, 1990, **55**, 2120 and references cited therein.

13 (*a*) S. H. Zhao, O. Samuel and H. B. Kagan, *Tetrahedron*, 1987, **43**, 5135; (*b*) H. B. Kagan and F. Rebiere, *Synlett*, 1990, 643; (*c*) S. H. Zhao, O. Samuel and H. B. Kagan, *Org. Synth.*, 1989, **68**, 49; (*d*) see also F. Di Furia, G. Modena and R. Seraglia, *Synthesis*, 1984, 325.

14 (*a*) F. A. Davis, R. T. Reddy and M. C. Weissmiller, *J. Am. Chem. Soc.*, 1989, **111**, 5964; (*b*) F. A. Davis, R. T. Reddy, W. Han and P. J. Carroll, *J. Am. Chem. Soc.*, 1992, **114**, 1428; (*c*) F. A. Davis, M. C. Weissmiller, C. K. Murphy, R. T. Reddy and B. C. Chen, *J. Org. Chem.*, 1992, **57**, 7274; (*d*) F. A. Davis, R. T. Reddy, W. Han and R. E. Reddy, *Pure Appl. Chem.*, 1993, **65**, 633.

15 For a report of comparative studies for enantioselective vinyl sulfide oxidation see C. Rossi, A. Fauvre, M. Madesclaire, D. Roche, F. A. Davis and R. T. Reddy, *Tetrahedron Asymm.*, 1992, **3**, 629. For other recent advances in asymmetric sulfur oxidation see M. Palucki, P. Hanson and E. N. Jacobsen, *Tetrahedron Lett.*, 1992, **33** 7111; N. Komatsu, Y. Nishibayashi, T. Sugita and S. Uemura, *Tetrahedron Lett.*, 1992, **33**, 5391; H. Fu, H. Kondo, Y. Ichikawa, G. C. Look and C. H. Wong, *J. Org. Chem.*, 1992, **57**, 7265; G. Carrea, B. Redigolo, S. Riva, S. Colonna, N. Gaggero, E. Battistel and D. Bianchi, *Tetrahedron Asymm.*, 1992, **3**, 1063.

16 For a discussion of terminology: C. H. Heathcock, *Asymmetric Synthesis*, ed. J. D. Morrison, Academic Press, New York, 1984, vol. 3, ch. 2, p. 112.

17 D. Seebach and V. Prelog, *Angew. Chem., Int. Ed. Engl.*, 1982, **21**, 654.

18 T. Aoyagi, T. Yamamoto, K. Kojiri, H. Morishima, M. Nagai, M. Hamada, T. Takeuchi and H. Umezawa, *J. Antibiot.*, 1989, **42**, 883; S. Knapp and T. G. Murali Dhar, *J. Org. Chem.*, 1991, **56**, 4096; B. M. Trost and D. L. Van Vranken, *J. Am. Chem. Soc.*, 1991, **113**, 6317.

19 T. Kajimoto, K. K.-C. Liu, R. L. Pederson, Z. Zhong, Y. Ichikawa, J. A. Porco, Jr. and C-H. Wong, *J. Am. Chem. Soc.*, 1991, **113**, 6187.

20 W. R. Roush and D. Gustin, *Tetrahedron Lett.*, 1994, **35**, 4931.

21 H. Hogeveen, G. Maccagnani and F. Montanari, *J. Chem. Soc.* (*C*), 1966, 1585; see also B. M. Trost and M. Fray, *Tetrahedron Lett.*, 1988, **29**, 2163.

22 (*a*) C. A. Kingsbury and R. A. Auerbach, *J. Org. Chem.*, 1971, **36**, 1737; (*b*) E. Brunet, J. L. Garcia Ruano, M. C. Martinez, J. H. Rodriguez and F. Alcudia, *Tetrahedron*, 1984, **40**, 2023; (*c*) see ref. 12*c*; (*d*) E. Brunet, J. L. Garcia Ruano, M. A. Hoyos, J. H. Rodriguez, P. Prados and F. Alucida, *Org. Magn. Reson.*, 1983, **21**, 643; (*e*) G. Solladie, G. Demailly and C. Greck, *Tetrahedron Lett.*, 1985, **26**, 435; (*f*) F. Alcudia, I. Fernandez, J. M. Llera, M. Trujillo and F. Zorrilla, *Magn. Reson. Chem.*, 1988, **26**, 687.

23 U. Folli, D. Iarossi and F. Taddei, *J. Chem. Soc., Perkin Trans. 2*, 1973, 848.

24 J. March, *Advanced Organic Chemistry*, Wiley, New York, 4th edn., 1992, pp. 75–79; see also ref. 22*a*.

25 For an interesting recent discussion on the use of hydroxy-group proton resonances in structure determination see C. M. Pearce and J. K. M. Sanders, *J. Chem. Soc., Perkin Trans. 1*, 1994, 1119.

26 R. R. Fraser, M. Kaufman, P. Marand and G. Govil, *Can. J. Chem.*, 1969, **47**, 403. See also ref. 22*a*.

27 (*a*) G. M. Sheldrick, *Acta Crystallogr., Sect. A*, 1990, **46**, 467; (*b*) G. M. Sheldrick, *J. Appl. Crystallogr.*, 1993, in preparation; (*c*) C. K. Johnson, *ORTEPII*, Report ORNL-5138, Oak Ridge National Laboratory, Tennessee, USA, 1976.

28 For an interesting comparative structure see M. A. Hoyos, S. Martinez and S. Garcia Blanco, *Acta Crystallogr., Sect. C*, 1983, **39**, 118.

29 As dienophiles: T. Koizumi, *Phosphorus, Sulphur Silicon Relat. Elem.*, 1991, **58**, 111 and references cited therein; R. Lopez and J. C. Carretero, *Tetrahedron Asymm.*, 1991, **2**, 93; M. C. Carreno, J. L. Garcia Ruano and A. Urbano, *Tetrahedron Lett.*, 1989, **30**, 4003; T. Koizumi, *J. Synth. Org. Chem. Jpn.*, 1986, **44**, 576; I. Alonso, J. C. Carretero and J. L. Garcia Ruano, *Tetrahedron Lett.*, 1989, **30**, 3853; L. A. Paquette, R. E. Moerck, B. Harirchian and P. D. Magnus, *J. Am. Chem. Soc.*, 1978, **100**, 1597; for use of a vinyl sulfoxide activated by conversion into the corresponding ethoxy or trimethylsiloxy sulfonium salt see: B. Ronan and H. B. Kagan, *Tetrahedron Asymm.*, 1991, **2**, 75. As dipolarophiles: T. Koizumi, H. Hirai and E. Yoshii, *J. Org. Chem.*, 1982, **47**, 4004; T. Takahashi, A. Fujii, J. Sugita, T. Hagi, K. Kitano, Y. Arai and T. Koizumi, *Tetrahedron Asymm.*, 1991, **2**, 1379. As Michael acceptors: for a review see: G. H. Posner, *Acc. Chem. Res.*, 1987, **20**, 72 and references cited therein; M. Mikotalczyk and W. H. Midura, *Tetrahedron Asymm.*, 1993, **4**, 1515.

30 For a review of the chemistry of vinyl sulfones see: N. S. Simpkins, *Tetrahedron*, 1990, **46**, 6951, and references cited therein; see also M. Isobe, Y. Ichikawa, Y. Funabashi, S. Mio and T. Goto, *Tetrahedron*, 1986, **42**, 2863; P. L. Fuchs and T. F. Braish, *Chem. Rev.*, 1986, **86**, 903.

31 E. Dominguez and J. C. Carretero, *Tetrahedron*, 1990, **46**, 7197; E. Dominguez, J. C. Carretero, A. Fernandez-Mayoralas and S. Conde, *Tetrahedron Lett.*, 1991, **32**, 5159; B. M. Trost and T. A. Grese, *J. Org. Chem.*, 1991, **56**, 3189; R. F. W. Jackson, S. P. Standen and W. Clegg, *Tetrahedron Lett.*, 1991, **32**, 5393; J. C. Carretero and E. Dominguez, *J. Org. Chem.*, 1993, **58**, 1596; E. Dominguez and J. C. Carretero, *Tetrahedron Lett.*, 1993, **34**, 5803. See also ref. 36.

32 J. C. Carretero, J. L. Garcia Ruano, A. Lorente and F. Yuste, *Tetrahedron Asymm.*, 1993, **4**, 177. For a recent synthesis of racemic γ-hydroxy-α,β-unsaturated sulfoxides and sulfones: M. E. Niyazymbetov, L. D. Konyushkin, Z. I. Niyazymbetova, V. E. Kalugin, V. P. Litvinov and V. A. Petrosyan, *Tetrahedron Lett.*, 1991, **32**, 1099. See also G. Solladie and G. Moine, *J. Am. Chem. Soc.*, 1984, **106**, 6097.

33 S. Takano, Y. Sugihara and K. Ogasawara, *Tetrahedron Lett.*, 1993, **34**, 845; *Synlett*, 1992, 668.

34 S.-K. Kang, D.-H. Lee, Y.-S. Kim and S.-C. Kang, *Synth. Commun.*, 1992, **22**, 1109.
35 S.-K. Kang, Y.-W. Park, S.-G. Kim and J.-H. Jeon, *J. Chem. Soc., Perkin Trans. 1*, 1992, 405.
36 Y. L. Bennani and J. B. Sharpless, *Tetrahedron Lett.*, 1993, **34**, 2083.
37 B. M. Trost, P. Seaone, S. Mignani and M. Acemoglu, *J. Am. Chem. Soc.*, 1989, **111**, 7487.
38 D. D. Perrin, W. L. F. Armarego and D. R. Perrin, *Purification of Laboratory Chemicals*, Pergamon Press, Oxford, 2nd edn., 1980.

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