Tetrahedron 67 (2011) 7517–7528

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Preliminary investigations on novel camphor-derived chiral sulfones: completely stereoselective formation of tricyclic β-hydroxy sulfones from 8- and 10-functionalized camphor derivatives

Frank W. Lewis *,†, Thomas C. McCabe, David H. Grayson

Centre for Synthesis and Chemical Biology, School of Chemistry, Trinity College, Dublin 2, Ireland

ARTICLE INFO

Article history:
Received 10 May 2011
Received in revised form 10 July 2011
Accepted 26 July 2011
Available online 31 July 2011

Keywords:
Sulfones
Camphor
Asymmetric synthesis
Chiral auxiliary
Carbanion

ABSTRACT

Some camphor-derived chiral allylic and benzylic sulfones in which the sulfonyl group is located at the C-10, C-9 or C-8 methyl groups of (+)-camphor were synthesized. The C-9 and C-8 substituted sulfones were obtained via Wagner–Meerwein rearrangements of the bicyclic camphor framework. On treatment with LDA, the C-10 and C-8 substituted sulfones cyclized with complete stereoselectivity, affording tricyclic β-hydroxy sulfones whose relative configurations were determined by X-ray crystallography. Tricyclic sulfones **23** and **24** underwent both β-elimination and retro-aldol reactions on further exposure to base. Reduction of the carbonyl group of the C-10 substituted sulfones afforded *exo*-configured isobornyl sulfones with high stereoselectivity. Reaction of the lithiated isobornyl benzyl sulfone **32** with benzaldehyde generated all four of the possible product diastereomers, of which three were isolated pure by chromatography. Attempted desulfonylation of these diastereomers failed to generate the desired optically active homobenzylic alcohols but the same sulfonyl carbanion trapping/desulfonylation sequence was successful in a model achiral series of compounds.

1. Introduction

The rigid bicyclic nature of the camphor skeleton is an attractive structural feature for chiral auxiliary applications.[1] As a result, many derivatives of camphor have found widespread use as chiral auxiliaries in asymmetric synthesis.[2] The most widely used auxiliary is Oppolzer's sultam **1**[3] (Fig. 1), which has been employed in an impressive range of reactions since its introduction in 1984.[4] In addition, 10-mercaptoisoborneol **2** has been used in a tandem Michael addition/Meerwein–Ponndorf–Verley (MPV) reduction with enones.[5] Many camphor derivatives have also been employed as chiral reagents and catalysts.[6] For example, amino-alcohol **3** gives high levels of stereoinduction when it is used as a chiral ligand in the asymmetric addition of dialkylzinc reagents to aldehydes,[7] and in asymmetric Reformatsky reactions.[8] Furthermore, sulfonium ylides derived from sulfide **4** have been used in asymmetric Corey–Chaykovsky reactions,[9] and in the asymmetric cyclopropanation of electron-deficient olefins.[10]

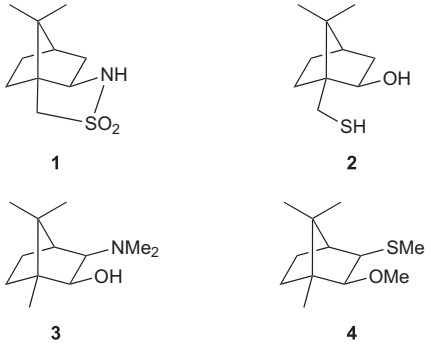


Fig. 1. Important camphor-derived chiral auxiliaries and reagents.

In recent decades, there has been a dramatic increase in the use of the sulfonyl functional group in organic synthesis.[11] However, in contrast to the sulfinyl group,[12] relatively little work has been carried out on the use of chiral sulfones in asymmetric synthesis.[13] A search of the literature reveals relatively few examples where camphor-derived chiral sulfones have been employed.[5,14] On the other hand, camphor-derived chiral

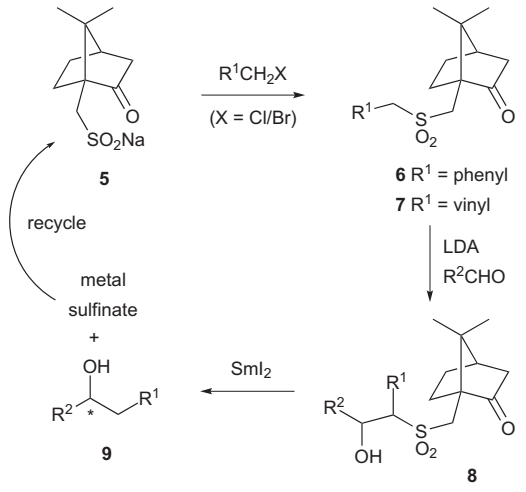
* Corresponding author. Tel.: +44 (0) 118 378 7417; fax: +44 (0) 118 378 6121; e-mail address: f.lewis@reading.ac.uk (F.W. Lewis).
† Present address: Department of Chemistry, University of Reading, Whiteknights, Reading RG6 6AD, UK.

0040-4020/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2011.07.081

sulfoxides have been widely used in asymmetric synthesis.[15] We considered that a chiral auxiliary approach to asymmetric synthesis using camphor-derived chiral sulfones would be a particularly attractive option, based on the variety of methods available for the introduction of the sulfonyl group and the ability to remove it after the asymmetric synthetic step has been performed. We have recently demonstrated the utility of the camphorsulfonyl-group as a recyclable chiral auxiliary in asymmetric Diels–Alder reactions.[16] In this paper, we describe the results of our investigations into the feasibility of employing the camphorsulfonyl-group as a recyclable chiral auxiliary in a different context.

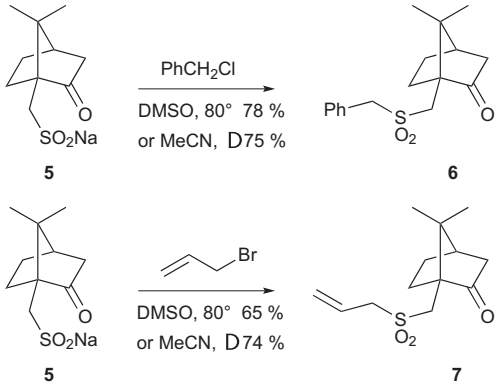
2. Results and discussion

Initially, we wished to examine the reactions of aldehydes with the anions derived from enantiopure camphor-based allylic and benzylic sulfones, and then to examine the reductive desulfonylation of the derived β-hydroxy sulfones as a means of preparing enantiomerically enriched homoallylic and homobenzylic alcohols. Thus, alkylation of sodium camphor-10-sulfinate **5**[17] with an allylic or benzylic halide would afford sulfones **6** or **7**. Treatment of **6** or **7** with a suitable base, followed by an aldehyde may afford diastereomeric adducts **8**. Desulfonylation with a suitable reagent (e.g.,: sodium amalgam or samarium(II) iodide) would potentially yield the product homoallylic or homobenzylic alcohol **9**, together with a metal sulfinate salt, which could then be recovered and recycled for further use (Scheme 1).



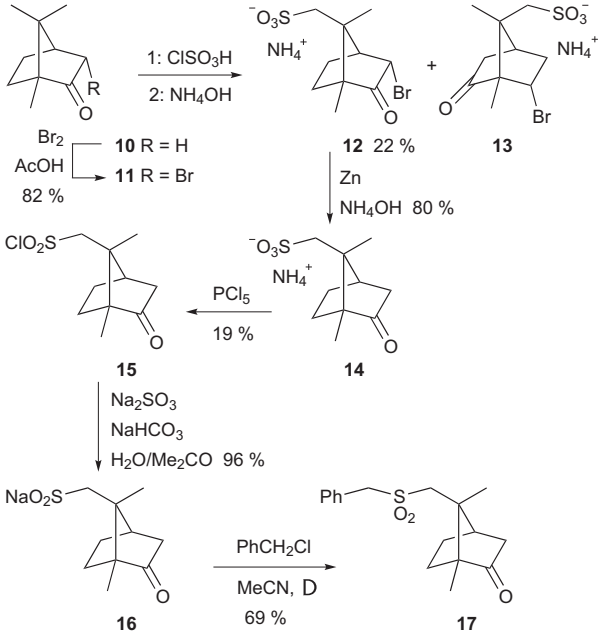
Scheme 1.

Accordingly, we proceeded to synthesize a number of regioisomeric sulfones where one of the three methyl groups of (+)-camphor was functionalized with a sulfonyl group. Sodium sulfinate **5** was synthesized from (+)-camphor-10-sulfonic acid as previously described.[18] Treatment of sodium (−)-camphor-10-sulfinate **5** with benzyl chloride or allyl bromide in DMSO at 80 °C, or in acetonitrile at reflux,[19] afforded the novel sulfones **6** and **7** in good yields (Scheme 2). None of the corresponding sulfinate esters (which could be obtained by O-alkylation of **5**) were formed in these reactions.



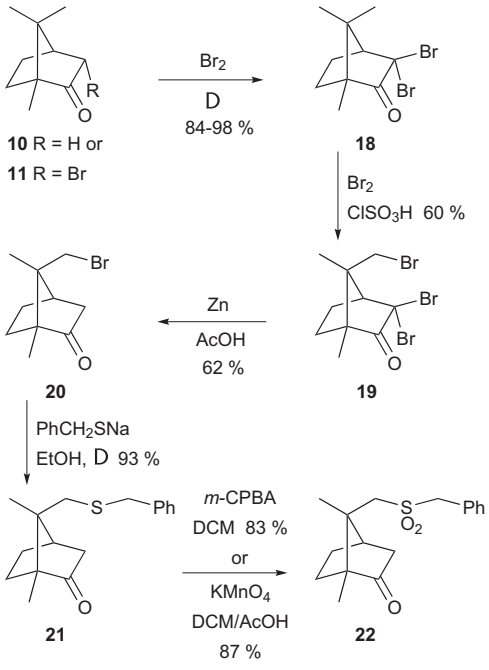
Scheme 2.

Sulfones **17** and **22** were obtained by the regioselective functionalization of (+)-camphor at either its C-9 or its C-8 methyl group, respectively. The functionalization of these methyl groups occurs via Wagner–Meerwein rearrangements of the bicyclic framework of camphor.[20] The method of Kipping and Pope was used to install the C-9 sulfonyl functionality of **17**.[21] Reaction of *endo*-(+)-3-bromocamphor **11** (prepared by the bromination[22] of (+)-camphor **10**) with chlorosulfonic acid afforded ammonium sulfonate salts **12** and **13** after neutralization.[21,23] Debromination of **12** using zinc dust in ammonium hydroxide afforded ammonium sulfonate **14**, which was then converted into sulfonyl chloride **15** using phosphorus pentachloride.[23] Reduction of **15** with sodium sulfite in the presence of sodium hydrogen carbonate gave the sodium sulfinate **16** contaminated with ca. 10% (^{1}H NMR spectroscopy) of the corresponding sodium sulfonate. This mixture was used without purification. Alkylation of **16** with benzyl chloride in acetonitrile[19] afforded the novel benzyl sulfone **17** in 69% yield (Scheme 3).



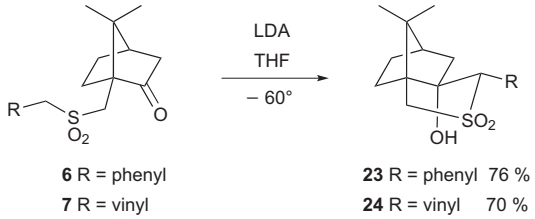
Scheme 3.

Sulfone **22** was obtained by utilising the regiospecific C-8 functionalization of (+)-camphor developed by Money.[24] Using the method of Money, 3,3-dibromocamphor **18**[25] (obtained by bromination of either (+)-camphor **10** or *endo*-(+)-3-bromocamphor **11**) was treated with bromine and chlorosulfonic acid to afford 3,3,8-tribromocamphor **19**. Regioselective C-3 debromination of **19** with zinc dust in acetic acid gave enantiopure (+)-8-bromocamphor **20** in 62% yield.[24,26] Despite its neopentyl structure, the bromo-substituent of **20** was smoothly displaced by the sodium salt of benzyl mercaptan to give the sulfide **21** in 93% yield.[27] Oxidation of sulfide **21** with either *m*-CPBA in DCM, or with $KMnO_4$ in DCM/AcOH,[28] afforded the sulfone **22** in good yield (Scheme 4).



Scheme 4.

With the regioisomeric sulfones **6**, **7**, **17** and **22** in hand, we proceeded to explore the reactions of the sulfonyl-stabilized carbanions derived from benzyl sulfone **6** and allyl sulfone **7** with electrophiles. Treatment of either allyl sulfone **7** or benzyl sulfone **6** with LDA in anhydrous THF at −60 °C, followed by the addition of benzaldehyde gave, after acidic quench and standard work up, an intractable mixture of products, which could not be cleanly separated by column chromatography. Intractable mixtures were also obtained when iodomethane was used as the electrophile. In order to verify if the anions derived from these sulfones were undergoing intramolecular 5-*exo trig* cyclization with the C-2 carbonyl group, we repeated these reactions in the absence of an electrophile. Thus, treatment of allyl sulfone **7** with LDA in THF at −60 °C gave, after acidic quench, tricyclic sulfone **24** as a single diastereomer (determined by ^{1}H NMR spectroscopy) in 70% yield, together with a small amount of unchanged sulfone **7**. Similarly, treatment of benzyl sulfone **6** under identical conditions gave tricyclic sulfone **23**, also as a single diastereomer, in lower yield, together with a significant amount (52%) of unreacted starting sulfone **6** (Scheme 5). The yield of **23** was improved to 76% by allowing the reaction mixture to warm to room temperature prior to quenching.



Scheme 5.

The outcome of these cyclization reactions suggests that the carbanions derived from **6** and **7** are in equilibrium with the tricyclic oxyanions leading to **23** and **24**. The fact that **7** cyclizes to a greater extent than **6** under the same conditions may be due to the greater steric effect of the bulky phenyl group in **6**. The relative stereochemistry of tricyclic sulfone **23** was unambiguously established by single crystal X-ray crystallography (Fig. 2). We were somewhat surprised to find that the hydroxyl group of **23** was in the *endo*-configuration, indicating that the carbanion derived from **6** underwent 5-*exo trig* cyclization with the carbonyl group from the more hindered top face. This is in contrast to the known precedent for stereoselective additions of metal hydrides and organometallic reagents to camphor, which give predominantly *exo*-configured products via axial attack from the less hindered bottom face.[29]

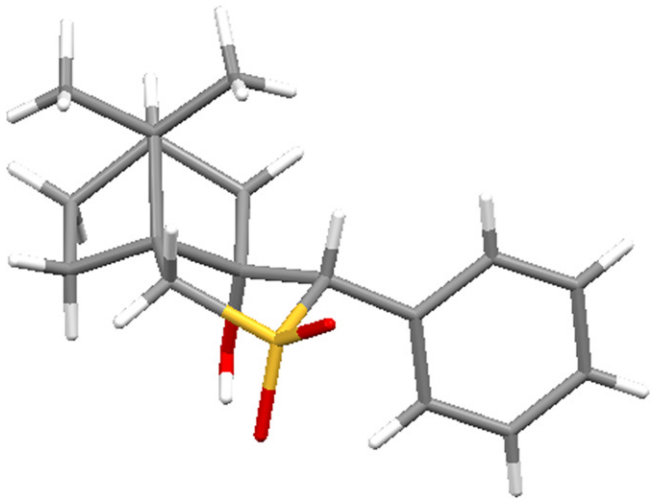
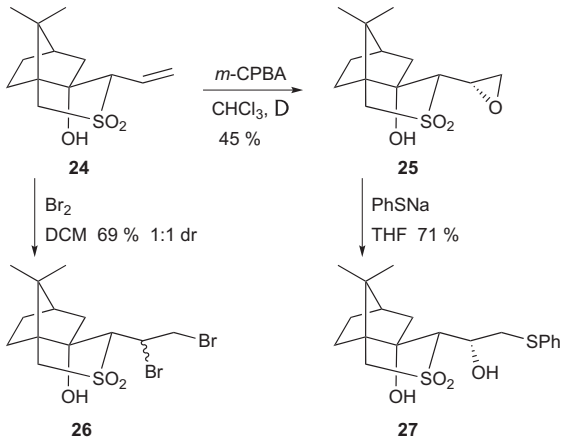


Fig. 2. Molecular structure in the crystal of sulfone **23** (CCDC: 822432). One of the two asymmetric units is omitted for clarity.

The finding that the sulfonyl-stabilized carbanions derived from **6** and **7** cyclized in a completely stereoselective manner prompted an investigation into the chemistry of these novel tricyclic compounds. Sulfone **24** in particular was of interest by virtue of the potential additional functionalization of its double bond. Henbest et al. discovered that epoxidation of cyclic allylic alcohols with peroxybenzoic acid occurs on the same side as the hydroxyl group to give *cis* epoxy alcohols.[30] We postulated that an analogous hydroxyl group-directed epoxidation of **24** would be possible. We were pleased to find that treatment of tricyclic sulfone **24** with *m*-CPBA in chloroform did indeed furnish the oxiranyl sulfone **25** as a single diastereomer. On the other hand, treatment of **24** with bromine in DCM gave both diastereomers of dibromosulfone **26** in ca. 1:1 ratio (^{1}H NMR spectroscopy), which were separable by chromatography. Regioselective ring-opening of the oxiranyl ring of **25** with sodium thiophenolate afforded the sulfonyldiol **27** as a single stereoisomer in good yield (Scheme 6).



Scheme 6.

The relative configurations of the three new stereocentres of oxiranyl sulfone **25** were established by X-ray crystallography (Fig. 3). It is evident that the base-mediated 5-*exo trig* cyclization reaction of sulfone **7** proceeded with the same stereochemical outcome as that of sulfone **6**. Also evident is the configuration of the oxiranyl group at C-4, held away from the bulky 10-*syn* methyl group. The configuration of the oxiranyl-ring carbon indicates that epoxidation of **24** occurred from the side of the double bond closest to the hydroxyl group. As suggested by the X-ray structure of **25**, the most stable conformation of alkene **24** is most likely one where the alkenyl-group is pointing up away from the sterically crowded *endo* face. The hydroxyl group of **24** then directs *O*-atom transfer to the side of the double bond facing the hydroxyl group.

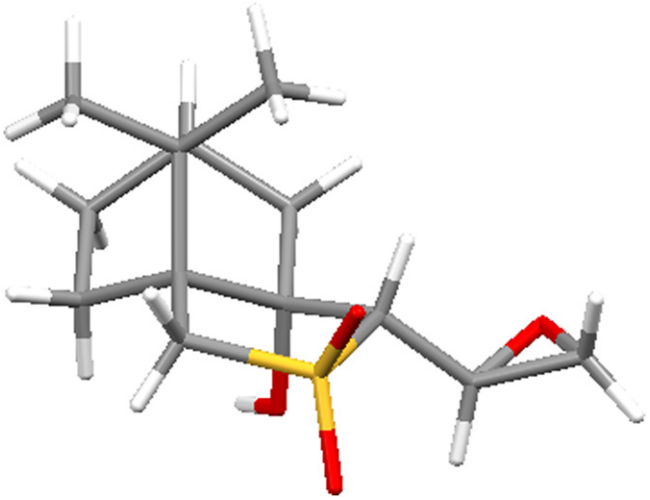
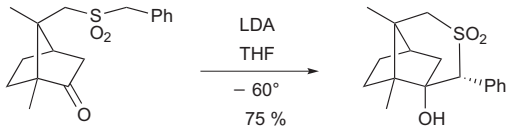


Fig. 3. Molecular structure in the crystal of sulfone **25** (CCDC: 822431).

We also found that the sulfonyl-stabilized carbanion derived from C8-substituted benzyl sulfone **22** cyclized in a completely stereoselective manner. Treatment of **22** with LDA in THF led, after acidic quenching and work-up, to a single diastereomer (^{1}H NMR spectroscopy) of the tricyclic sulfone **28** in 75% yield (Scheme 7). Once again, the relative stereochemistries at the two newly-formed stereocentres of **28** were determined by X-ray crystallography. Apart from the expected *endo*-configuration of the hydroxyl group (attack of the sulfonyl carbanion is only possible from the top face), a notable feature is the configuration of the benzylic carbon in which the bulky phenyl group is held away from the C-1 methyl group (Fig. 4).



Scheme 7.

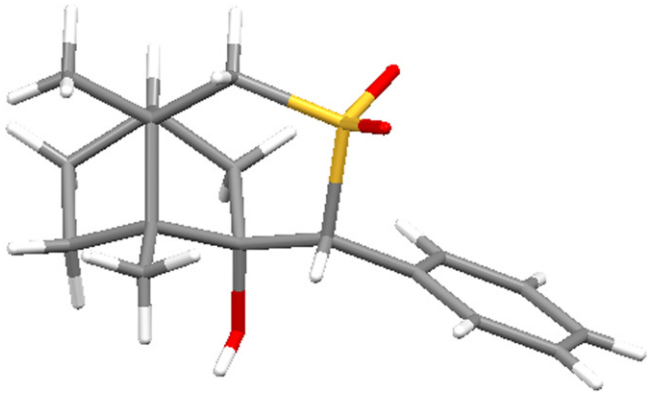
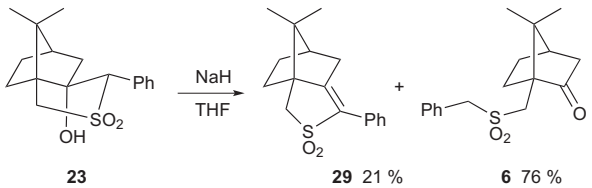


Fig. 4. Molecular structure in the crystal of sulfone **28** (CCDC: 822435). A single asymmetric unit is shown for clarity.

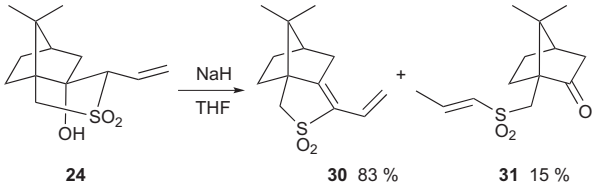
In view of the differing reactivities of sulfones **6** and **7** towards aldol cyclization, it was of interest to examine if and to what extent the tricyclic β-hydroxy sulfones **23** and **24** would undergo retro-aldol reactions[31] on treatment with a suitable base, followed by acidic quenching. This would give some indication of the feasibility of trapping the intermediate sulfonyl-stabilized carbanions with electrophiles. Thus, the reaction of sulfone **23** with sodium hydride in THF in the absence of an electrophile was first explored in order to provide an indication of the position of equilibrium of the anion formed by deprotonation of the hydroxyl group of **23**.

Treatment of tricyclic sulfone **23** with sodium hydride in THF at 0 °C, followed by warming to room temperature and acidic quenching gave two products. Separation by column chromatography yielded benzyl sulfone **6** as the major product (76%) together with a minor amount (21%) of the tricyclic vinyl sulfone **29** (Scheme 8). Vinyl sulfone **29** is most likely formed by deprotonation at the benzylic position followed by β-elimination of hydroxide ion.



Scheme 8.

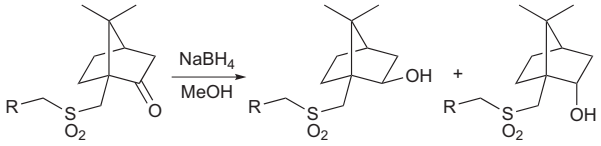
In contrast, treatment of **24** under identical conditions gave two products. Sulfonyldiene **30** was obtained as the major product (83%) in addition to a minor amount of (*E*)-propenyl sulfone **31** (Scheme 9). The sulfone **31** is clearly formed via retro-aldol reaction of the initially formed oxyanion of **24** and subsequent double bond isomerization prior to quenching. This result, in which the β-elimination reaction that yields **30** is the major pathway, contrasts with the result obtained for sulfone **23**, in which the retro-aldol reaction leading back to the parent sulfone **6** dominates. As



Scheme 9.

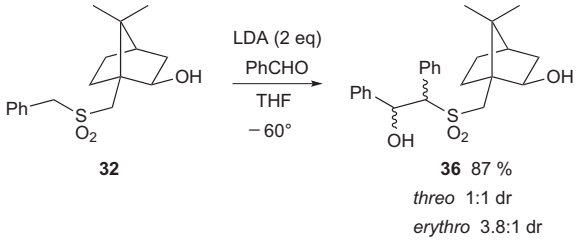
mentioned earlier, this may be due to a greater steric effect in **23** where the derived tricyclic oxyanion opens more readily than that obtained from **24**, to give the corresponding bicyclic sulfonyl carbanion in order to relieve steric strain. The formation of **6** and **31** by retro-aldol reactions of **23** and **24**, respectively, is further evidence that the carbanions derived from sulfones **6** and **7** equilibrate with the tricyclic oxyanions derived from **23** and **24** (Scheme 5). Disappointingly, attempts to trap intermediate sulfonyl carbanions by repeating the retro-aldol reactions of **23** and **24** in the presence of benzaldehyde or iodomethane met with no success.

The carbonyl group present in sulfones **6** and **7** was subsequently manipulated in order to remove the internal electrophile and allow for potential reactions of the lithiated sulfones with external electrophiles. Ketosulfones **6** and **7** were reduced to the corresponding *exo*-hydroxysulfones **32** and **34** using sodium borohydride in methanol. These reactions proceeded with high stereoselectivity, giving the *exo*-configured isobornyl sulfones **32** and **34** as the major products and the *endo*-configured bornyl sulfones **33** and **35** as minor products (Scheme 10). The two pairs of diastereomers were readily separated by column chromatography in each case. The major and minor isomers were identified by comparison of their ^{1}H and ^{13}C NMR data with those of isoborneol and borneol, respectively.[32] The high stereoselectivity observed for the *exo*-configured alcohols **32** and **34** (15.7:1 dr for **6**, 16.5:1 dr for **7**) is in keeping with that observed for the reduction of camphor with metal hydrides, which affords isoborneol as the major stereoisomer via axial attack from the less hindered *endo* face.[29]



Scheme 10.

With sulfones **32** and **34** in hand, we initially explored the reaction of the sulfonyl-stabilized carbanion derived from **32** with benzaldehyde. Treatment of sulfone **32** with LDA (2 equiv), followed by benzaldehyde gave a crude product whose ^{1}H NMR spectrum showed the presence of all four diastereomers of β-hydroxy sulfone **36**, in addition to a minor amount of unreacted starting material (Scheme 11). The ^{1}H NMR spectrum of the crude product showed a pair of closely spaced doublets at ca. δ 5.6 ppm, each with a coupling constant of 9.5 Hz and another pair at ca. δ 6.0 ppm, each with a coupling constant of 3.5 Hz. These resonances were assigned to the pairs of pseudo-enantiomeric *threo* and *erythro* diastereomers of **36**, respectively. It has been shown that the analogous achiral arylsulfonyl compounds reside in a preferred conformation in which the arylsulfonyl group and the phenyl group on the adjacent carbon are antiperiplanar, enabling the two diastereomers to be distinguished from the magnitude of their vicinal coupling constants.[33]



Scheme 11.

Integration of the relevant signals in the ^{1}H NMR spectrum of the crude product showed that the reaction was mildly *threo* selective (1.5:1 ratio), in agreement with previous observations on analogous achiral sulfones.[34] In addition, the pseudo-enantiomeric *threo* isomers were present in ca. 1:1 ratio, whereas the *erythro* isomers were present in ca. 3.8:1 ratio as determined by ^{1}H NMR. Thus, the aldol reaction of sulfone **32** with benzaldehyde proceeded with little or no stereoselectivity. Fortunately, three of the four diastereomers of **36** could be separated by careful column chromatography (the minor *erythro* diastereomer could not be isolated).

The relative configuration of one of the *threo* diastereomers **36C** was determined by X-ray crystallography. The molecular structure in the crystal revealed that the configurations at the two newly formed asymmetric centres were 1′*S*,2′*S* (Fig. 5). With this information, and the relative stereochemistry known from the vicinal coupling constant in the ^{1}H NMR spectrum, the relative configuration of the second *threo* diastereomer **36B** was determined as 1′*R*,2′*R*. The isobornylsulfonyl group and the phenyl group on the adjacent carbon are *anti*, placing the vicinal methine protons in an antiperiplanar relationship, in agreement with the conformational preference exhibited by the analogous arylsulfonyl compounds,[33] and with the large vicinal coupling constant (J 9.5 Hz) observed

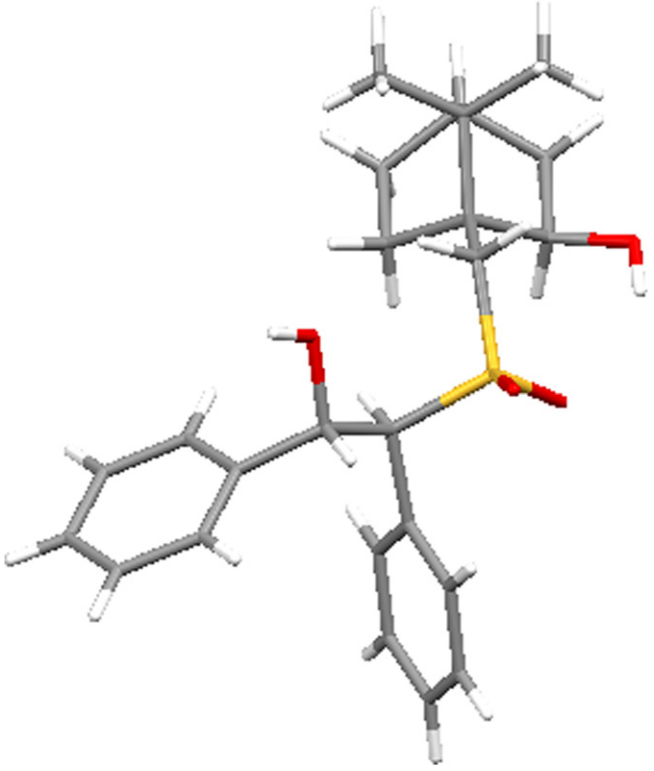


Fig. 5. Molecular structure in the crystal of sulfone **36C** (CCDC: 822433).

in the ^{1}H NMR spectrum. Similarly, the relative configuration of the major *erythro* diastereomer **36A** was determined by X-ray crystallography. The molecular structure in the crystal shows that the configurations at the sulfonyl side-chain are 1′*S*,2′*R* (Fig. 6). Hence the relative configuration of the minor *erythro* diastereomer (which is pseudo-enantiomeric at the sulfonyl side-chain) must be 1′*R*,2′*S*.

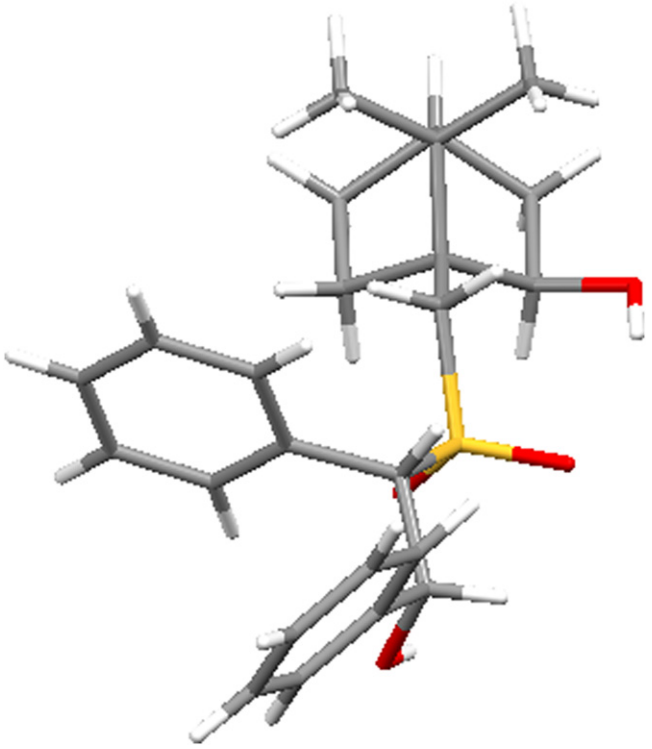
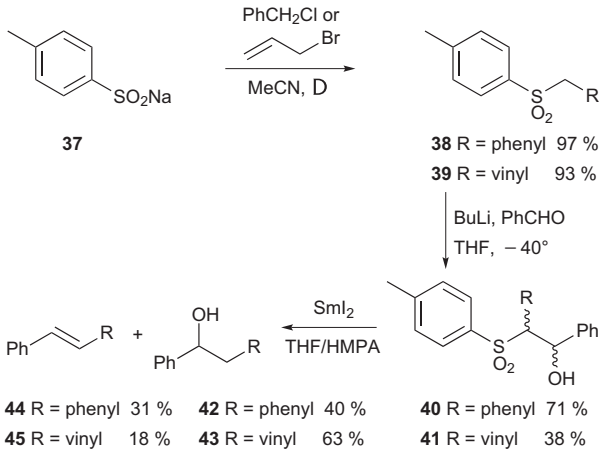


Fig. 6. Molecular structure in the crystal of sulfone **36A** (CCDC: 822434).

We then proceeded to examine the desulfonylation of each of the three isolated diastereomers of β-hydroxy sulfone **36**. Although sodium amalgam is the reducing agent typically used for the desulfonylation of arylsulfonyl compounds,[35] we anticipated that this would lead exclusively to the corresponding olefins via Julia-type elimination, with subsequent loss of stereochemistry.[36] On the other hand, samarium(II) iodide in THF/HMPA has been used for the desulfonylation of a variety of phenylsulfonyl compounds including β-hydroxy sulfones.[37] We consequently chose this reagent for the desulfonylation step. Unfortunately, each of the three diastereomers of **36** failed to react on treatment with an excess (10 equiv) of samarium(II) iodide in THF/HMPA, and were recovered unchanged.

In order to compare the above desulfonylation step with that of the corresponding achiral arylsulfones, we carried out the same sulfonyl carbanion alkylation/desulfonylation sequence on the corresponding achiral arylsulfonyl compounds **38** and **39** (Scheme 12). Alkylation of sodium *p*-toluenesulfinate **37** with benzyl chloride or with allyl bromide afforded sulfones **38** and **39**, respectively. Lithiated benzyl *p*-tolyl sulfone **38** reacted with benzaldehyde to form β-hydroxy sulfone adducts **40** as a mixture of *threo*/*erythro* diastereomers (71%) in ca. 2.2:1 ratio. These could not be separated by recrystallization and were contaminated with a trace amount of unreacted sulfone **38**. Similarly, lithiated allyl *p*-tolyl sulfone **39** on treatment with benzaldehyde formed a mixture of separable diastereomeric adducts **41** (38%) in ca. 2.6:1 ratio. A significant amount of double bond isomerization occurred during this reaction giving rise to the corresponding propenyl sulfone **46** in 16% yield (see Supplementary data).



Scheme 12.

The desulfonylation reactions of **40** and **41** with samarium(II) iodide were then examined. Treatment of **41** with excess samarium(II) iodide in THF/HMPA at −20 °C for 5 h gave a mixture of the desired homoallylic alcohol **43** and 1-phenylbuta-1,3-diene **45** in ca. 4:1 ratio. The homoallylic alcohol **43** was isolated in reasonable yield (63%) following column chromatography. Similarly, treatment of **40** with samarium(II) iodide led to a ca. 1.2:1 ratio of homobenzylic alcohol **42** (isolated in 40% yield) and *trans*-stilbene **44** (Scheme 12). Alternative desulfonylation procedures applied to **40** and **41** were less successful. Sulfones **40** and **41** were unreactive towards free-radical desulfonylation conditions using tri-*n*-butyltin hydride/AIBN,[38] whilst the attempted desulfonylation of **40** and **41** with $NaBH_4$ in the presence of $Pd(PPh_3)_4$[39] produced a mixture of benzyl alcohol and sulfones **38** and **39**, respectively, via retro-aldol reactions of **40** and **41**. The relative success of the desulfonylation step of achiral arylsulfones **40** and **41** compared to the chiral dialkylsulfones **36** could be due to the greater reactivity of arylsulfones towards reduction caused by delocalization into the aromatic ring of the intermediate radical anion formed by electron transfer.[40]

3. Conclusions

We have carried out preliminary studies on the feasibility of employing the camphorsulfonyl-group as a recyclable chiral auxiliary in asymmetric synthesis. Lithiated C-10 and C-8 substituted sulfones failed to react with external electrophiles but reacted instead with the carbonyl group of the auxiliary to generate tricyclic products with complete stereoselectivity. The lithiated C-10 substituted isobornyl sulfone **32** reacted with benzaldehyde to generate all of the four possible hydroxy sulfone product diastereomers and three of these were obtained pure by chromatography. X-ray crystallography established the relative configurations of the products. Attempted cleavage of the auxiliary by desulfonylation with samarium(II) iodide failed to generate the desired optically active homobenzylic alcohols. However, this reaction sequence was successful with the corresponding achiral *p*-tolyl sulfones, indicating a difference in reactivity between the two classes of sulfone towards reductive desulfonylation.

4. Experimental

4.1. General procedures

NMR spectra were recorded using a Bruker AVANCE DPX 400 MHz spectrometer (400.1 MHz for ^{1}H and 100.6 MHz for ^{13}C). Chemical shifts are reported in parts per million. Coupling

constants (*J*) are quoted in Hertz. Assignments were verified by appropriate $^{1}H-^{1}H$ COSY, $^{13}C-^{1}H$ COSY and ^{13}C-DEPT experiments. Optical rotations were measured using a Perkin–Elmer 141 polarimeter. IR spectra were recorded for Nujol mulls (N) or for neat liquid films (L) between sodium chloride plates using a Matteson Genesis II FTIR spectrometer. Uncorrected melting points (Mp) were measured in unsealed capillary tubes using a Griffin melting point apparatus. Mass spectra were obtained under electrospray conditions using a Micromass LCT instrument. Tetrahydrofuran (THF) was dried and distilled over sodium-benzophenone ketyl. Diisopropylamine was dried and distilled over calcium hydride. All solvents and reagents were purified by standard techniques. Organic extracts of reaction products were dried over anhydrous magnesium sulfate.

*4.1.1. (1S,4R)-1-[(Benzylsulfonyl)methyl]-7,7-dimethylbicyclo-[2.2.1] heptan-2-one (**6**). 4.1.1.1. Method A.* Sodium (−)-camphor-10-sulfinate **5** (5.00 g, 21 mmol) and sodium iodide (0.6 g, 20 mol %) were dissolved in DMSO (75 mL). The flask was warmed to 40 °C to dissolve the solids and benzyl chloride (3.14 mL, 27.2 mmol) was added. The solution was warmed at 80 °C for 12 h. The solution was then allowed to cool to room temperature, diluted with water (200 mL) and extracted with diethyl ether (2×200 mL). The combined organic extracts were washed with satd aq sodium sulfite (100 mL) and brine (50 mL), dried and evaporated to yield an oil, which later crystallized. Recrystallization from ethyl acetate afforded the title compound as a white solid (5.01 g, 78%).

4.1.1.2. Method B. Sodium (−)-camphor-10-sulfinate **5** (0.94 g, 3.9 mmol) was suspended in acetonitrile (15 mL) and triethylhexylammonium bromide (0.21 g, 20 mol %) was added. Benzyl chloride (0.5 mL, 4.3 mmol) was added and the mixture was heated under reflux for 24 h. The mixture was allowed to cool to room temperature, diluted with water (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield an oil, which later crystallized. Recrystallization from ethyl acetate afforded the title compound as a white solid (0.91 g, 75%). Mp 68–69 °C (from EtOAc); $[\alpha]_D^{22}$ +21.0 (*c* 0.48 in MeOH); ν_{max} (N)/cm^{-1} 2945, 1737 (C=O), 1455, 1411, 1375, 1314 (SO_2), 1263, 1198, 1153, 1118 (SO_2), 1052, 1029, 965, 931, 879, 857, 793, 744, 720, 701; δ_H(400.1 MHz; $CDCl_3$; Me_4Si) 0.85 (3H, s, 7-CH_3), 1.02 (3H, s, 7-CH_3), 1.44–1.51 (1H, m), 1.89–1.97 (1H, m), 1.97 (1H, d, ^{2}J 18.5, 3-CH_2-*endo*), 2.02–2.09 (1H, m), 2.13 (1H, t, ^{3}J 4.5, 4-C*H*), 2.32–2.45 (2H, m), 2.68 (1H, d, ^{2}J 15.0, alkyl CH_2SO_2), 3.40 (1H, d, ^{2}J 15.0, alkyl CH_2SO_2), 4.36 (1H, d, ^{2}J 13.5, benzyl CH_2SO_2), 4.72 (1H, d, ^{2}J 13.5, benzyl CH_2SO_2), 7.38–7.41 (3H, m, Ar–*H*), 7.46–7.49 (2H, m, Ar*H*); δ_C(100.6 MHz; $CDCl_3$; Me_4Si) 19.2 (7-CH_3), 19.3 (7-CH_3), 25.2 (C-5), 26.6 (C-6), 42.1 (C-4), 42.2 (C-3), 48.2 (C-7), 48.9 (alkyl CH_2SO_2), 58.7 (C-1), 61.6 (benzyl CH_2SO_2), 127.9 (Ar C-1), 128.4 (Ar C-3), 128.4 (Ar C-4), 130.5 (Ar C-2), 215.1 (C-2); *m*/*z* (CI) 329.1173 ([M+Na]$^+$); $C_{17}H_{22}O_3SNa$ requires 329.1187.

*4.1.2. (1S,4R)-1-[(Allylsulfonyl)methyl]-7,7-dimethylbicyclo-[2.2.1] heptan-2-one (**7**). 4.1.2.1. Method A.* Sodium (−)-camphor-10-sulfinate **5** (5.36 g, 22 mmol) and sodium iodide (0.67 g, 20 mol %) were dissolved in DMSO (50 mL). The mixture was warmed to 40 °C to dissolve the solids and allyl bromide (2.92 mL, 33 mmol) was added. The solution was warmed at 60 °C for 6 h. The solution was then allowed to cool to room temperature, diluted with water (200 mL) and extracted with diethyl ether (3×100 mL). The combined organic extracts were washed with satd aq sodium sulfite (100 mL) and brine (50 mL), dried and evaporated to yield an oil. Column chromatography on silica gel eluting with ethyl acetate/hexane (1:2) afforded the title compound as a colourless oil (3.77 g, 65%).

4.1.2.2. Method B. Sodium (−)-camphor-10-sulfinate **5** (0.94 g, 3.9 mmol) was suspended in acetonitrile (15 mL) and triethylhexylammonium bromide (0.21 g, 20 mol %) was added. Allyl bromide (0.38 mL, 4.3 mmol) was added and the mixture was heated under reflux for 24 h. The mixture was allowed to cool to room temperature, diluted with water (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield an oil. Column chromatography on silica gel eluting with ethyl acetate/hexane (1:2) afforded the title compound as a colourless oil (0.75 g, 74%). $[\alpha]_D^{22}$ +19.2 (*c* 0.51 in MeOH); ν_{max} (L)/cm^{-1} 3087, 2961, 1744 (C=O), 1638 (C=C), 1455, 1417, 1394, 1317 (SO_2), 1245, 1201, 1133 (SO_2), 1051, 994, 937, 876, 820, 773, 676; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.89 (3H, s, 7-CH_3), 1.07 (3H, s, 7-CH_3), 1.44–1.50 (1H, m), 1.81–1.89 (1H, m), 1.95 (1H, d, ^{2}J 18.4, 3-CH_2 *endo*), 2.01–2.11 (1H, m), 2.14 (1H, t, ^{3}J 4.5, 4-C*H*), 2.36–2.45 (2H, m), 2.75 (1H, d, ^{2}J 15.0, alkyl CH_2SO_2), 3.47 (1H, d, ^{2}J 15.0, alkyl CH_2SO_2), 3.80 (1H, dd, *J* 14.0 and 7.5, allyl CH_2SO_2), 4.12 (1H, dd, *J* 14.0 and 7.5, allyl CH_2SO_2), 5.52 (2H, m, CH=CH_2), 6.01 (1H, ddt, *J* 17.3, 10.0 and 7.5, C*H*=CH$_2$); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 19.2 (7-CH_3), 19.3 (7-CH_3), 24.9 (C-5), 26.6 (C-6), 42.1 (C-4), 42.2 (C-3), 48.2 (C-7), 48.6 (alkyl CH_2SO_2), 58.5 (C-1), 59.9 (allyl CH_2SO_2), 124.4 (CH=CH_2), 124.8 (C*H*=CH$_2$), 215.0 (C-2); *m*/*z* (CI) 279.1027 ([M+Na]$^+$); $C_{13}H_{20}O_3SNa$ requires 279.1030.

*4.1.3. Sodium (1R,4R,7R)-(1,7-dimethyl-2-oxobicyclo[2.2.1]hept-7-yl) methanesulfinate (**16**).* Sulfonyl chloride **15** (0.63 g, 2.5 mmol) in dry acetone (10 mL) was added dropwise over 1 h to a solution of sodium sulfite (0.63 g, 5.0 mmol) and sodium hydrogen carbonate (0.42 g, 5.0 mmol) in water (10 mL) maintained at 70 °C. The mixture was stirred for an additional 1 h at 70 °C and was then allowed to cool to room temperature and left stirring overnight. The mixture was evaporated to yield a white solid, which was taken up in boiling ethanol (50 mL) and filtered through Celite®. The filtrate was evaporated to afford the title compound as a white solid (0.58 g, 96%) together with ca. 10% (by ^{1}H NMR) of the corresponding sodium sulfonate. ν_{max} (N)/cm^{-1} 3344, 3188, 2921, 1739 (C=O), 1458, 1377, 1204, 1026 (S=O), 971 (S=O), 850, 721; δ_H (400.1 MHz; D_2O) 0.77 (3H, s, 1-CH_3), 0.92 (3H, s, 7-CH_3), 1.27–1.38 (2H, m), 1.65–1.73 (1H, m), 1.89 (1H, d, ^{2}J 19.0, 3-CH_2 *endo*), 1.94–2.01 (1H, m), 2.17 (1H, d, ^{2}J 13.5, CH_2SO_2Na), 2.36 (1H, dt, *J* 19.0 and 4.5, 3-CH_2 *exo*), 2.45 (1H, d, ^{2}J 13.5, CH_2SO_2Na), 2.55 (1H, t, ^{3}J 4.5, 4-C*H*); δ_C (100.6 MHz; D_2O) 7.9 (1-CH_3), 16.5 (7-CH_3), 25.3 (C-5), 28.5 (C-6), 39.9 (C-4), 41.9 (C-3), 47.6 (C-7), 59.6 (C-1), 64.7 (CH_2SO_2Na), 225.8 (C-2).

*4.1.4. (1R,4R,7R)-7-[(Benzylsulfonyl)methyl]-1,7-dimethylbicyclo-[2.2.1]heptan-2-one (**17**).* Sodium sulfinate **16** (0.36 g, 1.51 mmol) was suspended in acetonitrile (10 mL) and triethylhexylammonium bromide (0.08 g, 20 mol %) was added. Benzyl chloride (0.19 mL, 1.66 mmol) was added and the mixture was heated under reflux for 24 h. The mixture was allowed to cool to room temperature, diluted with water (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were dried and evaporated to yield an oil. Column chromatography on silica gel eluting with ethyl acetate/hexane (1:3) afforded the title compound as a white solid (0.32 g, 69%). Mp 93–94 °C (from EtOAc/hexane); $[\alpha]_D^{19}$ +75.8 (*c* 0.39 in $CHCl_3$); ν_{max} (N)/cm^{-1} 2923, 1737 (C=O), 1602, 1459, 1377, 1296 (SO_2), 1203, 1132 (SO_2), 1078, 1044, 950, 828, 753, 727, 698; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.87 (3H, s, 1-CH_3), 1.16 (3H, s, 7-CH_3), 1.35–1.46 (3H, m), 1.72–1.80 (1H, m), 1.90 (1H, d, ^{2}J 18.5, 3-CH_2 *endo*), 2.38 (1H, dt, *J* 18.5 and 4.5, 3-CH_2 *exo*), 2.72 (1H, d, ^{2}J 13.5, alkyl CH_2SO_2), 2.97 (1H, t, ^{3}J 4.5, 4-C*H*), 3.07 (1H, d, ^{2}J 13.5, alkyl CH_2SO_2), 4.25 (1H, d, ^{2}J 14.0, benzyl CH_2SO_2), 4.28 (1H, d, ^{2}J 14.0, benzyl CH_2SO_2), 7.44 (5H, s, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 8.9 (1-CH_3), 17.0 (7-CH_3), 25.9 (C-5), 28.8 (C-6), 39.9 (C-4), 42.0 (C-

3), 48.5 (C-7), 52.1 (alkyl CH_2SO_2), 59.5 (C-1), 62.3 (benzyl CH_2SO_2), 127.8 (Ar C-1), 128.6 (Ar C-3), 128.7 (Ar C-4), 130.0 (Ar C-2), 216.0 (C-2); *m*/*z* (CI) 329.1187 ($[M+Na]^+$); $C_{17}H_{22}O_3SNa$ requires 329.1186.

*4.1.5. (1R,4R,7S)-7-[(Benzylthio)methyl]-1,7-dimethylbicyclo-[2.2.1] heptan-2-one (**21**).* Freshly cut sodium metal (0.10 g, 4.67 mmol) was dissolved in isopropanol (10 mL) and benzyl mercaptan (0.73 mL, 6.23 mmol) was added. A solution of 8-bromocamphor **20** (0.36 g, 1.55 mmol) in isopropanol (5 mL) was added and the solution was heated under reflux for 4 days. The solution was allowed to cool to room temperature, diluted with water (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with 0.1 M aq potassium hydroxide (2×50 mL), dried and evaporated to yield an oil. Column chromatography on silica gel eluting with ethyl acetate/hexane (1:10) afforded the title compound as a clear oil (0.40 g, 93%). $[\alpha]_D^{21}$ +19.7 (*c* 1.01 in $CHCl_3$); ν_{max} (L)/cm^{-1} 3060, 3027, 2958, 1741 (C=O), 1601, 1492, 1450, 1413, 1380, 1282, 1240, 1200, 1154, 1069, 1040, 924, 759, 701; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.89 (3H, s, 1-C*H*$_3$), 1.04 (3H, s, 7-C*H*$_3$), 1.31–1.46 (2H, m), 1.67–1.74 (1H, m), 1.82 (1H, d, ^2J 18.5, 3-CH_2 *endo*), 1.86–1.93 (1H, m), 2.11–2.18 (1H, m, 3-CH_2 *exo*), 2.14 (1H, d, ^2J 12.0, alkyl CH_2S), 2.30 (1H, d, ^2J 12.0, alkyl CH_2S), 2.35 (1H, t, ^3J 4.5, 4-C*H*), 3.66 (1H, d, ^2J 13.5, benzyl CH_2S), 3.71 (1H, d, ^2J 13.5, benzyl CH_2S), 7.24–7.37 (5H, m, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 8.8 (1-*C*H$_3$), 15.6 (7-*C*H$_3$), 26.2 (C-5), 29.8 (C-6), 36.8 (alkyl *C*H$_2$S), 37.1 (benzyl *C*H$_2$S), 39.8 (C-4), 42.2 (C-3), 49.8 (C-7), 58.4 (C-1), 126.6 (Ar C-4), 128.0 (Ar C-3), 128.2 (Ar C-2), 137.6 (Ar C-1), 218.4 (C-2); *m*/*z* (CI) 297.1297 ($[M+Na]^+$); $C_{17}H_{22}OSNa$ requires 297.1288.

*4.1.6. (1R,4R,7S)-7-[(Benzylsulfonyl)methyl]-1,7-dimethylbicyclo-[2.2.1] heptan-2-one (**22**). 4.1.6.1. Method A.* Sulfide **21** (0.15 g, 0.54 mmol) was dissolved in dichloromethane (10 mL) and cooled to 0 °C. A solution of *m*-CPBA (0.296 g, 70%, 1.2 mmol) in dichloromethane (5 mL) was added dropwise over 15 min. The solution was stirred at 0 °C for 4 h. The solution was allowed to warm to room temperature and diluted with dichloromethane (100 mL). The solution was washed with satd aq sodium sulfite (50 mL) and satd aq sodium hydrogen carbonate (50 mL), dried and evaporated to yield an oil. Column chromatography on silica gel eluting with ethyl acetate/hexane (1:3) afforded the title compound as an oil (0.14 g, 83%), which crystallized on standing overnight.

4.1.6.2. Method B. Sulfide **21** (0.33 g, 1.2 mmol) was dissolved in dichloromethane (10 mL) and acetic acid (2 mL) and finely powdered potassium permanganate (0.38 g, 2.4 mmol) was added in small portions over 5 min. The mixture was stirred at room temperature for 5 h. The mixture was then diluted with dichloromethane (100 mL) and filtered and the filtrate was washed with water (3×50 mL), satd aq sodium sulfite (50 mL) and satd aq sodium hydrogen carbonate (50 mL) and then dried and evaporated to yield an oil (0.32 g, 87%), which crystallized on standing overnight. Mp 78–79 °C (from EtOAc/hexane); $[\alpha]_D^{15}$ +21.8 (*c* 0.33 in $CHCl_3$); ν_{max} (N)/cm^{-1} 2923, 2854, 1732 (C=O), 1603, 1459, 1376, 1313 (SO_2), 1263, 1202, 1120 (SO_2), 1073, 927, 888, 787, 723, 696; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.87 (3H, s, 1-C*H*$_3$), 1.25 (3H, s, 7-C*H*$_3$), 1.38–1.45 (1H, m), 1.62–1.71 (2H, m), 1.90 (1H, d, ^2J 19.0, 3-CH_2 *endo*), 1.95–2.00 (1H, m), 2.27 (1H, dt, *J* 19.0 and 4.0, 3-CH_2 *exo*), 2.54 (1H, d, ^2J 14.0, alkyl CH_2SO_2), 2.74 (1H, d, ^2J 14.0, alkyl CH_2SO_2), 2.95 (1H, t, ^3J 4.5, 4-C*H*), 4.20 (2H, s, benzyl CH_2SO_2), 7.36–7.43 (5H, m, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 8.7 (1-*C*H$_3$), 16.0 (7-*C*H$_3$), 26.5 (C-5), 27.8 (C-6), 39.4 (C-4), 42.5 (C-3), 48.6 (C-7), 53.2 (alkyl *C*H$_2$SO$_2$), 60.2 (C-1), 61.9 (benzyl *C*H$_2$SO$_2$), 127.4 (Ar C-1), 128.7 (Ar C-3), 128.8 (Ar C-4), 130.0 (Ar C-2), 217.6 (C-2); *m*/*z* (CI) 329.1185 ($[M+Na]^+$); $C_{17}H_{22}O_3SNa$ requires 329.1186.

*4.1.7. (1S,4S,5S,7R)-10,10-Dimethyl-4-phenyl-3-thiatricyclo-[5.2.1.0^{1,5}] decan-5-ol 3,3-dioxide (**23**).* *n*-Butyllithium (2.61 mL, 2.5 M, 6.5 mmol) was added to a solution of dry diisopropylamine (1.19 mL, 8.5 mmol) in dry tetrahydrofuran (10 mL) at −60 °C under an atmosphere of nitrogen. The solution was allowed to warm to 0 °C and then recooled to −60 °C. A solution of sulfone **6** (2.0 g, 6.5 mmol) in dry tetrahydrofuran (15 mL) was added dropwise via syringe and the solution was stirred at −60 °C for 15 min and then allowed to warm to room temperature and stirred for a further 3 h. The solution was then quenched with satd aq ammonium chloride (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield an oil (1.89 g). Column chromatography on silica gel eluting with ethyl acetate/hexane (1:3) afforded the title compound as a white solid (1.53 g, 76%), followed by unchanged starting sulfone **6** (0.28 g). Mp 83 °C (from EtOAc/hexane); $[\alpha]_D^{22}$ +4.4 (*c* 0.93 in MeOH); ν_{max} (N)/cm^{-1} 3515 (O–H), 2929, 1601, 1499, 1455, 1376, 1300 (SO_2), 1247, 1222, 1183, 1117 (SO_2), 1077, 1027, 944, 832, 794, 738, 716, 694; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 1.07 (3H, s, 10-C*H*$_3$), 1.23 (3H, s, 10-C*H*$_3$), 1.49 (1H, d, ^2J 13.5, 6-CH_2 *endo*), 1.53–1.58 (1H, m), 1.70–1.77 (1H, m), 1.87–1.90 (1H, m), 1.93 (1H, t, ^3J 3.5, 7-C*H*), 2.36 (1H, dt, *J* 13.5 and 3.5, 6-CH_2 *exo*), 2.44 (1H, m), 3.17 (1H, d, ^2J 14.5, 2-CH_2), 3.21 (1H, d, ^2J 14.5, 2-CH_2), 4.38 (1H, s, 4-C*H*), 7.41 (3H, t, ^3J 2.5, Ar–*H*), 7.64–7.67 (2H, m, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 21.6 (10-*C*H$_3$), 21.6 (10-*C*H$_3$), 26.1 (C-8), 26.9 (C-9), 42.3 (C-6), 43.9 (C-7), 50.3 (C-10), 51.4 (C-2), 56.2 (C-1), 71.9 (C-4), 81.9 (C-5), 126.8 (Ar C-1), 128.2(Ar C-3), 128.5 (Ar C-4), 130.2 (Ar C-2); *m*/*z* (CI) 329.1196 ($[M+Na]^+$); $C_{17}H_{22}O_3SNa$ requires 329.1186.

*4.1.8. (1S,4S,5S,7R)-10,10-Dimethyl-4-vinyl-3-thiatricyclo-[5.2.1.0^{1,5}] decan-5-ol 3,3-dioxide (**24**).* *n*-Butyllithium (0.80 mL, 2.5 M, 1.9 mmol) was added to a solution of dry diisopropylamine (0.36 mL, 2.5 mmol) in dry tetrahydrofuran (5 mL) at −60 °C under an atmosphere of nitrogen. The solution was allowed to warm to 0 °C and then recooled to −60 °C. A solution of sulfone **7** (0.51 g, 1.9 mmol) in dry tetrahydrofuran (4 mL) was added dropwise via syringe and the solution was stirred at −60 °C for 90 min. The solution was then allowed to warm to room temperature, quenched with satd aq ammonium chloride (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield an oil (0.41 g). Column chromatography on silica gel eluting with ethyl acetate/hexane (1:2) afforded the title compound as a white solid (0.36 g, 70%), followed by unchanged starting sulfone **7** (0.03 g). Mp 89–91 °C (from EtOAc/hexane); $[\alpha]_D^{22}$ −74.8 (*c* 1.11 in MeOH); ν_{max} (N)/cm^{-1} 3507 (O–H), 3465 (O–H), 2918, 1634 (C=C), 1461, 1409, 1375, 1300 (SO_2), 1221, 1182, 1116 (SO_2), 1023, 994, 931, 859, 831, 786, 741, 645; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 1.02 (3H, s, 10-C*H*$_3$), 1.12 (3H, s, 10-C*H*$_3$), 1.48 (1H, d, ^2J 13.5, 6-CH_2 *endo*), 1.49–1.56 (1H, m), 1.66–1.72 (1H, m), 1.84–1.91 (2H, m), 2.22 (1H, dt, *J* 13.5 and 3.5, 6-CH_2 *exo*), 2.33–2.39 (1H, m), 3.06 (1H, d, ^2J 14.5, 2-CH_2), 3.13 (1H, d, ^2J 14.5, 2-CH_2), 3.74 (1H, d, ^3J 8.5, 4-C*H*), 5.57 (1H, d, ^3J 17.0, CH=CH_2), 5.61 (1H, d, ^3J 10.5, CH=CH_2), 6.02 (1H, ddd, *J* 17.0, 10.5 and 8.5, C*H*=CH$_2$); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 21.4 (10-*C*H$_3$), 21.4 (10-*C*H$_3$), 26.1 (C-8), 26.7 (C-9), 41.9 (C-6), 43.7 (C-7), 50.3 (C-10), 51.0 (C-2), 56.5 (C-1), 72.7 (C-4), 82.1 (C-5), 122.7 (*C*H=CH$_2$), 125.2 (CH=*C*H$_2$); *m*/*z* (CI) 279.1035 ($[M+Na]^+$); $C_{13}H_{20}O_3SNa$ requires 279.1030.

*4.1.9. (1S,4S,5S,7R,2′S)-10,10-Dimethyl-4-oxiran-2′-yl-3-thiatricyclo [5.2.1.0^{1,5}]decan-5-ol 3,3-dioxide (**25**).* Sulfone **24** (0.25 g, 0.97 mmol) was dissolved in chloroform (5 mL) and a solution of *m*-CPBA (0.48 g, 70%, 1.95 mmol) in chloroform (5 mL) was added dropwise. The solution was heated under reflux for 4 h and then allowed to cool to room temperature and left stirring overnight. The mixture was diluted with chloroform (100 mL) and then washed with satd aq sodium hydrogen carbonate (2×50 mL) and brine (50 mL), dried and evaporated to yield a white solid (0.32 g). Column chromatography

on silica gel eluting with ethyl acetate/hexane (1:2) afforded the title compound as a white solid (0.12 g, 45%). Mp 152 °C (from EtOAc/hexane); $[\alpha]_D^{26}$ −40.0 (*c* 0.09 in MeOH); ν_{max} (N)/cm^{-1} 3506 (O–H), 2908, 1461, 1376, 1303 (SO_2), 1253, 1179, 1125 (SO_2), 1037, 878, 732; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 1.02 (3H, s, 10-C*H*$_3$), 1.07 (3H, s, 10-C*H*$_3$), 1.52–1.58 (1H, m), 1.66 (1H, d, ^2J 13.5, 6-C*H*$_2$ *endo*), 1.69–1.75 (1H, m), 1.85–1.89 (1H, m), 1.92 (1H, t, ^3J 4.0, 7-C*H*), 2.35–2.41 (1H, m), 2.44 (1H, dt, *J* 13.5 and 3.5, 6-C*H*$_2$ *exo*), 2.88 (1H, d, ^3J 7.0, 4-C*H*), 2.94 (1H, dd, *J* 4.5 and 2.5, 3′-C*H*$_2$ *anti*), 2.98 (1H, app t, *J* 4.5 and 4.0, 3′-C*H*$_2$ *syn*), 3.08 (1H, d, ^2J 14.5, 2-C*H*$_2$), 3.12 (1H, br s, O*H*), 3.13 (1H, d, ^2J 14.5, 2-C*H*$_2$), 3.58 (1H, qu, 2′-C*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 21.2 (10-*C*H$_3$), 21.4 (10-*C*H$_3$), 26.0 (C-8), 26.6 (C-9), 42.9 (C-6), 44.1 (C-3′), 44.1 (C-7), 44.5 (C-2′), 50.3 (C-10), 51.9 (C-2), 56.8 (C-1), 71.1 (C-4), 81.8 (C-5); *m*/*z* (CI) 295.0985 ([M+Na]$^+$); $C_{13}H_{20}O_4SNa$ requires 295.0979.

*4.1.10. (1S,4S,5S,7R,1′S)-10,10-Dimethyl-4-[1′-hydroxy-2′-(phenylthio) ethyl]-3-thiatricyclo[5.2.1.0^{1,5}]decan-5-ol 3,3-dioxide (**27**).* Thiophenol (0.076 mL, 0.73 mmol) was added to a suspension of sodium hydride (0.03 g, 60%, 0.73 mmol) in dry tetrahydrofuran (3 mL) at 0 °C under an atmosphere of nitrogen. After the evolution of hydrogen had ceased (ca. 5 min), a solution of sulfone **25** (0.10 g, 0.36 mmol) in dry tetrahydrofuran (4 mL) was added dropwise. The solution was allowed to warm to room temperature and stirred for 5 h. The solution was quenched with satd aq ammonium chloride (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield a semi-solid (0.27 g). Column chromatography on silica gel eluting with ethyl acetate/hexane (1:2) afforded the title compound as a white solid (0.10 g, 71%). Mp 124 °C (from EtOAc/hexane); $[\alpha]_D^{26}$ −93.7 (*c* 0.35 in MeOH); ν_{max} (N)/cm^{-1} 3407 (O–H), 2922, 1582, 1460, 1376, 1280 (SO_2), 1214, 1118 (SO_2), 1076, 984, 804, 735, 692; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 1.02 (3H, s, 10-C*H*$_3$), 1.15 (3H, s, 10-C*H*$_3$), 1.47–1.53 (1H, m), 1.57 (1H, d, ^2J 14.0, 6-C*H*$_2$ *endo*), 1.61–1.68 (1H, m), 1.81–1.85 (1H, m), 1.89 (1H, t, ^3J 4.5, 7-C*H*), 2.38 (1H, m), 2.52 (1H, dt, *J* 14.0 and 3.0, 6-C*H*$_2$ *exo*), 3.12 (1H, dd, *J* 14.3 and 7.5, 2′-C*H*$_2$), 3.17 (2H, s, 2-C*H*$_2$), 3.25 (1H, br s, O*H*), 3.49 (1H, d, ^3J 8.0, 4-C*H*), 3.56 (1H, br s, O*H*), 3.58 (1H, dd, *J* 14.3 and 3.5, 2′-C*H*$_2$), 4.46–4.54 (1H, m, 1′-CH), 7.23 (1H, t, ^3J 7.5, 4-Ar–*H*), 7.32 (2H, t, ^3J 7.5, 3-Ar–*H*), 7.44 (2H, d, ^3J 7.5, 2-Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 21.2 (10-*C*H$_3$), 21.3 (10-*C*H$_3$), 25.9 (C-8), 26.3 (C-9), 38.8 (C-2′), 44.7 (C-7), 46.0 (C-6), 49.7 (C-10), 52.9 (C-2), 56.7 (C-1), 65.9 (C-1′), 71.5 (C-4), 83.1 (C-5), 126.4 (Ar C-4), 128.7 (Ar C-2), 129.3 (Ar C-3), 133.6 (Ar C-1); *m*/*z* (CI) 405.1154 ([M+Na]$^+$); $C_{19}H_{26}O_4S_2Na$ requires 405.1169.

*4.1.11. (1S,4R,5S,7R)-10,10-Dimethyl-4-(1′,2′-dibromoethyl)-3-thiatricyclo[5.2.1.0^{1,5}]decan-5-ol 3,3-dioxide (**26**).* Sulfone **24** (0.20 g, 0.78 mmol) was dissolved in dichloromethane (5 mL) and the solution was cooled to 0 °C. A solution of bromine in dichloromethane (2.2 mL, 0.39 M, 0.85 mmol) was added dropwise and the solution was stirred at 0 °C for 30 min and then allowed to warm to room temperature and stirred for an additional 3 h. Water (50 mL) was added and the mixture was extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with satd aq sodium sulfite (50 mL) and brine (50 mL), dried and evaporated to yield a white solid (0.29 g) whose ^{1}H NMR spectrum showed it to consist of two diastereomers of **26** in ca. 1:1 ratio. Column chromatography on silica gel eluting with ethyl acetate/hexane (1:2) yielded two products. The first product to elute was diastereomer **26A** as a white solid (0.10 g, 31%). Mp 134 °C (from EtOAc/hexane); $[\alpha]_D^{27}$ −5.4 (*c* 0.33 in MeOH); ν_{max} (N)/cm^{-1} 3419 (O–H), 2924, 1607, 1461, 1376, 1308 (SO_2), 1246, 1178, 1120 (SO_2), 1028, 740; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 1.03 (3H, s, 10-C*H*$_3$), 1.18 (3H, s, 10-C*H*$_3$), 1.46–1.52 (1H, m), 1.59 (1H, d, ^2J 14.5, 6-C*H*$_2$ *endo*), 1.64–1.72 (1H, m), 1.82–1.88 (1H, m), 1.91 (1H, t, ^3J 4.5, 7-C*H*), 2.36 (1H, m), 2.66 (1H, dt, *J* 14.5 and 3.5, 6-C*H*$_2$ *exo*), 2.81 (1H, br s, O*H*), 3.16 (1H, d, ^2J 14.0, 2-C*H*$_2$), 3.21 (1H, d, ^2J 14.0, 2-C*H*$_2$), 3.83 (1H, d, ^3J 10.5, 4-C*H*), 4.02 (1H, dd, *J* 12.0 and 2.5, 2′-C*H*$_2$), 4.12 (1H, dd, *J* 12.0 and 4.5, 2′-C*H*$_2$), 4.78 (1H, ddd, ^3J 10.5, 4.5 and 2.5, 1′C*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 21.1 (10-*C*H$_3$), 21.1 (10-*C*H$_3$), 25.7 (C-8), 26.9 (C-9), 37.7 (C-6), 44.2 (C-7), 45.4 (C-1′), 47.2 (C-2′), 49.8 (C-10), 52.7 (C-2), 56.7 (C-1), 71.6 (C-4), 83.6 (C-5); *m*/*z* (CI) 438.9332 ([M+Na]$^+$); $C_{13}H_{20}O_3SBr_2Na$ requires 439.1598. The second product to elute was diastereomer **26B** as a white solid (0.12 g, 38%). Mp 172 °C (from EtOAc/hexane); $[\alpha]_D^{27}$ −58.8 (*c* 0.36 in MeOH); ν_{max} (N)/cm^{-1} 3419 (O–H), 2924, 1607, 1461, 1376, 1308 (SO_2), 1246, 1178, 1120 (SO_2), 1028, 740; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 1.01 (3H, s, 10-C*H*$_3$), 1.15 (3H, s, 10-C*H*$_3$), 1.45–1.50 (1H, m), 1.51 (1H, d, ^2J 13.0, 6-C*H*$_2$ *endo*), 1.66–1.74 (1H, m), 1.82–1.90 (1H, m), 1.93 (1H, t, ^3J 4.5, 7-C*H*), 2.18–2.24 (1H, m), 2.82 (1H, dt, *J* 13.0 and 3.5, 6-C*H*$_2$ *exo*), 3.16 (1H, d, ^2J 14.5, 2-C*H*$_2$), 3.20 (1H, d, ^2J 14.5, 2-C*H*$_2$), 3.74 (1H, d, ^3J 10.5, 4-C*H*), 3.95 (1H, dd, *J* 11.5 and 3.0, 2′-C*H*$_2$), 4.02 (1H, dd, *J* 11.5 and 3.0, 2′-C*H*$_2$), 4.80 (1H, dt, ^3J 10.5 and 3.0, 1′-C*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 20.9 (10-*C*H$_3$), 21.2 (10-*C*H$_3$), 25.9 (C-8), 26.6 (C-9), 38.4 (C-6), 43.1 (C-7), 43.4 (C-2′), 44.1 (C-1′), 50.4 (C-10), 52.2 (C-2), 55.4 (C-1), 71.7 (C-4), 83.6 (C-5); *m*/*z* (CI) 438.9332 ([M+Na]$^+$); $C_{13}H_{20}O_3SBr_2Na$ requires 439.1598.

*4.1.12. (1R,2S,5R,6S,8R)-1,2-Dimethyl-5-phenyl-4-thiatricyclo-[4.4.0.0^{2,8}]decan-6-ol 4,4-dioxide (**28**).* *n*-Butyllithium (0.42 mL, 2.5 M, 1.04 mmol) was added to a solution of dry diisopropylamine (0.2 mL, 1.35 mmol) in dry tetrahydrofuran (5 mL) at −60 °C under an atmosphere of nitrogen. The solution was allowed to warm to 0 °C and then recooled to −60 °C. A solution of sulfone **22** (0.32 g, 1.04 mmol) in dry tetrahydrofuran (6 mL) was added dropwise via syringe and the solution was stirred at −60 °C for 30 min and then allowed to warm to room temperature and stirred for a further 3.5 h. The solution was then quenched with satd aq ammonium chloride (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield a yellow solid (0.27 g). Column chromatography on silica gel eluting with ethyl acetate/hexane (1:2) afforded the title compound as a white solid (0.24 g, 75%). Also eluted was unchanged starting sulfone **22** (0.02 g). Mp 171 °C (from EtOAc/hexane); $[\alpha]_D^{15}$ +37.5 (*c* 0.37 in $CHCl_3$); ν_{max} (N)/cm^{-1} 3435 (O–H), 2921, 1600, 1459, 1377, 1289 (SO_2), 1217, 1105 (SO_2), 1055, 983, 924, 855, 786, 732, 693; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 1.05 (3H, s, 1-C*H*$_3$), 1.20 (3H, s, 2-C*H*$_3$), 1.40 (1H, d, ^2J 14.0, 7-C*H*$_2$ *endo*), 1.44–1.50 (2H, m), 1.84–1.92 (1H, m), 2.17 (1H, t, ^3J 4.5, 8-C*H*), 2.37–2.44 (1H, m), 3.34 (1H, d, ^2J 15.0, 3-C*H*$_2$), 3.52 (1H, d, ^2J 15.0, 3-C*H*$_2$), 3.64 (1H, ddd, *J* 14.0, 4.5 and 3.5, 7-C*H*$_2$ *exo*), 4.58 (1H, s, 5-C*H*), 7.43–7.46 (3H, m, Ar–*H*), 7.52–7.55 (2H, m, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 11.1 (1-*C*H$_3$), 19.3 (2-*C*H$_3$), 28.1 (C-9), 29.7 (C-10), 39.6 (C-7), 45.0 (C-8), 50.2 (C-2), 50.5 (C-1), 60.7 (C-3), 72.0 (C-5), 79.0 (C-6), 128.7 (Ar C-3), 129.2 (Ar C-2), 131.0 (Ar C-4), 131.1 (Ar C-1); *m*/*z* (CI) 329.1174 ([M+Na]$^+$); $C_{17}H_{22}O_3SNa$ requires 329.1186.

4.2. Retro-aldol reactions of tricyclic β-hydroxy sulfones (23) and (24): general procedure

A solution of sulfone **23** or **24** (0.30 g, 0.98 mmol) in dry tetrahydrofuran (8 mL) was added dropwise to a suspension of sodium hydride (0.043 g, 60%, 1.07 mmol) in dry tetrahydrofuran (6 mL) at 0 °C under an atmosphere of nitrogen. The mixture was stirred at 0 °C for 30 min and then allowed to warm to room temperature and stirred for an additional 90 min. The mixture was then quenched with satd aq ammonium chloride (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield an oil. Column chromatography on silica gel eluting with ethyl acetate/hexane (1:3) afforded the unsaturated sulfone **29** (0.06 g, 21%) or **30** (0.10 g, 83%) as a white solid, followed by benzyl sulfone **6** (0.23 g, 76%) or vinyl sulfone **31** (0.02 g, 15%), respectively.

*4.2.1. (1S,7R)-10,10-Dimethyl-4-phenyl-3-thiatricyclo[5.2.1.0^{1,5}]-dec-4-ene 3,3-dioxide (**29**).* White solid (0.06 g, 21%). Mp 97–99 °C (from EtOAc/hexane); $[\alpha]_D^{25}$ −69.2 (*c* 0.53 in MeOH); ν_{max} (N)/cm^{-1} 2919, 1720, 1649 (C=C), 1598, 1459, 1410, 1376, 1293 (SO_2), 1209, 1153, 1120 (SO_2), 756, 686; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.91 (3H, s, 10-CH_3), 1.09 (3H, s, 10-CH_3), 1.38–1.44 (1H, m), 1.89–1.95 (1H, m), 1.98–2.13 (2H, m), 2.16 (1H, t, ^3J 4.5, 7-C*H*), 2.40 (1H, d, ^2J 18.0, 6-CH_2 *endo*), 2.85 (1H, dt, *J* 18.0 and 3.5, 6-CH_2 *exo*), 3.23 (1H, d, ^2J 13.0, 2-CH_2), 3.28 (1H, d, ^2J 13.0, 2-CH_2), 7.33–7.38 (1H, m, Ar–*H*), 7.41–7.44 (2H, m, Ar–*H*), 7.66–7.68 (2H, m, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 18.5 (10-*C*H_3), 18.6 (10-*C*H_3), 26.7 (C-8), 30.9 (C-9), 34.4 (C-6), 44.9 (C-7), 47.7 (C-10), 53.1 (C-2), 54.4 (C-1), 126.7 (Ar C-3), 127.6 (Ar C-1), 128.2 (Ar C-4), 128.4 (Ar C-2) 130.6 (C-4), 156.3 (C-5); *m*/*z* (CI) 311.1079 ([M+Na]$^+$); $C_{17}H_{20}O_2SNa$ requires 311.1080.

*4.2.2. (1S,7R)-10,10-Dimethyl-4-vinyl-3-thiatricyclo[5.2.1.0^{1,5}]dec-4-ene 3,3-dioxide (**30**).* White solid (0.10 g, 83%). Mp 137 °C (decomposition); $[\alpha]_D^{26}$ −62.7 (*c* 0.29 in $CHCl_3$); ν_{max} (N)/cm^{-1} 2923, 1666 (C=C), 1457, 1375, 1288 (SO_2), 1155, 1116 (SO_2), 981, 923, 742; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.83 (3H, s, 10-CH_3), 1.04 (3H, s, 10-CH_3), 1.31–1.36 (1H, m), 1.78–1.83 (1H, m), 1.92–2.06 (2H, m), 2.11 (1H, t, ^3J 4.5, 7-C*H*), 2.19 (1H, d, ^2J 18.5, 6-CH_2 *endo*), 2.63 (1H, dd, *J* 18.5 and 4.5, 6-CH_2 *exo*), 3.11 (1H, d, ^2J 13.5, 2-CH_2), 3.16 (1H, d, ^2J 13.5, 2-CH_2), 5.45 (1H, d, ^3J 11.0, CH=CH_2), 5.83 (1H, d, ^3J 18.0, CH=CH_2), 6.25 (1H, dd, *J* 18.0 and 11.0, C*H*=CH$_2$); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 18.4 (10-*C*H_3), 18.5 (10-*C*H_3), 26.6 (C-8), 30.6 (C-9), 32.8 (C-6), 44.8 (C-7), 47.9 (C-10), 53.1 (C-2), 54.2 (C-1), 118.7 (CH=*C*H_2), 121.2 (*C*H=CH$_2$), 129.5 (C-4), 157.3 (C-5); *m*/*z* (CI) 261.0936 ([M+Na]$^+$); $C_{13}H_{18}O_2SNa$ requires 261.0924.

*4.2.3. (1S,4R)-1-({[(1′E)-Prop-1′-enyl]sulfonyl}methyl)-7,7-dimethylbicyclo[2.2.1]heptan-2-one (**31**).* Colourless oil (0.02 g, 15%). $[\alpha]_D^{25}$ +34.5 (*c* 0.9 in MeOH); ν_{max} (L)/cm^{-1} 2960, 1744 (C=O), 1641 (C=C), 1440, 1393, 1315 (SO_2), 1216, 1131 (SO_2), 1051, 956, 828, 806, 678; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.87 (3H, s, 7-CH_3), 1.09 (3H, s, 7-CH_3), 1.42–1.49 (1H, m), 1.68–1.75 (1H, m), 1.93 (1H, d, ^2J 18.5, 3-CH_2 *endo*), 1.96 (3H, dd, *J* 7.0 and 1.5, 3′-CH_3), 2.01–2.10 (1H, m), 2.13 (1H, t, ^3J 4.5, 4-C*H*), 2.38 (1H, dt, *J* 18.5 and 4.0, 3-CH_2 *exo*), 2.46–2.53 (1H, m), 2.84 (1H, d, ^2J 15.0, CH_2SO_2), 3.43 (1H, d, ^2J 15.0, CH_2SO_2) 6.55 (1H, dq, *J* 15.0 and 1.5, 1′-C*H*), 6.89 (1H, dq, *J* 15.0 and 7.0, 2′-C*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 16.8 (C-3′), 19.2 (7-*C*H_3), 19.3 (7-*C*H_3), 24.2 (C-5), 26.6 (C-6), 42.0 (C-4), 42.1 (C-3), 47.9 (C-7), 51.4 (*C*H_2SO_2), 58.2 (C-1), 131.3 (C-1′), 142.5 (C-2′), 214.5 (C-2); *m*/*z* (CI) 279.1021 ([M+Na]$^+$); $C_{13}H_{20}O_3SNa$ requires 279.1030.

4.3. Reduction of sulfones (6) and (7) with sodium borohydride: general procedure

Sulfone **6** or **7** (1.00 g, 3.26 mmol) was dissolved in methanol (25 mL) and sodium borohydride (0.49 g, 13.0 mmol) was added. The solution was stirred at room temperature for 6 h. The solution was then diluted with satd aq ammonium chloride (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield a solid product (0.86 g) whose ^{1}H NMR spectrum showed it to consist of two diastereomers in approx. 15.7:1 (**32**/**33**) or 16.5:1 (**34**/**35**) ratio. The crude product was purified by chromatography on silica gel, eluting with ethyl acetate/hexane (1:3) to yield two products. The first product to elute was *exo*-sulfone **32** or **34**. The second product to elute was *endo*-sulfone **33** or **35**.

*4.3.1. (1S,2R,4R)-1-[(Benzylsulfonyl)methyl]-7,7-dimethylbicyclo-[2.2.1]heptan-2-ol (**32**).* White solid (0.72 g, 71%). Mp 107–108 °C (from EtOAc/hexane); $[\alpha]_D^{26}$ −38.4 (*c* 0.44 in MeOH); ν_{max} (N)/cm^{-1} 3494 (O–H), 2919, 1456, 1376, 1299 (SO_2), 1267, 1208, 1143, 1106 (SO_2), 1029, 982, 884, 792, 698; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.78 (3H, s, 7-CH_3), 1.02 (3H, s, 7-CH_3), 1.12–1.17 (1H, m), 1.57–1.62 (1H, m), 1.65–1.84 (5H, m), 2.76 (1H, d, ^2J 13.0, alkyl CH_2SO_2), 3.31 (1H, d, ^2J 13.0, alkyl CH_2SO_2), 4.15 (1H, dd, *J* 8.0 and 4.5, 2-C*H*), 4.28 (1H, d, ^2J 14.5, benzyl CH_2SO_2), 4.31 (1H, d, ^2J 14.5, benzyl CH_2SO_2), 7.44 (5H, s, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 19.3 (7-*C*H_3), 20.0 (7-*C*H_3), 26.9 (C-5), 29.9 (C-6), 38.5 (C-3), 43.6 (C-4), 48.6 (C-7), 49.7 (alkyl *C*H_2SO_2), 50.0 (C-1), 61.3 (benzyl *C*H_2SO_2), 75.7 (C-2), 127.3 (Ar C-1), 128.6 (Ar C-3), 128.7 (Ar C-4), 130.1 (Ar C-2); *m*/*z* (CI) 331.1333 ([M+Na]$^+$); $C_{17}H_{24}O_3SNa$ requires 331.1343.

*4.3.2. (1S,2S,4R)-1-[(Benzylsulfonyl)methyl]-7,7-dimethylbicyclo-[2.2.1]heptan-2-ol (**33**).* White solid (0.1 g, 9%). Mp 88–90 °C (from EtOAc/hexane); $[\alpha]_D^{26}$ +19.6 (*c* 0.27 in MeOH); ν_{max} (N)/cm^{-1} 3513, 3433 (O–H), 2925, 2855, 1456, 1375, 1296 (SO_2), 1259, 1113 (SO_2), 1066, 1020, 770, 696; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.86 (3H, s, 7-CH_3), 0.88 (3H, s, 7-CH_3), 1.14 (1H, dd, *J* 13.3 and 3.0, 3-CH_2 *endo*), 1.40–1.47 (1H, m), 1.50–1.58 (1H, m), 1.66 (1H, t, ^3J 4.5, 4-C*H*), 1.78–1.87 (1H, m), 2.26–2.34 (1H, m), 2.50–2.56 (1H, m), 2.96 (1H, d, ^2J 14.0, alkyl CH_2SO_2), 2.99 (1H, d, ^2J 14.0, alkyl CH_2SO_2), 4.29 (1H, dt, *J* 10.0 and 2.5, 2-C*H*), 4.29 (1H, d, ^2J 13.5, benzyl CH_2SO_2), 4.33 (1H, d, ^2J 13.5, benzyl CH_2SO_2), 7.43 (5H, s, Ar–*H*); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 18.4 (7-*C*H_3), 20.0 (7-*C*H_3), 23.4 (C-5), 27.8 (C-6), 37.5 (C-3), 43.3 (C-4), 50.9 (C-7), 51.6 (C-1), 54.4 (alkyl *C*H_2SO_2), 60.8 (benzyl *C*H_2SO_2), 74.5 (C-2), 128.0 (Ar C-1), 128.6 (Ar C-3), 128.8 (Ar C-4), 130.3 (Ar C-2); *m*/*z* (CI) 331.1328 ([M+Na]$^+$); $C_{17}H_{24}O_3SNa$ requires 331.1343.

*4.3.3. (1S,2R,4R)-1-[(Allylsulfonyl)methyl]-7,7-dimethylbicyclo-[2.2.1]heptan-2-ol (**34**).* White solid (0.33 g, 76%). Mp 49–50 °C (from EtOAc/hexane); $[\alpha]_D^{26}$ −26.4 (*c* 0.25 in MeOH); ν_{max} (N)/cm^{-1} 3424 (O–H), 2927, 1638 (C=C), 1456, 1374, 1312 (SO_2), 1240, 1197, 1122 (SO_2), 1075, 1027, 996, 943, 879, 829, 721; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.84 (3H, s, 7-CH_3), 1.08 (3H, s, 7-CH_3), 1.14–1.19 (1H, m), 1.59–1.66 (1H, m), 1.70–1.88 (5H, m), 2.86 (1H, d, ^2J 13.0, alkyl CH_2SO_2), 3.38 (1H, d, ^2J 13.0, alkyl CH_2SO_2), 3.78 (2H, d, ^3J 7.5, allyl CH_2SO_2), 4.17 (1H, dd, *J* 8.0 and 4.0, 2-C*H*), 5.51 (1H, dd, *J* 17.3 and 1.0, CH=CH_2 *trans*), 5.55 (1H, dd, *J* 10.0 and 1.0, CH=CH_2 *cis*), 5.99 (1H, ddt, *J* 17.3, 10.0 and 7.5, C*H*=CH$_2$); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 19.8 (7-*C*H_3), 20.5 (7-*C*H_3), 27.4 (C-5), 30.4 (C-6), 38.9 (C-3), 44.0 (C-4), 49.1 (C-7), 50.0 (alkyl *C*H_2SO_2), 50.3 (C-1), 60.0 (allyl *C*H_2SO_2), 76.1 (C-2), 124.9 (CH=*C*H_2), 125.0 (*C*H=CH$_2$); *m*/*z* (CI) 281.1188 ([M+Na]$^+$); $C_{13}H_{22}O_3SNa$ requires 281.1186.

*4.3.4. (1S,2S,4R)-1-[(Allylsulfonyl)methyl]-7,7-dimethylbicyclo-[2.2.1]heptan-2-ol (**35**).* Colourless oil (0.02 g, 4%). $[\alpha]_D^{26}$ +22.5 (*c* 0.16 in MeOH); ν_{max} (L)/cm^{-1} 3483 (O–H), 2953, 1639 (C=C), 1452, 1391, 1310 (SO_2), 1262, 1126 (SO_2), 1069, 1020, 938, 874, 792; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.91 (3H, s, 7-CH_3), 0.93 (3H, s, 7-CH_3), 1.14 (1H, dd, *J* 13.0 and 3.0, 3-CH_2 *endo*), 1.41–1.47 (1H, m), 1.50–1.58 (1H, m), 1.68 (1H, t, ^3J 4.5, 4-C*H*), 1.79–1.88 (1H, m), 2.29–2.36 (1H, m), 2.48–2.54 (1H, m), 3.01 (1H, d, ^2J 13.5, alkyl CH_2SO_2), 3.08 (1H, d, ^2J 13.5, alkyl CH_2SO_2), 3.80 (2H, d, ^3J 7.5, allyl CH_2SO_2), 4.34 (1H, dt, *J* 9.8 and 2.5, 2-C*H*), 5.50 (1H, dd, *J* 17.0 and 1.0, CH=CH_2 *trans*), 5.55 (1H, dd, *J* 10.0 and 1.0, CH=CH_2 *cis*), 5.97 (1H, ddt, *J* 17.0, 10.0 and 7.5, C*H*=CH$_2$); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 18.4 (7-*C*H_3), 20.0 (7-*C*H_3), 23.3 (C-5), 27.8 (C-6), 37.5 (C-3), 43.3 (C-4), 50.8 (C-7), 51.6 (C-1), 54.2 (alkyl *C*H_2SO_2), 59.1 (allyl *C*H_2SO_2), 74.5 (C-2), 124.4 (*C*H=CH$_2$), 124.6 (CH=*C*H_2); *m*/*z* (CI) 281.1183 ([M+Na]$^+$); $C_{13}H_{22}O_3SNa$ requires 281.1186.

4.4. Aldol reaction of sulfone (32) with benzaldehyde

n-Butyllithium (0.6 mL, 2.5 M, 1.49 mmol) was added to a solution of dry diisopropylamine (0.23 mL, 1.64 mmol) in dry tetrahydrofuran (6 mL) at −60 °C under an atmosphere of nitrogen. The solution was allowed to warm to 0 °C and then recooled to −60 °C.

A solution of sulfone **32** (0.22 g, 0.71 mmol) in dry tetrahydrofuran (8 mL) was added dropwise via syringe. After 20 min, freshly distilled benzaldehyde (0.08 mL, 0.78 mmol) was added and the solution was stirred at −60 °C for 3 h. The solution was then allowed to warm to room temperature, quenched with satd aq ammonium chloride (50 mL) and extracted with diethyl ether (3×50 mL). The combined organic extracts were washed with brine (50 mL), dried and evaporated to yield an oil. The crude product was purified by chromatography on silica gel, eluting with ethyl acetate/hexane (1:3) to yield three diastereomers. The first diastereomer to elute was sulfone **36A**. The second diastereomer to elute was sulfone **36B**. The third diastereomer to elute was sulfone **36C**. Sulfones **36A** and **36B** were contaminated with minor traces of unreacted starting sulfone **32**.

*4.4.1. (1S,2R,4R,1′S,2′R)-1-{[(1′,2′-Diphenyl-2′-hydroxyethyl)-sulfonyl]methyl}-7,7-dimethylbicyclo[2.2.1]heptan-2-ol (**36A**).* Colourless oil (0.08 g, 27%). ν_{max} (N)/cm^{-1} 3485 (O–H), 3432 (O–H), 2924, 1602, 1455, 1375, 1309 (SO_2), 1248, 1126 (SO_2), 1056, 1025, 877, 805, 697; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.62 (3H, s, 7-CH_3), 0.90 (3H, s, 7-CH_3), 1.54–1.80 (7H, m), 2.62 (1H, d, ^2J 13.0, CH_2SO_2), 3.03 (1H, d, ^2J 13.0, CH_2SO_2), 4.14 (1H, dd, J 7.8 and 4.5, 2-CH), 4.23 (1H, d, ^3J 3.5, 1′-CH), 5.96 (1H, d, ^3J 3.5, 2′-CH), 7.17–7.28 (5H, m, Ar–H), 7.33–7.46 (5H, m, Ar–H); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 19.2 (7-CH_3), 19.9 (7-CH_3), 26.9 (C-5), 29.9 (C-6), 38.5 (C-3), 43.5 (C-4), 48.6 (C-7), 50.1 (C-1), 50.3 (CH_2SO_2), 70.6 (C-1′), 75.7 (C-2), 75.8 (C-2′), 125.8 (Ar C-3), 127.6 (Ar C-4), 127.9 (Ar C-3), 128.1 (Ar C-2), 128.7 (Ar C-1), 128.8 (Ar C-4), 130.2 (Ar C-2), 139.2 (Ar C-1); m/z (CI) 437.1770 ([M+Na]$^+$); $C_{24}H_{30}O_4SNa$ requires 437.1761.

*4.4.2. (1S,2R,4R,1′R,2′R)-1-{[(1′,2′-Diphenyl-2′-hydroxyethyl)-sulfonyl]methyl}-7,7-dimethylbicyclo[2.2.1]heptan-2-ol (**36B**).* Colourless oil (0.10 g, 33%). ν_{max} (L)/cm^{-1} 3482 (O–H), 3063, 3031, 2954, 1953, 1890, 1804, 1719, 1602, 1493, 1455, 1390, 1292 (SO_2), 1117 (SO_2), 1056, 1026, 912, 879, 790, 731, 698; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.82 (3H, s, 7-CH_3), 1.00 (3H, s, 7-CH_3), 1.08–1.19 (1H, m), 1.57–1.83 (6H, m), 3.35 (1H, d, ^2J 14.0, CH_2SO_2), 3.39 (1H, d, ^2J 14.0, CH_2SO_2), 4.14 (1H, dd, J 7.8 and 4.5, 2-CH), 4.44 (1H, d, ^3J 9.5, 1′-CH), 5.57 (1H, d, ^3J 9.5, 2′-CH), 7.16 (5H, s, Ar–H), 7.22 (5H, s, Ar–H); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 19.3 (7-CH_3), 20.1 (7-CH_3), 27.0 (C-5), 29.8 (C-6), 38.5 (C-3), 43.6 (C-4), 48.8 (C-7), 50.6 (C-1), 53.3 (CH_2SO_2), 74.2 (C-1′), 75.8 (C-2), 76.1 (C-2′) 126.5 (Ar C-3), 127.8 (Ar C-4), 127.8 (Ar C-3), 128.3 (Ar C-2), 128.7 (Ar C-4), 129.4 (Ar C-2), 130.0 (Ar C-1), 139.5 (Ar C-1); m/z (CI) 437.1770 ([M+Na]$^+$); $C_{24}H_{30}O_4SNa$ requires 437.1761.

*4.4.3. (1S,2R,4R,1′S,2′S)-1-{[(1′,2′-Diphenyl-2′-hydroxyethyl)-sulfonyl]methyl}-7,7-dimethylbicyclo[2.2.1]heptan-2-ol (**36C**).* White solid (0.08 g, 27%). Mp 168 °C (from EtOAc/hexane); $[\alpha]_D^{22}$ −10.4 (c 0.25 in $CHCl_3$); ν_{max} (N)/cm^{-1} 3473 (O–H), 3345 (O–H), 2924, 1954, 1887, 1803, 1601, 1455, 1375, 1299 (SO_2), 1249, 1119 (SO_2), 1047, 942, 880, 826, 762, 698; δ_H (400.1 MHz; $CDCl_3$; Me_4Si) 0.77 (3H, s, 7-CH_3), 1.06 (3H, s, 7-CH_3), 1.10–1.16 (1H, m), 1.56–1.61 (1H, m), 1.69–1.78 (5H, m), 2.93 (1H, d, ^2J 13.5, CH_2SO_2), 3.92 (1H, d, ^2J 13.5, CH_2SO_2), 4.21 (1H, dd, J 7.8 and 4.5, 2-CH), 4.44 (1H, d, ^3J 9.5, 1′-CH), 5.58 (1H, d, ^3J 9.5, 2′-CH), 7.17 (5H, s, Ar–H), 7.23 (5H, s, Ar–H); δ_C (100.6 MHz; $CDCl_3$; Me_4Si) 19.4 (7-CH_3), 20.0 (7-CH_3), 27.0 (C-5), 30.0 (C-6), 38.3 (C-3), 43.7 (C-4), 48.7 (C-7), 50.6 (C-1), 53.8 (CH_2SO_2), 74.4 (C-1′), 76.0 (C-2), 76.0 (C-2′), 126.5 (Ar C-3), 127.7 (Ar C-4), 127.8 (Ar C-3), 128.2 (Ar C-2), 128.4 (Ar C-4), 129.4 (Ar C-2), 129.9 (Ar C-1), 139.6 (Ar C-1); m/z (CI) 437.1757 ([M+Na]$^+$); $C_{24}H_{30}O_4SNa$ requires 437.1761.

Acknowledgements

The authors gratefully acknowledge Dr. John E. O'Brien and Dr. Manuel Reuther for obtaining NMR spectra and Dr. Martin Feeney for obtaining mass spectra. One of us (F.W.L.) received financial support from Trinity College Dublin.

Supplementary data

Procedures and characterization data for known compounds. Details of X-ray crystallographic structure determination. Mol files of new compounds. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication nos. CCDC 822431–822435. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 (0) 1223 336033 or e-mail: deposit@ccdc.cam.ac.uk). Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2011.07.081. These data include MOL files and InChiKeys of the most important compounds described in this article.

References and notes

1. For recent reviews on chiral auxiliaries, see: (a) Roos, G. *Compendium of Chiral Auxiliary Applications*; Academic: New York, NY, 2002; (b) Adam, W.; Zhang, A. *Synlett* **2005**, 1047; (c) Gnas, Y.; Glorius, F. *Synthesis* **2006**, 1899; (d) Pellissier, H. *Tetrahedron* **2006**, *62*, 1619; (e) Evans, D. A.; Helmchen, G.; Rüping, M. In *Asymmetric Synthesis: The Essentials*, 2nd ed.; Christmann, M., Bräse, S., Eds.; Wiley-VCH: Weinheim, 2008; pp 3–9; (f) Meggers, E. *Chem.—Eur. J.* **2010**, *16*, 752.
2. (a) Oppolzer, W. *Tetrahedron* **1987**, *43*, 1969; (b) Polywka, M. E. C. *Chim. Oggi* **1992**, *10*, 33; (c) Liu, W. In *Handbook of Chiral Chemicals*, 2nd ed.; Ager, D., Ed.; CRC LLC: Boca Raton, 2006; pp 59–74; (d) Langlois, Y.; Kouklovsky, C. *Synlett* **2009**, 3065.
3. (a) Oppolzer, W. *Pure Appl. Chem.* **1990**, *62*, 1241; (b) Kim, B. H.; Curran, D. P. *Tetrahedron* **1993**, *49*, 293.
4. Oppolzer, W.; Chapuis, C.; Bernardinelli, G. *Helv. Chim. Acta* **1984**, *67*, 1397.
5. Nishide, K.; Ozeki, M.; Kunishige, H.; Shigeta, Y.; Patra, P. K.; Hagimoto, Y.; Node, M. *Angew. Chem., Int. Ed.* **2003**, *42*, 4515.
6. (a) Chelucci, G. *Chem. Soc. Rev.* **2006**, *35*, 1230; (b) Pellissier, H. *Tetrahedron* **2007**, *63*, 1297.
7. (a) Kitamura, M.; Suga, S.; Kawai, K.; Noyori, R. *J. Am. Chem. Soc.* **1987**, *109*, 5551; (b) Kitamura, M.; Oka, H.; Noyori, R. *Tetrahedron* **1999**, *55*, 3605.
8. Kloetzing, R. J.; Thaler, T.; Knochel, P. *Org. Lett.* **2006**, *8*, 1125.
9. (a) Aggarwal, V. K.; Hynd, G.; Picoul, W.; Vasse, J.-L. *J. Am. Chem. Soc.* **2002**, *124*, 9964; (b) Aggarwal, V. K.; Charmant, J. P. H.; Fuentes, D.; Harvey, J. N.; Hynd, G.; Ohara, D.; Picoul, W.; Robiette, R.; Smith, C.; Vasse, J.-L.; Winn, C. L. *J. Am. Chem. Soc.* **2006**, *128*, 2105.
10. Huang, K.; Huang, Z.-Z. *Synlett* **2005**, 1621.
11. For leading reviews, see: (a) Magnus, P. D. *Tetrahedron* **1977**, *33*, 2019; (b) Trost, B. M. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 107; (c) Simpkins, N. S. *Sulphones in Organic Synthesis*; Pergamon: Oxford, 1993; (d) Toru, T.; Bolm, C. *Organosulfur Chemistry in Asymmetric Synthesis*; Wiley-VCH: Weinheim, 2008; (e) El-Awa, A.; Noshi, M. N.; Jourdin, X. M.; Fuchs, P. L. *Chem. Rev.* **2009**, *109*, 2315.
12. (a) *Chiral Sulfur Reagents*; Mikołajczk, M., Drabowicz, J., Kiełbasiński, P., Eds.; CRC: New York, NY, 1997; (b) Carmen Carreno, M.; Hernandez-Torres, G.; Ribagorda, M.; Urbano, A. *Chem. Commun.* **2009**, 6129.
13. Achiral sulfones are being increasingly used as substrates in asymmetric synthesis, see: (a) Honma, M.; Takeda, H.; Takano, M.; Nakada, M. *Synlett* **2009**, 1695; (b) Nielsen, M.; Jacobsen, C. B.; Holub, N.; Paixão, M. W.; Jorgensen, K. A. *Angew. Chem., Int. Ed.* **2010**, *49*, 2668; (c) Alba, A.-N. R.; Companyo, X.; Rios, R. *Chem. Soc. Rev.* **2010**, *39*, 2018.
14. (a) Hundscheid, F. J. A.; Tandon, V. K.; Rouwette, P. H. F. M.; Van Leusen, A. M. *Tetrahedron* **1987**, *43*, 5073; (b) Caamano, O.; Eirin, A.; Fernandez, F.; Gomez, G.; Uriarte, E. *Heterocycles* **1988**, *27*, 2839; (c) Opitz, G.; Deissler, M.; Ehlis, T.; Rieth, K.; Irngartinger, H.; Ziegler, M. L.; Nuber, B. *Liebigs Ann.* **1995**, 2137; (d) Opitz, G.; Deissler, M.; Rieth, K.; Wegner, R.; Irngartinger, H.; Nuber, B. *Liebigs Ann.* **1995**, 2151; (e) Node, M.; Nishide, K.; Shigeta, Y.; Shiraki, H.; Obata, K. *J. Am. Chem. Soc.* **2000**, *122*, 1927; (f) Pinho e Melo, T. M. V. D.; Cardoso, A. L.; Rocha Gonsalves, A. M. d'A. *Tetrahedron* **2003**, *59*, 2345; (g) Pinho e Melo, T. M. V. D.; Cardoso, A. L.; Rocha Gonsalves, A. M. d'A.; Pessoa, J. C.; Paixao, J. A.; Beja, A. M. *Eur. J. Org. Chem.* **2004**, 4830; (h) Milen, M.; Hazai, L.; Kolonits, P.; Kalaus, G.; Szabo, L.; Goemoery, A.; Szantay, C. *Cent. Eur. J. Chem.* **2005**, *3*, 118; (i) Liu, P.-M.; Chang, C.; Reddy, R. J.; Ting, Y.-F.; Kuan, H.-H.; Chen, K. *Eur. J. Org. Chem.* **2010**, 42.
15. For some recent examples, see: (a) Aversa, M. C.; Barattucci, A.; Bonaccorsi, P.; Giannetto, P.; Nicolo, F.; Rizzo, S. *Tetrahedron: Asymmetry* **1999**, *10*, 3907; (b) Aversa, M. C.; Barattucci, A.; Bonaccorsi, P.; Bonini, B. F.; Giannetto, P.; Nicolo, F. *Tetrahedron: Asymmetry* **1999**, *10*, 3919; (c) Aversa, M. C.; Barattucci, A.; Bonaccorsi, P.; Giannetto, P.; Policicchio, M. *J. Org. Chem.* **2001**, *66*, 4845; (d) Aversa, M. C.; Barattucci, A.; Bonaccorsi, P.; Bruno, G.; Caruso, F.; Giannetto, P. *Tetrahedron: Asymmetry* **2001**, *12*, 2901; (e) Gonzalez-Temprano, I.; Sotomayor, N.; Lete, E. *Synlett* **2002**, 593; (f) Takahashi, T.; Yamakoshi, Y.; Okayama, K.;

Yamada, J.; Ge, W.-Y.; Koizumi, T. *Heterocycles* **2002**, *56*, 209; (g) Aversa, M. C.; Barattucci, A.; Bilardo, M. C.; Bonaccorsi, P.; Giannetto, P. *Synthesis* **2003**, 2241; (h) Gonzalez-Temprano, I.; Osante, I.; Lete, E.; Sotomayor, N. *J. Org. Chem.* **2004**, *69*, 3875; (i) Ozeki, M.; Nishide, K.; Teraoka, F.; Node, M. *Tetrahedron: Asymmetry* **2004**, *15*, 895; (j) Camarero, C.; Gonzalez-Temprano, I.; Gomez-SanJuan, A.; Arrasate, S.; Lete, E.; Sotomayor, N. *Tetrahedron* **2009**, *65*, 5787.
16. Grayson, D. H.; Menhaji, E. unpublished results.
17. (a) Lacour, J.; Monchaud, D.; Bernardinelli, G.; Favarger, F. *Org. Lett.* **2001**, *3*, 1407; (b) Lacour, J.; Monchaud, D.; Mareda, J.; Favarger, F.; Bernardinelli, G. *Helv. Chim. Acta* **2003**, *86*, 65.
18. Lewis, F. W.; Egron, G.; Grayson, D. H. *Tetrahedron: Asymmetry* **2009**, *20*, 1531.
19. Abrunhosa, I.; Gulea, M.; Masson, S. *Synthesis* **2004**, 928.
20. For a review, see: (a) Money, T. *Nat. Prod. Rep.* **1985**, *2*, 253; (b) Money, T. *Org. Synth.: Theory Appl.* **1996**, *3*, 1.
21. Kipping, F. S.; Pope, W. J. *J. Chem. Soc.* **1893**, 548.
22. (a) Corey, E. J.; Chow, S. W.; Scherrer, R. A. *J. Am. Chem. Soc.* **1957**, *79*, 5773; (b) Meyer, W. L.; Lobo, A. P.; McCarty, R. N. *J. Org. Chem.* **1967**, *32*, 1754; (c) Stevens, R. V.; Gaeta, F. C. A.; Lawrence, D. S. *J. Am. Chem. Soc.* **1983**, *105*, 7713; (d) Vaillancourt, V.; Agharahimi, M. R.; Sundram, U. N.; Richou, O.; Faulkner, D. J.; Albizati, K. F. *J. Org. Chem.* **1991**, *56*, 378.
23. Kipping, F. S.; Pope, W. J. *J. Chem. Soc.* **1895**, 354.
24. (a) Eck, C. R.; Mills, R. W.; Money, T. *J. Chem. Soc., Chem. Commun.* **1973**, 911; (b) Eck, C. R.; Mills, R. W.; Money, T. *J. Chem. Soc., Perkin Trans. 1* **1975**, 251.
25. (a) Shive, B.; Crouch, W. W.; Lochte, H. L. *J. Am. Chem. Soc.* **1941**, *63*, 2979; (b) Kuo, D. L.; Money, T. *Can. J. Chem.* **1988**, *66*, 1794; (c) Lu, T.-J.; Liu, S.-W.; Wang, S.-H. *J. Org. Chem.* **1993**, *58*, 7945.
26. Cachia, P.; Darby, N.; Eck, C. R.; Money, T. *J. Chem. Soc., Perkin Trans. 1* **1976**, 359.
27. For an analogous procedure, see: Komarov, I. V.; Gorichko, M. V.; Kornilov, M. Yu. *Tetrahedron: Asymmetry* **1997**, *8*, 435.
28. See for example: (a) Blanco, J. M.; Caamaño, O.; Fernández, F. *Tetrahedron* **1995**, *51*, 935; (b) Shaabani, A.; Mirzaei, P.; Naderi, S.; Lee, D. G. *Tetrahedron* **2004**, *60*, 11415.
29. See for example: (a) Eliel, E. L.; Nasipuri, D. *J. Org. Chem.* **1965**, *30*, 3809; (b) Welch, S. C.; Prakasa Rao, A. S. C.; Lyon, J. T.; Assercq, J.-M. *J. Am. Chem. Soc.* **1983**, *105*, 252; (c) Hutchins, R. O.; Learn, K.; El-Telbany, F.; Stercho, Y. P. *J. Org. Chem.* **1984**, *49*, 2438; (d) Konishi, K.; Aida, T.; Inoue, S. *J. Org. Chem.* **1990**, *55*, 816; (e) Khalilov, L. M.; Parfenova, L. V.; Pechatkina, S. V.; Ibragimov, A. G.; Genet, J. P.; Dzhemilev, U. M.; Beletskaya, I. P. *J. Organomet. Chem.* **2004**, *689*, 444; (f) Serra, M. E. S.; Murtinho, D.; de Melo, D. *Quimica* **2005**, *96*, 72.
30. Henbest, H. B.; Wilson, R. A. L. *J. Chem. Soc.* **1957**, 1958.
31. See for example: Field, L. *J. Am. Chem. Soc.* **1952**, *74*, 3919.
32. (a) Lippmaa, E.; Pehk, T.; Paasivirta, J.; Belikova, N.; Platé, A. *Org. Magn. Reson.* **1970**, *2*, 581; (b) Abraham, R. J.; Barlow, A. P.; Rowan, A. E. *Magn. Reson. Chem.* **1989**, *27*, 1074.
33. (a) Kingsbury, C. A.; Auerbach, R. A. *J. Org. Chem.* **1971**, *36*, 1737; (b) Cassidei, L.; Fiandanese, V.; Marchese, G.; Sciacovelli, O. *J. Chem. Soc., Perkin Trans. 2* **1980**, 1642; (c) Nakamura, S.; Nakagawa, R.; Watanabe, Y.; Toru, T. *J. Am. Chem. Soc.* **2000**, *122*, 11340.
34. (a) Kingsbury, C. A. *J. Org. Chem.* **1972**, *37*, 102; (b) Capet, M.; Cuvigny, T.; Hervé du Penhoat, C.; Julia, M.; Loomis, G. *Tetrahedron Lett.* **1987**, *28*, 6273.
35. For a review, see: (a) Nájera, C.; Yus, M. *Tetrahedron* **1999**, *55*, 10547; (b) Alonso, D. A.; Nájera, C. *Org. React.* **2008**, *72*, 367.
36. See for example: (a) Taguchi, T.; Tomizawa, G.; Nakajima, M.; Kobayashi, Y. *Chem. Pharm. Bull.* **1985**, *33*, 4077; (b) Craig, D.; Smith, A. M. *Tetrahedron Lett.* **1990**, *31*, 2631; (c) Alonso, D. A.; Fuensanta, M.; Nájera, C.; Varea, M. *J. Org. Chem.* **2005**, *70*, 6404.
37. Künzer, H.; Stahnke, M.; Sauer, G.; Wiechert, R. *Tetrahedron Lett.* **1991**, *32*, 1949.
38. Ueno, Y.; Aoki, S.; Okawara, M. *J. Am. Chem. Soc.* **1979**, *101*, 5414.
39. (a) Kotake, H.; Yamamoto, T.; Kinoshita, H. *Chem. Lett.* **1982**, 1331; (b) Inomata, K.; Igarashi, S.; Mohri, M.; Yamamoto, T.; Kinoshita, H.; Kotake, H. *Chem. Lett.* **1987**, 707.
40. For a discussion, see: Bergamini, J.-F.; Hapiot, P.; Lagrost, C.; Preda, L.; Simonet, J.; Volanschi, E. *Phys. Chem. Chem. Phys.* **2003**, *5*, 4846.