Mild, effective and regioselective ring-opening of oxiranes using several thiosilanes promoted by tetrabutylammonium fluoride as catalyst

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The smooth and regioselective ring-opening of oxiranes with isothiocyanatotrimethylsilane 1 (TMSNCS), *O*-trimethylsilyl thioacetate 2 (TMSOCSMe) and phenylthiotrimethylsilane 3 (TMSSPh) proceeds under mild conditions promoted by 0.02 equiv. of TBAF (tetrabutylammonium fluoride) catalyst in a homogeneous system. In most cases, the TBAF catalyst works as an effective promoter. 1,2-Epoxyoctane 4, styrene oxide 5, glycidyl 4-(*tert*-butyl)benzoate 6, 1,2-epoxycyclohexane 7, methyl epoxybutanoate 8 and (2*R*)-glycidyl toluene-*p*-sulfonate 14 undergo smooth ring-opening in moderate to high yields. When ambiphilic TMSNCS 1 and TMSOCSMe 2 are used as reactants, the sulfur position exclusively attacks the oxiranes. No substantial thiirane formation and/or decyanation occurs when 1 is used. Deacetylation also fails to occur when 2 is used.

Oxirane ring-opening with various nucleophiles is well recognized as a useful starting point for the synthesis of multifunctionalized organic compounds. Of such reactions, that with thiols plays an important part in organosulfur chemistry.[1] This ring-opening is catalysed by a number of compounds: organic and inorganic bases,[2] Lewis acids such as $BF_3{\cdot}OEt_2$,[3] tin(II) salts,[4] lanthanide chlorides,[5] lithium perchlorate,[6] cobalt(III) chloride,[7] neutral alumina,[8] borohydride exchange resin[9] or quaternary 'onium' salts including TBAF (tetrabutylammonium fluoride).[10] Thiosilanes in place of thiols also serve as nucleophiles for simple and specific oxiranes.[11] All these methods, however, are limited to the use of simple alkane- or arene-thiols.

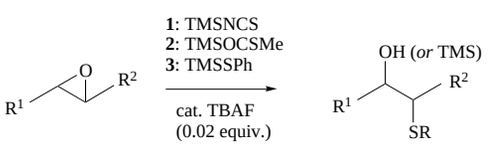
Introduction of thiocyanato (NCS) and acetylthio (MeCOS) groups into organic molecules is considered useful for synthesizing organosulfur compounds, since these groups are not only important themselves but also serve as a masked mercapto group and as a precursor for sulfur-containing heterocyclic compounds.[12] Recently, natural products containing the NCS function are also attracting attention.[13] However, the nucleophilicities of NCS (or NCSH) and MeCOS (or MeCOSH) are relatively poor compared with those of simple thiols so that the desired ring-openings are generally limited or require harsh reaction conditions. In addition, the thiocyanohydrins, which are obtained from oxiranes and NCS (or NCSH), are liable to undergo thiirane-formation with the elimination of the cyanide.[14] Acetylthiohydrins are also somewhat unstable as a result of the weakness of the acetyl–sulfur bond which is adjacent to the hydroxy group.

To overcome these problems, Sharpless' $Ti(OPr^i)_4$-mediated reaction using NH_4SCN, which is a heterogeneous system, enabled the preparation of a thiocyanohydrin.[15] Tamura and Kawasaki *et al.* reported a method using the $Ph_3Ph/(SCN)_2$ reagent.[16] Although both methods are useful, they are limited to specific oxiranes and are not applicable to the introduction of a MeCOS group.

During the course of our studies on useful synthetic reactions based on the effective activation of silicon–heteroatom bonds, we have recently reported that catalytic TBAF efficiently promoted the silyl-transfer reactions from silazanes, hydrosilanes and disilanes to hydroxy groups,[17] wherein hypervalent silicates behaved as the reactive intermediate.[18] As another heteroatom-transfer type reaction, we showed that the isothiocyanatotrimethylsilane **1** (TMSNCS[19])–SO_2Cl_2 reagent conducted the direct introduction of an NCS group into the α-position of ketones and aldehydes.[20a] We now report an effective method for regioselective oxirane ring-opening with TMSNCS **1**, *O*-trimethylsilyl thioacetate **2** (TMSOCSMe),[21] and phenylthiotrimethylsilane **3** (TMSSPh) in a *homogeneous system*, wherein catalytic TBAF (0.02 equiv.) works as the effective promoter.†

Results and Discussion

Several oxiranes such as 1,2-epoxyoctane **4**, styrene oxide **5**, glycidyl 4-(*tert*-butyl)benzoate **6**, 1,2-epoxycyclohexane **7** and methyl epoxybutanoate **8** were found to undergo smooth ring-openings with the aforementioned thiosilanes (Scheme 1).



4 **9a–c**
5 **10a–c**
6 **11a,b**
7 **12a,b**
8 **13a–c**

Scheme 1

The following features are worth noting; (1) the TBAF catalyst (0.02 equiv.) was essential in most cases, particularly when nonpolar benzene was used as the solvent; (2) when ambiphilic TMSNCS **1** and TMSOCSMe **2** were used as reactants, the sulfur position exclusively attacked the oxiranes; (3) no substantial thiirane formation and/or decyanation occurred in the case using TMSNCS **1**; (4) the deacetylation also failed to occur

† Strictly speaking, silyl reactants **1** and **2** are not 'thiosilanes'. However, they show the ambident character of the 'thiosilanes' in the present reaction, so that we regard **1** and **2** as thiosilanes for convenience throughout this paper.

Table 1 Ring-opening of oxiranes using thiosilanes promoted by TBAF catalyst (0.02 equiv. *vs.* oxiranes)[a]

Entry	Oxiranes	Thiosilanes	Equiv.	Solvent	*T*/°C	*t*/h	Product yield(%)			
								OH	OTMS	Total
1	**4**	**1**	(1.0)	Benzene	50	2	**9a**	63	25	88
2	**4**	**1**	(1.0)	DMF	RT	1	**9a**	52	41	93
3	**4**	**2**	(1.0)	Benzene	50	8	**9b**	8	65	73
4	**4**	**2**	(2.0)	Benzene	50	5	**9b**	0	89	89
5	**4**	**2**	(1.0)	DMF	50	8	**9b**	55	Trace	55
6	**4**	**3**	(1.0)	Benzene	50	6	**9c**	63	Trace	63
7[b]	**5**	**1**	(1.0)	DMF	RT	4	**10a**	68	Trace	68
8	**5**	**2**	(1.0)	DMF	RT	4	**10b**	26	Trace	26
9	**5**	**3**	(1.0)	Benzene	50	24	**10c**	69	Trace	69
10	**6**	**1**	(1.0)	Benzene	50	3	**11a**	56	30	86
11	**6**	**1**	(2.0)	Benzene	50	3	**11a**	6	90	96
12[c]	**6**	**1**	(1.0)	DMF	50	2	**11a**	58	10	68
13	**6**	**2**	(1.0)	Benzene	50	4	**11b**	18	62	80
14	**6**	**2**	(1.0)	DMF	50	24	**11b**	41	6	47
15[d]	**7**	**1**	(1.0)	Benzene	RT	2	**12a**	46	32	78
16	**7**	**2**	(1.0)	Benzene	RT	24	**12b**	26	22	48
17	**7**	**2**	(1.0)	THF	RT	24	**12b**	19	39	58
18	**8**	**1**	(1.5)	Benzene	50	24	**13a**	40	18	58
19	**8**	**2**	(1.0)	Benzene	50	24	**13b**	3	53	56
20	**8**	**3**	(1.0)	Benzene	RT	16	**13c**	30	58	88
21[e]	**4**	**1**	(1.0)	Benzene	RT	24	**9a**	52	47	99
22[f]	**4**	**1**	(1.0)	Benzene	RT	24	**9a**	44	47	91
23[e]	**6**	**1**	(1.0)	Benzene	50	3	**11a**	58	30	88

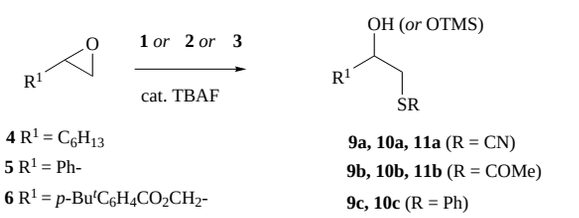
[a] The yields of reactions without TBAF catalyst under the same conditions gave only traces of product unless otherwise specified (entries 7 and 12). [b] The yields without TBAF were 64% (OH) and a trace (OTMS). [c] The yields without TBAF were 14% (OH), 38% (OTMS) and 18% (regioisomer **11a**-**3**). [d] Small amounts of isothiocyanato (NCS) isomer **12a**′ was obtained as the by-product (9%). [e] $PhCH_2Me_3N^+F^-\cdot xH_2O$ catalyst was used in the place of TBAF. [f] $PhCH_2Me_3N^+HF_2^-$ catalyst was used in the place of TBAF. RT = room temp.

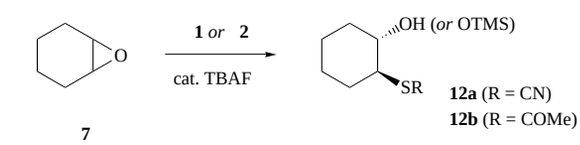
in the case using TMSOCSMe **2**; (5) reactions of TMSSPh **3** also proceeded under similar conditions; (6) all three thiosilanes **1**, **2** and **3** regioselectively attacked the less hindered site of the 1,2-epoxy substrates **4**, **5** and **6**; (7) the 2-position of methyl epoxybutanoate **8** regioselectively reacted with thiosilanes **1**, **2** and **3**; (8) *trans*-adducts were exclusively obtained in each case with 1,2-epoxycyclohexane **7** and methyl epoxybutanoate **8**; (9) the products were generally mixtures of silyl ethers and the corresponding desilylated alcohols; (10) when a slight excess (2 mol equiv.) of thiosilanes was used, the reaction gave more of the silyl ethers than the corresponding alcohols; and (11) as catalysts, $PhCH_2Me_3N^+F^-\cdot xH_2O$ and $PhCH_2Me_3N^+HF_2^-$ were similarly effective, but other ammonium salts such as $PhEt_3N^+Cl^-$ and $Bu_4N^+Br^-$ were inferior to TBAF. Scheme 2 and Table 1 show these results.

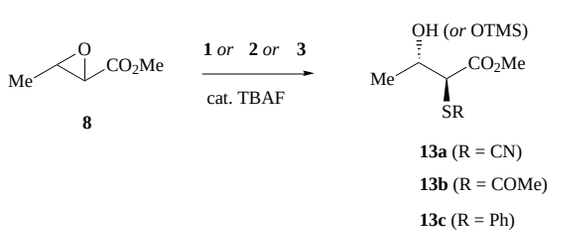
These reaction conditions were sufficiently mild for them to be applied to an important but labile, optically active glycidyl substrate; thus, (2*R*)-glycidyl toluene-*p*-sulfonate **14** underwent the desired smooth ring-opening without the chirality and toluene-*p*-sulfonate function being affected (Scheme 3).

The characteristics of this ring-opening parallel those of the TBAF-promoted cyclocondensation with sulfur-containing silyl derivatives for the synthesis of the anti-PAF (platelet activating factor) thiazolidin-4-ones and their analogues.[20b,c] Thus, activation of the silicon–heteroatom bond by fluoride ion contributes to smooth ring-opening *via* hypervalent silicate intermediates.[18] A plausible reaction mechanism is proposed in Scheme 4. In this, the TBAF catalyst first attacks the thiosilane to produce the reactive pentavalent thiosilicate which, in turn, coordinates to the oxygen of the oxirane and spontaneously forces the thiol group towards the carbon centre of the oxirane. After the resultant oxirane ring-opening, the fluoride anion is immediately transferred from the alkoxy(fluoro)silicate to another molecule of thiosilane with the release of the silyl ether of thiohydrin and concomitant reforming of the thiosilicate.

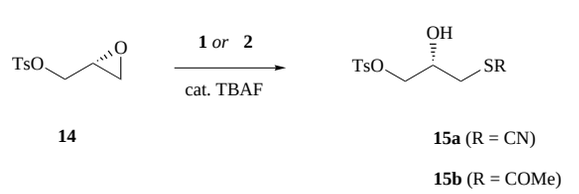
We checked that TMSNCS **1** and TMSOCSMe **2**–cat. TBAF could not silylate alcohols, even for reactive octan-1-ol, in contrast to the case of silazanes.[17a] The lack of silylation ability of these thiosilane agents seems to indicate that the TMS ethers of the products **9**–**13** were formed spontaneously with the ring-opening and not in a stepwise fashion.



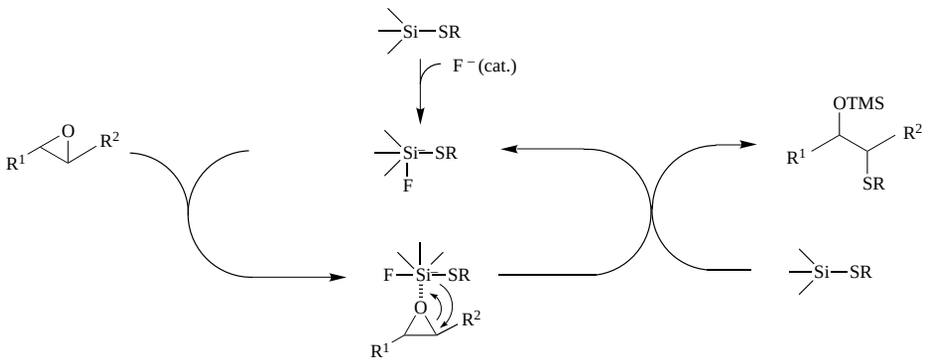




Scheme 2



Scheme 3



Scheme 4

We also examined reactions of MeCOSH with 1,2-epoxyoctane in DMF (at room temp. or 50 °C) and in benzene (at room temp. or reflux), but these experiments gave only complex mixtures. These results demonstrate the utility of TMSOCSMe **2**–cat. TBAF. In two cases, ring-opening proceeded without using catalytic TBAF (Table 1; entries 7 and 12). The reaction of TMSNCS **1** with glycidyl 4-(*tert*-butylbenzoate **6** without TBAF catalyst, however, gave a small amount of 2-benzoate product **11a**–**3** (18%) through undesirable 1,2-acyl migration. The use of TBAF significantly suppressed the migration (Table 1, entry 12).

In conclusion, the oxirane ring-opening described provides a general method for the preparation of thiocyanohydrins and acetylthiohydrins which have potential as starting materials for sulfur-containing heterocycles and other compounds.

Experimental

^{1}H NMR Spectra were recorded on a JEOL EX-90 (90 MHz) and/or JEOL α (400 MHz) spectrometer in $CDCl_3$ using a $SiMe_4$ internal standard. ^{13}C NMR Spectra were recorded on a JEOL α (100 MHz) spectrometer in $CDCl_3$ using a $SiMe_4$ internal standard. IR spectra were recorded on a Hitachi 270–30 spectrophotometer. All of the reagents and solvents were purified prior to use. Silica gel column chromatography was performed on a Merck Art. 7734 or 9385. TMSNCS **1** and TMSSPh **3** are commercially available. TMSOCSMe **2** was prepared by the reported method.[21] A 1 M THF solution of TBAF (commercial grade) was used without drying or purification.

A typical procedure for ring-opening exemplified by the reaction of TMSNCS 1 with 1,2-epoxyoctane 4

2-Hydroxyoctyl thiocyanate 9a-1 and its TMS ether 9a-2. TBAF solution (1 M in THF; 20 μl, 0.02 mmol) and TMSNCS **1** (131 mg, 1.0 mmol) were successively added to a stirred solution of 1,2-epoxyoctane **4** (128 mg, 1.0 mmol) in DMF (2.0 cm^3) at room temp. The mixture was stirred at 50 °C for 3 h and then diluted with water and extracted with EtOAc. The extract was washed with water and brine, dried (Na_2SO_4) and concentrated. The resulting crude oil was purified by silica gel column chromatography (hexane–ethyl acetate, 4:1) to give the *products* **9a-1** (96 mg, 52%) and **9a-2** (107 mg, 41%). Compound **9a-1**: a colourless liquid (Found: C, 57.38; H, 8.88. $C_9H_{17}NOS$ requires C, 57.71; H, 9.15%); ν_{max}(neat)/cm^{-1} 3100–3700, 2150 and 1460; δ_H(90 MHz) 0.70–1.10 (3 H, t, *J* 7.0), 1.10–1.80 (10 H, m), 2.10–2.30 (1 H, br s, OH), 2.95 (1 H, dd, J_{gem} 13.0, *J* 7.0), 3.10 (1 H, dd, J_{gem} 13.0, *J* 3.0) and 3.70–4.20 (1 H, m); δ_C(100 MHz) 14.0, 22.5, 25.4, 29.0, 31.6, 35.9, 41.0, 70.2, 112.0. Compound **9a-2**: a colourless liquid; ν_{max}(neat)/cm^{-1} 2950, 2160 and 1260; δ_H(90 MHz) 0.17 (9 H, s), 0.70–1.10 (3 H, t, *J* 7.0), 1.10–1.80 (10 H, m), 2.95 (1 H, dd, J_{gem} 14.0, *J* 7.0), 3.10 (1 H, dd, J_{gem} 14.0, *J* 3.5) and 3.70–4.20 (1 H, m).

(*S*)-2-Hydroxyoctyl ethanethioate 9b-1 and its TMS ether 9b-2. Compound **9b-1**: a pale yellow liquid (Found: C, 58.64; H, 9.69. $C_{10}H_{20}O_2S$ requires C, 58.78; H, 9.87%); ν_{max}(neat)/cm^{-1} 3100–3700, 2950 and 1700; δ_H(90 MHz) 0.80–1.00 (3 H, t, *J* 7.0), 1.10–1.70 (10 H, m), 1.90–2.10 (1 H, br s, OH), 2.35 (3 H, s), 2.90 (1 H, dd, J_{gem} 15.0, *J* 7.0), 3.12 (1 H, dd, J_{gem} 15.0, *J* 4.0) and 3.60–3.90 (1 H, m). Compound **9b-2**: a light brown liquid; δ_H(90 MHz) 0.15 (9 H, s), 0.80–1.00 (3 H, t, *J* 7.0), 1.10–1.70 (10 H, m), 2.35 (3 H, s), 3.00 (2 H, d, *J* 7.0) and 3.60–3.90 (1 H, m).

1-Phenylthiooctan-2-ol 9c.[22] Compound **9c**: a colourless liquid; ν_{max}(neat)/cm^{-1} 3050–3700, 2970 and 1540; δ_H(90 MHz) 0.80–1.00 (3 H, t, *J* 7.0), 1.10–1.70 (10 H, m), 2.30–2.50 (1 H, br s, OH), 2.85 (1 H, dd, J_{gem} 13.5, *J* 8.0), 3.15 (1 H, dd, J_{gem} 13.5, *J* 4.0), 3.55–3.90 (1 H, m) and 7.10–7.60 (5 H, m).

2-Phenyl-2-hydroxyethyl thiocyanate 10a. Compound **10a**: a colourless liquid (Found: C, 60.67; H, 5.43. C_9H_9NOS requires C, 60.31; H, 5.06%); ν_{max}(neat)/cm^{-1} 3200–3700, 2200 and 1740; δ_H(90 MHz) 2.55–2.75 (2 H, m), 3.95–4.20 (1 H, m) and 7.10–7.60 (5 H, m).

(*S*)-2-Hydroxy-2-phenyl ethanethioate 10b. Compound **10b**: a pale yellow liquid (Found: C, 60.77; H, 5.94. $C_{10}H_{12}O_2S$ requires C, 61.20; H, 6.16%); ν_{max}(neat)/cm^{-1} 3100–3700, 2950 and 1700; δ_H(90 MHz) 2.35 (3 H, s), 2.65–2.75 (1 H, br s, OH), 3.15 (1 H, dd, J_{gem} 10.0, *J* 8.0), 3.30 (1 H, dd, J_{gem} 10.0, *J* 4.0), 4.80 (1 H, dd, *J* 8.0, *J* 4.0) and 7.20–7.45 (5 H, m).

2-Phenylthio-1-phenylethanol 10c.[22] Compound **10c**: a colourless liquid; ν_{max}(neat)/cm^{-1} 3050–3700, 2980 and 1530; δ_H(90 MHz) 2.80 (1 H, d, *J* 2.0, OH), 3.10 (1 H, dd, J_{gem} 14.0, *J* 9.5), 3.35 (1 H, dd, J_{gem} 14.0, *J* 4.5), 4.60–4.80 (1 H, m) and 7.15–7.50 (10 H, m).

2-Hydroxy-3-thiocyanatopropyl *p-tert*-butylbenzoate 11a-1 and its TMS ether 11a-2. Compound **11a-1**: a colourless liquid (Found: C, 61.17; H, 6.41. $C_{15}H_{19}NO_3S$ requires C, 61.41; H, 6.53%); ν_{max}(neat)/cm^{-1} 3100–3700, 2970, 2160 and 1735; δ_H(400 MHz) 1.34 (9 H, s), 3.17 (1 H, dd, J_{gem} 13.2, *J* 7.6), 3.25 (1 H, dd, J_{gem} 13.2, *J* 4.4), 4.30–4.40 (1 H, m), 4.40–4.55 (2 H, m), 7.48 (2 H, d, *J* 8.0) and 7.97 (2 H, d, *J* 8.0).

Compound **11a-2**: a colourless liquid; ν_{max}(neat)/cm^{-1} 2970, 2160 and 1735; δ_H(400 MHz) 0.22 (9 H, s), 1.35 (9 H, s), 3.07 (1 H, dd, J_{gem} 13.4, *J* 7.0), 3.27 (1 H, dd, J_{gem} 13.4, *J* 3.5), 4.25–4.31 (2 H, m), 4.40 (1 H, dd, J_{gem} 10.0, *J* 7.0), 7.45 (2 H, d, *J* 8.0) and 7.95 (2 H, d, *J* 8.0); δ_C(100 MHz) 0.06, 31.08, 35.14, 38.63, 66.06, 68.89, 112.43, 125.52, 126.05, 129.59, 157.18 and 166.23.

3-Thiocyanato-1-trimethylsilyloxy-2-propyl *p-tert*-butylbenzoate 11a-3. Compound **11a-3**: a colourless liquid; ν_{max}(neat)/cm^{-1} 2970, 2160 and 1735; δ_H(90 MHz) 0.15 (9 H, s), 1.32 (9 H, s), 3.40 (1 H, dd, J_{gem} 13.5, *J* 5.5), 3.50 (1 H, dd, J_{gem} 13.5, *J* 4.5), 3.85 (1 H, dd, J_{gem} 11.0, *J* 6.5), 3.90 (1 H, dd, J_{gem} 11.0, *J* 4.5), 5.20–5.45 (1 H, m), 7.45 (2 H, d, *J* 8.0) and 8.00 (2 H, d, *J* 8.0).

3-Acetylthio-2-hydroxypropyl *p-tert*-butylbenzoate 11b-1 and its TMS ether 11b-2. Compound **11b-1**: a colourless liquid

(Found: C, 61.75; H, 7.02. $C_{16}H_{22}O_4S$ requires C, 61.91; H, 7.14%); ν_{max}(neat)/cm^{-1} 3100–3700, 2955 and 1700–1730; δ_H(90 MHz) 1.35 (9 H, s), 2.35 (3 H, s), 2.72 (1 H, br s, OH), 3.08 (1 H, dd, J_{gem} 13.0, *J* 8.0), 3.15 (1 H, dd, J_{gem} 13.0, *J* 5.0), 4.00–4.45 (3 H, m), 7.45 (2 H, d, *J* 8.0) and 8.00 (2 H, d, *J* 8.0).

Compound **11b-2**: a colourless liquid; δ_H(90 MHz) 0.18 (9 H, s), 1.35 (9 H, s), 2.35 (3 H, s), 3.08 (1 H, dd, J_{gem} 13.0, *J* 7.0), 3.15 (1 H, dd, J_{gem} 13.0, *J* 5.5), 3.95–4.35 (3 H, m), 7.45 (2 H, d, *J* 8.0) and 8.00 (2 H, d, *J* 8.0).

2-Hydroxycyclohexyl thiocyanate 12a-1[23] and its TMS ether 12a-2. Compound **12a-1**: a pale yellow liquid; ν_{max}(neat)/cm^{-1} 3100–3700, 2950, 2180 and 1080; δ_H(90 MHz) 1.10–2.40 (8 H, m), 2.40–2.70 (1 H, br s, OH), 2.75–3.10 (1 H, m) and 3.30–3.70 (1 H, m).

Compound **12a-2**: a pale yellow liquid; ν_{max}(neat)/cm^{-1} 2950, 2150 and 1100; δ_H(90 MHz) 0.20 (9 H, s), 1.10–2.40 (8 H, m), 2.80–3.15 (1 H, m) and 3.30–3.70 (1 H, m).

1-Isothiocyanato-2-trimethylsilyloxycyclohexane 12a′.[23] A pale yellow liquid; ν_{max}(neat)/cm^{-1} 3100–3700, 2900, 2000–2300 and 1290; δ_H(90 MHz) 0.20 (9 H, s), 0.85–2.30 (9 H, m) and 3.30–3.65 (1 H, m).

(*S*)-2-Hydroxycyclohexyl ethanethioate 12b-1 and its TMS ether 12b-2. Compound **12b-1**: a light brown liquid (Found: C, 54.88; H, 7.81. $C_8H_{14}O_2S$ requires C, 55.14; H, 8.10%); ν_{max}(neat)/cm^{-1} 3050–3700, 2940 and 1710; δ_H(90 MHz) 1.20–2.20 (8 H, m), 2.35 (3 H, s) and 3.25–3.50 (2 H, m).

Compound **12b-2**: a light brown liquid; δ_H(90 MHz) 0.10 (9 H, s), 1.10–2.20 (8 H, m), 2.30 (3 H, s), 2.60–2.95 (1 H, m) and 3.30–3.55 (1 H, m).

2-Phenylthiocyclohexan-1-ol 12c-1[22] and its TMS ether 12c-2. Compound **12c-1**: a colourless liquid; δ_H(90 MHz) 0.90–2.23 (8 H, m), 2.55–3.00 (1 H, m), 2.90 (1 H, br s, OH), 3.10–3.50 (1 H, m) and 7.20–7.60 (5 H, m).

Compound **12c-2**: a colourless liquid; δ_H(90 MHz) 0.10 (9 H, s), 1.10–2.20 (8 H, m), 2.90–3.25 (1 H, m), 3.40–3.70 (1 H, m) and 7.10–7.60 (5 H, m).

***threo*-Methyl 3-hydroxy-2-thiocyanatobutanoate 13a-1 and its TMS ether 13a-2.** Compound **13a-1**: a pale yellow liquid (Found: C, 40.88; H, 4.96. $C_6H_9NO_3S$ requires C, 41.13; H, 5.18%); ν_{max}(neat)/cm^{-1} 3050–3700, 2955, 2155 and 1720; δ_H(90 MHz) 1.42 (3 H, d, *J* 8.0), 2.80–2.90 (1 H, br s, OH), 3.75 (1 H, d, *J* 6.0), 3.80 (3 H, s) and 4.15–4.50 (1 H, m). Containing small amounts of the *erythro*-isomer: δ_H(90 MHz) 1.45 (3 H, d, *J* 7.0), 3.80 (3 H, s), 4.10 (1 H, d, *J* 7.0) and 4.15–4.50 (1 H, m).

Compound **13a-2**: a pale yellow liquid; δ_H(90 MHz) 0.15 (9 H, s), 1.33 (3 H, d, *J* 6.0), 3.75 (1 H, d, *J* 6.0), 3.80 (3 H, s) and 4.15–4.50 (1 H, m). Containing small amounts of the *erythro*-isomer: δ_H(90 MHz) 0.20 (9 H, s), 1.50 (3 H, d, *J* 8.0), 3.80 (3 H, s), 4.00 (1 H, d, *J* 7.0) and 4.15–4.50 (1 H, m).

***threo*-Methyl 2-acetylthio-3-hydroxybutanoate 13b-1 and its TMS ether 13b-2.** Compound **13b-1**: a light brown liquid (Found: C, 43.49; H, 6.03. $C_7H_{12}O_4S$ requires C, 43.74; H, 6.29%); ν_{max}(neat)/cm^{-1} 3100–3700, 2955 and 1710–1740; δ_H(90 MHz) 1.30 (3 H, d, *J* 5.5), 2.40 (3 H, s), 2.60–2.80 (1 H, br s, OH), 3.75 (3 H, s) and 3.95–4.35 (2 H, m).

Compound **13b-2**: a light brown liquid; δ_H(90 MHz) 0.10 (9 H, s), 1.20 (3 H, d, *J* 6.0), 2.38 (3 H, s), 3.72 (3 H, s) and 4.05–4.35 (2 H, m).

***threo*-Methyl 3-hydroxy-2-phenylthiobutanoate 13c-1 and its TMS ether 13c-2.** Compound **13c-1**: a pale yellow liquid (Found: C, 53.08; H, 5.98. $C_{11}H_{14}O_3S$ requires C, 53.38; H, 6.24%); ν_{max}(neat)/cm^{-1} 3100–3700, 2950 and 1720; δ_H(90 MHz) 1.40 (3 H, d, *J* 7.0), 2.70 (1 H, br d, *J* 8.0, OH), 3.58 (1 H, d, *J* 8.0), 3.70 (3 H, s), 3.90–4.35 (1 H, m) and 7.20–7.60 (5 H, m).

Compound **13c-2**: a pale yellow liquid; δ_H(90 MHz) 0.10 (9 H, s), 1.35 (3 H, d, *J* 7.0), 3.60 (1 H, d, *J* 9.0), 3.65 (3 H, s), 4.00–4.32 (1 H, m) and 7.20–7.55 (5 H, m).

(2*S*)-2-Hydroxy-3-thiocyanatopropyl toluene-*p*-sulfonate 15a. Reaction of (2*R*)-glycidyl tosylate **14** and TMSNCS **1** (2.0 equiv.) in the presence of TBAF (0.02 equiv.) in benzene at room temp. for 24 h gave the product **15a** (86%) as a pale yellow liquid (Found: C, 45.71; H, 4.45. $C_{11}H_{13}NO_4S_2$ requires C, 45.98; H, 4.56%); δ_H(90 MHz) 2.45 (3 H, s), 2.80–3.05 (1 H, br s, OH), 3.00–3.20 (2 H, m), 3.95–4.35 (3 H, m), 7.35 (2 H, d, *J* 8.5) and 7.80 (2 H, d, *J* 8.5); ν_{max}(neat)/cm^{-1} 3100–3700, 2950 and 2160; $[\alpha]_D^{25.3}$ +39.5 (*c* 1.12, $CHCl_3$).

(2*S*)-3-Acetylthio-2-hydroxypropyl toluene-*p*-sulfonate 15b. Reaction of (2*R*)-glycidyl tosylate **14** and TMSOCSMe **2** (5.0 equiv.) in the presence of TBAF (0.02 equiv.) in benzene at 50 °C for 24 h gave the *product* **15b** (56%) as a light brown liquid (Found: C, 47.07; H, 5.04. $C_{12}H_{16}O_5S_2$ requires C, 47.35; H, 5.30%); δ_H(90 MHz) 2.35 (3 H, s), 2.45 (3 H, s), 2.70–2.85 (1 H, m), 2.95–3.15 (1 H, m), 3.85–4.10 (3 H, m), 7.33 (2 H, d, *J* 8.5) and 7.80 (2 H, d, *J* 8.5); ν_{max}(neat)/cm^{-1} 3100–3700, 2945 and 1710; $[\alpha]_D^{24.2}$ +14.0 (*c* 0.85, $CHCl_3$).

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