Electrophilic Ene-type Reactions of Phenyl Vinyl Sulfoxide with Alkenes[1]

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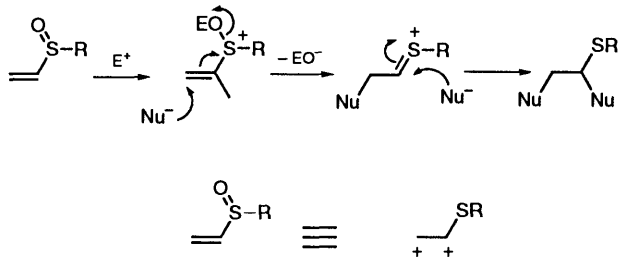
Phenyl vinyl sulfoxide **1** can be made to react as an α,β-dicarbocation with alkenes by formation of one or two new C–C bonds. These reactions take place at or below room temperature, under the conditions of the Pummerer reaction, *i.e.* trifluoroacetic acid and its anhydride. The key step is an electrophilic ene-type reaction between a thionium ion and the alkene. The primary β-trifluoroacetoxy sulfides thus formed then undergo rearrangement *via* an episulfonium ion to the more stable, secondary isomer.

The Pummerer reaction[2] of alkyl sulfoxides leads to α-functionalised sulfides. Vinyl sulfoxides, however, usually undergo additive Pummerer reaction,[3] giving α,β-difunctionalised sulfides. The vinyl sulfoxide thus reacts like a sulfide α,β-dicarbocation. After activation of the oxygen atom by the electrophile, a thionium ion (α-alkyl- or aryl-thiocarbocation) is generated by addition of nucleophile at the β position, and loss of the oxygen atom. A second nucleophile then adds to the α position (Scheme 1).



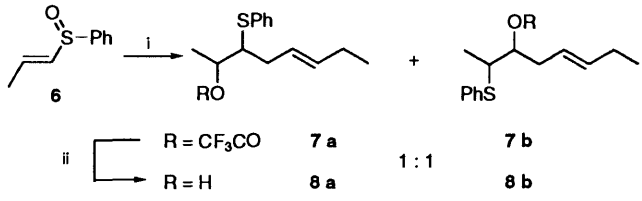
Scheme 1

The use of carbon nucleophiles in the Pummerer reaction leads to C–C bond formation, often under rather mild conditions. Vinylic sulfoxides, reacting as α,β-dicarbocations, can form two C–C bonds in one step. This very attractive methodology has been applied by using ketene silyl acetals[4] or Grignard reagents.[5] We have studied the reaction with simple, non-activated alkenes.

Results

Phenyl vinyl sulfoxide **1** is mixed with an excess of an alkene **2**, and the mixture was cooled to −20 °C. Trifluoroacetic acid (TFA) and its anhydride (TFAA) are then added, and the mixture was slowly brought back to room temperature. Depending on which alkene is used, two types of products are obtained. Isobutene **2a** gives a double-addition product, **3**. The monosubstituted or 1,2-disubstituted alkenes **2b–g** give monoalkylated products **4b–g**.† These compounds are distilled, or hydrolysed to the corresponding alcohol **5** which is then distilled. The yields are good (see Scheme 2).

A similar reaction takes place between 1-phenylsulfinylpropene **6** and pent-1-ene **2d** under the same conditions, to yield a 1:1 mixture of monoalkylated products **7a** and **7b** which are hydrolysed to the corresponding alcohols, **8a** and **8b** (Scheme 3).

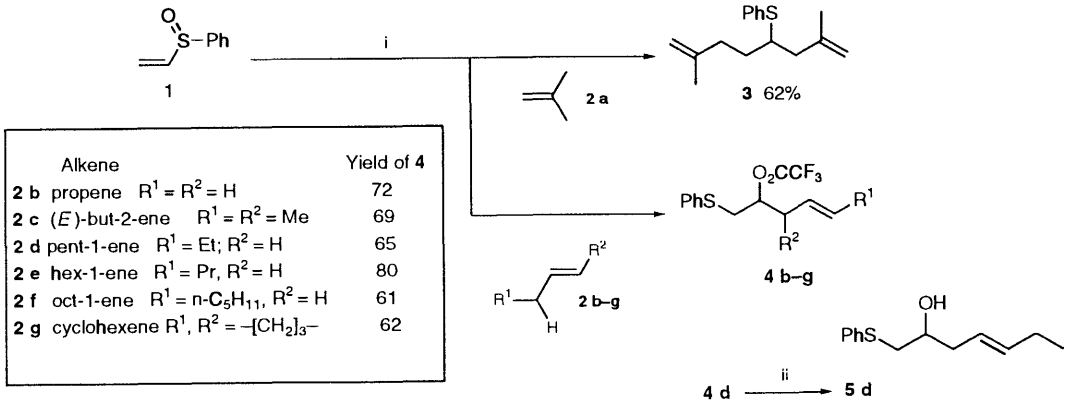


Scheme 3 *Reagents and conditions:* i, TFAA, TFA, −20 °C to room temp., 72 h, **2d**; ii, NaOH, MeOH, room temp., 1 h, 63% from **6**

All these products **3**, **4** and **8** are obtained as single positional isomers of the double bond. Products **4c**, **4g**, **8a** and **8b** are mixtures of diastereoisomers.

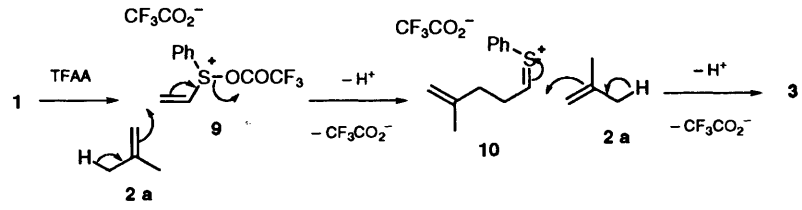
Mechanism.—The formation of sulfide **3** appears to follow the general scheme for additive Pummerer reactions. Activation

† Other 1,1-disbustituted alkenes such as 2-phenylpropene, methylidenecyclohexane, β-pinene, and 2-methylbut-1-ene, or the trisubstituted alkene 1-methylcyclopentene, lead to complex mixtures of products.



Alkene	Yield of 4
2 b propene $R^1 = R^2 = H$	72
2 c (*E*)-but-2-ene $R^1 = R^2 = Me$	69
2 d pent-1-ene $R^1 = Et$; $R^2 = H$	65
2 e hex-1-ene $R^1 = Pr$, $R^2 = H$	80
2 f oct-1-ene $R^1 = n\text{-}C_5H_{11}$, $R^2 = H$	61
2 g cyclohexene R^1, $R^2 = -[CH_2]_3-$	62

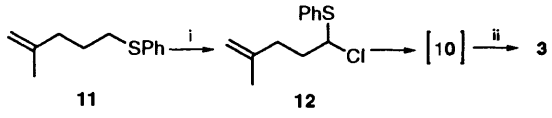
Scheme 2 *Reagents and conditions:* i, TFAA–TFA, −20 °C to room temp., 14 h; ii, NaOH, MeOH, room temp., 1 h



Scheme 4

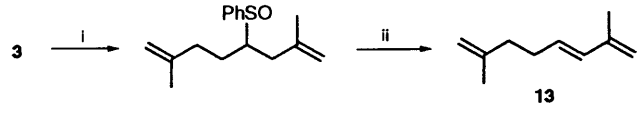
with TFAA gives the intermediate **9**. Isobutene **2a** adds in the β position, with loss of trifluoroacetate and a proton, to give the thionium ion **10**. A second mole equivalent of isobutene **2a** then adds in the α position, to give compound **3**. Both additions of isobutene **2a** take place in an ene-type fashion (see Scheme 4).

To establish this mechanism, we are able to obtain compound **3** by the same ene reaction, but from a different starting material. Methyl 4-methylpent-4-enoate[6] is reduced with $LiAlH_4$ (LAH) to give 4-methylpent-4-en-1-ol,[7]* which is converted into the sulfide **11**. Chlorination with *N*-chlorosuccinimide (NCS) gives the α-chloro sulfide **12**,[8] which reacts with isobutene in TFA to provide compound **3**, *via* the same intermediate, **10** (Scheme 5).



Scheme 5 *Reagents and conditions:* i, NCS, CCl_4, room temp., 14 h; ii, TFA (2.5 mol equiv.), **2a**, −6 °C, 1 h, 49% from **11**

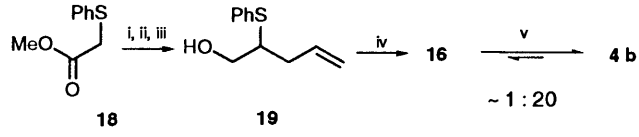
Compound **3** can be converted selectively into the known[9] 2,7-dimethylocta-1,3,7-triene **13** by oxidative elimination of the phenylthio group (Scheme 6).



Scheme 6 *Reagents and conditions:* i, $NaIO_4$, aq. MeOH, room temp., 14 h; ii, 130 °C, 30 min, 58% from **3**

The other, monoalkylated, products are formed by a different route: the alkenes **2b–g** are less nucleophilic than isobutene **2a**, so it is trifluoroacetate that adds to the activated sulfoxide **9**, to give the known[10] bistrifluoroacetate **15**, in equilibrium with the thionium ion **14**. This species reacts, as above, by ene-type addition to the alkene, to give intermediate **16** when the alkene is propene **2b**. Under the reaction conditions compound **16** is in equilibrium, *via* the episulfonium ion **17**, with regioisomer **4b** (see Scheme 7).

Evidence for this sequence is as follows: The reaction was indifferently carried out from sulfoxide **1** or preformed diester **15**; and ester **16**, prepared independently, equilibrates to compound **4b** under the reaction conditions. Methyl 2-(phenylthio)acetate **18** is chlorinated with NCS, alkylated with allyltrimethylsilane, then reduced with LAH to give the alcohol **19**, which is trifluoroacetylated in dichloromethane at 0 °C to give compound **16**. This compound rearranges almost quantitatively to compound **4b** under conditions similar to those used for the reactions of sulfoxide **1**: dissolution in a small volume of pentane, at 0 °C, and stirring with 3 mol equiv. of TFA for 2 days at room temp. (see Scheme 8). The ratio **16**:**4b** is then



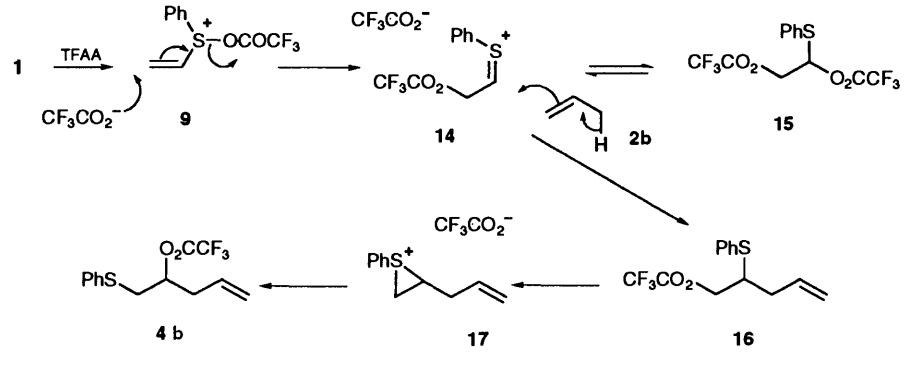
Scheme 8 *Reagents and conditions:* i, NCS, CCl_4, room temp., 14 h; ii, $H_2C{=}CHCH_2SiMe_3$, CH_2Cl_2, $ZnCl_2$, room temp., 3 h; iii, LAH, Et_2O, room temp., 14 h, 61% over three steps; iv, TFAA, pyridine, CH_2Cl_2, 0 °C, 2 h, quant.; v, pentane–TFA, room temp., 2 days

approximately 1:20. An equilibrium constant of 1:20 at room temperature is equivalent to a ΔG-value of 1.8 kcal mol^{-1}.†

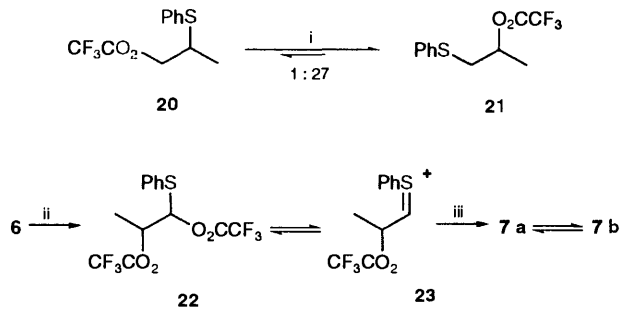
A similar rearrangement is observed, under the same conditions, with the trifluoroacetate **20** of 2-(phenylthio)propan-1-ol,[11] to give compound **21**, with an observed ratio of 1:27 (Scheme 9). The trifluoroacetoxy group thus appears to 'prefer' the secondary position over the primary one. This also explains the observed 1:1 ratio of compounds **7a** and **7b** obtained from sulfoxide **6**. Here again, the first step is formation of the known[10] TFAA adduct, **22**. Ene reaction of the thionium ion **23** leads to the adduct **7a**, which is in equilibrium with its isomer **7b**. Since both positions in these compounds are secondary, they are equally favoured.

* The authors used a Wittig reaction with ethyl levulinate to synthesize the ester. We found this preparation to be cumbersome, and preferred the method described in ref. 6, by alkylation, then demethoxycarbonylation, of dimethyl malonate.

† 1 cal = 4.184 J.

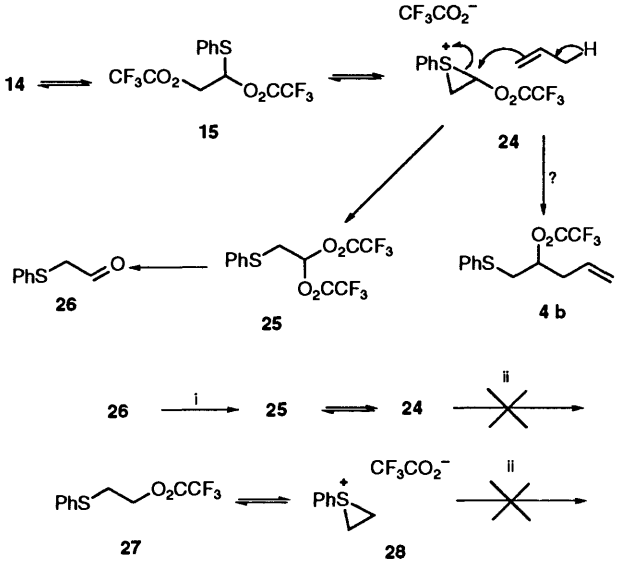


Scheme 7



Scheme 9 *Reagents and conditions:* i, pentane–TFA, room temp., 2 days; ii, TFAA–TFA; iii, **2d**

Our previous assumption[1] that the reaction proceeds by ionisation of diester **15** to the episulfonium ion **24**, and nucleophilic opening of this species by the alkene must now be discounted. It is known that allylsilanes,[12] and, in certain special cases, alkenes[13] are able to effect the opening of episulfonium ions. The isolation of ~10% of (phenylthio)-acetaldehyde **26** as a by-product confirms that ionisation of diester **15** to episulfonium **24** is indeed taking place under the reaction conditions: Trifluoroacetate reopening of species **24** leads to the acylal (geminal diester) **25**, which can undergo easy hydrolysis to aldehyde **26** (Scheme 10). To test this mechanism,



Scheme 10 *Reagents and conditions:* i, TFAA, $CHCl_3$, room temp., 14 h, 70%; ii, TFA, **2d**, room temp.

we synthesized compounds **25** and **27** (acylals such as **25** are formed by reaction of an anhydride with an aldehyde, at or under room temperature in the case of TFAA).[14] They do not react with pent-1-ene **2d** in TFA, where they are expected to be in equilibrium with the corresponding episulfonium ions **24** and **28**. Starting material is recovered.

Discussion

We have established a new pathway for alkylation of simple alkenes by phenyl vinyl sulfoxide **1**, which reacts as an α,β-dicarbocation, leading to two types of product, **3** and **4b–g**. The key steps in these reactions are ene-type reactions of the alkyl-substituted thionium ions **10** and **14** with simple, non-activated alkenes **2**.

The ene-type reaction of several thionium ions $RCH\overset{+}{S}R'$ [R = H, $SiMe_3$, $P(O)(OR'')_2$, CO_2R'' or $CONR''_2$] with monosubstituted alkenes has been described.[15] There has been no report, to our knowledge, of ene reactions of thionium ions stabilised by an alkyl group (R = alkyl). Such species do react with more nucleophilic compounds such as allylsilanes or silyl enol ethers.[16] Analogous studies of ene reactions of aldehydes[17] have established that formaldehyde is more reactive than aliphatic aldehydes, and that those activated by an electron-withdrawing group, such as glyoxylate esters, are even more reactive.[18] For example, formaldehyde reacts with 1,2-disubstituted alkenes in the presence of the Lewis acid Me_2AlCl, whereas aliphatic aldehydes only react with 1,1-disubstituted or trisubstituted alkenes. Our results confirm that thionium ions substituted with an alkyl group, such as compounds **10** or **14**, are electrophilic enough to undergo ene-type reaction with monosubstituted alkenes.

The completely regioselective formation of the new double bond, in the less stable, anti-Zaitsev position, is surprising and has not yet been explained. It does not necessarily involve a concerted mechanism. Several ene reactions have been shown to proceed stepwise, *via* a carbocation, with the selective deprotonation controlled by diverse other factors.[17,19] We are currently examining this question.

The formation of compounds **4b–g** involves a further, unforeseen step: The rearrangement of the intermediate adducts such as **16** to give the thermodynamically more stable species **4**. Similar rearrangements have been reported in the literature, concerning sulfide β-trifluoroacetates,[20] methanesulfonates,[11] and chlorides,[21] with similar ratios being observed. This relatively small thermodynamic bias has not, to our knowledge, been accounted for. We notice that the favoured isomer is the one in which the electronegative group (Cl, CF_3CO_2, . . .) is bonded to the more procationic (secondary or tertiary) centre.

Experimental

IR spectra were recorded on a Nicolet 205 FT–IR spectrophotometer. ^1H NMR spectra were recorded at 200 MHz (Varian Gemini 200) or at 500 MHz (Bruker AM 500), in $CDCl_3$, using tetramethylsilane as the internal reference. ^{13}C NMR spectra were recorded at 50 or 125 MHz on the same instruments, using the central resonance of deuteriochloroform (77 ppm) as the internal reference. Chemical shifts are expressed in δ-units, coupling constants (*J*) in Hz. Electron-impact mass spectra were recorded on Varian Matt 44S or Finnagan-MAT TSQ-70 instruments. Solvents were dried and distilled prior to use, and reactions were carried out in flame-dried apparatus. Solutions were dried with magnesium sulfate prior to evaporation. Silica gel was used for chromatography. Light petroleum refers to the fraction boiling in the range 50–60 °C.

General Procedure I for Reactions of Sulfoxide **1** *with Alkenes* **2**.—Phenyl vinyl sulfoxide **1** (0.5 g, 3.3 mmol) was stirred at −20 °C with an alkene **2** (5 cm^3). (Gaseous alkenes were condensed into the reaction flask with a solid CO_2–acetone condenser.) TFA (0.51 cm^3, 6.6 mmol) then TFAA (0.7 cm^3, 4.9 mmol) were injected through a septum. The cooling bath was removed, and the reaction mixture was stirred at room temperature overnight. It was then diluted with dichloromethane (20 cm^3), washed successively with saturated aq. $NaHCO_3$ (10 cm^3) and with water (20 cm^3), dried, and evaporated to yield the crude product as a yellow oil.

2,7-Dimethyl-4-(phenylthio)octa-1,7-diene **3**. *From isobutene* **2a**. Chromatography with dichloromethane led to a pale yellow oil (0.50 g, 62%), $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 3080 (=CH) and 1650 (C=C); δ_H(200 MHz) 1.68 and 1.70 (each s, Me), 1.5–1.7 (m, 5-H_2), 2.1–2.4 (m, 3- and 6-H_2), 3.24 (tdd, *J* 7.9, 6.4 and 4.8, 4-H), 4.7–4.85 (m, 2 × $=CH_2$) and 7.2–7.5 (m, Ph); δ_C(50 MHz) 22.0 and 22.2 (Me), 31.4 (C-5), 34.5 (C-6), 43.5 (C-3), 45.9 (C-4), 110.5 and 113.1 (C-1 and -8), 126.1 (arom. C–S), 126.9 (*p*-C), 128.9

(*o*-C), 132.4 (*m*-C) and 142.9 and 145.3 (C-2 and -7); *m/z* 246 (M^+), 218, 191, 169, 137 and 109.

5-*Phenylthio*-4-(*trifluoroacetoxy*)*pent*-1-*ene* **4b**. *From propene* **2b**. The crude product was purified by Kugelrohr distillation (0.01 mmHg, 60 °C) (0.69 g, 72%); $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 3055–2990 (=CH), 1785 (C=O) and 1220–1160 (C–F); δ_H(200 MHz) 2.4–2.6 (m, 3-H_2), 3.14 (d, *J* 6.1, 5-H^a), 3.15 (*J* 6.6, 5-H^b), 5.1–5.2 (m, 4-H), 5.0–5.2 (m, $=CH_2$), 5.55–5.75 (m, =CH) and 7.2–7.4 (m, Ph); δ_C(50 MHz) 37.1 (C-5), 37.1 (C-3), 76.5 (C-4), 114.5 (CF_3), 119.7 (C-1), 127.3 (*p*-C), 129.3 (*o*-C), 130.5 (*m*-C), 131.0 (C-2), 134.7 (arom. C–S) and 156.9 (C=O); *m/z* 290 (M^+), 176, 109, 69 and 67.

3-*Methyl*-5-*phenylthio*-4-(*trifluoroacetoxy*)*pent*-1-*ene* **4c**. *From* (E)-*butene* **2c**. The crude product was purified by Kugelrohr distillation (0.01 mmHg, 60 °C), and was a *pale yellow oil* (0.69 g, 69%) (Found: C, 55.3; H, 5.35. $C_{14}H_{15}F_3O_2S$ requires C, 55.25; H, 4.97%); $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 3075–2930 (C–H), 1785 (C=O) and 1220–1170 (C–F); NMR data for the major isomer: δ_H(200 MHz) 1.04 (d, *J* 7.1, Me), 2.64 (sext., *J* 7.1, 3-H), 3.10 (d, *J* 7.1, 5-H_2), 5.0–5.1 (m, 4-H), 5.0–5.15 (m, $=CH_2$), 5.65 (ddd, *J* 17.7, 9.8 and 7.1, =CH) and 7.2–7.5 (m, Ph); δ_C(50 MHz) 14.6 (Me), 36.0 (C-5), 40.7 (C-3), 79.8 (C-4), 114.6 (CF_3), 117.1 (C-1), 127.1 (*p*-C), 129.1 (*o*-C), 130.6 (*m*-C), 133.2 (arom. C–S), 136.9 (C-2) and 156.8 (C=O); *m/z* 304 (M^+), 249, 191, 135, 109 and 81.

7-*Phenylthio*-6-(*trifluoroacetoxy*)*hept*-3-*ene* **4d**. *From pent*-1-*ene* **2d**. The crude product was purified by Kugelrohr distillation (0.01 mmHg, 70 °C) to yield a yellow oil (0.68 g, 65%), $\nu_{max}(CHCl_3)/cm^{-1}$ 3010–2880 (C–H), 1780 (C=O) and 1210 and 1180 (C–F); δ_H(200 MHz) 0.94 (t, *J* 7.4, 1-H_3), 1.99 (quint, *J* 7.4, 2-H_2), 2.3–2.6 (m, 5-H_2), 3.21 (d, *J* 6.4, 7-H_2), 5.18 (quint, *J* 6.4, 6-H), 5.33 (dt, *J* 15.2 and 7.4, 4-H), 5.64 (dt, *J* 15.2 and 7.4, 3-H) and 7.2–7.5 (m, Ph); δ_C(50 MHz) 13.5 (C-1), 25.5 (C-2), 36.1 (C-5), 37.2 (C-7), 77.1 (C-6), 114.6 (CF_3), 121.5 (C-4), 127.0 (*p*-C), 129.2 (*o*-C), 130.5 (*m*-C), 134.7 (arom. C–S), 137.7 (C-2) and 156.9 (C=O); *m/z* 318 (M^+), 204, 109, 95 and 69.

1-(*Phenylthio*)*hept*-4-*en*-2-*ol* **5d**. Compound **4d** was stirred for 1 h at room temp. in methanol with NaOH (1.5 mol equiv.). The solvent was removed, diethyl ether was added, and the solution was washed with water, dried, and concentrated to give a quantitative yield of crude *compound* **5d**, which was purified by Kugelrohr distillation (0.002 mmHg, 97 °C) (Found, C, 70.2; H, 8.2; S, 14.45. $C_{13}H_{18}OS$ requires C, 70.22; H, 8.16; S, 14.42%).

1-*Phenylthio*-2-(*trifluoroacetoxy*)*oct*-4-*ene* **4e**. From *hex*-1-*ene* **2e**. The crude product was purified by Kugelrohr distillation (0.02 mmHg, 80 °C) to yield a yellow oil (0.87 g, 80%), $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 2960–2870 (C–H), 1785 (C=O) and 1220 and 1160 (C–F); δ_H(200 MHz) 0.87 (t, *J* 7.1, 8-H_3), 1.35 (sext, *J* 7.1, 7-H_2), 1.96 (q, *J* 7.1, 6-H_2), 2.3–2.55 (m, 3-H_2), 3.14 (d, *J* 6.4, 1-H_2), 5.12 (quint, *J* 6.4, 2-H), 5.28 (m, 4-H), 5.53 (dt, *J* 15.1 and 7.1, 5-H) and 7.25–7.45 (m, Ph); δ_C(50 MHz) 13.4 (C-8), 22.3 (C-7), 34.5 (C-6), 36.0 (C-3), 37.1 (C-1), 77.0 (C-2), 114.5 (CF_3), 122.6 (C-4), 127.2 (*p*-C), 129.3 (*o*-C), 130.7 (*m*-C), 134.7 (arom. C–S), 136.2 (C-5) and 156.9 (C=O); *m/z* 332 (M^+), 218, 109 and 69.

1-*Phenylthio*-2-(*trifluoroacetoxy*)*dec*-4-*ene* **4f**. From *oct*-1-*ene* **2f**. The crude product was purified by Kugelrohr distillation (0.1 mmHg, 110 °C) to yield a yellow oil (0.72 g, 61%), $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 2960–2860 (C–H), 1785 (C=O) and 1220 and 1160 (C–F); δ_H(200 MHz) 0.90 (t, *J* 6.8, 10-H_3), 1.2–1.45 (m, 7-, 8- and 9-H_2), 2.00 (q, *J* 7.0, 6-H_2), 2.3–2.6 (m, 3-H_2), 3.15 (d, *J* 6.3, 1-H_2), 5.15 (m, 2-H), 5.29 (m, 4-H), 5.56 (dt, *J* 15.2 and 7.0, 5-H) and 7.2–7.5 (m, Ph); δ_C(50 MHz) 13.7 (C-10), 22.3 (C-9), 28.6 (C-7), 31.1 (C-8), 32.3 (C-6), 35.9 (C-3), 37.0 (C-1), 76.9 (C-2), 114.6 (CF_3), 122.6 (C-4), 127.1 (*p*-C), 129.2 (*o*-C), 130.6 (*m*-C), 135.0 (arom. C–S), 136.5 (C-5) and 157.0 (C=O); *m/z* 360 (M^+), 247, 137, 109 and 69.

3-[2′-*Phenylthio*-1′-(*trifluoroacetoxy*)*ethyl*]*cyclohexene* **4g**. *From cyclohexene* **2g**. The product was a mixture of diastereoisomers, and was purified by Kugelrohr distillation (0.1 mmHg, 130 °C), then by chromatography (eluent CH_2Cl_2) to yield a yellow oil (0.67 g, 62%), ν_{max}(film)/cm^{-1} 3065–2860 (C–H), 1785 (C=O) and 1225–1165 (CF_3); NMR data for the major isomer: δ_H(200 MHz) 1.2–2.2 (m, 4-, 5- and 6-H_2), 2.55–2.7 (m, 3-H), 3.15 (dd, *J* −8.6 and 4.5, 2′-H^a), 3.21 (dd, *J* −8.6 and 6.8, 2′-H^b), 5.17 (dt, *J* 6.8 and 4.5, 1′-H), 5.45 (dm, *J* 10.1) and 5.85 (dm, *J* 10.1, 1- and 2-H) and 7.2–7.6 (m, Ph); δ_C(50 MHz) 20.6, 23.2 and 24.7 (C-4, -5, and -6), 35.8 (C-2′), 38.5 (C-3), 79.5 (C-1′), 114.6 (CF_3), 125.3 (C-1 or -2), 127.3 (*p*-C), 129.3 (*o*-C), 130.8 (*m*-C), 133.8 (C-2 or -1), 134.8 (arom. C–S) and 156.9 (C=O); *m/z* 330 (M^+), 218, 216, 109, 79 and 69.

3-(*Phenylthio*)*oct*-5-*en*-2-*ol* **8a** *and* 2-(*Phenylthio*)*oct*-5-*en*-3-*ol* **8b**. *Following general procedure I, with a* 1:1 *mixture of the isomers of* 1-(*phenylsulfinyl*)*propene* **6** (0.5 g, 3.0 mmol) *and pent*-1-*ene* **2d**. The reaction mixture was stirred for 72 h at room temperature then was worked up as before. The crude trifluoroacetates **7a** and **7b** were hydrolysed by being stirred at room temperature for 1 h in methanol (20 cm^3) with NaOH (2 mol equiv.). The solvent was then removed, and the residue was taken up in diethyl ether, washed with water, and then dried. After removal of the solvent, the products **8a** and **8b** are separated by chromatography with CH_2Cl_2–diethyl ether (19:1). Overall yield was 0.47 g (63%). Both compounds were obtained as a mixture of diastereoisomers (NMR data for the major diastereoisomer). Compound **8a** δ_H(500 MHz) 0.90 (t, *J* 7.5, 8-H_3), 1.21 (d, *J* 6.3, 1-H_3), 1.95 (quint, *J* 7.5, 7-H_2), 2.18 (m, 4-H^a), 2.38 (dt, ^2J −14.6, ^3J 5.7, 4-H^b), 2.94 (m, 3-H), 3.74 (m, 2-H), 5.45–5.55 (m, 5- and 6-H) and 7.1–7.4 (m, Ph); δ_C(125 MHz) 13.7 (C-8), 20.2 (C-1), 25.6 (C-7), 34.8 (C-4), 58.6 (C-3), 68.8 (C-2), 125.6 (C-5), 127.1 (*p*-C), 128.9 (*o*-C), 132.2 (*m*-C), 132.4 (arom. C–S) and 135.1 (C-6); *Compound* **8b** (Found: C, 71.2; H, 8.50; S, 13.6. $C_{14}H_{20}OS$ requires C, 71.1; H, 8.53; S, 13.6%); ν_{max}(film)/cm^{-1} 3610–3450 (O–H) and 3050–2875 (C–H); δ_H(500 MHz) 0.96 (t, *J* 7.4, 8-H_3), 1.31 (d, *J* 7.0, 1-H_3), 2.02 (qd, *J* 7.4 and 6.4, 7-H_2), 2.16 (dt, ^2J −14.2, ^3J 7.7, 4-H^a), 2.42 (m, 4-H^b), 3.22 (qd, *J* 7.0 and 6.0, 2-H), 3.55 (m, 3-H), 5.41 (m, 5-H), 5.54 (dt, *J* 15.4 and 6.4, 6-H) and 7.2–7.45 (m, Ph); δ_C(50 MHz) 13.7 (C-8), 17.9 (C-1), 25.6 (C-7), 36.8 (C-4), 49.9 (C-2), 73.4 (C-3), 124.4 (C-5), 127.1 (*p*-C), 128.9 (*o*-C), 132.7 (*m*-C), 133.9 (arom. C–S) and 135.9 (C-6); *m/z* 236 (M^+), 167, 149, 137 and 109.

2-*Methyl*-5-(*phenylthio*)*pent*-1-*ene* **11**. 4-Methylpent-4-en-1-ol[7] (7.0 g, 70 mmol) was mixed with pyridine (14.0 g, 177 mmol) at 0 °C. Toluene-*p*-sulfonyl chloride (17.3 g, 90 mmol) was added by portions to the strongly stirred mixture, which was then left for 3 days at room temp. The resulting mass was dissolved with dil. aq. hydrochloric acid (200 cm^3) and diethyl ether (150 cm^3). The aqueous phase was further extracted with diethyl ether (2 × 150 cm^3), and the combined organic phases were washed successively with dil. HCL (50 cm^3) then with dil. aq. $NaHCO_3$ (50 cm^3). After drying, the solvent was removed. The crude tosyl ester was added, at 0 °C, to a solution of thiophenol (7.69 g, 70 mmol) and 85% potassium hydroxide (4.60 g, 70 mmol) in methanol (250 cm^3). The mixture was stirred for 14 h at room temp., refluxed for 1 h, and the solvent was then removed. The residue was dissolved in water (200 cm^3), and was extracted twice with light petroleum (200 cm^3). The combined organic phases were then washed with dil. aq. potassium carbonate, dried, and evaporated. Distillation (75 °C, 0.3 mmHg) gave *compound* **11** (7.30 g, 54%) (Found: S, 16.85. $C_{12}H_{16}S$ requires S, 16.7%); ν_{max}(film)/cm^{-1} 3070 (=CH), 2970–2910 (C–H) and 1649 (C=C); δ_H(200 MHz), 1.69 (s, Me), 1.77 (quint, *J* 7.4, 4-H_2), 2.14 (t, *J* 7.4, 3-H_2), 2.90 (t, *J* 7.4, 5-H_2), 4.67 (s) and 4.73 (s, 1-H_2) and 7.1–7.4 (m, Ph); δ_C(50 MHz), 22.2 (Me), 26.8 (C-4), 32.9 (C-5), 36.6 (C-3), 110.6 (C-1), 125.6 (*p*-C), 128.7 (*o*-C), 129.0 (*m*-C), 136.7 (arom. C–S) and 144.5 (s, C-2); *m/z* 192 (M^+), 136, 123, 110 and 109.

Synthesis of diene **3** *from ene* **11**. The sulfide **11** (2.0 g, 10.4 mmol) was dissolved in tetrachloromethane (5 cm^3) and the solution was added to a cooled (0 °C) suspension of NCS (1.46 g, 10.9 mmol) in CCl_4 (20 cm^3). After 14 h at room temp., the succinimide was filtered off and the solvent was removed. The crude chloro sulfide **12** was dissolved in isobutene **2a** (5 cm^3) condensed by a solid CO_2–acetone condenser, and TFA (2 cm^3, 26 mmol) was added dropwise. The reaction mixture was stirred for 1 h under reflux of the alkene (−6 °C), then was diluted with diethyl ether (100 cm^3). The solution was washed twice with dil. aq. potassium carbonate (each 50 cm^3), then once with brine (25 cm^3), dried, and concentrated. Chromatography (cyclohexane) yielded compound **3** (1.25 g, 49%).

Oxidative elimination from sulfide **3**. The sulfide **3** (1.17 g, 4.8 mmol) was dissolved in methanol (40 cm^3) and the solution was cooled to 0 °C. Aq. sodium metaperiodate (1.25 g, 5.8 mmol in 20 cm^3) was then added, and the mixture was stirred overnight at room temp. After evaporation of the methanol, water (75 cm^3) was added, and the sulfoxide was extracted with diethyl ether (100 cm^3), which was then washed with water (50 cm^3) and dried. After removal of the solvent, the crude product was heated for 30 min at 130 °C in a Kugelrohr distillation apparatus under 20 mmHg pressure. The distillate thus obtained (0.40 g, 58%) gave the same ^1H NMR spectra as reported[9] for 2,7-dimethylocta-1,3,7-triene **13**.

2-*(Phenylthio)pent-4-en-1-ol* **19**. A solution of methyl (phenylthio)acetate **18** (4.0 g, 22 mmol) in CCl_4 (10 cm^3) was added to a solution of NCS (3.08 g, 23 mmol) in CCl_4 (50 cm^3). After the mixture had been stirred overnight at room temp., the succinimide was filtered off and the filtrate was concentrated. The crude chloro sulfide was mixed in CH_2Cl_2 (80 cm^3) with allyltrimethylsilane (2.88 g, 25 mmol), and the mixture was cooled to −30 °C. A solution of 2.2 mol dm^{-3} $ZnCl_2$·Et_2O in CH_2Cl_2 (2 cm^3, 4.4 mmol) was added, and the mixture was stirred for 3 h at room temp., washed with water (50 cm^3), dried, and concentrated. The crude methyl 2-(phenylthio)pent-4-enoate[22] was of satisfactory purity. It was dissolved in diethyl ether (20 cm^3) and the solution was slowly added at −20 °C to a slurry of LAH (0.58 g, 15 mmol) in diethyl ether (50 cm^3). After this addition, the mixture was stirred overnight at room temp., and quenched by methanol (5 cm^3), then with dil. sulfuric acid (50 cm^3). The organic phase was washed with dilute aq. $NaHCO_3$ (20 cm^3), dried, and concentrated. Chromatography with light petroleum–ethyl acetate (6:1) gave compound **19** (2.61 g, 61%) (Found: C, 67.4; H, 7.2; S, 16.3. $C_{11}H_{14}OS$ requires C, 67.99; H, 7.26; S, 16.50%); ν_{max}(film)/cm^{-1} 3500–3300 (O–H) and 1640 (C=C); δ_H(200 MHz) 2.3 (br s, OH), 2.39 (t, *J* 6.9, 3-H_2), 3.23 (m, 2-H), 3.56 and 3.65 (ABX, ^2J −11.5, ^3J 5.1, 6.0, 1-H_2), 5.1–5.2 (m, 5-H_2), 5.89 (ddt, *J* 16.9, 10.3 and 6.9, 4-H) and 7.2–7.5 (m, Ph); δ_C(50 MHz) 35.7 (C-3), 51.5 (C-2), 63.2 (C-1), 117.5 (C-5), 127.5 (*p*-C), 129.0 (*o*-C), 132.8 (*m*-C) and 134.9 (C-4); *m/z* 194 (M^+), 153, 135, 110, 109 and 91.

General Procedure II for Trifluoroacetylation of Alcohols.—The alcohol (1 mol equiv.) was mixed with 1.5 mol equiv. of both pyridine and TFAA at 0 °C in CH_2Cl_2, and the mixture was stirred for 2 h at that temperature. The solution was then washed with dil. aq. $NaHCO_3$, dried, and concentrated to yield a liquid. The crude product was generally of high purity.

2-*(Phenylthio)pent-4-enyl trifluoroacetate* **16**. The alcohol **19** (0.17 g, 0.88 mmol) gave crude ester **16** (0.26 g, 100%), δ_H(200 MHz) 2.45 (m, 3-H_2), 3.42 (m, 2-H), 4.36 and 4.40 (ABX, ^2J −11.2, ^3J 5.3 and 7.6, 1-H_2), 5.1–5.2 (m, 5-H_2), 5.88 (m, 4-H) and 7.2–7.5 (m, Ph); δ_C(50 MHz) 35.5 (C-3), 46.2 (C-2), 68.6 (C-1), 114.4 (CF_3), 118.6 (C-5), 128.0 (*p*-C), 129.2 (*o*-C), 132.8 (arom. C–2), 132.9 (*m*-C), 133.4 (C-4) and 157.1 (C=O).

2-*(Phenylthio)propyl trifluoroacetate* **20**. 2-(Phenylthio)-propan-1-ol[11] (1.0 g, 5.9 mmol) gave compound **20** in quantitative yield, δ_H(200 MHz) 1.36 (d, *J* 7.0, Me), 3.47 (m, 2-H), 4.23 and 4.40 (ABX, ^2J −11, ^3J 5.1 and 8.3, 1-H_2) and 7.25–7.5 (m, Ph); δ_C(50 MHz) 17.3 (Me), 40.9 (C-2), 70.6 (C-1), 114.5 (CF_3), 128.0, 129.2 and 133.0 (arom. C–H) and 132.7 (arom. C–S) (C=O not observed).

1-*Methyl-2-(phenylthio)ethyl trifluoroacetate* **21**. 1-(Phenylthio)propan-2-ol[11] (1.0 g, 5.9 mmol) gave compound **21** in quantitative yield, δ_H(200 MHz) 1.44 (d, *J* 6.3), 3.05 and 3.21 (ABX, ^2J −14.1, ^3J 6.2 and 6.6, 2-H_2), 5.17 (sext, *J* 6.4, 1-H) and 7.25–7.45 (m, Ph); δ_C(50 MHz) 18.7 (Me), 38.9 (C-2), 74.6 (C-1), 114.4 (CF_3), 127.0, 129.1 and 130.4 (arom. C–H), 134.6 (arom. C–S) and 156.8 (C=O).

General Procedure III for Isomerisation of Trifluoroacetates.—The trifluoroacetate (~2 mmol) was stirred at room temp. for 2 days with pentane (2 cm^3) and TFA (0.5 cm^3). CH_2Cl_2 (30 cm^3) was added, and the solution was washed with dil. aq. $NaHCO_3$ (20 cm^3), dried, and concentrated. The ratio of starting and rearranged compounds was estimated by ^1H NMR spectroscopy.

Primary ester **16** *to secondary ester* **4b**. With compound **16** (0.63 g, 2.17 mmol). ^1H NMR analysis of the crude product showed a 1:20 ratio of isomers **16**:**4b**. Kugelrohr distillation (0.03 mmHg, 90 °C) gave secondary ester **4b** (0.42 g, 67%).

Primary ester **20** *to secondary ester* **21**. The ratio of the two compounds was estimated (ratio of the two Me resonances) to be 1:27.

2-*(Phenylthio)ethyl trifluoroacetate* **27**.[23] Prepared following General procedure II, with 2-(phenylthio)ethanol (10.0 g, 65 mmol). The crude product was distilled (75 °C, 0.7 mmHg) to yield compound **27** (14.8 g, 91%), ν_{max}(film)/cm^{-1} 1787 (C=O) and 1150 (C–F); δ_H(200 MHz) 3.17 (t, *J* 7, 2-H_2), 4.43 (t, *J* 7, 1-H_2) and 7.2–7.5 (m, Ph); δ_C(50 MHz) 31.8 (C-2), 65.9 (C-1), 114.4 (CF_3), 127.2 (*p*-C), 129.2 (*o*-C), 130.6 (*m*-C), 133.9 (arom. C–S) and 157.1 (C=O).

2-*Phenylthio-1,1-bis(trifluoroacetoxy)ethane* **25**. (Phenylthio)acetaldehyde **26** (1 g, 6.6 mmol) was stirred overnight at room temp. with $CHCl_3$ (4 cm^3) and TFAA (4.0 g, 19 mmol). The solvent and the excess of TFAA were evaporated off, to yield crude diester **25** of satisfactory purity, which yielded a liquid (1.67 g, 70%) by Kügelrohr distillation (120 °C, 0.6 mmHg), ν_{max}(film)/cm^{-1} 1815 (C=O) and 1230–1100 (C–F); δ_H(200 MHz) 3.38 (d, *J* 5.8, 2-H_2), 6.96 (t, *J* 5.8, 1-H) and 7.3–7.55 (m, Ph); δ_C(50 MHz) 36.9 (C-2), 92.5 (C-1), 113.9 (CF_3), 128.3 (*p*-C), 129.5 (*o*-C), 131.7 (*m*-C), 132.5 (arom. C–S) and 155.1 (C=O); *m/z* 362 (M^+), 248, 123, 109 and 69.

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