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The methoxycarbonylcarbene insertion into 1,3-dithiolane and 1,3-oxathiolane rings

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Abstract—Treatment of substituted 1,3-dithiolanes and 1,3-oxathiolanes with methyl diazoacetate in the presence of $Rh_2(OAc)_4$ effects ring expansion to the corresponding substituted 1,4-dithiane-2-carboxylates and 1,4-oxathiane-3-carboxylates. The sulfur ylides initially generated in these reactions undergo Stevens rearrangement in competition with both [2,3]-C–C-sigmatropic rearrangement and intramolecular fragmentation. In the case of 2-styryl-substituted 1,3-oxathiolane and 1,3-dithiolane, ring expansion on one-, three- and four-carbons subsequently takes place.

1. Introduction

The formation of ylides by intermolecular or intramolecular reactions of carbenes or metal carbenoids with heteroatom-bearing molecules such as sulfides,[1] ethers,[2] or amines,[3] has been widely investigated. Sulfur ylides have become increasingly useful intermediates in synthetic organic chemistry. Their chemistry has been thoroughly discussed in a number reviews.[4] These ylides can undergo three types of reaction: (a) intramolecular fragmentation, (b) [1,2]-C–C-shift (Stevens rearrangement), (c) [2,3]-C–C-sigmatropic rearrangement. With simple allyl sulfides the [2,3]-C–C-sigmatropic rearrangement is the major reaction pathway,[5] and the advantage of using this method has recently been demonstrated in the synthesis of penicillins and 3-piperidinol alkaloids.[6,7] Previous studies of the metal-catalysed reactions of diazo compounds have shown that ylides derived from *O*,*O*-,[8] *O*,*N*-[9] and *S*,*S*-cyclic acetals[10] undergo the [1,2]-C–C-shift to form new carbon–carbon bonds with the expansion of the heterocycle.

2. Results and discussion

In this work, the interaction of methoxycabonylcarbene with 2-phenyl- and 2-styryl-1,3-dithiolanes, with 2-phenyl- and 2-styryl-1,3-oxathiolanes has been studied. It was established that the reaction of methyl diazoacetate with 2-phenyl-1,3-dithiolane **1** in the presence of 0.5 mol% $Rh_2(OAc)_4$ resulted in the formation of ring expansion products, *cis*-**2** and *trans*-**3** dithianes, in a ratio 5:1 with a combined yield of 42% with the diester **4** in 6% yield (Scheme 1). Separation of the reaction mixture by column chromatography on silica afforded *cis*-dithiane **2** (31%), diester **4** (6%) and a fraction, which contained a 1:2 mixture of **2** and **3**. The composition and structures of esters **2** and **4** were confirmed by elemental and spectral analysis. The ^{1}H NMR spectra of compounds **2** and **3** have doublet signals at δ 3.73 and 4.57 (J=3.5 Hz) and δ 4.19 and 4.39 (J=10.2 Hz), respectively, belonging to the methine protons at the C(2) and C(3) atoms of ester **2** and **3**, respectively. From X-ray diffraction analysis data it was determined that, in ester **2**, the phenyl group occupies the equatorial position, and the ethyl ester occupies the axial position (Fig. 1). The olefinic proton of the diester **4** is seen at δ 5.9. Hydrolysis of diester **4** afforded diacid **7**.

Treatment of 2,2-disubstituted 1,3-dithiolanes **8a**,**b** with methyldiazoacetate (1.2-fold excess of diazo ester) in the presence of rhodium(II) acetate leads to 1,4-dithianes **9a**,**b** (yields of 37 and 44%, respectively) and 1,4-dithiepanes

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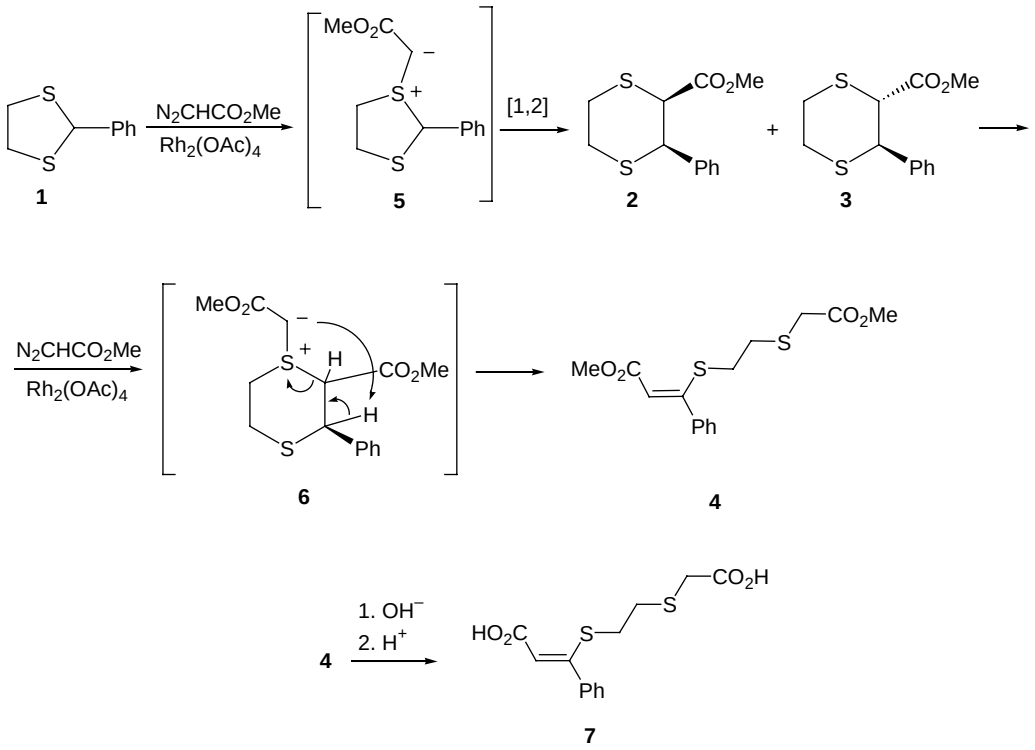


Scheme 1.

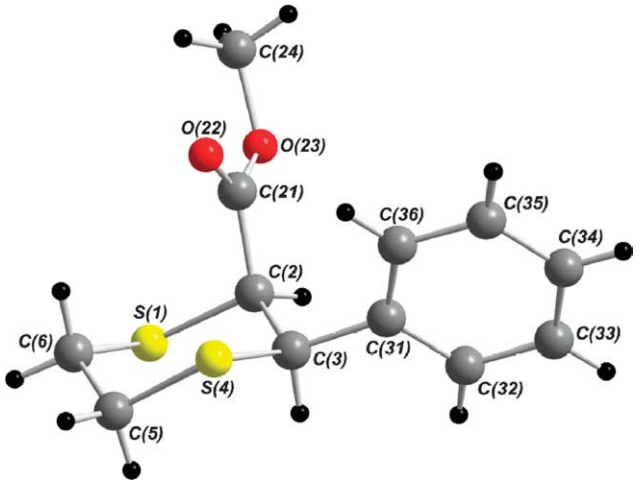


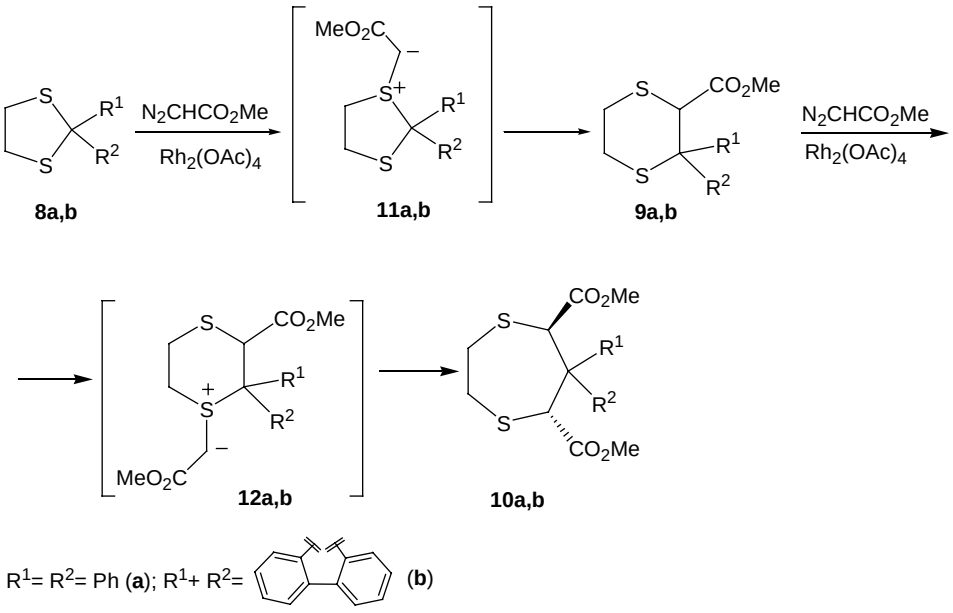
Figure 1. The X-ray crystal structure of compound **2**.

10a,**b** (in 11 and 8% yield, respectively) (Scheme 2). The composition and the structures of compounds **9a**,**b** and **10a**,**b** were confirmed by elemental and spectral analysis. The ^{1}H NMR spectra of compounds **9a**,**b** exhibit signals for the methine proton at the C(2) atom at δ 4.36 and 4.68, respectively. The shift of the signal of the ester groups to a higher field [δ 3.39 (**9a**) and 3.25 (**9a**)] is due to the shielding effect induced by the benzene rings. The ^{1}H NMR spectra of compounds **10a**,**b** show singlet signals for the methine protons at the C(2) and C(4) atoms at δ 5.24 (2H) and 5.08 (2H), respectively. The trans-arrangement of the esters groups in compound **10a** was confirmed by X-ray diffraction studies (Fig. 2).

Recently, it has been noted that the treatment of 2-phenyl-1,3-oxathiolane **13** with ethyl diazoacetate in the presence of copper(II) acetylacetonate leads to a ring expansion, giving a mixture of cis- and trans-isomers of ethyl 2-phenyl-1,4-oxathiane-3-carboxylate in 19% yield.[11] In the present study, it has been established that the reaction of 1,3-oxathiolane **13** with methyl diazoacetate in the presence of $Rh_2(OAc)_4$ affords a mixture of *cis*-**14** and *trans*-**15** isomers of methyl 2-phenyl-1,4-oxathiane with 48% yield, in a ratio of 1:1.8, respectively (Scheme 3). The diester **16** was produced in 5% yield after column chromatography on silica. The pure trans-isomer **15** was obtained by recrystallisation at low temperatures of the isomeric mixture.

^{1}H NMR spectra of 1,4-oxathianes **14** and **15** exhibit doublet signals at δ 3.39 and 4.95 (J=3.1 Hz) and δ 3.85 and 4.78 (J=9.3 Hz), respectively, belonging to the methine protons at the C(2) and C(3) atoms of ester **14** and **15**, respectively. The olefinic proton of the diester **16** is observed at δ 5.3. The reaction of 2,2-diphenyl-1,3-oxathiolane **19** with methoxycarbonylcarbene, which was generated under the same conditions, resulted in the formation of methyl 3,3-diphenyl-1,3-oxathiane-2-carboxylate **20** in 51% yield (Scheme 4).

The results obtained in the present study provide evidence that methoxycarbonylcarbene reacts with dithiolanes **1**, **8a**,**b** and oxathiolanes **13**, **19** to form *S*-ylides **5**, **11a**,**b**, **17** and **21**, which undergo the Stevens rearrangement with ring expansion to produce dithiane and oxathiane derivatives. In the reactions of methoxycarbonylcarbene with oxathiolanes **13** and **19**, the formation of isomeric oxathianes, which should be obtained as a result of the rearrangement of the corresponding *O*-ylides, was not observed. Therefore, it



Scheme 2.

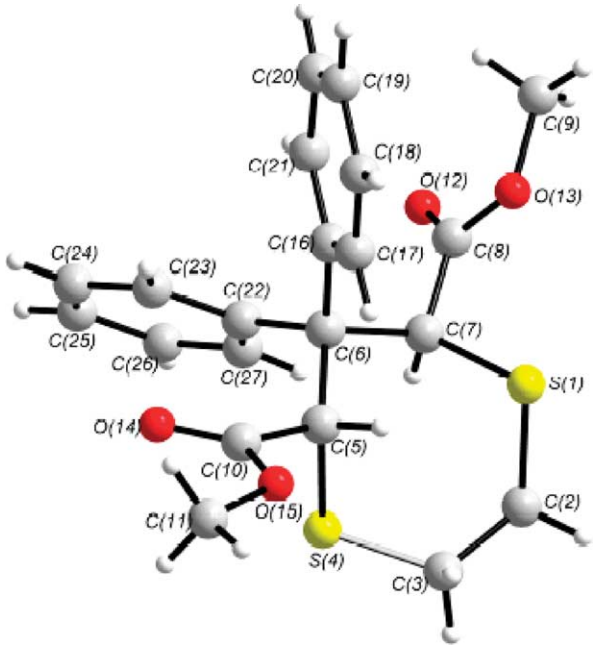


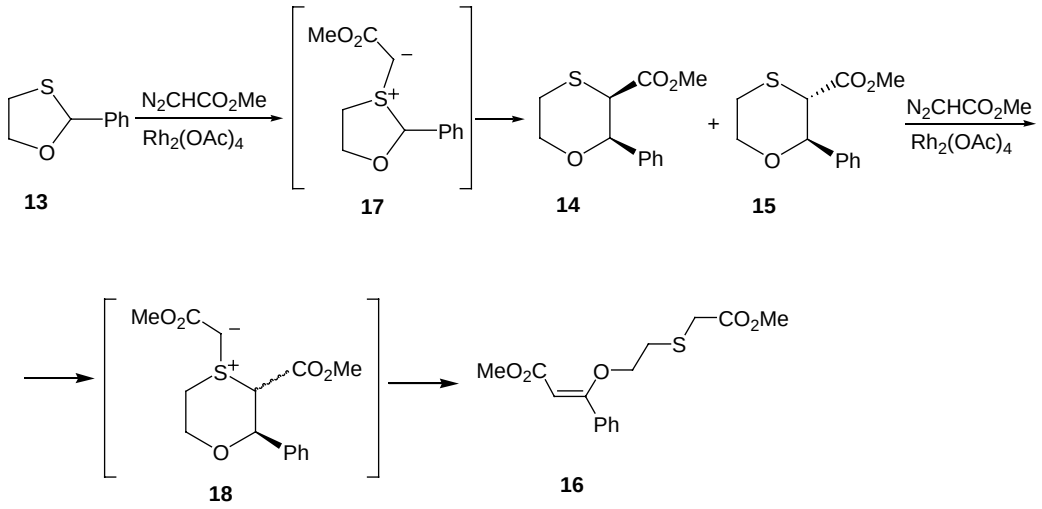
Figure 2. The X-ray crystal structure of compound **10a**.

can be proposed that this reaction occurs only through the formation of *S*-ylides. The subsequent reactions of esters **9a**,**b** with methoxycarbonylcarbene also gave *S*-ylides **12a**,**b**, which rearranged into diesters **10a**,**b**. The esters **2**, **3**, **14**, **15** also react with methoxycarbonylcarbene to give sulfur ylides **6** and **18**. In these cases it appears that intermediate ylides suffer a fragmentation process rather than undergoing ring expansion. It should be noted that such fragmentation products have been found earlier in the reaction of ethyl diazoacetate with substituted 1,3-dithianes.[10] It seems that intramolecular fragmentation in both cases results in the formation of olefins **4** and **16**.

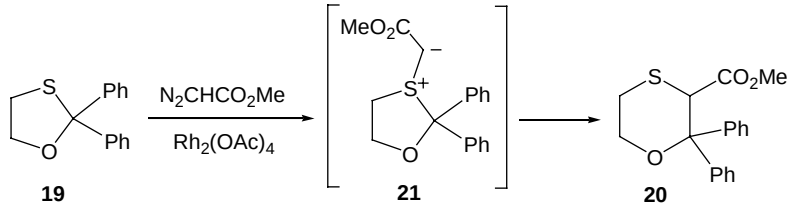
The treatment of 2-styryl-1,3-dithiolane **22** with methyl diazoacetate in the presence of 0.5 mol% $Rh_2(OAc)_4$ afforded a complex mixture of products. Column chromatography of this mixture made it possible to isolate methyl *cis*-6-phenyl-2,3,5,6-tetrahydro-1,4-dithiocine-5-carboxylate **23** in 34% yield and also *cis*-**24** and *trans*-**25** dimethyl 6-phenyl-2,3,6,9-tetrahydro-5*H*-1,4-dithionine-5,9-dicarboxylates in yields of, 7 and 3%, respectively (Scheme 5).

The ^{1}H NMR spectrum of ester **23** exhibit signals for the methine protons at the C(8) and C(7) atoms at δ 3.76 (d, J=2.2 Hz) and 5.05 (dd, J=8.7, 2.2 Hz), respectively, and signals for the olefinic protons at the C(5) and C(6) atoms at δ 6.26 (d, J=8.7 Hz) and 7.01 (t, J=8.7 Hz), respectively. The coupling constants are indicative of a cis-arrangement of the substituents at the C(8) and C(7) atoms. The coupling constant for the olefinic protons is 8.7 Hz, indicating that there is a cis-double bond in compound **23**.[12] The ^{1}H NMR spectra of the diesters **24** and **25** exhibit signals of δ 6.14, 6.65 and δ 5.95, 6.25, respectively, belonging to the olefinic protons. The coupling constant for the olefinic protons is both 16.1 Hz, indicating that there is a trans-double bond in compounds **24** and **25**. The structures of compounds **24** and **25** were confirmed by X-ray diffraction studies (Figs. 3 and 4).

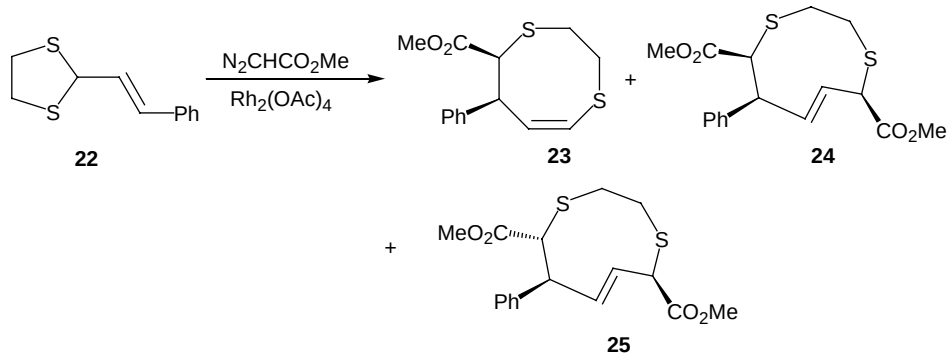
The results above provide evidence that methoxycarbonylcarbene reacts with dithiolane **22** to form the *S*-ylide **26**, which undergoes the [2,3]-C–C-sigmatropic rearrangement with the ring expansion to produce dithiocine **23** (path A). Alternatively conversion of the *S*-ylide **26** by the Stevens rearrangement may form the styryl-dithiane **27** (path B). Compound **27** then reacts with methoxycarbonylcarbene to form the *S*-ylide **28**, and as a result of [2,3]-C–C-sigmatropic rearrangement of *S*-ylide **28**, the isomeric diesters **24** and **25** are formed (Scheme 6). It is important to note that signals corresponding to dithiane **27** were not observed in the ^{1}H NMR spectra of reaction mixtures.



Scheme 3.



Scheme 4.



Scheme 5.

The interaction of 2-styryl-1,3-oxathiolane **29** with methoxycarbonylcarbene afforded a complex mixture of products. The esters **30** and **31** were produced in 13 and 24% yield, respectively, after column chromatography on silica (Scheme 7). The ^{1}H NMR spectra of esters **30** and **31** exhibit signals for the olefinic protons at δ 5.65 (dd, J=5.8, 4.9 Hz) and 6.19 (d, J=5.8 Hz) for compound **30** and δ 6.22 (dd, J=16.2, 6.2 Hz) and 6.70 (dd, J=16.2, 1.5 Hz) for compound **31**, and signals for the methine protons at δ 3.67 (d, J=2.3 Hz) and 4.55 (dd, J=4.9, 2.3 Hz) for compound **30** and δ 3.32 (d, J=2.3 Hz) and 4.57 (ddd, J=6.2, 2.3, 1.5 Hz) for compound **31**. The coupling constants (2.3 Hz in both cases) are indicative of a cis-arrangement of the substituents at the C(2) and C(3) atoms in ester **31** and also at the C(7) and C(8) atoms in ester **30**. On the basis of this data, it can be proposed that transformation of ylide **32**, which is formed by the reaction of oxathiolane **29** with methoxycarbonylcarbene, may occur by two different

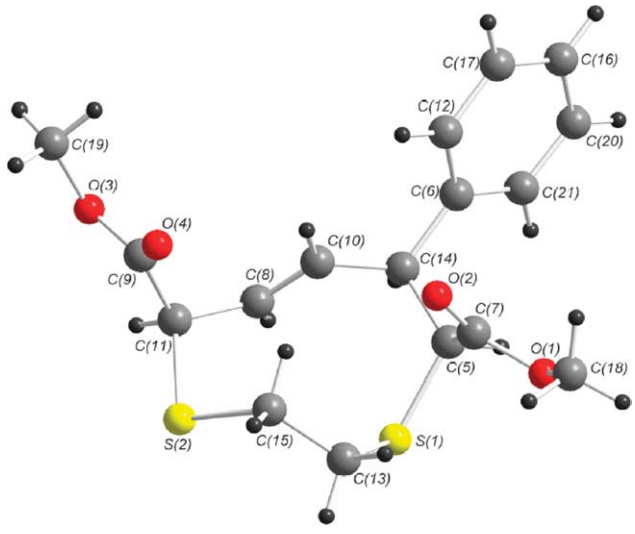


Figure 3. The X-ray crystal structure of compound **24**.

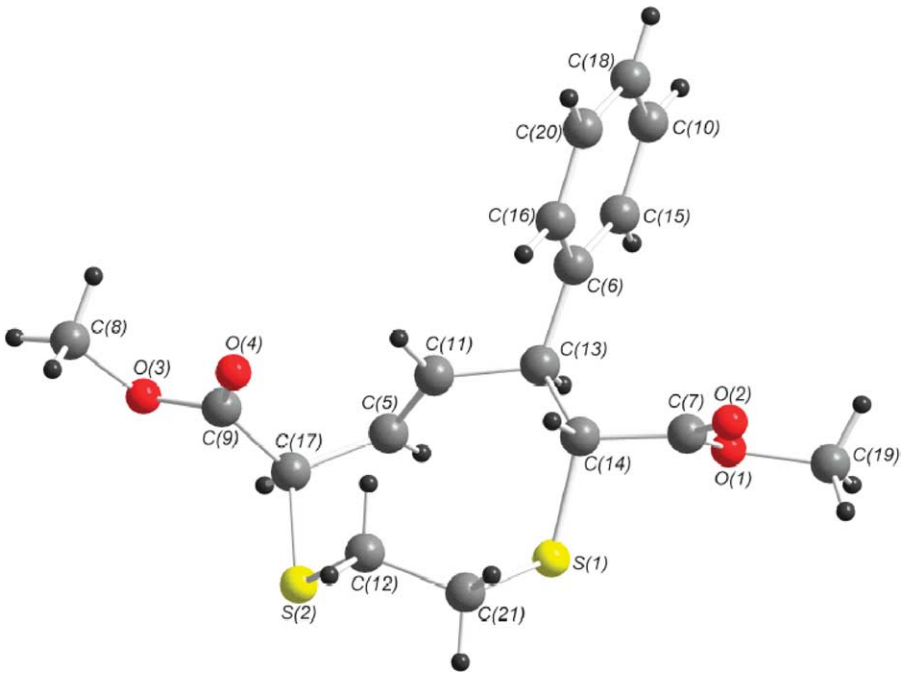
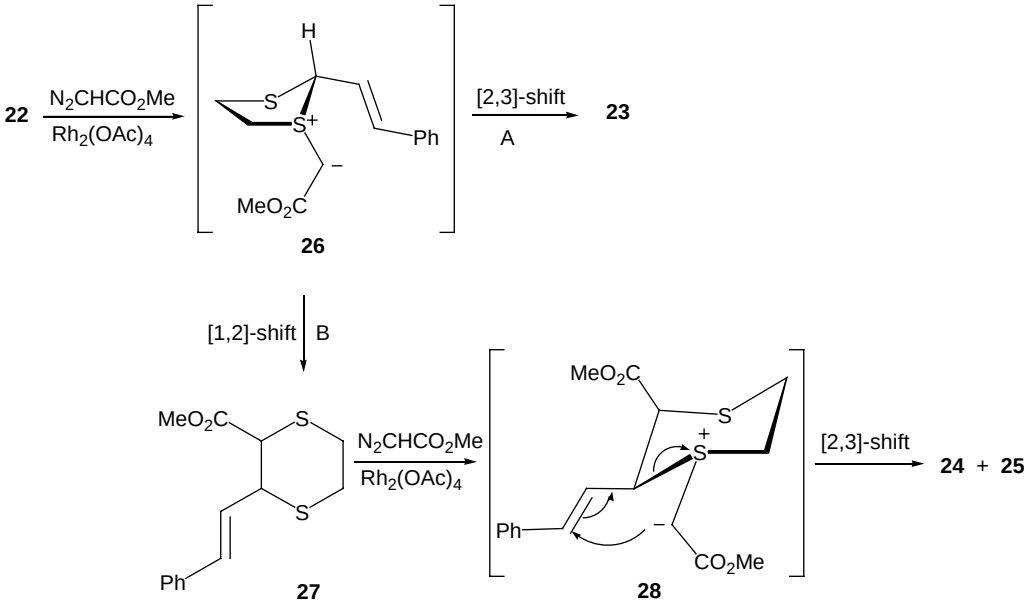


Figure 4. The X-ray crystal structure of compound **25**.

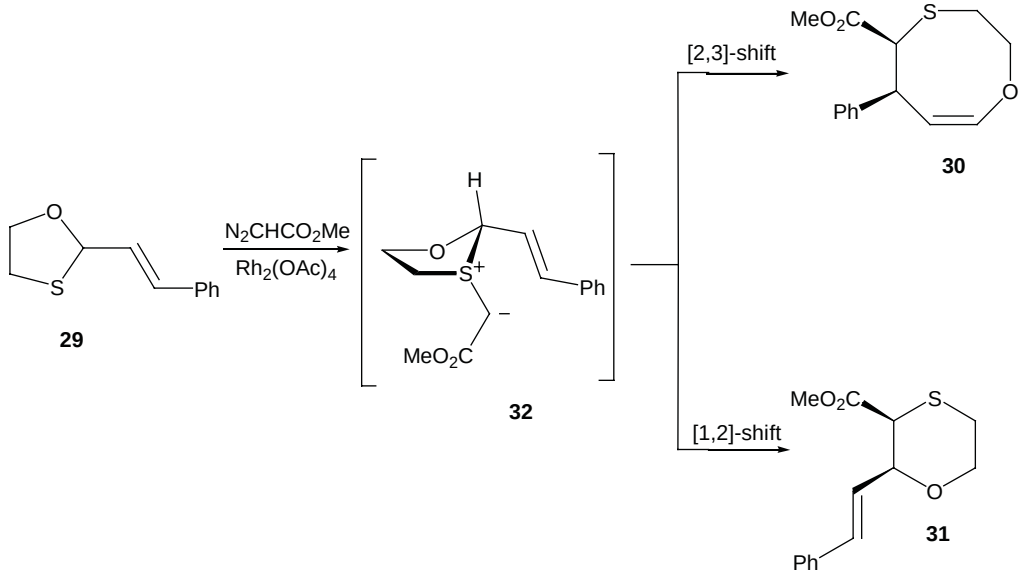
paths: both [2,3]-C–C-sigmatropic rearrangement, with formation of ester **30**, and Stevens rearrangement, with formation of ester **31**.

3. Conclusion

In summary, we have established that ring expansion of 2-substituted 1,3-dithiolanes and 1,3-oxathiolanes may be carried out by treatment with methyl diazoacetate in the presence of $Rh_2(OAc)_4$ in a moderate yield. It has been shown that the initially generated *S*-ylides in the reaction of methoxycarbonylcarbene with these compounds can undergo [1,2]-C–C-shift with the expansion of the five membered rings. *S*-Ylides, which are formed in the reaction of methoxycarbonylcarbene with 2-styryl-1,3-dithiolane and 2-styryl-1,3-oxathiolane undergo [1,2]- and [2,3]-C–C-sigmatropic rearrangement. The *S*-ylides generated from $Rh_2(OAc)_4$ catalyzed reactions of methyl diazoacetate with substituted 1,4-dithianes and 1,4-oxathianes undergo [1,2]-C–C-shift in competition with intramolecular fragmentation.



Scheme 6. A plausible mechanism of formation products **23**–**25**.



Scheme 7.

4. Experimental

4.1. General

Melting points are uncorrected and were determined with a Boetius hot stage. Elemental analyses were performed on a Hewlet–Packard 185B CHN analyzer. IR spectra were recorded on a UR-20 spectrophotometer as a 2% solution in $CHCl_3$. ^1H and ^{13}C NMR spectra were recorded with a Bruker DPX-300 spectrometer (300 and 75 MHz, respectively). Purity checking of products and analysis of reaction mixtures were carried out by TLC on Silufol UV-254 plates. Column chromatography was performed on silica gel 30–70 and 40–100 mesh eluted with hexane/ethyl acetate mixtures. Methyl diazoacetate,[13] 1,3-dithiolane[14] **1**, **5a**,**b**, **17** and 1,3-oxathiolane[15] **10**, **14**, **24** were synthesized according to known procedures.

4.2. Experimental procedures

4.2.1. Methyl *cis*-3-phenyl-1,4-dithiane-2-carboxylate (2), methyl *trans*-3-phenyl-1,4-dithiane-2-carboxylate (3) and (*Z*)-methyl 3-(2-methoxycarbonylmethylsulfanyl-ethylsulfanyl)-3-phenyl-acrylate (4). Methyl diazoacetate (0.24 g, 2.4 mmol) was added with rapid stirring to a mixture of dithiolane **1** (0.4 g, 2.2 mmol) and $Rh_2(OAc)_4$ (4.4 mg, 0.01 mmol) in benzene (2 ml) at 80 °C during 2 h. The reaction mixture was stirred at this temperature for 45 min and then cooled. The solvent was distilled off in vacuo. Separation of the reaction mixture on a column with silica gel using a 6:1 hexane/ethyl acetate mixture as the eluent afforded **2** (0.17 g, 31%), **4** (43 mg, 6%) and a fraction, which contained a 1:2 mixture of **2** and **3**.

Compound **2**. Colorless crystals; mp 111–112 °C (recryst. from MeOH); IR ($CHCl_3$) 3040, 1730, 1490, 1450, 1350, 1240, 1160 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.68–2.75 (1H, m, CH_2), 3.03–3.09 (1H, m, CH_2), 3.16–3.28 (1H, m, CH_2), 3.49–3.56 (1H, m, CH_2), 3.59 (3H, s, OCH_3), 3.73 (1H, d, J=3.5 Hz, $CHCO_2Me$), 4.57 (1H, d, J=3.5 Hz, *CH*Ph), 7.28–7.34 (5H, m, Ar-*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.7 (CH_2), 31.0 (CH_2), 44.2 (C-2), 47.6 (C-3), 52.3 (OMe), 128.0, 128.4, 129.0, 140.5 (aromatic), 170.4 (CO). MS (EI): *m*/*z* (%) 254 (35) [M^+], 194 (33), 134 (19), 122 (100), 121 (34), 103 (17), 92 (23). Anal. Calcd for $C_{12}H_{14}O_2S_2$: C, 56.66; H, 5.55. Found: C, 56.61; H, 5.54.

Compound **3**. ^1H NMR (300 MHz, $CDCl_3$) δ 2.89–2.98 (2H, m, CH_2), 3.31–3.39 (2H, m, CH_2), 3.44 (3H, s, OCH_3), 4.19 (1H, d, J=10.2 Hz, $CHCO_2Me$), 4.39 (1H, d, J=10.2 Hz, *CH*Ph), 7.27–7.41 (5H, m, Ar-*H*).

Compound **4**. Pale yellow oil; IR ($CHCl_3$) 3050, 2960, 1730, 1590, 1440, 1350, 1290, 1160, 1020 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.88 (2H, t, J=6.3 Hz, SCH_2CH_2-SCH_2), 2.97 (2H, t, J=6.3 Hz, $SCH_2CH_2SCH_2$), 3.20 (2H, s, SCH_2CO_2Me), 3.54 (3H, s, OCH_3), 3.73 (3H, s, OCH_3), 5.87 (1H, s, *CH*=C), 7.28–7.36 (5H, m, Ar-*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 31.5 (CH_2), 32.2 (CH_2), 33.7 (CH_2), 51.5 (OMe), 52.9 (OMe), 111.8 (MeO_2C–*C*H=C), 128.4, 128.7, 129.5, 137.1 (aromatic), 159.1 (CH=*C*-Ph), 164.9 (CO), 170.9 (CO). Anal. Calcd for $C_{15}H_{18}O_4S_2$: C, 55.19; H, 5.56. Found: C, 55.22; H, 5.51.

4.2.2. (*Z*)-3-(2-Carboxymethylsulfanyl-ethylsulfanyl)-3-phenyl-acrylic acid (7). A solution of **4** (40 mg, 0.12 mmol) and KOH (27 mg, 0.48 mmol) in MeOH (1 ml) was refluxed for 3 h. After removal of MeOH, the aqueous solution was neutralized with 10% aqueous HCl. The crystalline precipitate was filtered off, washed with water and air dried to give **7** (31 mg, 87%) as colorless crystals; mp 124–125 °C; IR ($CHCl_3$) 3430, 3050, 2960, 1720, 1620, 1450, 1300, 1190, 1120, 1040 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$/$(CD_3)_2CO$) δ 2.44 (2H, t, J=6.3 Hz, $SCH_2CH_2SCH_2$), 2.56 (2H, t, J=6.3 Hz, $SCH_2CH_2SCH_2$), 2.77 (2H, s, CH_2CO_2H), 5.38 (1H, s, *CH*=C), 6.77–6.89 (7H, m, Ar-*H*, $2CO_2H$); ^{13}C NMR (75 MHz, $CDCl_3$/$(CD_3)_2CO$) δ 30.6 (CH_2), 31.7 (CH_2), 32.9 (CH_2), 111.5 (MeO_2C–*C*H=C), 127.7, 128.3, 128.7, 137.0 (aromatic), 158.4 (CH=*C*-Ph), 165.2 (CO), 171.2 (CO). Anal. Calcd

for $C_{13}H_{14}O_4S_2$: C, 52.33; H, 4.73. Found: C, 52.33; H, 4.69.

4.2.3. Methyl 3,3-diphenyl-1,4-dithiane-2-carboxylate (9a) and dimethyl (5*R,7*R**)-6,6-diphenyl-1,4-dithiepane-5,7-dicarboxylate (10a).** Methyl diazoacetate (0.17 g, 1.7 mmol) was added under rapid stirring to a mixture of dithiolane **8a** (0.4 g, 1.5 mmol) and rhodium(II) acetate (4.4 mg, 0.01 mmol) in benzene (2 ml) at 80 °C for 2 h. The reaction mixture was stirred at this temperature for 1.5 h and then cooled. After removal of the solvent, the oily residue was purified by column chromatography (6:1 hexane/ethyl acetate) to afford **9a** (0.18 g, 37%) and **10a** (66 mg, 11%).

Compound **9a**. Colorless crystals; mp 142–143 °C (recryst. from MeOH); IR ($CHCl_3$) 3050, 1740, 1460, 1420, 1390, 1310, 1160 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.60–2.67 (1H, m, CH_2), 2.83–2.88 (2H, m, CH_2), 3.39 (3H, s, OCH_3), 3.50–3.59 (1H, m, CH_2), 4.36 (1H, s, $CHCO_2Me$), 7.19–7.36 (8H, m, Ar-*H*), 7.72 (2H, d, $J=7.2$ Hz, Ar-*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.6 (CH_2), 28.2 (CH_2), 47.1 (C-2), 52.3 (OMe), 54.3 (C-3), 127.4, 127.7, 128.3, 128.4, 128.5, 129.8, 144.0, 144.5 (aromatic), 170.7 (CO). MS (EI): *m*/*z* (%) 330 (69) [M^+], 269 (50), 207 (17), 198 (100), 178 (25), 165 (52), 121 (31), 92 (87). Anal. Calcd for $C_{18}H_{18}O_2S_2$: C, 65.42; H, 5.49. Found: C, 65.51; H, 5.47.

Compound **10a**. Colorless crystals; mp 153–155 °C (recryst. from MeOH); IR ($CHCl_3$) 3050, 2960, 1730, 1610, 1510, 1440, 1420, 1290, 1170, 1040 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.11–3.21 (4H, m, CH_2CH_2), 3.36 (6H, s, $2OCH_3$), 5.24 (2H, s, 2*CH*), 7.23–7.36 (8H, m, Ar-*H*), 7.51 (2H, d, $J=7.1$ Hz, Ar-*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 39.0 ($2CH_2$), 52.4 (C-5 and C-7), 58.9 (2OMe), 60.5 (C-6), 127.3, 128.5, 130.6, 139.9 (aromatic), 170.9 (2CO). MS (EI): *m*/*z* (%) 402 (2) [M^+], 238 (98), 237 (36), 207 (59), 179 (45), 178 (41), 165 (20), 105 (100), 92 (25). Anal. Calcd for $C_{21}H_{22}O_4S_2$: C, 62.66; H, 5.51. Found: C, 62.73; H, 5.46.

4.2.4. Methyl spiro[fluorene-9′,2-[1,4]dithiane-2-carboxylate] (9b) and dimethyl spiro[fluorene-9′,6-[1,4]dithiepane-5,7-dicarboxylate] (10b). Methyl diazoacetate (0.23 g, 2.3 mmol) was added with intense stirring to a mixture of dithiolane **8b** (0.5 g, 1.9 mmol) and rhodium(II) acetate (6 mg, 0.014 mmol) in benzene (4 ml) at 80 °C for 2.5 h. The reaction mixture was stirred at this temperature for 2 h and then cooled. After removal of the solvent, the oily residue was purified by column chromatography (6:1 hexane/ethyl acetate) to afford **9b** (0.21 g, 44%) and **10b** (61 mg, 8%).

Compound **9b**. Colorless crystals; mp 131–133 °C (recryst. from MeOH); IR ($CHCl_3$) 3050, 1740, 1470, 1450, 1330, 1290, 1150 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.98–3.03 (1H, m, CH_2), 3.25 (3H, s, OCH_3), 3.30–3.44 (2H, m, CH_2), 3.53–3.62 (1H, m, CH_2), 4.68 (1H, s, *CH*), 7.35–7.48 (4H, m, Ar-*H*), 7.76 (3H, br t, $J=8.0$ Hz, Ar-*H*), 8.51 (1H, d, $J=7.3$ Hz, Ar-*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 28.5 (CH_2), 30.4 (CH_2), 50.7 (C-3), 52.4 (C-2), 52.6 (OMe), 120.5, 120.6, 124.8, 126.6, 127.6, 127.9, 128.7, 129.4, 139.7, 140.0, 146.6, 148.0 (aromatic), 168.8 (CO). MS (EI): *m*/*z* (%) 328 (54) [M^+], 236 (100), 205 (27), 196 (72), 176 (15), 165 (21), 92 (23). Anal. Calcd for $C_{18}H_{16}O_2S_2$: C, 65.83; H, 4.91. Found: C, 65.78; H, 4.92.

Compound **10b**. Colorless crystals; mp 193–195 °C (recryst. from EtOH); IR ($CHCl_3$) 3050, 2950, 1730, 1600, 1450, 1410, 1300, 1160, 1040 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.08 (6H, s, $2OCH_3$), 3.24–3.35 (4H, m, CH_2CH_2), 5.08 (2H, s, 2*CH*), 7.35 (2H, t, $J=6.9$ Hz, Ar-*H*), 7.40 (2H, t, $J=6.9$ Hz, Ar-*H*), 7.63 (2H, d, $J=6.9$ Hz, Ar-*H*), 7.98 (2H, d, $J=6.9$ Hz, Ar-*H*). ^{13}C NMR (75 MHz, $CDCl_3$) δ 38.6 ($2CH_2$), 49.7 (C-5 and C-7), 57.1 (2OMe), 62.8 (C-6), 119.4, 120.2, 124.1, 134.9, 147.5, 149.1 (aromatic), 169.6 (2CO). MS (EI): *m*/*z* (%) 400 (2) [M^+], 236 (100), 205 (37), 178 (17), 165 (23), 105 (24). Anal. Calcd for $C_{21}H_{20}O_4S_2$: C, 62.98; H, 5.03. Found: C, 62.94; H, 5.09.

4.2.5. Methyl *cis*-2-phenyl-1,4-oxathiane-3-carboxylate (14), methyl *trans*-2-phenyl-1,4-oxathiane-3-carboxylate (15) and (*Z*)-methyl 3-(2-methoxycarbonylmethylsulfanyl-ethoxy)-3-phenyl-acrylate (16). Methyl diazoacetate (0.4 g, 4 mmol) was added with intense stirring to a mixture of oxathiolane **13** (0.55 g, 3.3 mmol) and rhodium(II) acetate (5 mg, 0.011 mmol) in benzene (5 ml) at 80 °C during 2 h. The reaction mixture was stirred at this temperature for 1 h and then was cooled. The solvent was distilled off in vacuo. Separation of the reaction mixture on a silica gel column, using a 6:1 hexane/ethyl acetate mixture as the eluent, afforded fractions, which contained a 1:1.8 mixture of **14** and **15** (0.38 g, 48%) and **16** (51.2 mg, 5%). Pure trans-isomer **15** was obtained by means of cooling the mixture of isomers in mixture of liquid nitrogen–isooctane and then filtration and recrystallisation of the crystalline product from methanol.

Compound **14**. ^1H NMR (300 MHz, $CDCl_3$) δ 2.25–2.29 (1H, m, SCH_2), 3.39 (1H, d, $J=3.1$ Hz, S*CH*), 3.50 (3H, s, OCH_3), 3.58–3.68 (1H, m, SCH_2), 3.97–4.05 (1H, m, OCH_2), 4.53–4.57 (1H, m, OCH_2), 4.95 (1H, d, $J=3.1$ Hz, O*CH*), 7.29–7.40 (5H, m, Ar-*H*). ^{13}C NMR (75 MHz, $CDCl_3$) δ 23.5 (C-5), 42.4 (C-3), 52.1 (OMe), 70.1 (C-6), 80.0 (C-2), 125.8, 127.3, 128.3, 140.1 (aromatic), 170.8 (CO). Anal. Calcd for $C_{12}H_{14}O_3S_2$: C, 60.48; H, 5.92. Found: C, 60.47; H, 5.88.

Compound **15**. Colorless crystals; mp 51–52 °C (recryst. from MeOH); IR ($CHCl_3$) 3050, 1720, 1450, 1310, 1160, 1090, 1030, 1010 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.52–2.56 (1H, m, SCH_2), 3.11–3.20 (1H, m, SCH_2), 3.48 (3H, s, OCH_3), 3.85 (1H, d, $J=9.3$ Hz, S*CH*), 3.96–4.03 (1H, m, OCH_2), 4.37–4.41 (1H, m, OCH_2), 4.78 (1H, d, $J=9.3$ Hz, O*CH*), 7.25–7.37 (5H, m, Ar-*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 27.5 (C-5), 48.9 (C-3), 52.7 (OMe), 69.7 (C-6), 82.6 (C-2), 127.3, 128.9, 129.1, 139.5 (aromatic), 169.8 (CO). MS (EI): *m*/*z* (%) 238 (12) [M^+], 132 (100), 107 (35), 105 (48), 104 (53), 91 (10). Anal. calcd for $C_{12}H_{14}O_3S_2$: C, 60.48; H, 5.92. Found: C, 60.51; H, 5.87.

Compound **16**. Pale yellow oil; IR ($CHCl_3$) 3050, 2970, 1720, 1590, 1450, 1280, 1170 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.05 (2H, t, $J=6.3$ Hz, CH_2CH_2S), 3.30 (2H, s, CH_2CO_2Me), 3.59 (3H, s, OCH_3), 3.73 (3H, s, OCH_3), 4.15

(2H, t, J=6.3 Hz, OCH_2), 5.27 (1H, s, CH=C), 7.36–7.47 (5H, m, Ar-H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 32.8 (CH_2), 35.3 (CH_2), 50.6 (OMe), 51.7 (OMe), 58.4 (CH_2), 114.6 (MeO_2C–CH=C), 127.5, 128.1, 128.9, 135.3 (aromatic), 163.6 (CH=C-Ph), 165.7 (CO), 171.2 (CO). Anal. Calcd for $C_{15}H_{18}O_5S_2$: C, 58.05; H, 5.85. Found: C, 57.94; H, 5.92.

4.2.6. Methyl 2,2-diphenyl-1,4-oxathiane-3-carboxylate (20). Methyl diazoacetate (0.5 g, 4.8 mmol) was added with intense stirring to a mixture of oxathiolane **19** (1.0 g, 4 mmol) and rhodium(II) acetate (6 mg, 0.014 mmol) in benzene (5 ml) at 80 °C for 2.5 h. The reaction mixture was stirred at this temperature for 2 h and then cooled. The crystalline precipitate was filtered off, washed with hexane and recrystallised from ethanol to afford pure **20** (0.71 g, 51%) as colorless crystals; mp 169–170 °C; IR ($CHCl_3$) 3050, 1730, 1510, 1480, 1340, 1250, 1170, 1080, 1010 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.14–2.18 (1H, m, SCH_2), 3.38 (3H, s, OCH_3), 3.65–3.73 (1H, m, SCH_2), 3.86–3.94 (1H, m, OCH_2), 4.14–4.20 (1H, m, OCH_2), 4.21 (1H, s, SCH), 7.16–7.49 (10H, m, Ar-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 23.8 (C-5), 42.5 (C-3), 52.2 (OMe), 62.6 (C-6), 78.1 (C-2), 126.1, 127.3, 127.8, 128.2, 128.3, 128.4, 128.9, 141.9, 145.3 (aromatic), 170.9 (CO). MS (EI): m/z (%) 314 (8) [M^+], 183 (49), 132 (100), 105 (86), 104 (27). Anal. Calcd for $C_{18}H_{18}O_3S_2$: C, 68.77; H, 5.77. Found: C, 68.70; H, 5.74.

4.2.7. Methyl (5R^*,6R^*)-6-phenyl-2,3,5,6-tetrahydro-1,4-dithiocine-5-carboxylate (23), dimethyl (5R^*,6R^*,9S^*)-6-phenyl-2,3,6,9-tetrahydro-5H-1,4-dithionine-5,9-dicarboxylate (24), dimethyl (5R^*,6S^*,9R^*)-6-phenyl-2,3,6,9-tetrahydro-5H-1,4-dithionine-5,9-dicarboxylate (25). Methyl diazoacetate (0.45 g, 4.5 mmol) was added with intense stirring to a mixture of dithiolane **22** (0.63 g, 3 mmol) and rhodium(II) acetate (6 mg, 0.015 mmol) in benzene (6 ml) at 80 °C over the period of 2 h. The reaction mixture was stirred at this temperature for a further 1 h and then cooled. The solvent was distilled in vacuo. Separation of the reaction mixture on a silica gel column, using a 7:1 hexane/ethyl acetate mixture as the eluent, afforded **23** (0.29 g, 34%), **24** (74 mg, 7%) and **25** (32 mg, 3%).

Compound **23**. Colorless crystals; mp 82–83 °C (recryst. from MeOH); IR ($CHCl_3$) 3050, 1730, 1520, 1490, 1460, 1250, 1210, 1140 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.63–2.76 (1H, m, CH_2), 2.91–2.97 (1H, m, CH_2), 3.27–3.35 (2H, m, CH_2), 3.71 (3H, s, OCH_3), 3.76 (1H, d, J=2.2 Hz, S$CH$$CO_2$Me), 5.05 (1H, dd, J=8.7, 2.2 Hz, CHPh), 6.26 (1H, d, J=8.7 Hz, SCH=CH), 7.01 (1H, t, J=8.7 Hz, SCH=CH), 7.23–7.36 (5H, m, Ar-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 27.4 (C-3), 39.9 (C-2), 49.7 (C-6), 50.2 (C-5), 52.6 (OMe), 119.4 (S–CH=CH), 127.7, 127.8, 129.5, 142.0 (aromatic), 149.2 (S–CH=CH), 171.7 (CO). MS (EI): m/z (%) 280 (25) [M^+], 220 (34), 219 (58), 187 (75), 161 (18), 147 (100), 128 (15), 115 (20), 92 (11). Anal. Calcd for $C_{14}H_{16}O_2S_2$: C, 59.97; H, 5.75. Found: C, 59.88; H, 5.81.

Compound **24**. Colorless crystals; mp 125–126.5 °C (recryst. from MeOH); IR ($CHCl_3$) 3050, 2960, 1730, 1610, 1440, 1350, 1170 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.38–2.50 (1H, m, CH_2), 2.92–3.23 (2H, m, CH_2), 3.26–3.36 (1H, m, CH_2), 3.57–3.64 (4H, m, OCH_3 and SCHCHPh), 3.77 (3H, s, OCH_3), 4.12–4.21 (2H, CHPh and SCHCH=CH), 6.14 (1H, dd, J=16.0, 6.5 Hz, SCHCH=CH), 6.65 (1H, br s, SCHCH=CH), 7.25–7.34 (5H, m, Ar-H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 31.1 (C-3), 32.6 (C-2), 48.4 (C-6), 50.3 (C-5), 51.4 (C-9), 52.2 (OMe), 52.7 (OMe), 120.3 (Ph-CH–CH=CH), 124.4 (Ph-CH–CH=CH), 125.8, 127.9, 128.7, 140.6 (aromatic), 169.1 (CO), 171.9 (CO). Anal. Calcd for $C_{17}H_{20}O_4S_2$: C, 57.93; H, 5.72. Found: C, 58.01; H, 5.84.

Compound **25**. Colorless crystals; mp 170–171.5 °C (recryst. from MeOH); IR ($CHCl_3$) 3050, 2970, 1730, 1600, 1440, 1350, 1170 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.39–2.51 (1H, m, CH_2), 2.99–3.31 (4H, CH_2 and SCHCHPh), 3.46–3.52 (4H, m, OCH_3 and CHPh), 3.70 (3H, s, OCH_3), 4.15 (1H, d, J=5.8 Hz, SCHCH=CH), 5.95 (1H, dd, J=16.1, 10.2 Hz, SCHCH=CH), 6.25 (1H, dd, J=16.1, 5.8 Hz, SCHCH=CH), 7.24–7.33 (5H, m, Ar-H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 29.8 (C-3), 31.5 (C-2), 47.8 (C-6), 50.9 (C-5), 51.2 (C-9), 51.8 (OMe), 52.5 (OMe), 118.6 (Ph-CH–CH=CH), 123.7 (Ph-CH–CH=CH), 126.7, 128.9, 129.4, 141.5 (aromatic), 168.8 (CO), 172.6 (CO). Anal. Calcd for $C_{17}H_{20}O_4S_2$: C, 57.93; H, 5.72. Found: C, 58.89; H, 5.77.

4.2.8. Methyl (5R^*,6R^*)-6-phenyl-2,3,5,6-tetrahydro-1,4-oxathiocine-5-carboxylate (30) and methyl *cis*-2-styryl-1,4-oxathiane-3-carboxylate (31). Methyl diazoacetate (0.22 g, 2.2 mmol) was added with intense stirring to a mixture of oxathiolane **29** (0.35 g, 1.8 mmol) and rhodium-(II) acetate (4 mg, 0.01 mmol) in benzene (4 ml) at 80 °C for 1.5 h. The reaction mixture was stirred at this temperature for 1.5 h and then cooled. After removal of the solvent, the oily residue was purified by column chromatography (8:1 hexane/ethyl acetate) to afford **30** (62 mg, 13%) and **31** (0.11 g, 24%).

Compound **30**. Pale yellow oil; IR ($CHCl_3$) 3050, 2940, 1730, 1610, 1510, 1480, 1360, 1180, 1040 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.52–2.57 (1H, m, SCH_2), 3.53–3.60 (1H, m, SCH_2), 3.66 (3H, s, OCH_3), 3.67 (1H, d, J=2.3 Hz, SCH), 3.99–4.09 (2H, m, OCH_2), 4.55 (1H, dd, J=4.9, 2.3 Hz, CHPh), 5.65 (1H, dd, J=5.8, 4.9 Hz, O–CH=CH–), 6.19 (1H, d, J=5.8 Hz, O–CH=CH–), 7.23–7.35 (5H, m, Ar-H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.8 (C-3), 39.5 (C-5), 45.7 (C-6), 51.7 (OMe), 66.8 (C-2), 96.4 (CH=CH–O), 124.3, 128.5, 129.9, 136.5 (aromatic), 141.6 (CH=CH–O), 171.2 (CO). Anal. Calcd for $C_{14}H_{16}O_3S$: C, 63.61; H, 6.10. Found: C, 63.70; H, 6.03.

Compound **31**. Pale yellow oil; IR ($CHCl_3$) 3050, 1730, 1510, 1480, 1360, 1320, 1160, 1110 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.29 (1H, dt, J=11.6, 2.3 Hz, SCH_2), 3.32 (1H, d, J=2.3 Hz, SCH), 3.39–3.50 (1H, m, SCH_2), 3.72 (3H, s, OCH_3), 3.92 (1H, dt, J=11.6, 2.3 Hz, OCH_2), 4.44 (1H, dt, J=11.6, 2.3 Hz, OCH_2), 4.57 (1H, ddd, J=6.2, 2.3, 1.5 Hz, OCH–CH=CH-Ph), 6.22 (1H, dd, J=16.2, 6.2 Hz, –CH=CH-Ph), 6.70 (1H, dd, J=16.2, 1.5 Hz, –CH=CH-Ph), 7.26–7.40 (5H, m, Ar-H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 24.0 (C-5), 41.8 (C-3), 52.5 (OMe), 69.0 (C-6), 78.2 (C-2), 127.0 (Ph-CH=CH), 127.1 (aromatic), 128.4 (Ph-CH=CH), 129.0, 132.3, 136.8

(aromatic), 170.9 (CO). Anal. Calcd for $C_{14}H_{16}O_3S$: C, 63.61; H, 6.10. Found: C, 63.67; H, 6.14.

4.3. X-ray diffraction study

Crystallographic data for the structures **2**, **10a**, **24** and **25** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 269652 (**2**), CCDC 268293 (**10a**), CCDC 270097 (**24**) and CCDC 270098 (**25**). Copies of the data can be obtained on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (email: deposit@ccdc.cam.ac.uk).

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