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Synthesis and properties of sultines, cyclic esters of sulfinic acids

O B Bondarenko, L G Saginova, N V Zyk

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Abstract. Data on the synthesis and chemical properties of sultines, cyclic esters of sulfinic acids, are reviewed. The known methods for synthesising sultines are considered, the reaction mechanisms and stereochemistry of the compounds obtained are discussed. The chemical transformations of sultines, including photolysis, thermolysis, redox reactions, and interaction with nucleophiles, are described. The bibliography includes 109 references.

I. Introduction

Lactones of sulfinic acids, i.e., sultines, were first mentioned as early as the end of the last century.[1] However, the chemical transformations of sultines long remained little studied due to their inaccessibility. The chemistry of sultines began to develop successfully only in recent decades. Many studies on methods for the synthesis of compounds of this class and their properties were published; the interest both of synthetic chemists and theoreticians in them has grown significantly. From the theoretical viewpoint, sultines are promising as models for studying the stereochemistry of sulfur, since the S atom in them is located at a vertex of a stable pyramid and does not have identical substituents, i.e. it is a chiral centre. The asymmetry of the molecule caused by the S atom can be easily removed by oxidising the sultine to the corresponding sultone.[2,3] Owing to the existence of a rather high barrier to inversion of the sulfoxide group, the introduction of at least one substituent into the sultine ring results in the appearance of diastereomers differing in the mutual arrangement (*cis* or *trans*) of the sulfoxide group and the substituent relative to the ring plane, i.e., geometric isomerism appears. Sultines are interesting as synthons because they possess hidden (latent) bifunctionality: cleavage of the heterocycle at the S–O bond leads to the simultaneous appearance of two functional groups in the product.

Owing to the increasing interest in studies on sultines and their transformations, we have attempted to systematise the data on the compounds of this class. It is noteworthy that sultines are mentioned in several reviews devoted to sulfinic acids and their derivatives;[4–6] however, these data are not systematic but very fragmentary and given only in outline.

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II. Methods for synthesising sultines

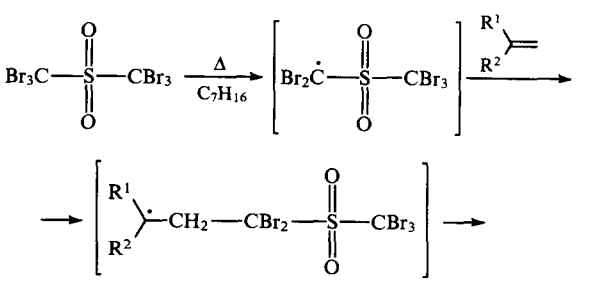
Three main groups can be distinguished among the known methods for sultine synthesis; these groups differ in the approach used to create the sultine structure. One group of reactions involves fragmentation-cyclisation transformations of sulfones. Another group combines cyclisations of bifunctional sulfur-containing compounds, usually thiols, sulfides, or sulfoxides, in which the hydroxyl group serves as the second function. The third group, not the most common but very interesting, involves sultine ring formation reactions with simultaneous introduction of three heteroatoms into the molecule upon addition of sulfur dioxide to unsaturated molecules.

1. Rearrangements of sulfones

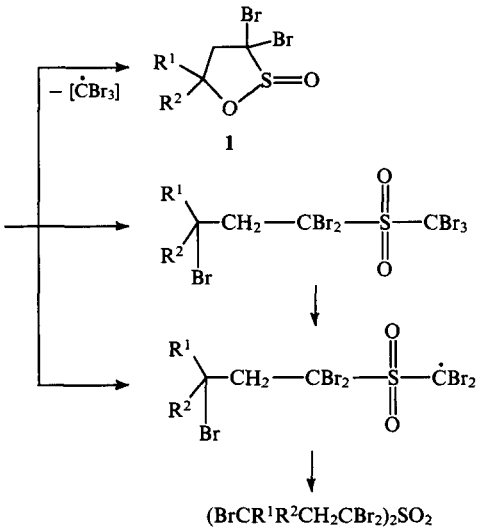
A number of studies of both homo- and heterolytic sulfone rearrangements, which result in sultine formation, have been described. The driving force for these reactions frequently originates from a decrease in strain in the starting structure due to an increase in the heterocycle size by one atom, as, for example, in the case of four-membered cyclic sulfones, or from the presence of a good leaving group in the molecule.

a. Reactions of sulfones involving homolytic cleavage of a C–S bond

The formation of 5-substituted 3,3-dibromo-1,2-oxathiolane 2-oxides **1** was found to occur in the radical addition of bis(tribromomethyl)sulfone to alkenes.[7] Most probably, sultine **1** is formed through intramolecular cyclisation of radical **2**. The subsequent elimination of the very stable tribromomethyl radical is the driving force for this unusual cyclisation. Sultine **1** is formed in a low yield, the main processes being chain transfer. However, it cannot be ruled out that a decrease in the concentrations of the sulfone and alkene in solution, i.e., higher dilution, would lead to an increase in the lifetime of radical **2** and, hence, to increased probability of its cyclisation into sultine **1**.



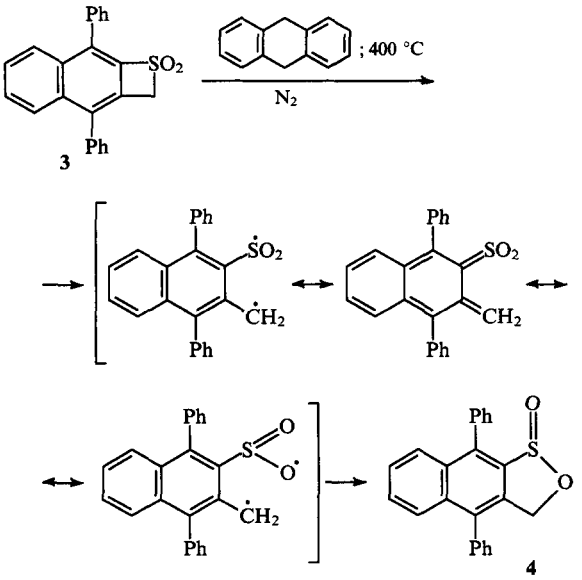
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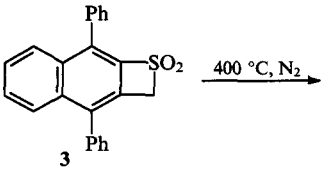
R^1 = Ph, R^2 = H;
$R^1 = R^2$ = Me.

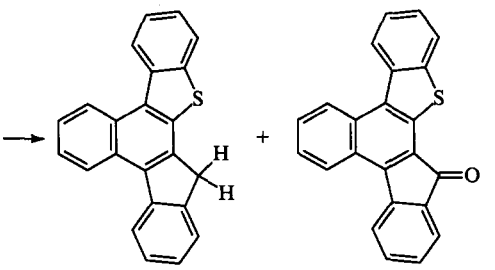
b. Reactions of sulfones and 1,2,3-thiadiazine 1,1-dioxides via a concerted mechanism

The thermal decomposition of 3,8-diphenylnaphthothiete 1,1-dioxide **3** at 400 °C under nitrogen in the presence of 9,10-dihydroanthracene affords naphthosultine **4** in 78% – 81% yield.[8] The reaction presumably involves a step in which an intermediate (possibly, a dipolar or biradical compound) is formed, which gives sultine **4** upon subsequent cyclisation.



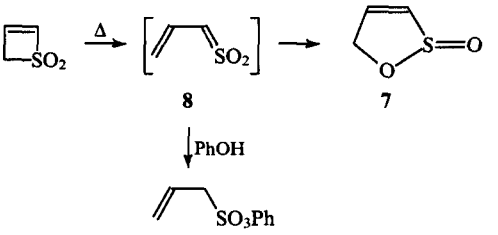
The role of 9,10-dihydroanthracene in this transformation is unclear; however, in its presence the decomposition of sulfone **3** stops at the stage of sultine **4**. In the absence of 9,10-dihydroanthracene, the reaction proceeds further to give the fused-ring fluorene **5** and fluorenone **6**, i.e. the same products as those from the thermolysis of sultine **4**.



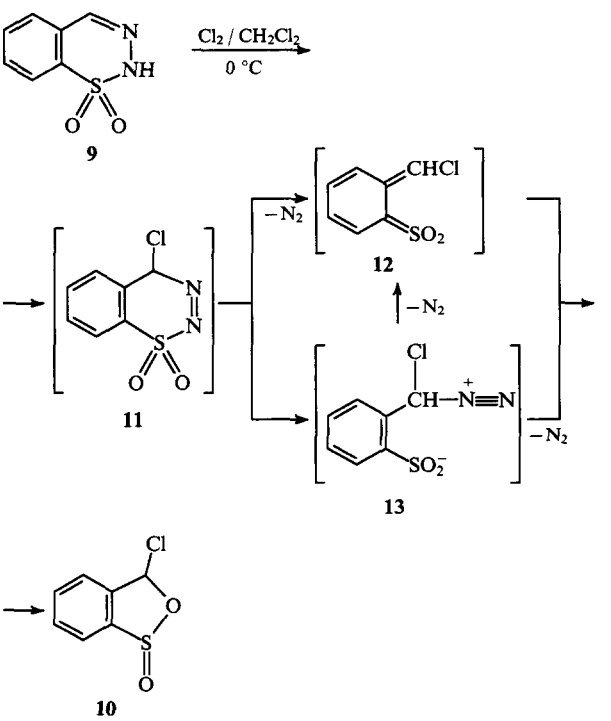


5 (11%) **6** (33%)

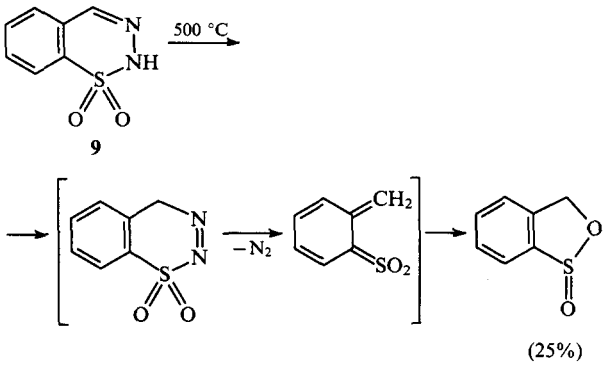
Thermolysis of the unsubstituted thiete 1,1-dioxide in the gas phase at 400 °C or in a degassed benzene or cyclohexane solution at 200 °C also gives the sultine **7** in high yields (up to 90%). It is likely that this transformation involves the vinylsulfene **8** as an intermediate. This is confirmed by the fact that this reaction, in the presence of phenol, gives phenyl allylsulfonate in 15% yield.[9]



The formation of the vinylsulfene **8** and its subsequent transformation into the sultine **7** are believed to occur via a concerted mechanism.[9] The fact that reaction of 2*H*-1,2,3-benzothiadiazine 1,1-dioxide **9** with chlorine in an anhydrous medium gives the chlorosultine **10** is considered[10] to support this mechanism. It is assumed that in this case the chlorination product **11** initially formed decomposes with elimination of the very stable nitrogen molecule and formation of the vinylsulfene **12**. The latter then cyclises to the chlorosultine **10**. However, it cannot be ruled out that compound **11** gives the diazonium sulfinate **13** by heterolytic cleavage of the S – N bond. Diazo compound **13** can also eliminate a nitrogen molecule to give the same vinylsulfene **12** or be directly transformed into the chlorosultine **10**.

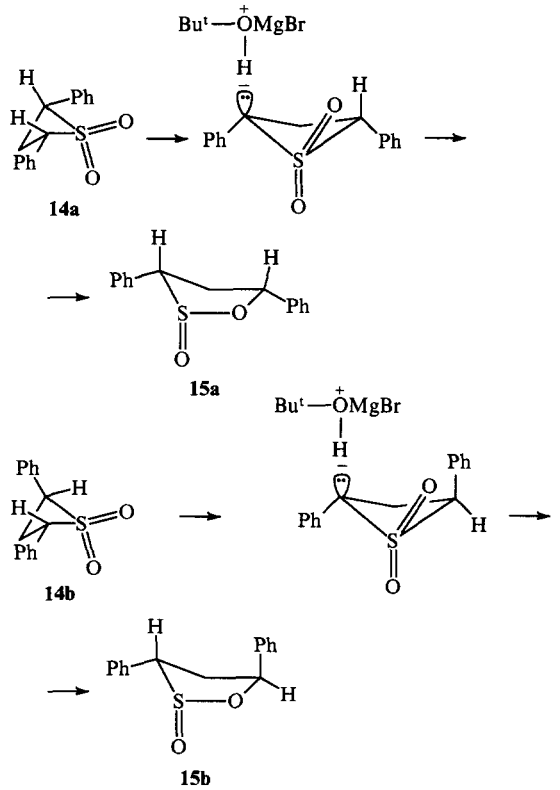


Clearly, the thermal decomposition of compound **9** also follows a similar scheme.[11]



c. Reactions of sulfones involving heterolytic cleavage of the C–S bond

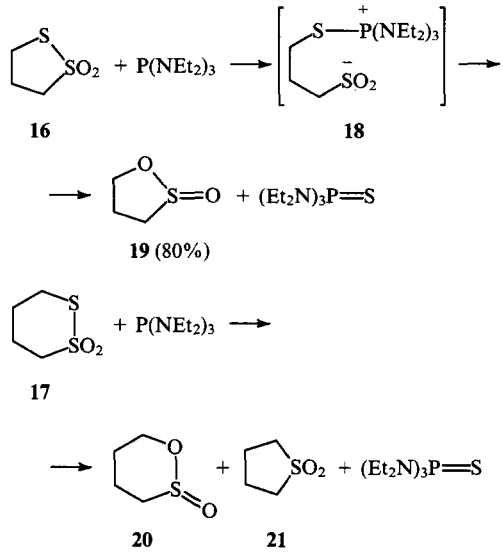
The rearrangement of the four-membered cyclic sulfones **14a,b** on treatment with a base, *tert*-butoxymagnesium bromide, to give the corresponding 3,5-diphenyl-1,2-oxathiolane 2-oxides **15a,b** via an ionic mechanism has been reported.[12,13]



Unlike the majority of transformations that result in mixtures of diastereomeric sultines, this reaction is stereospecific with respect to the phenyl substituents and stereoselective with respect to the sulfonyl group oxygen. This is explained[12,13] by the unique structure of the reagent, *tert*-butoxymagnesium bromide, which, together with diethyl ether as a solvent, exerts a 'cage' effect around the sulfone. It is assumed that *tert*-butoxymagnesium bromide initially abstracts a proton from the sulfone. The resulting carbanion and *tert*-butyl alcohol appear in close proximity to each other, which permits fast reprotonation of the anion before and after the rearrangement, and hence makes it possible to avoid side reactions. The above scheme reflects the stereochemical features of the reaction. The unusual cleavage of the C–S bond remote from the reaction centre formed initially is explained in terms of molecular orbital theory.

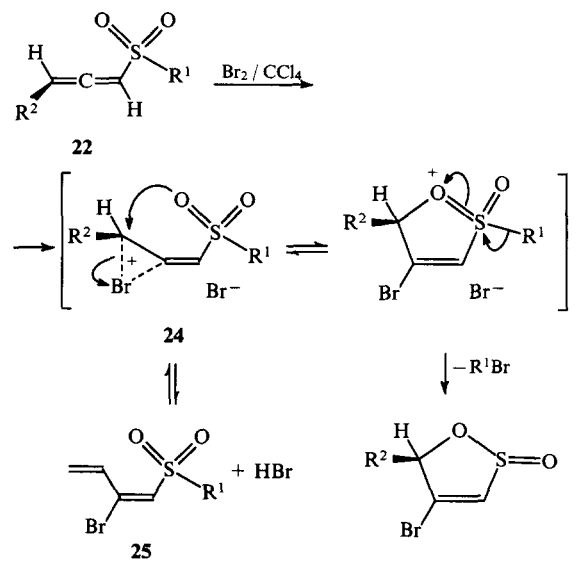
It is also interesting to note that prolonged reaction with sultine **15b**, containing *trans*-oriented phenyl substituents, results in its complete isomerisation to *cis*-3,5-diphenyl-1,2-oxathiolane (2,3-*cis*) 2-oxide **15a**. The latter is probably more thermodynamically stable, since the two bulky phenyl substituents in this compound occupy pseudo-equatorial positions.[14]

The synthesis of γ- and δ-sultines by the desulfurisation of the cyclic thiolsulfonates **16** and **17** on treatment with tris(diethylamino)phosphine has been proposed.[15] According to ^{31}P NMR data, the reaction occurs *via* the intermediate phosphonium salt **18**.



The cyclisation of the salt **18** through one of the nucleophilic centres of the sulfinyl group, the O or S atom, accompanied by elimination of the aminophosphine sulfide molecule can give a sultine or a cyclic sulfone, respectively. The determining factor is probably the size of the resulting heterocycle. For example, the reaction with 1,2-dithiolane 1,1-dioxide **16** gives exclusively 1,2-oxathiolane 2-oxide **19**, whereas desulfurisation of 1,2-dithiane 1,1-dioxide **17** gives the sultine **20** and the sulfone **21** in a 9:1 ratio.

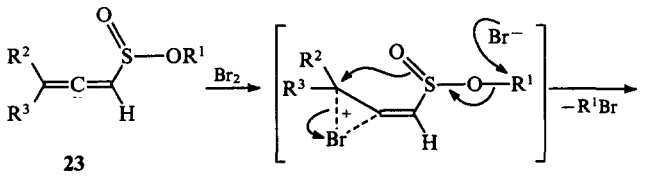
Braverman et al.[2,3,16,17] synthesised unsaturated γ-sultines by cyclisation of the sulfones **22** or sulfinates **23** on treatment with bromine. It is believed that the reaction begins with the electrophilic addition of bromine to the allene moiety with the formation



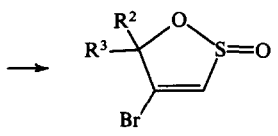
R^1 = Me, $CH_2C{\equiv}CH$, C_6H_4Me R^2 = Bu^t, $CMe_2C{\equiv}CH$

of the bridged bromonium ion **24**. This allows one to explain the retention of chirality at the γ-carbon atom in the optically active sulfones **22** during subsequent nucleophilic attack by the O atom of the sulfonyl group. The subsequent transformation of intermediates **24** into sultines occurs only when the former can eliminate a stable carbocation, such as *tert*-butyl or dimethylpropargyl, and probably proceeds via an S_N1 mechanism. When there is no good leaving group, a proton is eliminated and an acyclic product **25** is formed.

The fragmentation of sulfinates **23**, unlike that of the sulfones **22**, occurs via an S_N2 mechanism in which there is nucleophilic attack by the bromide anion resulting in cyclisation to a sultine with simultaneous elimination of an alkyl bromide molecule.



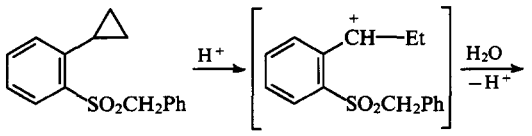
23



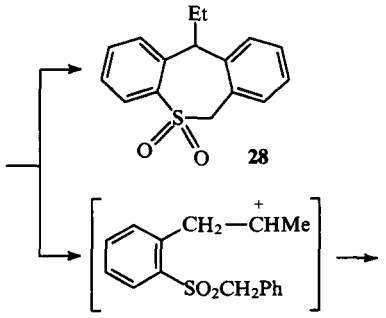
R^1	R^2	R^3
Me	Me	Me
Et	Me	Me
Et	Me	H
Et	H	H

It is believed that the reactions of a number of sulfones **22**, e.g. with R^1 = Me, cannot occur via the S_N2 mechanism due to steric and electronic effects of the sulfonyl group.[2,3,16,17]

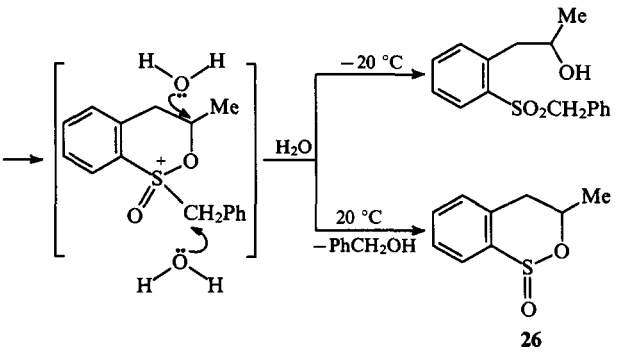
A six-membered sultine, 3-methylbenzo[*c*][2.1]oxathiine 1-oxide **26**, was obtained along with the usual reaction product, the thiepine **28**, upon isomerisation of benzyl (2-cyclopropylphenyl) sulfone **27** in presence of acid.[18] The formation of sultine **26** is explained by rearrangement of the benzyl α-carbocation formed initially to a β-carbocation followed by its nucleophilic stabilisation by the sulfonyl group and by elimination of the benzyl fragment.



27



28



26

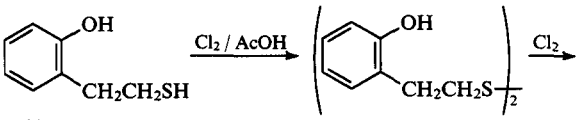
It is to be noted that the ratio of the reaction products strongly depends on the reaction temperature, and at 20 °C one can obtain sultine **26** in up to 84% yield.

2. Cyclisation of bifunctional sulfur-containing compounds

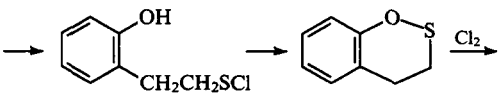
The cyclisation of bifunctional sulfur-containing compounds is the most frequently used method for the synthesis of sultines. This group of reactions is represented by diverse transformations.

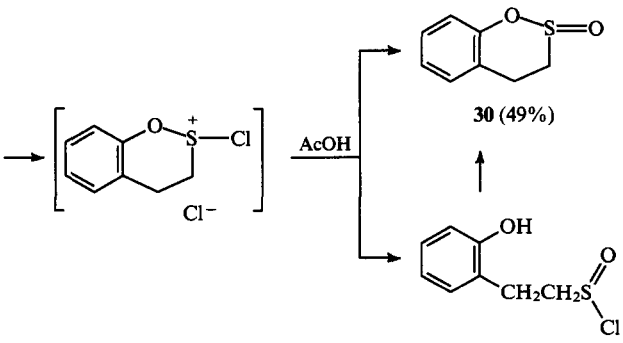
a. Oxidation of α,ω-mercaptoalcohols, disulfides and β-thiolactones

A number of syntheses of sultines by the oxidative chlorination of mercaptoalcohols in various systems have been reported. For example, benzo[*c*][1,2]oxathiine 2-oxide **30** can be obtained by treatment of β-(*o*-hydroxyphenyl)ethanethiol **29** with chlorine in glacial acetic acid.[19] The mechanism of this reaction proposed by the authors is presented below.

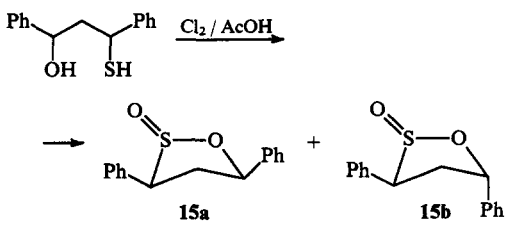


29

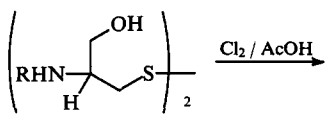




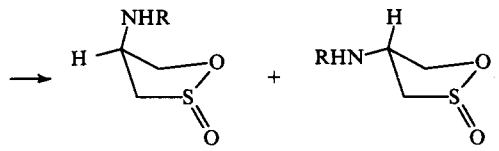
The same method was used to synthesise 3,5-diphenyl-1,2-oxathiolane 2-oxide **15** from 3-hydroxy-1,3-diphenylpropanethiol[12] and 4-[(benzyloxycarbonyl)amino]-1,2-oxathiolane 2-oxide **31** from hydroxypropyl disulfide **32**.[20]



15a **15b**



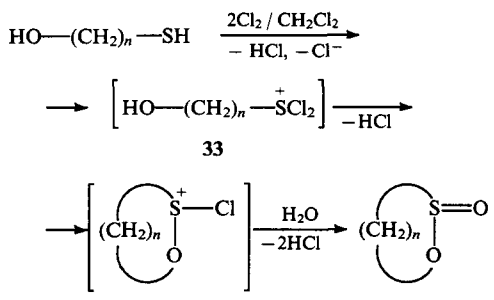
32



31a (7%) 31b (28%)

However, the yields of the isomeric sultines **15a,b** and **31a,b** did not exceed 40%. It is likely that the C–O bonds in compounds **15** and **31** are weaker than the Ar–O bond in the sultine **30** and undergo extensive nucleophilic cleavage by the chloride anions present in excess. This accounts for their considerably lower yields compared with that of sultine **30**. The yield of sultine **31** could be increased to 86%–90% by maintaining the concentration of the halogen at a sufficiently low level, which is possible when *N*-bromosucinimide (NBS) or *N*-chlorosucinimide (NCS) are used as halogenating agents.

A synthesis of the simplest sultines by the cyclisation of α,ω-mercaptoalcohols on treatment with chlorine in nonpolar solvents followed by hydrolysis (see Table 1) has been proposed.[21] The authors suggest that when 2 equiv. chlorine are used in the reaction, the acyclic chlorosulfonium ion **33** is formed; the latter is transformed into the cyclic ion **34**, which then gives the sultine on treatment with 1 equivalent of water.

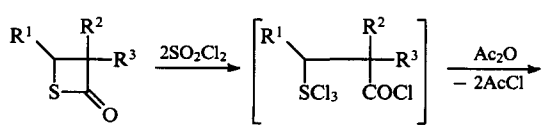


33

34

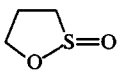
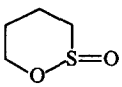
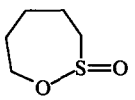
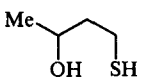
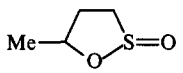
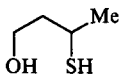
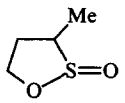
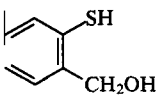
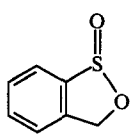
It should be noted that when the distance between the reacting centres increases, polymerisation prevails over cyclisation, which decreases the yields of sultines.

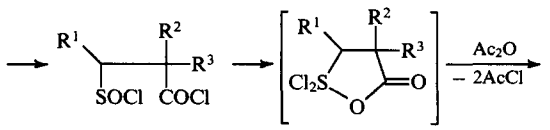
A preparative method for synthesising cyclic mixed anhydrides of β-sulfinocarboxylic acids **38**[22] is based on oxidative chlorination of substituted β-thiolactones **35** (with chlorine or sulfuryl chloride) in acetic anhydride. It was demonstrated that β-(chlorosulfinyl)alkanoyl chlorides **36** are formed in high yields (75%–80%) for a reagent ratio **35**: Cl_2: Ac_2O = 1:2:1, and that the SOCl group is, most probably, formed due to interaction of a trichlorosulfurane intermediate with acetic anhydride. With excess acetic anhydride (**35**: Cl_2: Ac_2O = 1:2:2), sulfinyl chlorides isomerise to the cyclic sulfuranes **37**, which react with acetic anhydride to give 1,2-oxathiolan-5-one 2-oxides **38**.



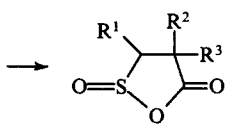
35a–d

Table 1. Synthesis of the simplest sultines by chlorination of mercaptoalcohols.

Thiol	Sultine	Yield (%)
$HO(CH_2)_3SH$		90
$HO(CH_2)_4SH$		85
$HO(CH_2)_5SH$		10
		70
		70
		80



36a–d 37a–d

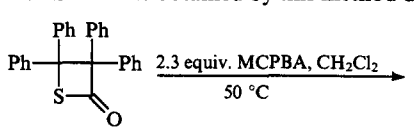


38a–d

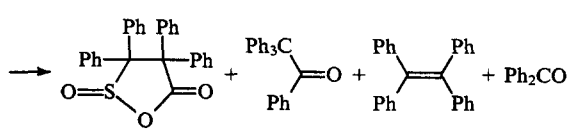
38	R^1	R^2	R^3	Yield (%)
a	H	H	H	25–40
b	Me	H	H	73–77
c	H	Me	H	87–97
d	H	Me	Cl	100

The cyclic anhydrides **38** are highly reactive and find use in the synthesis of physiologically active compounds.

The formation of tetraphenyloxathiolanone oxide **39** by the oxidation of the corresponding β-thiolactone **40** with *m*-chloroperbenzoic acid (MCPBA) has been reported.[23] However, the yield of the sultine obtained by this method did not exceed 18%.

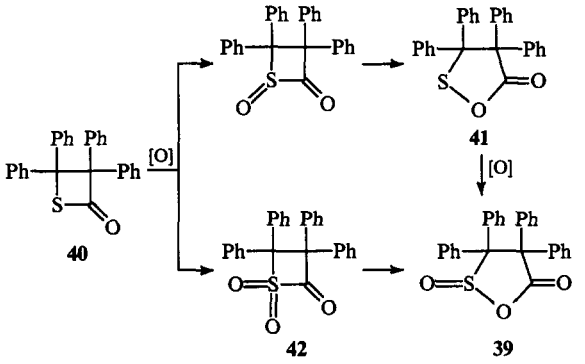


40

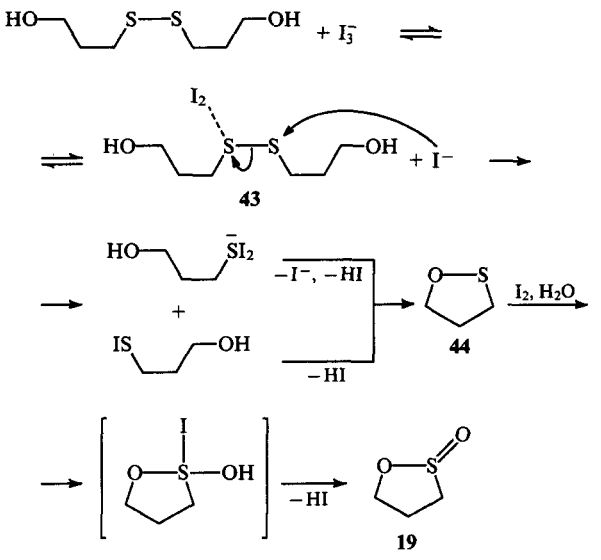


39 (18%) (17%) (15%) (24%)

The authors[23] consider that compound **39** could be formed either by the oxidation of the initial thietanone **40** to α-oxosulfoxide followed by its isomerisation to the sultene **41** and transformation of the latter into the sultine **39** (cf. Ref. 41) or by the oxidation of the initial thiolactone **40** to the thietanone dioxide **42**, which subsequently rearranges into the sultine **39**.



The oxidative cleavage of 3,3′-dithiodipropanol with aqueous KI–I_2 solution followed by cyclisation gave 1,2-oxathiolane 2-oxide **19** in 77% yield.[24] A kinetic study[24] allowed the following reaction mechanism to be put forward:

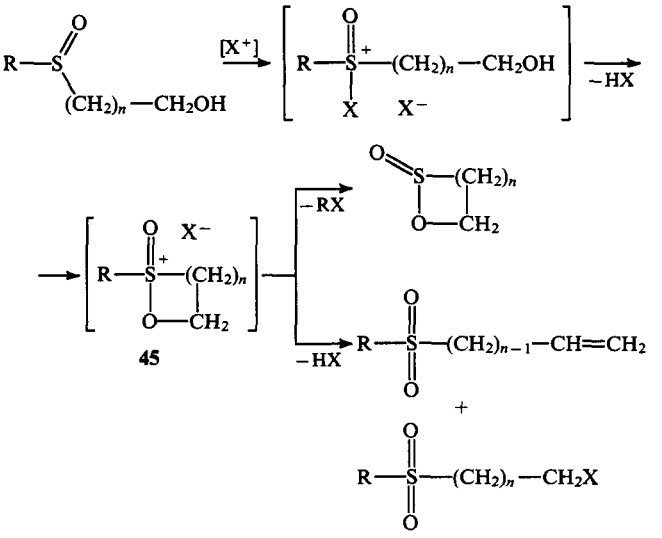


The attack of the disulfide–iodine complex **43** formed initially by an iodide anion cleaves the S–S bond in the disulfide. It was shown that hydroxy groups do not exert nucleophilic assistance in the cleavage, and that the cyclisation of sulfenyl iodide as well as the thiolate–iodine complex occurs in the next step. The resulting sultene **44** undergoes subsequent oxidation and hydrolysis to give 1,2-oxathiolane 2-oxide **19** as the final product. It is noteworthy that this reaction is not general. For example, 4,4′-dithiodibutanol is oxidised by an aqueous solution of iodine to give 4-sulfobutanol, possibly because the distance between the reaction centres involved in the cyclisation increases. Under the same conditions, 3,3′-dithiodipropionic acid is transformed into 3-sulfopropionic acid.

b. Cyclisation of α,ω-hydroxysulfoxides

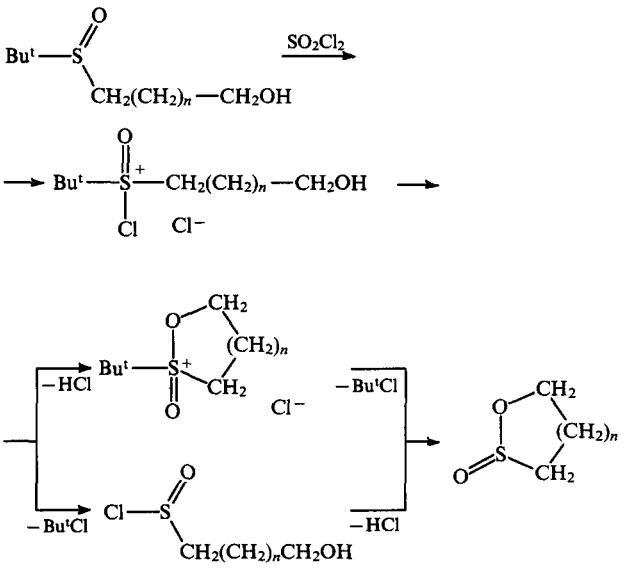
The cyclisation of hydroxyalkyl sulfoxides in the presence of halogenating agents, such as NBS, NCS or SO_2Cl_2, results in the formation of sultines[25–28] or sulfones,[29–34] depending on the structure of the starting compound.

In all cases, the existence of a cyclic intermediate of type **45** is assumed,[33,34] which can be opened at the C–O bond to give sulfones or, when R is a good leaving group, can give the corresponding sultine by cleavage of the R–S bond.



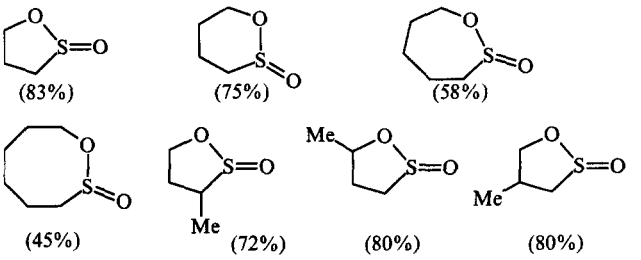
X = Cl, Br; n = 1–4

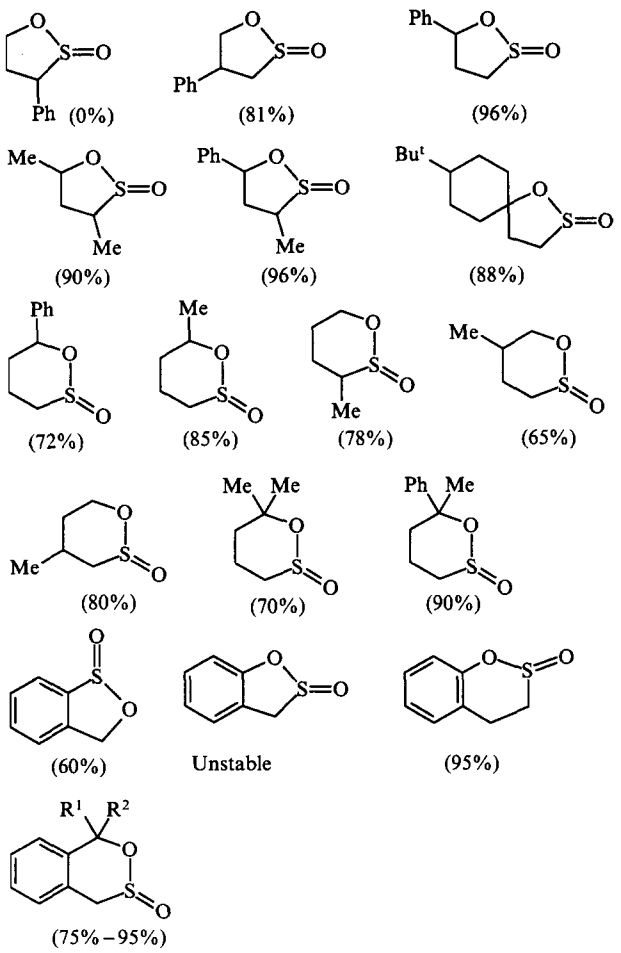
Durst and co-workers[26] used this approach to synthesise sultines containing from five to eight atoms in the heterocycle by reactions of *tert*-butyl ω-hydroxyalkyl sulfoxides with sulfuryl chloride.



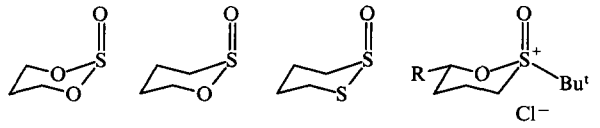
n = 1–4

In this case, the *tert*-butyl group serves as a good leaving group. Sultines are formed in high, nearly quantitative yields for n = 1, 2 (see Table 2). When n increases, i.e., the reaction centres become more distant from each other, the probability of the cyclisation and hence the yields of the sultine decrease. The yields of sultines obtained by the cyclisation of *tert*-butyl hydroxyalkyl sulfoxides in the presence of halogenating agents (NBS, NCS, SO_2Cl_2) are given below.





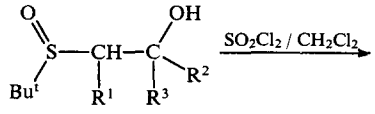
Certain stereochemical features of this reaction are of interest. γ-Sultines with substituents in the ring were isolated as mixtures of diastereomers, whereas the formation of δ-sultines (six-membered heterocycles) occurs stereoselectively and results exclusively, or predominantly, in one isomer having a chair conformation with an axially oriented S=O bond and a substituent in an equatorial position.[35] The preference for a conformation with an axially oriented S=O bond for cyclic trimethylene sulfites and their analogues is obviously related to the anomeric effect.[36,37]

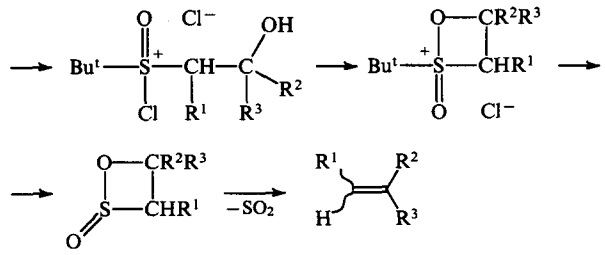


46

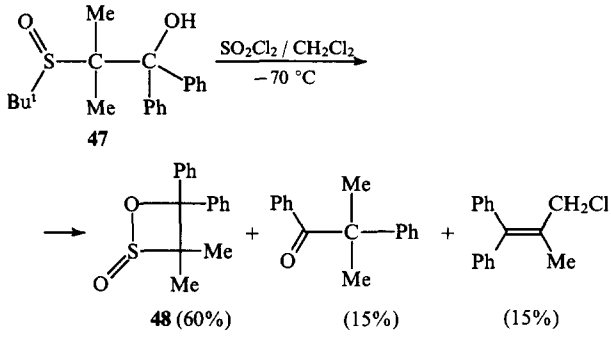
The high selectivity of the transformations in the synthesis of δ-sultines is explained[26] by the isomerisation of products under the reaction conditions or during isolation, on the one hand, and by the predominant formation of some of the isomers during the reaction, on the other hand. It cannot be ruled out that this preference manifests itself at the alkoxyoxosulfonium salt formation stage, for which the conformation **46**, with both substituents in equatorial positions, is the most favourable.

Attempts to synthesise β-sultines from *tert*-butyl 2-hydroxyalkyl sulfoxides failed due to their instability: at 20 °C, they eliminate sulfur dioxide in several minutes to give unsaturated compounds.[38,39] This is probably caused by the significant strain in the four-membered ring.



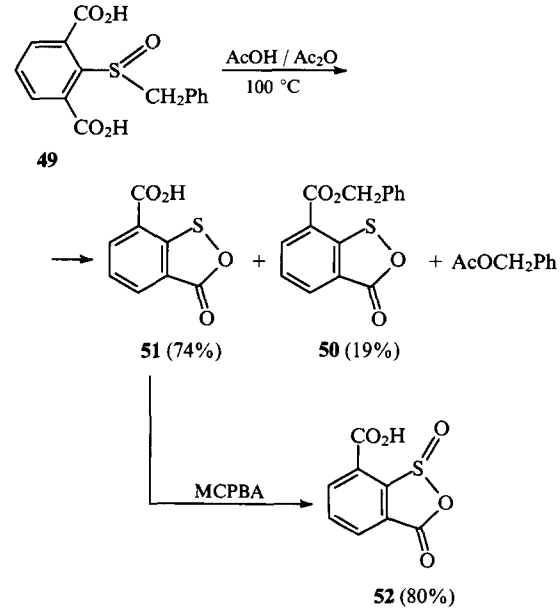


It was only in the case of *tert*-butyl 2-hydroxy-1,1-dimethyl-2,2-diphenylethyl sulfoxide **47** that the corresponding sultine, 3,3-dimethyl-4,4-diphenyl-1,2-oxathietane 2-oxide **48**, which is stable at 20 °C over a period of several days, was isolated and characterised.[40]



However, despite all failures to synthesise β-sultines, the generality of this method leading to heterocycles with 5 to 8 atoms in the ring and the possibility of synthesising various sultines by introducing substituents into the alkyl chain of the initial *tert*-butyl ω-hydroxyalkyl sulfoxide make this reaction a promising preparative method.

The cyclisation of 2-(benzylsulfinyl)isophthalic acid **49** gives the sultenes **50** and **51**. The latter was oxidised with MCPBA to give the corresponding sultine **52**.[41,42] The reaction mechanism was not discussed in detail; however, it can be assumed that cyclisation of the sulfoxide in an AcOH/Ac_2O mixture probably occurs by an intramolecular Pummerer reaction followed by nucleophilic participation of the neighbouring carboxyl group.

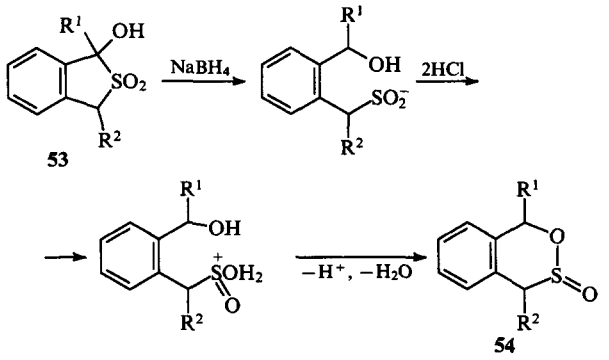


c. Cyclisation of hydroxysulfinates

The sultine ring is also formed through the cyclisation of hydroxysulfinates in acidic media. They can be generated using various methods.

For example, Durst et al.[43] suggest that hydroxysulfinates can be obtained by the reduction of 1-hydroxy-1*H*,3*H*-benzo[*c*]-thiophene 2,2-dioxides **53** with sodium tetrahydroborate. Subsequent cyclisation of hydroxysulfinates gave 1*H*,4*H*-benzo-[*d*][2,3]oxathiine 3-oxides **54**.

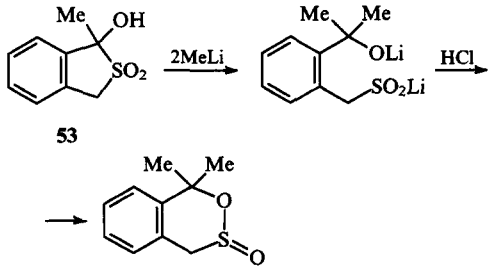
It is believed[43] that hydroxysulfinate cyclisation in acidic media involves the participation of the protonated form of sulfinic acid. The possibility of this transformation was shown for the acid hydrolysis of methyl toluene-*p*-sulfinate in $H_2{}^{18}O$.[44]



53 **54**

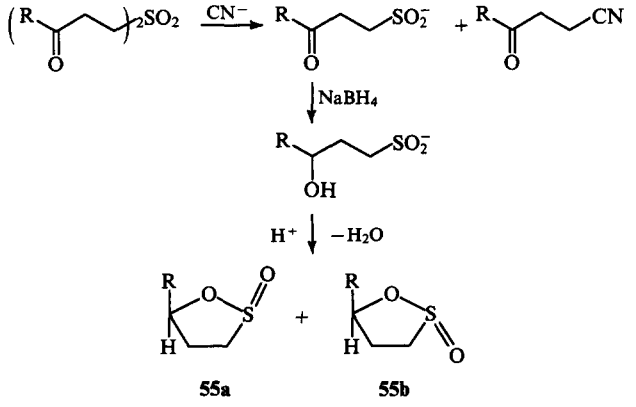
$R^1 = R^2 = H$ (70%); R^1 = Me, R^2 = H (55%); R^1 = H, R^2 = Ph (79%)

The generation of a hydroxysulfinate followed by cyclisation also occurs during the metallation of the cyclic sulfone **53** with organolithium reagents. It was proposed to synthesise various sultines using functionalised lithium derivatives.[43,45]



53

Messinger[46,47] obtained hydroxysulfinates by the cleavage of γ,γ′-dioxosulfones with the cyanide anion followed by their reduction with sodium tetrahydroborate.



55a **55b**

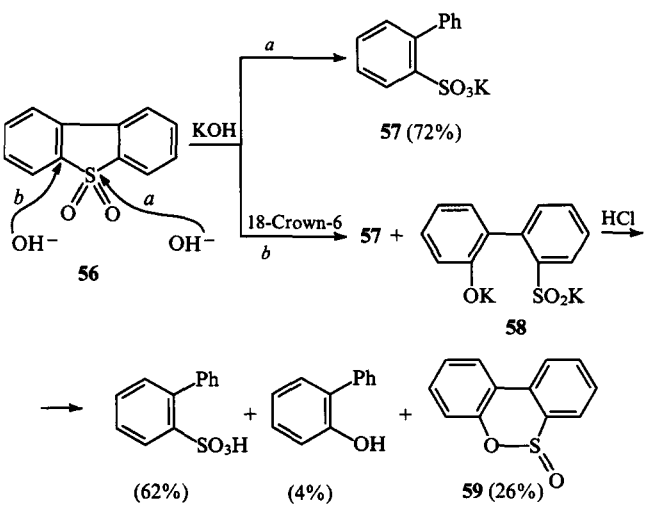
55a: R = *p*-ClC_6H_4 (65%), *p*-MeC_6H_4 (60%), *p*-$MeOC_6H_4$ (63%);

55a+**55b**: R = Ph_2CH (72%), $C_{10}H_7$ (42%)

It is interesting to note that upon subsequent acidification of phenyl-substituted hydroxysulfinates (R = *p*-ClC_6H_4, *p*-MeC_6H_4, or *p*-$MeOC_6H_4$) their cyclisation to sultines occurs stereospecifically and gives exclusively *cis*-diastereomers **55a**. It is likely that this feature of the reaction is due to steric effects of the substituents, since 5-(β-naphthyl)- and 5-(diphenylmethyl)-sultines, obtained under the same conditions, consist of a mixture of isomers **55a**+**55b**.

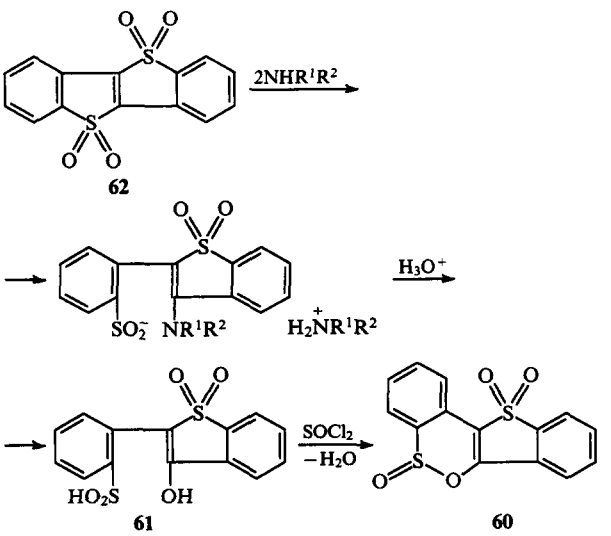
The alkaline cleavage of dibenzothiophene dioxide **56** in the presence of 18-crown-6 gave potassium biphenyl-2-sulfonate **57** and dipotassium 2′-hydroxybiphenyl-2-sulfinate **58**. Acidification of the mixture gave mainly biphenyl-2-sulfonic acid and the sultine **59**.[48]

It is remarkable that in the absence of a crown ether, potassium biphenyl-2-sulfonate **57** is formed exclusively, i.e. only the S atom is attacked by the hydroxide ion (pathway *a*). It is assumed that the loss of reaction selectivity in the presence of the crown ether is due to the appearance of free hydroxide ions, which are more reactive than the solvated ions. This allows the hydroxide ions to attack the aromatic ring (pathway *b*) to give the dipotassium salt **58**.



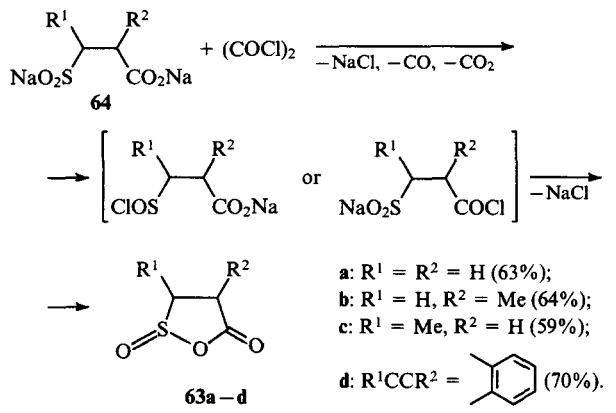
56 **57** (72%) **58** (62%) (4%) **59** (26%)

The synthesis of the sultine **60** by the cyclisation of the corresponding hydroxysulfinic acid **61** on treatment with thionyl chloride or acetyl chloride has been reported.[49] The hydroxysulfinic acid **61** was obtained from benzothienobenzo-thiophenedisulfone **62** by nucleophilic cleavage of the C – S bond by the amine and subsequent hydrolysis.



62 **61** **60**

A general method for the synthesis of 1,2-oxathiolane-5-one 2-oxides **63a–c** and 2,1-benzoxathiol-3-one 1-oxide **63d** by treatment of bis-sodium β-(hydroxysulfinyl)carboxylates **64** with oxalyl chloride according to the following scheme has been proposed:[50]

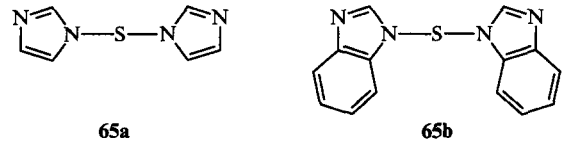


Mixed anhydrides of β-sulfinocarboxylic acids **63** are unstable and can be isolated only if moisture is completely absent.

d. Cyclisation of bifunctional compounds with simultaneous introduction of a sulfur-containing group

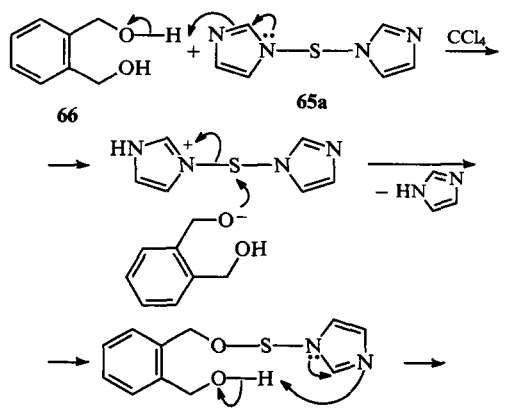
Let us consider several examples demonstrating the syntheses of sultines by the cyclisation of bifunctional compounds involving the introduction of a sulfur-containing group.

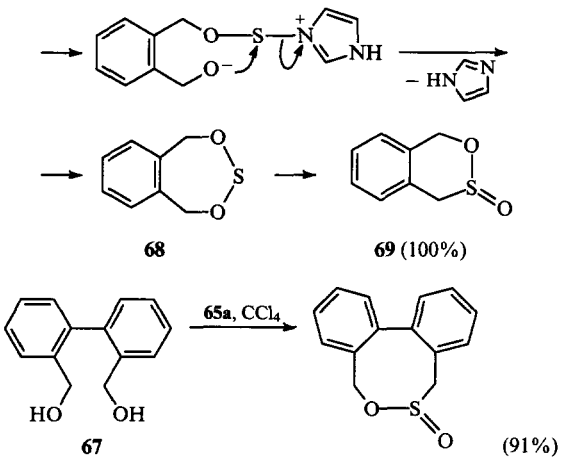
In their study of new sulfur transfer reagents, Harpp and coworkers [51] proposed the synthesis of sultines by the reactions of *N,N'*-thiobisimidazole **65a** and *N,N'*-thiobisbenzimidazole **65b** with certain diols.



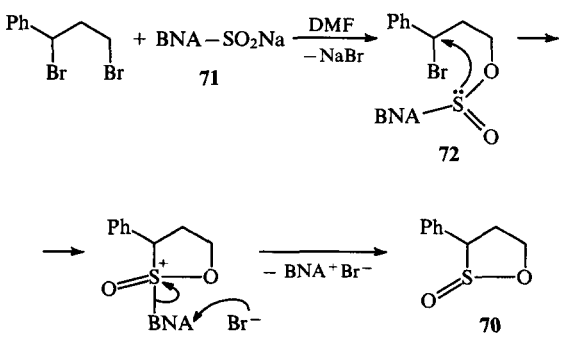
Compounds of type **65a,b** are reactive toward nucleophiles containing an active hydrogen atom (OH, SH, NHR). This is explained by the protonation of the leaving group of the reagent in the first reaction step followed by its nucleophilic substitution (when it is eliminated as a neutral molecule).

The mechanism of the transformation of the diols **66** and **67** into the corresponding sultines has not been discussed;[51] however, one can assume that formation of the cyclic sulfoxylate **68** occurs initially, and the latter then rearranges to the sultine **69**. Similar rearrangements are known for acyclic allyl and benzyl sulfoxylates.[52]

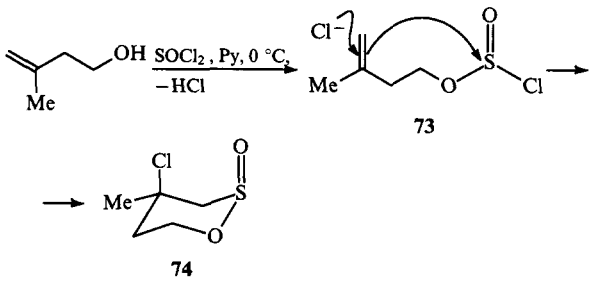




The synthesis of 3-phenyl-1,2-oxathiolane 2-oxide **70** by treatment of 1,3-dibromo-1-phenylpropane with sodium 1-benzyl-1,4-dihydronicotinamide-4-sulfinate **71** has been reported.[53] The initial step obviously involves the formation of the sulfinic ester **72** with elimination of a bromide anion, the cyclisation of this ester then occurs by nucleophilic attack by the S atom at the C atom of the benzyl fragment. Subsequent elimination of 1-benzyl-1,4-dihydronicotinamide (BNA) yields sultine **70**.

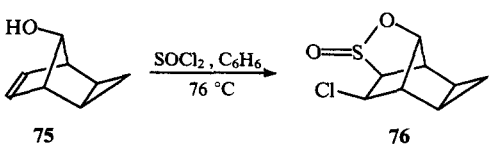


The synthesis of γ-sultines by treatment of γ,δ-unsaturated alcohols with thionyl chloride in the presence of pyridine has been suggested.[54] In this reaction, the intermediate **73** undergoes cyclisation involving the double bond, which in this case acts as a second functional group.



It should be noted that 4-chloro-4-methyl-1,2-oxathiane 2-oxide **74** was isolated as one diastereomer with *cis*-axial orientation of the S = O group and the Cl atom.

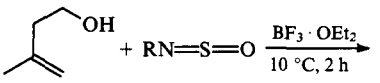
An analogous combination of a double bond and a hydroxyl group is also present in the tricyclic alcohol **75**, which gives the sultine **76** on treatment with thionyl chloride.[55]

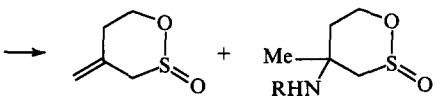


It was shown that the result of the reaction in the rigid structure **75** is largely determined by the mutual orientation of the reaction centres — the hydroxyl group and the double bond — in the molecule and by the distance between them. Another interesting feature of the reaction should be noted: this is an unusual example of an electrophilic *exo-cis*-addition to a double bond. This conclusion was based on the spectral characteristics of the reaction product, the sultine **76**.

The reactions of unsaturated alcohols with *N*-sulfinyltoluene-*p*-sulfonamide in the presence of $BF_3 \cdot OEt_2$ gave diverse chiral six- and seven-membered mono- and bi-cyclic sultines (see Table 2).[56] The high stereoselectivity of the reaction was noted: the stereochemistry of ring annelation is determined by the configuration of the starting alcohol; in each case, the molecules of the resulting sultines contained an axially oriented S = O bond and an exocyclic methylene fragment.

Alcohols **A** and **F** (see Table 2) gave the sultine **77** and the product **78**, which retained the amine residue; this did not allow the authors[56] to make an unambiguous conclusion about the reaction mechanism.

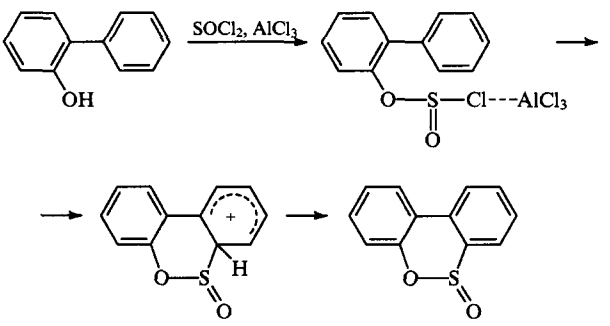




77 **78**

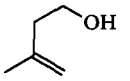
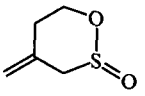
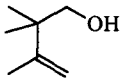
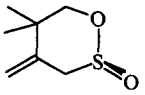
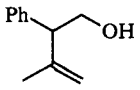
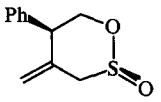
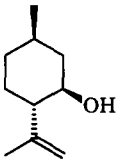
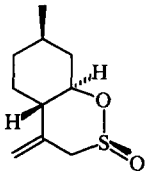
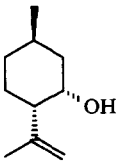
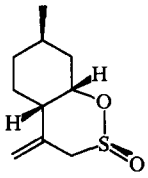
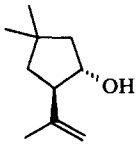
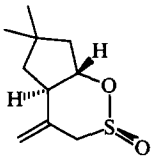
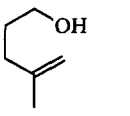
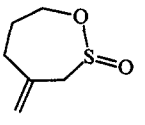
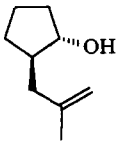
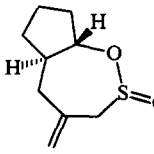
R = $MeC_6H_4SO_2^-$

The synthesis of dibenzoxathiine oxide **59** from *o*-hydroxybiphenyl and thionyl chloride in the presence of Lewis acids[57] can be formally assigned to the above type of reactions for the aromatic series. In this case, the second reaction step involves typical electrophilic substitution in the aromatic ring.



59 (51%)

Table 2. Syntheses of sultines by the reaction of unsaturated alcohols with *N*-sulfinyltoluene-*p*-sulfonamide in the presence of $BF_3 \cdot OEt_2$.

Alcohol	Formula	Product	Yield (%)
A			32
B			64
C			69
D			55
E			75
F			17
G			46
H			47

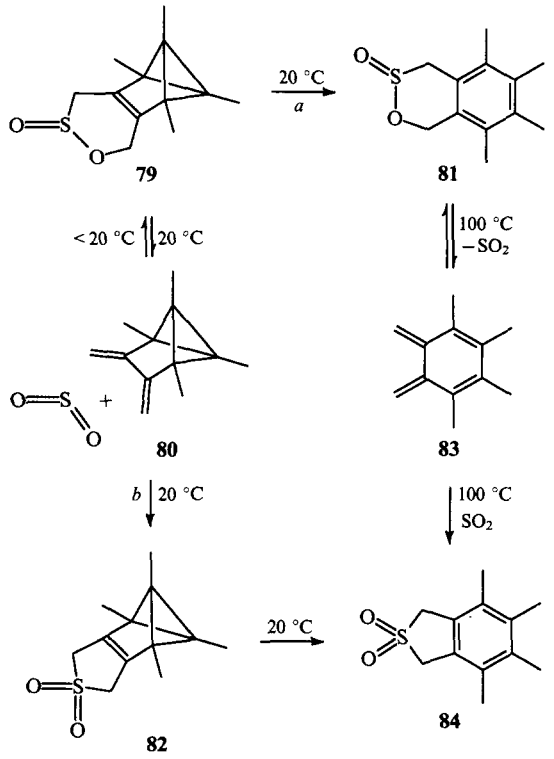
3. Syntheses of sultines with participation of sulfur dioxide

We assigned reactions involving sulfur dioxide as one of the reagents to the third group of transformations resulting in the formation of the sultine ring. When considering these reactions, attention should be paid to particular features of the structure of sulfur dioxide, in the molecule of which the S atom has simultaneously a nonbonding electron pair and vacant *d*-orbitals. It is by virtue of the latter that sulfur dioxide forms charge-transfer complexes with various Lewis bases, namely, amines,[58] aromatic compounds,[59-61] ethers, alcohols[62] and alkenes.[63] Sometimes, as in the case of trimethylamine, these complexes are so stable that they can be isolated in the crystalline state.[64, 65]

a. Reactions of sulfur dioxide with 1,3-dienes

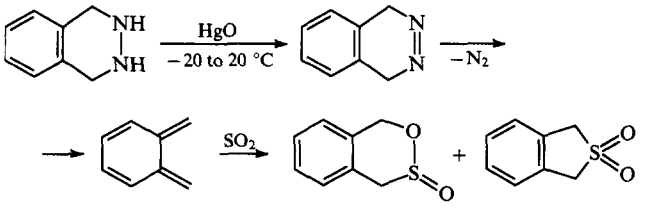
The well-known cheletropic addition of sulfur dioxide to conjugated polyenes in the presence of inhibitors of radical processes involves both the vacant *d*-orbitals and the lone electron pair of the S atom. This transformation occurs as the $[2+4][n+\pi\pi]$ cycloaddition to give five-membered cyclic sulfones, i.e. sulfolenes.[66] However, it was noted that, in some cases, an atypical mode of addition of sulfur dioxide to dienes involving the S = O bond gives unstable unsaturated six-membered sultines, which undergo retrocycloaddition and rapidly decompose into the starting compounds.[26]

For example, the formation of a kinetically controlled reaction product, the sultine **79**, in the course of $[2+4][\pi+\pi\pi]$ cycloaddition of sulfur dioxide to substituted dimethylene-tricyclohexane **80**, a reactive diene in the Diels–Alder reaction, has been reported.[67]



The sultine **79**, which is unstable at room temperature, is transformed into the sultine **81** (up to 90%) by isomerisation of the tricyclic fragment into a benzene ring (pathway *a*), or into the sulfone **82** by retroaddition (pathway *b*). Heating of the sultine **81** in *o*-dichlorobenzene at 80–100 °C results in its dissociation into sulfur dioxide and *o*-quinodimethane **83** with subsequent recombination into the thermodynamically controlled product sulfone **84**, a product of $[2+4][n+\pi\pi]$ cycloaddition. The same sulfone was obtained by isomerisation of the tricyclic fragment in compound **82**. It was also noted that the addition of diene **80** to liquid sulfur dioxide at −50 °C gave only the aromatic sultine **81**, which is probably due to the isomerisation of the sultine **79** to **81** catalysed by liquid sulfur dioxide.

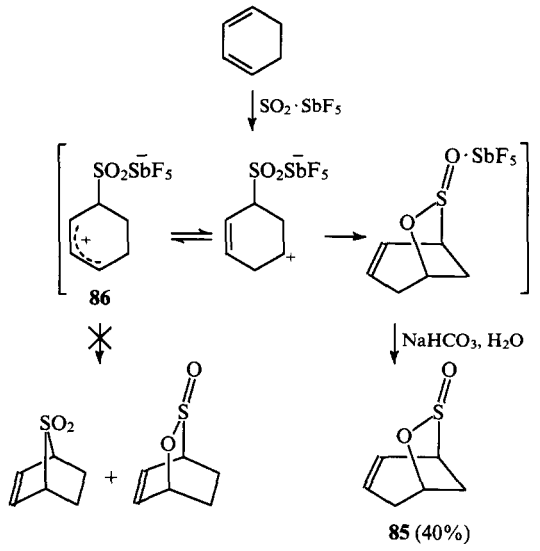
The preferential formation of the sultine **69**, the product of the $[2+4][\pi+\pi\pi]$-cycloaddition of sulfur dioxide to *o*-quinodimethane under kinetic control, together with a sulfone (in a 9 : 1 ratio) was noted.[68]



69

In some cases, the addition of sulfur dioxide to conjugated polyenes is catalysed by Lewis acids.[69–72] The latter form complexes with sulfur dioxide,[73] which then behaves with enhanced electrophilicity. The reactions occur stepwise with intermediate formation of carbocations.

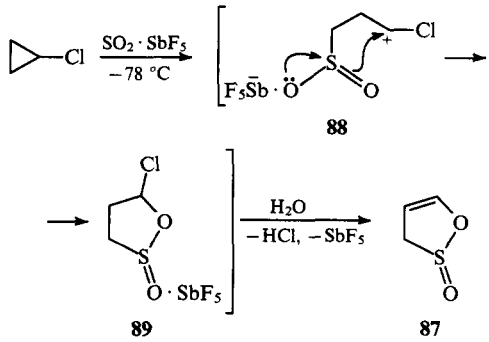
For example, the reaction of cyclohexadiene with the $SO_2 \cdot SbF_5$ complex[74] gives the bicyclic sultine **85**. The authors[74] assume that the formation of **85** occurs through a 1,2-hydride shift in the allylic intermediate **86**.



It is interesting that the reaction with 1,3-cyclohexadiene occurs stereospecifically and gives the isomer **85** as the only product; its structure was confirmed by X-ray diffraction analysis. On the other hand, reactions of sulfur dioxide with cyclohepta- or cycloocta-1,3-dienes give complex mixtures of addition products.

b. Reactions of sulfur dioxide with cyclopropanes

The formation of the cyclic sulfinate **87** by the addition of sulfur dioxide to cyclopropyl chloride in the presence of SbF_5 was observed by Olah and co-workers[75] when attempting to obtain dicyclopropylhalogenonium ions from cyclopropyl halides. The mechanism of this transformation has not been discussed; however, it can be assumed that the first step of the reaction involves electrophilic attack on the cyclopropane ring by the $SO_2 \cdot SbF_5$ complex with the cleavage of the C(1)–C(2) bond to form the carbocation **88**. Subsequent intramolecular cyclisation involving an O atom of sulfur dioxide gives the sultine **89**, which eliminates an HCl molecule to give the cyclic sulfinate **87**.



Several papers[76–81] have described the addition of sulfur dioxide to arylcyclopropanes in the presence of trifluoroacetic acid. The reaction occurs regioselectively and results exclusively in 5-aryl-1,2-oxathiolane 2-oxides **90** in good yields (Table 3).

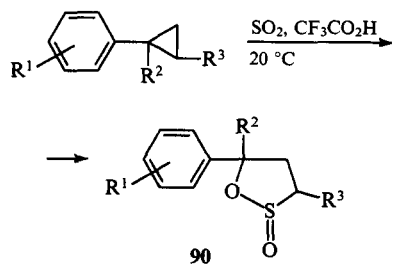
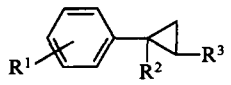


Table 3. Synthesis of sultines by the addition of sulfur dioxide to arylcyclopropanes in the presence of trifluoroacetic acid.[81]



Arylcyclopropane			Product yield (%)	Diastereomeric composition of the sultine (%) [a]			
R^1	R^2	R^3		A	B	C	D
H	H	H	76	60	40	—	—
p-Me	H	H	88	60	40	—	—
p-MeO	H	H	92	60	40	—	—
p-Br	H	H	45	55	45	—	—
p-I	H	H	93	55	45	—	—
o-Cl	H	H	22	65	35	—	—
o-Br	H	H	51	55	45	—	—
o-I	H	H	44	60	40	—	—
H	H	Ph (*cis*)	70	50	50	—	—
H	H	Ph (*trans*)	Does not react	—	—	—	—
p-F	H	*p*-FPh (*cis*)	80	50	50	—	—
p-Me	H	*p*-MePh (*cis*)	84	50	50	—	—
p-MeO	H	*p*-MeOPh (*cis*)	95	60	40	—	—
p-Me	H	*p*-MePh (*trans*)	65	55	16	16	13
p-MeO	H	*p*-MeOPh (*trans*)	94	61	15	13	11
H	Ph	Ph	95	100	—	—	—
H	H	Me	60 [b]	30	5	10	—
H	Me	H	75	50	50	—	—

[a] The diastereomers **A**–**D** are shown in Scheme 1. [b] In this case 10% of a structural isomer — 4-methyl-5-phenyl-1,2-oxathiolane 2-oxide was isolated.

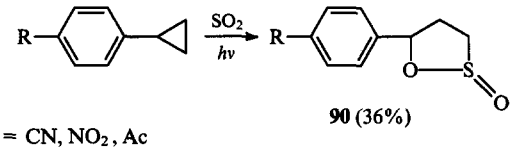
A study of this reaction with a series of arylcyclopropanes substituted in the trimethylene and benzene rings indicated that it is an electrophilic reaction.

The resulting γ-sultines are mixtures of diastereomers (the addition was stereospecific only in the case of 1,1,2-triphenylcyclopropane).

It was suggested that the reaction proceeds through a step involving formation of an open carbocation according to Scheme 1.[76–81] This is consistent with the steric requirements of the reaction products obtained. The preferential formation of isomer **A** in the case of *trans*-diarylcyclopropanes is explained by its thermodynamic stability arising from the fact that the bulky phenyl substituents in the latter, which are in a *cis*-position to each other, occupy the most favourable pseudo-equatorial positions in the molecule.[14]

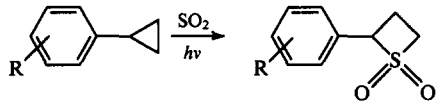
The above reaction is a convenient method for obtaining 5-aryl-1,2-oxathiolane 2-oxides, which can be used as synthons in organic syntheses for the bifunctionalisation of hydrocarbons.

The photochemical addition of sulfur dioxide to certain arylcyclopropanes to give 5-aryl-1,2-oxathiolane 2-oxides **90** has also been reported.[82] In this case, cyclopropanes containing electron-withdrawing groups in the aromatic ring were found to be reactive. *p*-Nitrophenylcyclopropane gives the sultine **90** and the cyclic sulfone **91**; the latter becomes the only reaction product in the case of the *o*-nitro isomer. It is noteworthy that, of the systems studied,[82] a number of cyclopropanes (phenylcyclopropane, *p*-biphenylylcyclopropane, 1-methyl-2-phenylcyclopropane, *p*-halophenylcyclopropanes, cyanocyclopropane, acetylcyclopropane and cyclopropanecarboxylic acid) did not undergo photochemical addition of sulfur dioxide.



90 (36%)

R = CN, NO_2, Ac

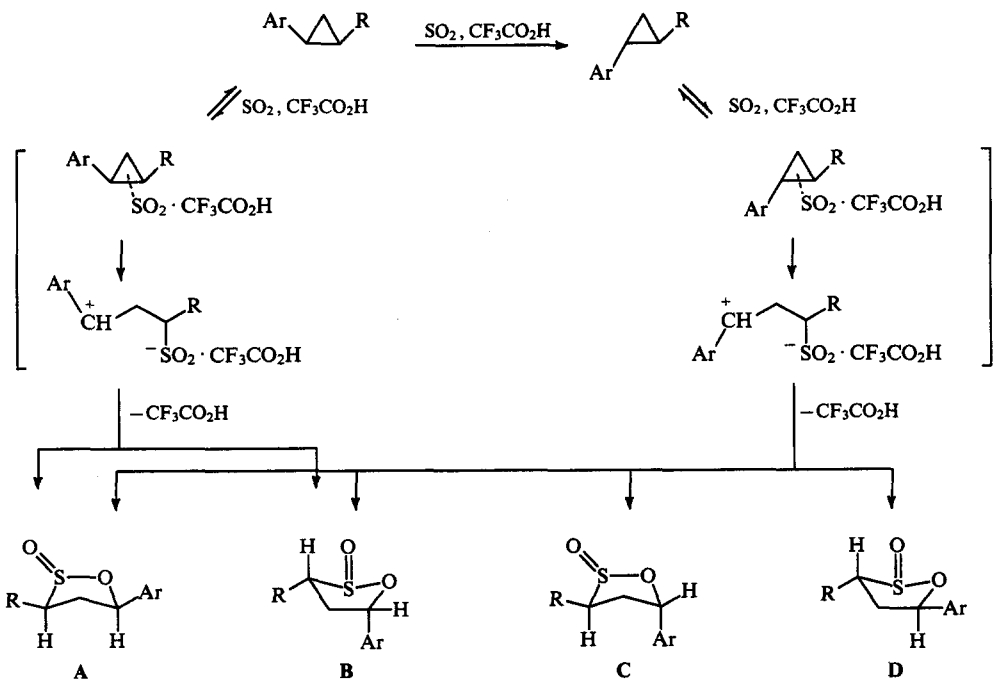


91

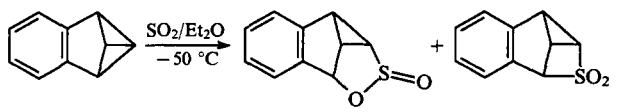
R = *o*-, *p*-NO_2

The addition of sulfur dioxide to substituted benzvalenes to give mixtures of isomeric sultines and sulfones has been

Scheme 1

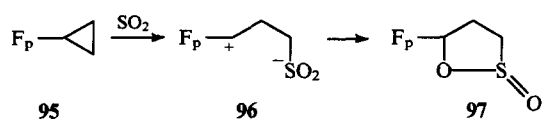


reported.[83,84] In the case of benzobenzvalene **92**, the sultine **93** is the main reaction product (the product ratio **93**:**94** = 3:1).



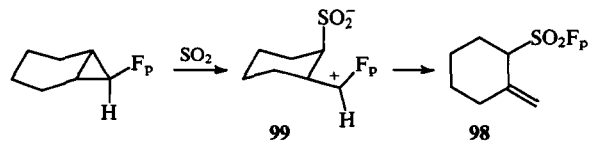
92 **93** (40.5%) **94** (13.5%)

The addition of sulfur dioxide to the cyclopropyl-F_p complex **95** [where F_p = $(\eta^5\text{-}C_5H_5)Fe(CO)_2$] has been reported.[85] Sulfur dioxide is usually inserted into the C–M bond of such compounds, but the reaction involving complex **95** follows a non-standard pathway with opening of the trimethylene ring and formation of the carbocation **96**, which is then transformed into the sultine **97**.



95 **96** **97**

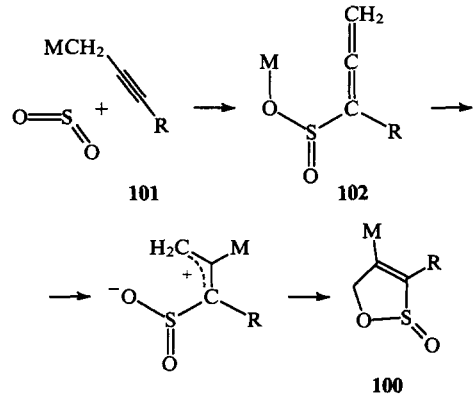
However, the reaction of the norcarane-F_p complex with sulfur dioxide results exclusively in the sulfone **98**. It is assumed that the reaction goes through the intermediate ion **99** having a *trans*-configuration, which makes cyclisation impossible.



99 **98**

c. Reactions of sulfur dioxide with organometallic compounds

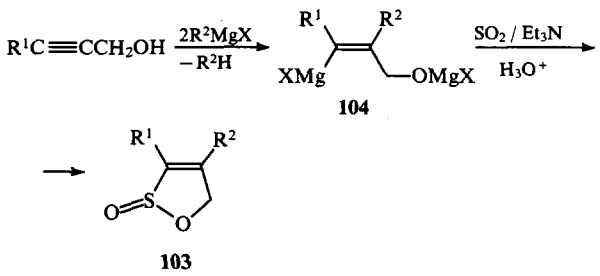
Quite unexpectedly, the sultines **100** were found to be formed in reactions between sulfur dioxide and 2-alkynyl derivatives of transition metals **101**.[86] The initial electrophilic attack is at the C≡C triple bond. The scheme presented below is supported by the fact that the reaction between sulfur dioxide and the $Ph_3SnCH_2C{\equiv}CH$ complex gives the stable sulfinate $Ph_3Sn[O\text{-}S(O)CH{=}C{=}CH_2]$, the structure of which is similar to that of intermediate **102**.



101 **102** **100**

M	R	M	R
$\eta^5\text{-}C_5H_5Fe(CO)_2$	Me	$Mn(CO)_5$	Me
$\eta^5\text{-}C_5H_5Fe(CO)_2$	Ph	$\eta^5\text{-}C_5H_5Mo(CO)_3$	H
$Mn(CO)_5$	H	$\eta^5\text{-}C_5H_5Mo(CO)_3$	Me

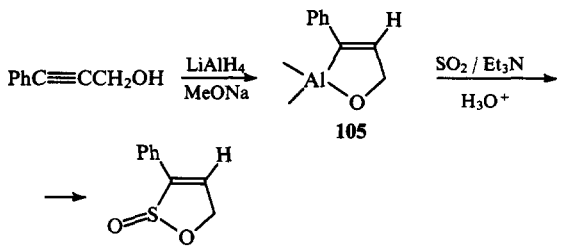
Conversely, the reaction between sulfur dioxide and Grignard reagents or organolithium compounds occurs in the typical way, sulfur dioxide being inserted into the C–M bond. For example, the α,β-unsaturated γ-sultines **103** were synthesised[87] by the addition of sulfur dioxide to the Grignard reagents **104** obtained from propargyl alcohols. The hydroxysulfinate formed initially undergoes cyclisation to the sultine **103** upon subsequent hydrolysis (see Section II.2.c).



104 **103**

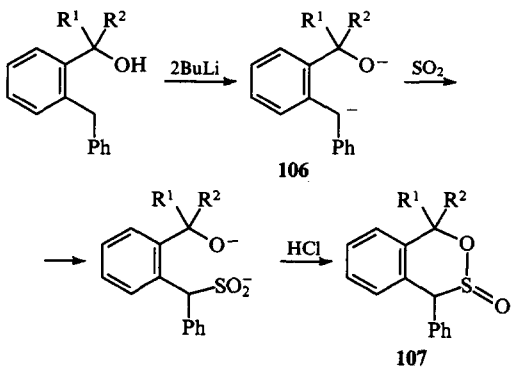
R^1	R^2	Yield (%)
H	Et	30
H	Ph	60
H	$CH_2CH{=}CH_2$	32
Ph	Et	40
Ph	Ph	24

A sultine with R^2 = H was isolated in a low yield when the organoaluminium compound **105** containing a vinylic fragment was used instead of the Grignard reagent.



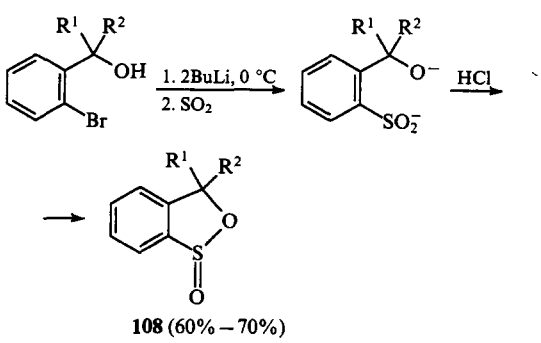
105 (7%)

Durst et al.[43] proposed that hydroxysulfinates be obtained by adding sulfur dioxide to the previously formed dianion **106**. This approach was used to synthesise benzoxathiine oxides **107** and benzoxathiol oxides **108**.



106 **107**

$R^1 = R^2 = H$ (50%–70%); $R^1 = R^2 = Me$ (38%)



108 (60%–70%)

$R^1 = R^2 = H$; $R^1 = H$, $R^2 = Me$; $R^1 = R^2 = Me$

d. Electrochemical synthesis of sultines involving sulfur dioxide

In several papers on the cathodic reduction of sulfur dioxide in aprotic solvents (DMF, acetonitrile),[88-90] a synthesis of five- and six-membered sultines by treatment of alkylene dihalides with the $SO_2^{\cdot-}$ anion radical was proposed. The following mechanism of reaction of the latter in the presence of alkylene dihalides was assumed:

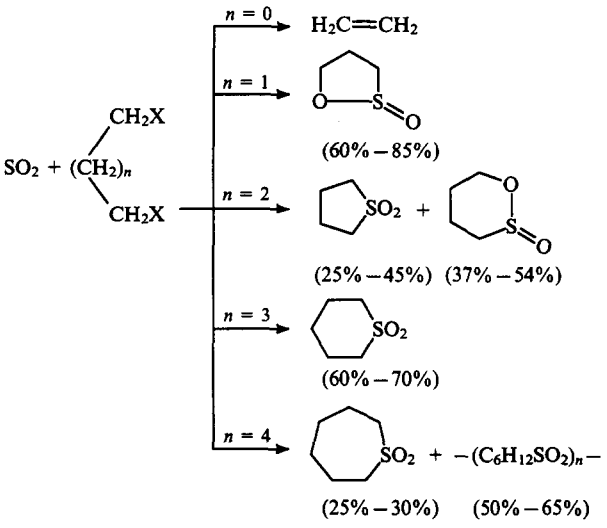
$$SO_2 + \bar{e} \longrightarrow SO_2^{\cdot-};$$

$$SO_2^{\cdot-} + RX \longrightarrow RSO_2^{\cdot} + X^-;$$

$$RSO_2^{\cdot} + SO_2^{\cdot-} \longrightarrow RSO_2^- + SO_2;$$

$$RSO_2^- + RX \longrightarrow RSO_2R + X^-.$$

The yields of sultines or cyclic sulfones depend on the distance between the reaction centres in the alkylene dihalide. This can be demonstrated by the scheme below.



X = Cl, Br, OTs

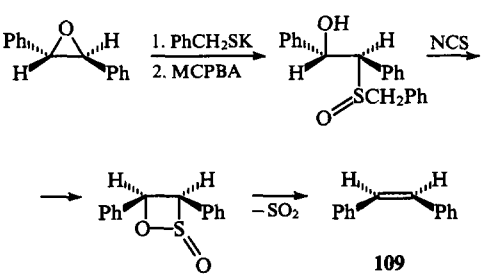
III. Properties of sultines

The limited number of convenient methods for the synthesis of sultines has meant that their chemistry has been studied inadequately, and data on their reactions are rather fragmentary. The thermal and photochemical decomposition of sultines as well as the oxidation, reduction, and cleavage of the sultine ring by nucleophiles have been studied in more detail.

1. Thermolysis and photolysis of sultines

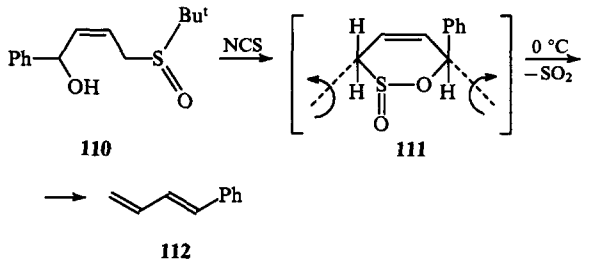
The thermal stability of sultines is primarily determined by the size of the heterocyclic ring, the nature and position of substituents in the ring, and to a lesser extent by other features of their structure.

For example, with rare exceptions, β-sultines are very unstable and decompose even at room temperature in several minutes with the evolution of sulfur dioxide and formation of unsaturated compounds[38-40] (see Section II.2). This is probably a consequence of the considerable strain in the four-membered heterocycle. The loss of sulfur dioxide occurs stereospecifically by *cis*-elimination, which was demonstrated in the formation of *cis*-stilbene **109** (> 99%).



109

β,γ-Unsaturated six-membered sultines — 3,6-dihydro-1,2-oxathiine 2-oxides — are unstable at temperatures above 0 °C and decompose into 1,3-dienes and sulfur dioxide.[25,67] The stereospecific nature of this reaction was shown for the *cis*-hydroxysulfoxide **110**, which gave exclusively *trans*-1-phenylbuta-1,3-diene **112** (> 99.5%) by fragmentation of the intermediate sultine **111**.

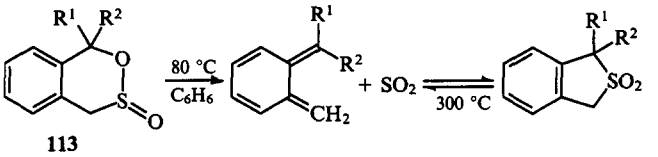


110 **111**

112

This process is characterised by extremely easy sulfur dioxide elimination: the decomposition of 3,6-dihydro-1,2-oxathiine 2-oxide into the corresponding 1,3-diene and sulfur dioxide occurs at a temperature lower by 125 °C than that required for the similar decomposition of 2,5-dihydrothiophene 1,1-dioxide.

Unlike the 3,6-dihydro-1,2-oxathiine 2-oxides already considered, benzoxathiine oxides **113** are more stable and decompose into the corresponding *o*-quinodimethanes and sulfur dioxide only at 80 °C, whereas the elimination of sulfur dioxide from the corresponding sulfones occurs only at 300 °C.[25,45,67] In the absence of other dienophiles, the resulting diene once again traps the sulfur dioxide molecule to give a cyclic sulfone isomeric with the original sultine **113**.

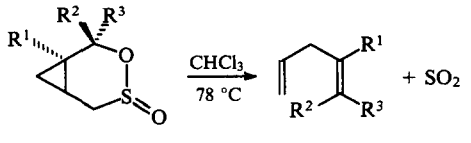


113

R^1 = H; R^2 = H, Ph, Me; R^1 = R^2 = Me.

The ease of sulfur dioxide elimination allows one to use this reaction for generating such reactive dienes as *o*-quinodimethanes by cycloaddition in situ under mild conditions.

The fragmentation of 3,4-oxathiabicyclo[4.1.0]heptane 4-oxides **114** in boiling chloroform into a 1,4-diene and sulfur dioxide occurs stereospecifically.[91] This reaction produces *cis*- and *trans*-4-phenylhexa-1,4-dienes **115a** and **115b** from sultines **114a** and **114b** with > 99.5% isomeric purity.



114a–c **115a–c**

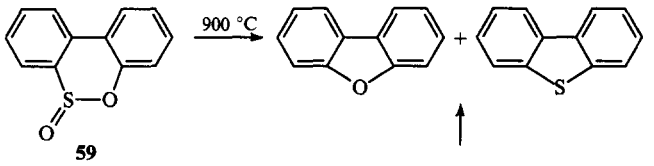
a: R^1 = Ph, R^2 = H, R^3 = Me;
b: R^1 = Ph, R^2 = Me, R^3 = H;
c: R^1 = R^2 = R^3 = H

The stereochemistry of the sulfinyl group and the mutual arrangement of substituents considerably affect the de-composition rate. It should be noted that the decomposition of sultines again occurs at a temperature 100 °C lower than that required for the decomposition of the isomeric sulfone, 3-thia-bicyclo[3.1.0]-hexane 3,3-dioxide.

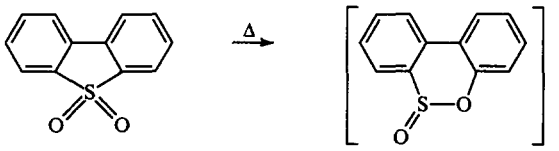
All the above examples of the thermal decomposition of sultines occur apparently as concerted processes, which is suggested by the stereospecificity of the transformations and the ease (low temperatures) of sulfur dioxide elimination.

The examples of the thermal and photochemical degradation of six- and five-membered sultines described below are likely to be radical processes. The reactions occur at very high temperatures (400–900 °C), and their course significantly depends on the structure of the initial sultine and on the nature of the substituents.

For example, the thermolysis of dibenzoxathiine oxide **59** yields a mixture of dibenzofuran and dibenzothiophene in a 6 : 1 ratio.[48] The pyrolysis of dibenzothiophene 1,1-dioxide **56** gives the same products and in the same ratio, which makes it possible to assume the intermediate formation of the sultine **59**.[92]

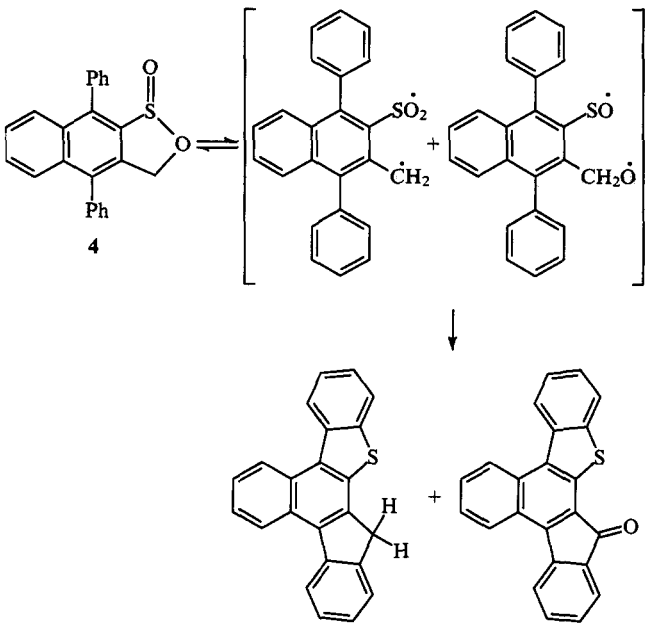


59



56 **59**

The thermolysis of diphenylnaphthoxathiole oxide **4** results in two cyclisation products, compounds **5** and **6**, which are formed by the interaction of radical centres with the neighbouring phenyl groups.[7]

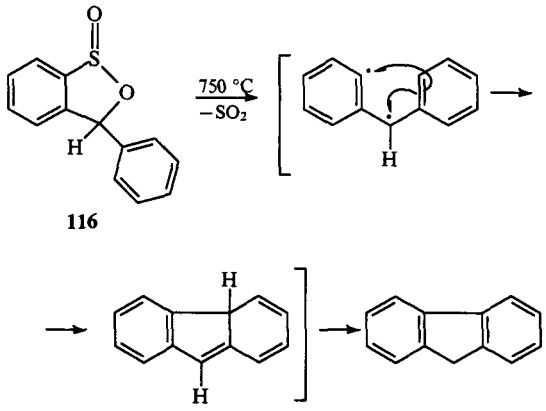


4

5 (7.8%) **6** (21.2%)

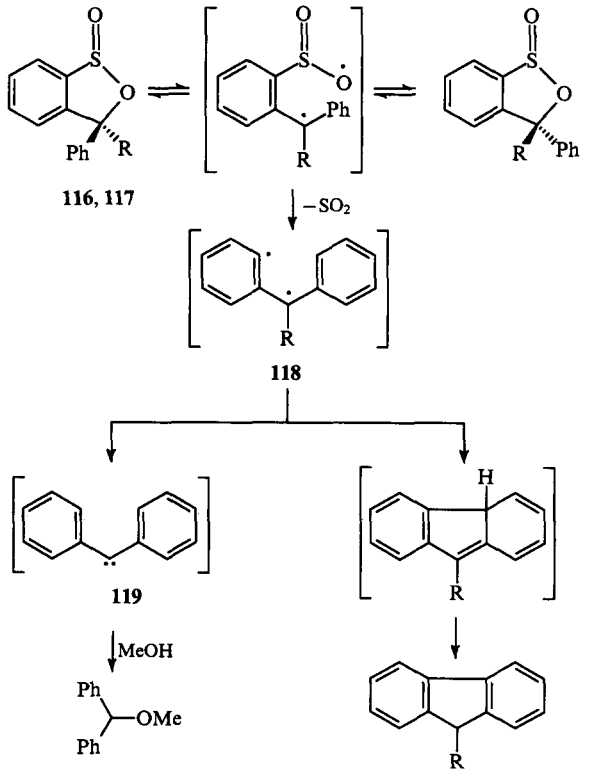
In general, the presence of stabilising phenyl groups adjacent to the reaction centres in the molecule has a decisive effect on the thermal and photolytic transformations of sultines.

For example, the thermal decomposition of phenyl-benzoxathiol oxide **116** at 750 °C occurs by the elimination of a sulfur dioxide molecule to give a 1,3-biradical, which then rearranges to fluorene. However, the thermolysis of the unsubstituted analogue under the same conditions results in an uncharacterised mixture of degradation products.[93]



116

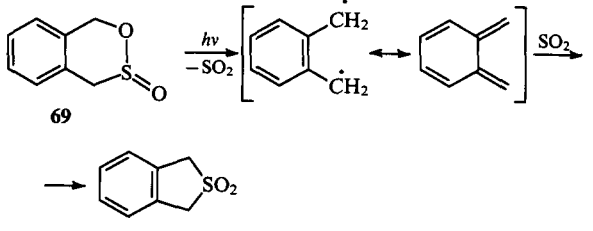
A complete analogy between the reactions was also observed in the photolytic decomposition of the sultines **116** and **117**.[94] It was shown that the resulting 1,3-biradical **118** can also rearrange to the carbene **119**, which was identified by its reaction with methanol.



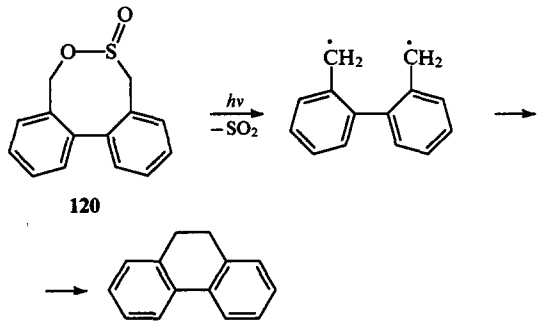
116, 117 **118** **119**

R = H (27%), Ph (42%)

The photolysis of six-membered (**69**) and eight-membered (**120**) sultines in methanol gave a sulfone and 9,10-dihydrophenanthrene, respectively.

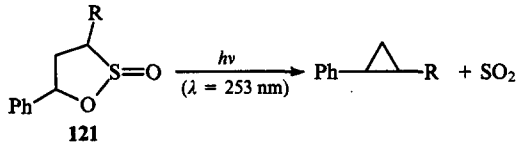


69



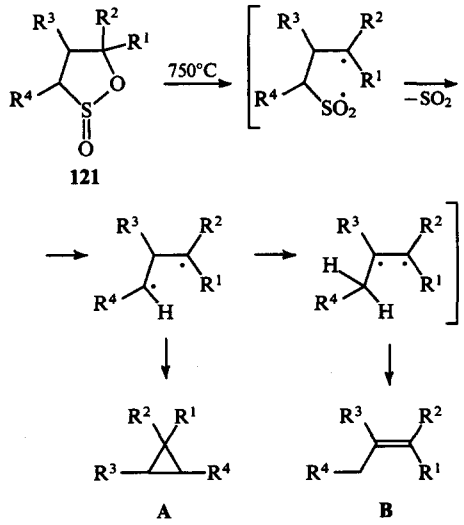
120

The thermolysis and photolysis of 5-phenyl-1,2-oxathiolane 2-oxides **121** are accompanied by the formation of a 1,3-biradical, in which one centre is located on the C atom of the benzyl group. This radical then recombines to give the corresponding cyclopropane. If other substituents are attached at the C(5) atom, stabilisation of the 1,3-biradical leads predominantly to isomeric alkenes.[93,94]



121

R = H (95%), Me (98%)

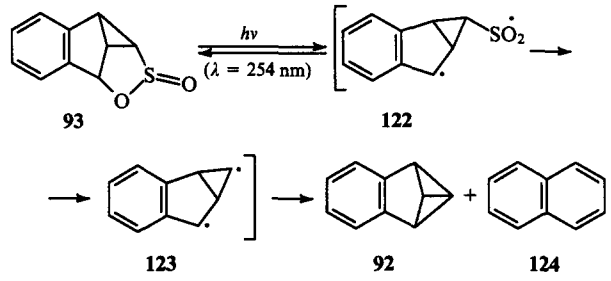


A B

R^1	R^2	R^3	R^4	Product yield (%)	
				A	B
Ph	H	H	H	100	—
Ph	Me	H	H	100	—
H	H	Me	H	37	62
H	H	Ph	H	—	†
Me	H	H	H	45	35

The addition of sulfur dioxide to benzobenzvalene, like the addition to arylcyclopropanes (see Section II.3.b), was found to be photochemically reversible. When the sultine **93** was irradiated with UV light, it evolved sulfur dioxide with the regeneration of the original benzobenzvalene **92** and formation of naphthalene in a 1 : 3 ratio.[84]

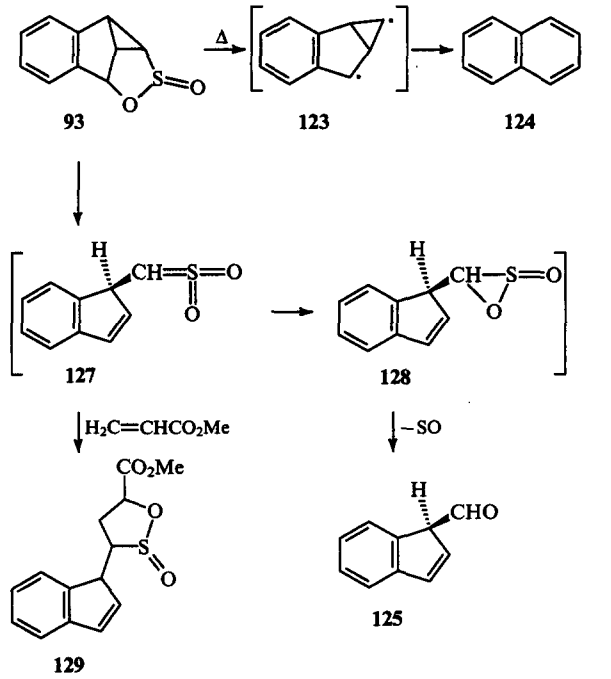
† Compound **B** is the only product; yield is not reported.[93]



93 122 123 92 124

This reaction is believed[84] to occur by reversible homolytic cleavage of the sultine to give the biradicals **122** and **123**. The latter, which is in a singlet state, gives benzobenzvalene **92**; alternatively, naphthalene **124** is formed by bond cleavage in the cyclopropane fragment.

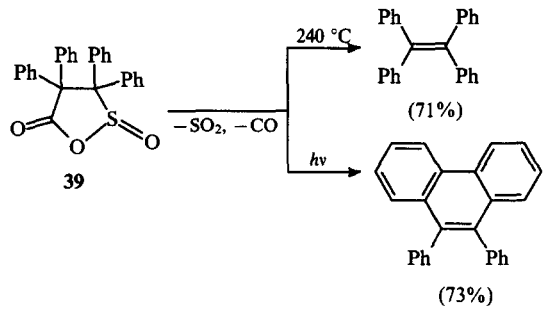
The pyrolysis of the sultine **93** gives a complex mixture of products; 1*H*-indene-1-carboxaldehyde **125** and 1*H*-indene-3-carboxaldehyde **126** together with naphthalene were isolated from it in the proportion **124** : **125** : **126** : **92** = 52 : 22 : 16 : 9.5.[95] It is assumed that naphthalene is also formed due to the cleavage of the C–C bond in the intermediate biradical **123**. The formation of aldehydes in the reaction mixture was explained[95] by the generation of sulfene **127** and its subsequent cyclisation to the oxathiirane *S*-oxide **128**. In the final step, the oxathiirane *S*-oxide **128** loses a sulfur monoxide molecule to give the aldehyde **125**.



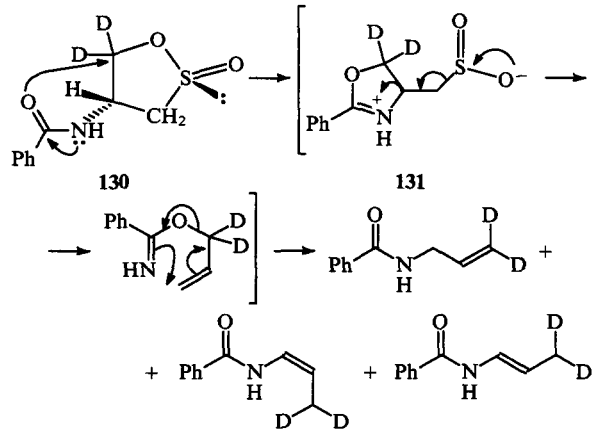
93 123 124 127 128 129 125

The presence of the sulfene **127** in the reaction mixture was proved by performing the pyrolysis with a tenfold excess of methyl methacrylate. This gave naphthalene (22%) and the sultine **129** (58%), the product of the 1,3-dipolar cycloaddition of the sulfene. The formation of aldehydes was not observed in this case.

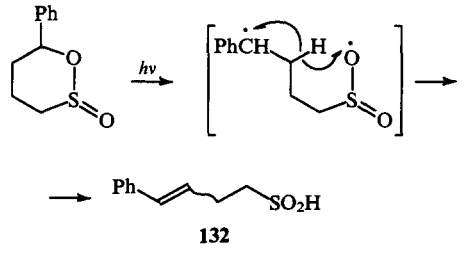
The thermolysis and photolysis of the γ-sultine **39** give different products.[23] In the former case, the elimination of sulfur dioxide and carbon monoxide molecules gives tetraphenylethene, while in the latter, the intermediate is stabilised by participation of the neighbouring phenyl groups to give 9,10-diphenyl-phenanthrene.



The thermal transformation of the functionally-substituted γ-sultine **130** considered below leads to a mixture of *N*-allylamide and enamides owing to heterolytic bond cleavage with participation of neighbouring functional groups.[96] This decomposition is considered to involve most probably the formation of oxazolinium species **131** due to intramolecular nucleophilic attack by the amide oxygen atom at the C–O bond in the sultine ring.[96]

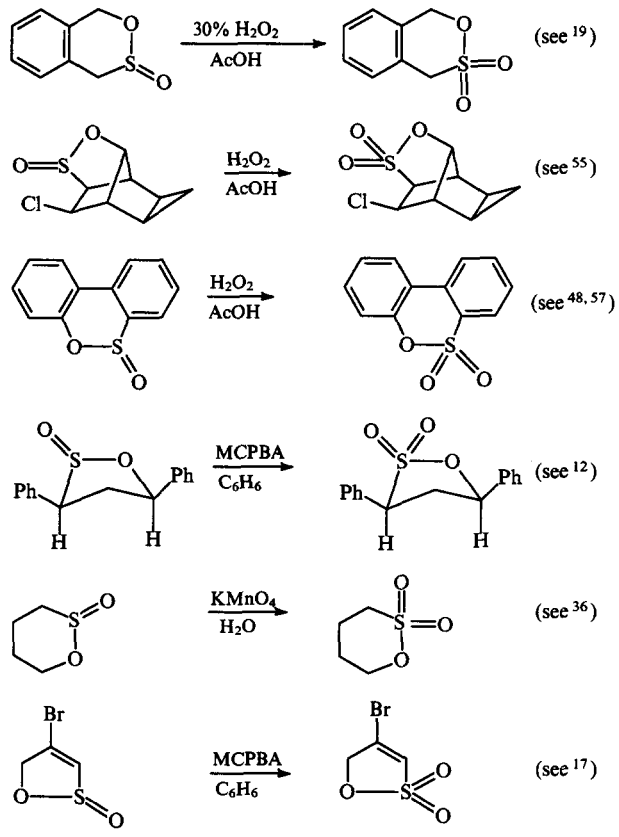


The thermal and photolytic decomposition of six-membered saturated sultines has scarcely been studied. Only the photolysis of 6-phenyl-1,2-oxathiane 2-oxide to give the unsaturated sulfinic acid **132** has been reported.[94]

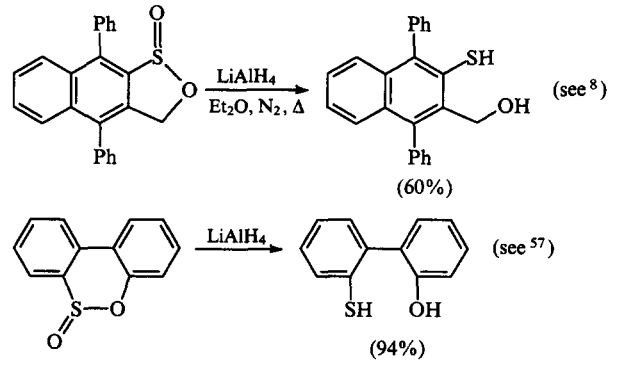


2. Redox reactions of sultines

One of the most typical reactions, which is often used to prove the presence of a sulfinyl group in the compound under investigation, is the oxidation of sultines. The reaction gives sultones, cyclic esters of sulfonic acid, with characteristic frequencies at 1300–1360 cm^{-1} in their IR spectra. This distinguishes them from sultines, which unlike sultones, do not have this characteristic band in their IR spectra, and absorption is observed only at 1100–1150 cm^{-1}. (For the methods of preparation and reactions of sultones, see Ref. 97). As a rule, a 30% solution of hydrogen peroxide in glacial acetic acid[9,19,48,55,57,82] or MCPBA[12,17,24,26] are used as oxidants; the latter permits oxidation under mild conditions. In addition, potassium permanganate,[36] chromic acid[98] and potassium hydropersulfate[87] are also used for the oxidation of sultines. A few typical reactions are given below:

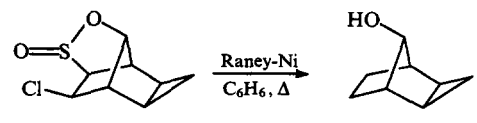


Unlike the oxidation of heterocycles containing an SO fragment in the ring, which can be carried out in stages, passing from sulfenyl to sulfinyl group[41] and then to the sulfonyl group, the known sultine reduction reactions proceed exhaustively omitting the sultene formation stage. In this case, cleavage of the sultine ring at the S–O bond occurs leading, as a rule, to mercaptoalcohols.



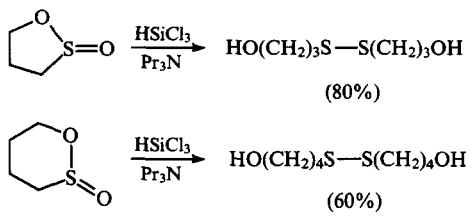
The latter reaction is of interest because this is a convenient method for the bifunctionalisation of biphenyl.[57]

The reduction of sultines in the presence of Raney nickel or with a great excess of lithium tetrahydroaluminate results in the total desulfurization of the compound to give the corresponding alcohol.[55]



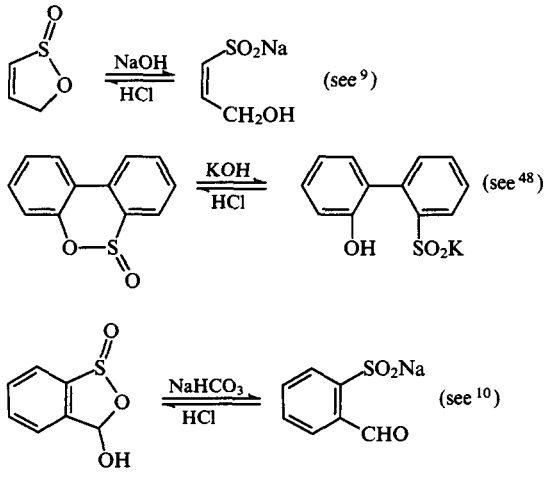
The reduction of γ- and δ-sultines with trichlorosilane in the presence of tri(*n*-propyl)amine affords symmetrical dihydroxydisulfides in high yields.[99] The reduction mechanism is unclear;

however, the reaction does not occur in the absence of the amine noted above. The latter may react with the ether–trichlorosilane complex formed initially.



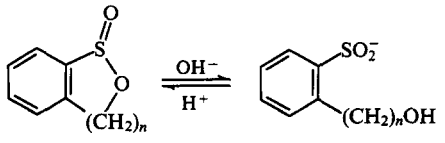
3. Cleavage of the sultine ring by nucleophiles

Sultines are stable in acidic and neutral media but undergo alkaline hydrolysis. In this case, nucleophilic attack results in the cleavage of the sultine ring to form hydroxysulfinates.



This reaction is reversible, and acidification leads to the cyclisation of the hydroxysulfinate formed to give the original sultine. The reverse reaction is often used to synthesise sultines from hydroxysulfinates.[43,45–49]

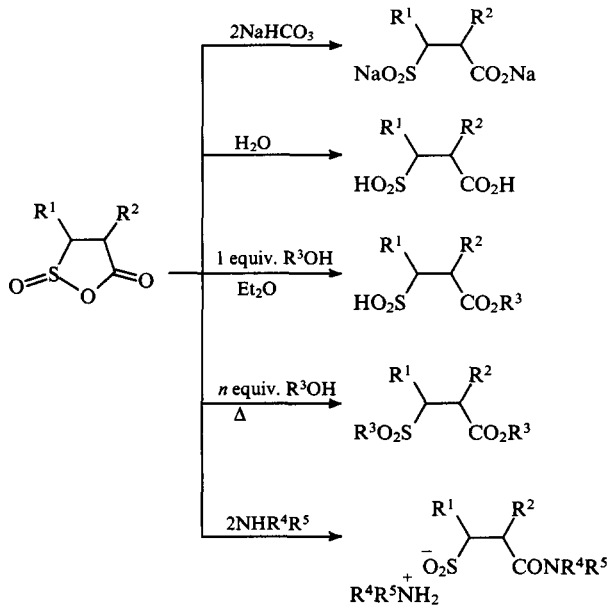
The kinetics of sultine ring opening under alkaline hydrolysis conditions and cyclisation in an acidic medium have been studied for the sultines **133** and **134** as examples.[100]



n = 1 (**133**), 2 (**134**)

In both cases, a five-membered sultine is more reactive than a six-membered one. However, the rate of ^{18}O-isotope exchange, which was found to involve the O atom of the sulfinyl group in acidic media, was higher for the six-membered sultine. This result, which seems contradictory at first sight, can be explained in terms of molecular orbital theory.

1,2-Oxathiolan-5-one 2-oxides, i.e. mixed anhydrides of β-sulfinocarboxylic acids, are particularly reactive towards nucleophiles. They readily undergo hydrolysis and can be isolated only in the total absence of moisture. They are cleaved by nucleophiles (ROH, R_2NH) under mild conditions, and in this case, opening of the sultine ring occurs only at the O–CO bond to give the corresponding derivatives of β-(hydroxysulfinyl)alkanoic acids.[101–103]

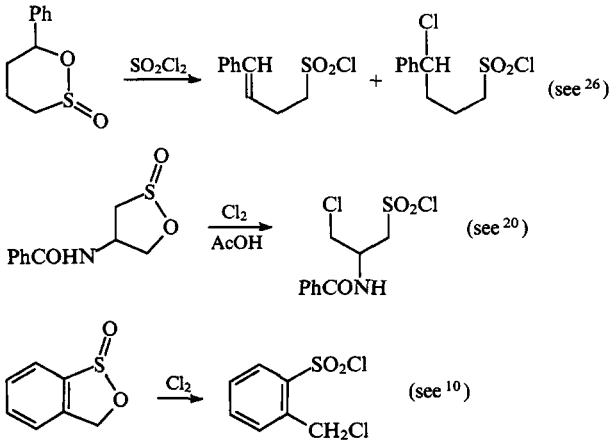


R^1 = H: R^2 = H, Me;
R^1 = Me: R^2 = H

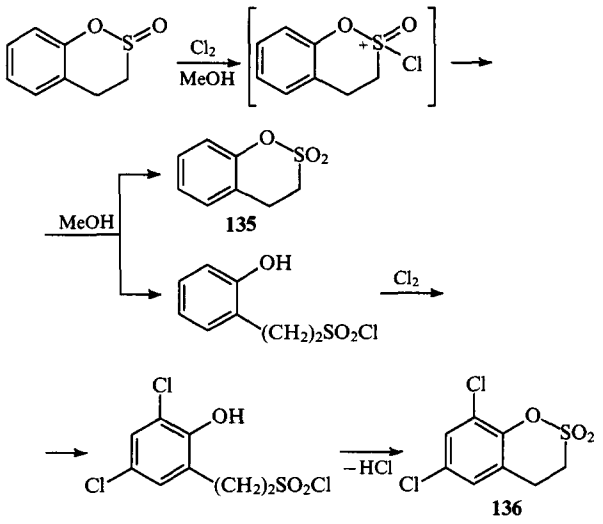
The cleavage of 1,2-oxathiolan-5-one 2-oxides by nucleophiles is interesting as a promising method for the synthesis of biologically active compounds. Compounds possessing radioprotective activity have been found among the products of the aminolysis of 1,2-oxathiolan-5-one 2-oxides.[102,103]

Unlike alkyl-substituted 1,2-oxathiolan-5-one 2-oxides, 2,1-benzoxathiol-3-one 1-oxide is cleaved by alcohols both at the O–CO and O–SO bonds.

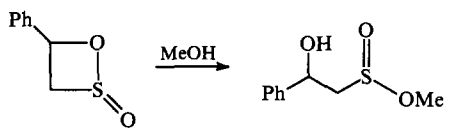
The cleavage of sultines by halide ions begins with attack at the C atom adjacent to the O atom of the sulfinyl group by the anion, breaking the C–O bond and forming sulfonyl chlorides. This reaction is the reason for the decrease in the yields of sultines when they are synthesised with the use of chlorinating agents (Cl_2/AcOH, NSC, SO_2Cl_2) taken in great excess.



Unlike the examples considered above, 1,2-benzoxathiine 2-oxide is inert to the action of chlorine under similar conditions.[19] The difference between the reactivities of the sultines may be explained by the fact that the aryl–oxygen bond is probably stronger than the alkyl–oxygen bond, and the strain in the six-membered ring is less than that in the five-membered ring. On the other hand, in more nucleophilic solvents, such as alcohols, 1,2-benzoxathiine 2-oxide is oxidised by chlorine to the sultones **135** and **136**, probably by the following scheme.

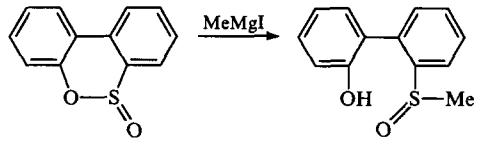


In the case of the alcoholysis of a four-membered sultine, 4-phenyl-1,2-oxathietane 2-oxide, nucleophilic attack is directed at the S atom giving hydroxysulfinate esters.[38]

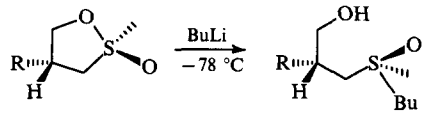


Thus, nucleophilic attack can be directed to both the C and S atoms, probably depending on the structure of the starting compounds. These data are consistent with the results obtained for sultones: the decomposition of sultones with fused aromatic rings occurs both through the cleavage of the C–O bond [104, 105] and the S–O bond,[106, 107] depending on their structure and reaction conditions, but, as a rule, β-sultones react with nucleophiles through the sulfur atom, while the reactions of larger-ring sultones involve the carbon atom.

The cleavage of sulfinate esters with organomagnesium compounds to give sulfoxides is well known. In the case of the cyclic esters, i.e. sultines, this cleavage results in the corresponding hydroxysulfoxides.[48, 108]



The reactions of sultines with alkyllithium compounds proceeds in a similar way; hydroxyalkyl sulfoxides are also formed as a result of nucleophilic attack at the S atom.[20]



R = Bu^{t}CONH

Interesting data on the ability of sultines to form crystalline molecular complexes with organotin compounds (of the composition $RSnCl_3$: L = 1 : 2 where L is 3,5-diaryl-1,2-oxathiolane 2-oxide), which may possess biological activity, have been published.[109]

As already mentioned, the chemistry of the sultines has not yet been adequately studied, although their presently known reactions make them rather promising reagents for use in organic synthesis. This inadequacy is partly related to the lack of convenient methods for the synthesis of sultines. Therefore, the development of new methods of synthesis of sultines and the study of their properties remain of great current interest.

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