Sulfur-Assisted Ring Expansion of the Potassium Salts of 1-Vinylcyclobutanols. A Versatile Synthesis of Cyclohexanones

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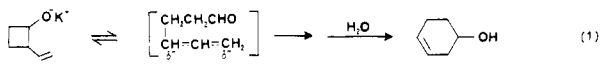
Readily available 2-(phenylthio)-1-vinylcyclobutanols undergo a facile potassium hydride induced ring expansion to 4-(phenylthio)cyclohexanones. The sulfur substituent plays a key role. Evidence for a fragmentation to an enone–anion intermediate is discussed. Acid induced rearrangement of a similar substrate to a five-membered ring is demonstrated.

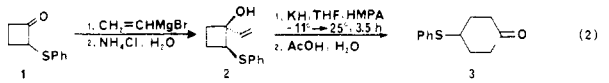
We have recently shown that the potassium salts of 2-vinylcyclobutanols readily rearrange to cyclohex-3-en-1-ols, apparently via fragmentation to an intermediate aldehyde–allylic anion (e.g., eq 1).[1] Insight into the mechanism was attained by the observation that cis–trans isomerization of the reactant is competitive with the ring expansion and that the stereochemistry of the latter in a fused system could be controlled by the presence or absence of complexing agents for potassium ion.[1b]



(1)

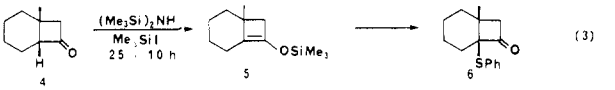
We now report that the potassium salts of 1-vinylcyclobutanols undergo a possibly related rearrangement (e.g., **2** → **3**) with equal facility *provided that a sulfur substituent is present at the 2-position.* This reaction provides not only a new, synthetically useful route to cyclohexanones, functionalized with the enormously versatile phenylthio group, but also a striking demonstration of the ability of sulfur to facilitate rearrangements.

The reactants are readily available by treatment of 2-(phenylthio)cyclobutanones with vinylmetallic reagents (e.g., eq 2).[2] The results of these additions are compiled in Table I. Except in the case of addition of 1-lithiocyclohexene to 2-allyl-2-(phenylthio)cyclobutanone (**19**), in which the carbonyl group is hindered and the enolizable protons are quite exposed, the degree of enolization appeared to be low and the yields of addition products were satisfactory; the major byproducts in the case of **19** appear to arise by enolization of the cyclobutanone and addition of the enolate ion to unreacted ketone (see Experimental Section). In each case, the addition is stereospecific, and it is assumed that the isomer that is formed is that which arises by attack of the anion from the side opposite that bearing the phenylthio substituent; further evidence in support of these assignments is given below.



(2)

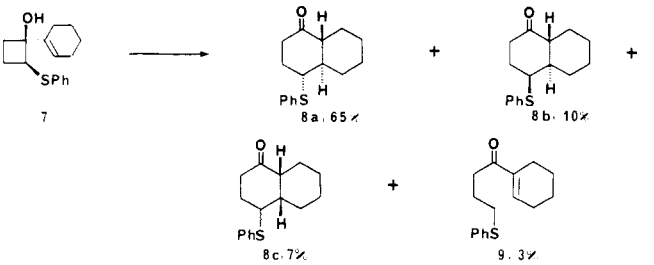
2-(Phenylthio)cyclobutanone (**1**) itself is prepared in three steps from commercially available material.[2] Its 2-allyl derivative **19** was prepared by allylation of the derived enolate anion. The bicyclic analogue **6** was prepared by sulfenylation of the thermodynamic[3] enol silyl ether **5** derived from **4**,[4] the reduction product of the adduct of 1-methylcyclohexene and dichloroketene (eq 3). There are extant literature syntheses for other fused[5a] and spirobicyclic[5b] 2-(phenylthio)cyclobutanones.



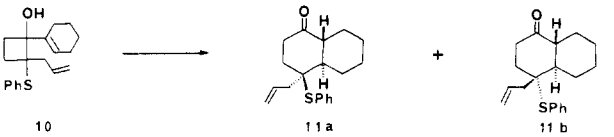
(3)

The results of the rearrangements are summarized in Table I. The yields of rearrangement product are reasonable in most cases, falling off, however, in the two cases in which the sulfur-bearing carbon atoms are fully substituted.

The rearrangement of **7** gave mainly the most stable isomer (**8a**) of the product which, as determined by analysis of its proton NMR spectrum, possesses an equatorial phenylthio group and a trans ring junction. The epimer (**8b**) about the sulfur-bearing carbon atom was formed in 10% yield and 7% of a cis fused isomer (**8c**) was obtained as a mixture with 3% of the fragmentation product **9**.



The rearrangement of **10** produced a 2:1 mixture of epimers (**11**) both of which possessed a trans ring fusion; the chemical shift of the axial proton C-8a in the major isomer is close to that of the analogous proton in **8b**, one which is strongly deshielded by the cis axial phenylthio group, and this isomer is thus assigned the configuration **11a** in which the phenylthio group is axial. The fact that

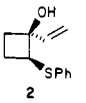
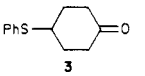
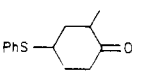
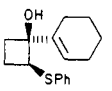
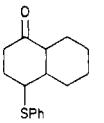
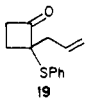
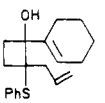
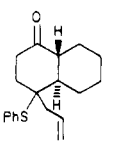
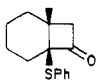
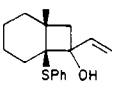
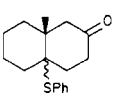
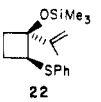
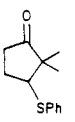


the major rearrangement products from **7** and **10** have the largest group at the 4-position in the equatorial configuration is easily rationalized by assuming a chair transition state for the cyclohexanone formation (see below).

(1) (a) Cohen, T.; Bhupathy, M.; Matz, J. R. *J. Am. Chem. Soc.* **1983**, *105*, 520. (b) Bhupathy, M.; Cohen, T. *Ibid.* **1983**, *105*, 6978.
(2) Cohen, T.; Ouellette, D.; Senartne, K. P. A.; Yu, L.-C. *Tetrahedron Lett.* **1981**, *22*, 3377.
(3) Brownbridge, P. *Synthesis* **1983**, 1.
(4) Clark, G. R.; Lin, J.; Nikaido, M. *Tetrahedron Lett.* **1984**, *25*, 2645.
(5) (a) Ishida, M.; Minami, T.; Agawa, T. *J. Org. Chem.* **1979**, *44*, 2067. Trost, B. M.; Godleski, S. A.; Ippen, J. *Ibid.* **1978**, *43*, 4559. Michel, P.; O'Donnell, M.; Biname, R.; Hesbain-Frisque, A. M.; Ghosez, L.; DeClercq, J. P.; Germain, G.; Arte, E.; Van Meerssche, M. *Tetrahedron Lett.* **1980**, *21*, 2577. (b) Trost, B. M.; Hiroi, K. *J. Am. Chem. Soc.* **1975**, *97*, 6911.

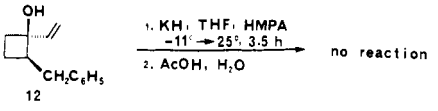
0022-3263/85/1950-4596$01.50/0

Table I. Preparation and Rearrangement of 1-Vinylcyclobutanols

cyclobutanone	vinylmetallic	cyclobutanol	% yield (% enol)[a]	cyclohexanone	% yield
 1	CH_2=CHMgBr	 2	82 (4)	 3	60
1	CH_2=C(Me)Li	 13	82 (*b*)	 15	69[c]
1		 7	83 (8)	 8	82[c,d]
 19		 10	49[e] (42)	 11	44[f]
 6	CH_2=CHMgBr	 20	70[e] (*b*)		45
		 22	63[g] (*b*)	 23	62

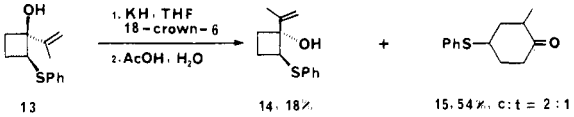
[a] Yield of unreacted ketone or aldol condensation products arising from enolate anion. [b] Not determined. [c] See text for the isomeric composition of this product. [d] A 3% yield of **9** was also produced. [e] Single product of unknown stereochemistry. [f] See text for structural assignments of the two isomers formed in a 2:1 ratio. [g] Acid catalysis.

The effect of sulfur was demonstrated by comparing the ease of rearrangement of (*E*)-2-(phenylthio)-1-vinylcyclobutanol (**2**) with that of (*E*)-2-benzyl-1-vinylcyclobutanol (**12**). The latter was prepared by benzylation of **1** in the presence of potassium *tert*-butoxide,[2] reductive lithiation[2] of the product by using lithium 1-(dimethylamino)-naphthalenide,[2,6] and treatment of the resulting ketone with vinylmagnesium bromide. When **12** was subjected to the conditions which caused complete rearrangement of **2**, only unchanged starting material was recovered.



12

Some experimental information concerning the stereochemistry of the vinylcyclobutanols and a clue as to the possible mechanism of the rearrangement was gleaned from studies of the rearrangement of 1-isopropenyl-2-(phenylthio)cyclobutanol (**13**). The normal rearrangement product (**15**, cis:trans, 5:1) was produced in 69% yield under the usual conditions. However, when a catalytic quantity of 18-crown-6 was used instead of HMPA, the cis and trans products **15** were formed in yields of 36% and 18%, respectively, and the epimerized cyclobutanol **14** was isolated in 18% yield. This result clearly implies that the potassium salt (**16**) of the epimerized cyclobutanol is more thermodynamically stable than that (**16**) of the reactant, a result that can be rationalized by assuming that the latter experiences greater dipolar and possibly steric repulsions from the interaction of the phenylthio group with the alkoxide ion and its associated ligands. The ^{1}H NMR spectrum of the epimeric isopropenylcyclobutanols lends credence to these stereochemical assignments; all of the protons of the isopropenyl group of the *E* epimer (**14**) absorb at lower field than those of the *Z* isomer (**13**), a pattern that is typical for protons in close proximity to a phenylthio group. The lower mobility of the epimerized product than of the reactant in TLC is also completely consistent with the assignment of *E* stereochemistry to the former since the less sterically encumbered hydroxyl group of the *E* isomer would certainly be expected to bind to silica more strongly.

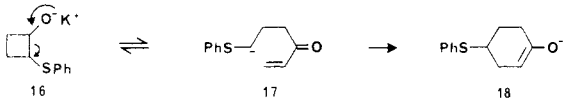


13 14, 18% 15, 54%, c:t = 2:1

While there is too little information to assign a mechanism to this rearrangement, the simplest postulation would involve a fragmentation to an intermediate which is capable of reclosure to the epimerized cyclobutane or closure to the ring expanded product, as appears on the basis of more extensive evidence to occur in the case of the 2-vinylcyclobutanol rearrangement.[1b] A readily pictured intermedite is the enone–anion **17** which could recombine in either a 1,2 or 1,4 fashion, but the radical anion generated by moving an electron from the sulfur-bearing carbon atom to the enone system cannot be ruled out. The existence of an intermediate is also consistent with the product **9**, formed in small yield from the rearrangement of **7**, along with the normal six-membered ring and the analogous fragmentation product formed quantitatively

(6) Cohen, T.; Sherbine, J. P.; Matz, J. R.; Hutchins, R. R.; McHenry, B. M.; Willey, P. R. *J. Am. Chem. Soc.* **1948**, *106*, 3245 and references cited therein.

when the analogue of 7 with a 2-furyl group in place of the cyclohexenyl group is treated with KH[2]; these products could arise by a proton or hydrogen atom transfer in the intermediate. Fragmentation of the salts of cyclobutanols bearing anion-stabilizing groups at the 2-position is precedented.[7]



16 17 18

Sano and co-workers[8] have reported an example of a similar rearrangement in a more complex system. In that work, the alkoxide group was generated by treatment of the corresponding trimethylsilyl ether with tetrabutylammonium fluoride. It is of interest that the migrating carbon atom carried a phenyl substituent which presumably served the same purpose as the phenylthio group in the present system, namely, stabilization of the negative charge in the intermediate; a mechanism for the rearrangement was not discussed.

The rearrangement described herein is probably also related to the potassium hydride induced ring expansion of the vinylmetallic adducts of the monodithiane derivatives of a 13-membered ring 1,2-dione discovered by Wilson[9] and assumed to proceed by an anion–enone. In that case two sulfur atoms were required; when the dithiane ring was replaced by a single phenylthio group, the rearrangement did not occur. In the present system the ring strain leads to sufficient activation by a single sulfur atom; in addition, the proximity of the functional groups of the intermediate leads to considerably better yields.

The present rearrangement may also be related to that of the adducts of vinylmetallics to the ethanedithiol monoketal of benzocyclobutenedione in which an intermediate somewhat analogous to **17** has been postulated.[10] However, the extra unsaturation in that system leads to an intermediate in which the negative charge is, at least formally, conjugated with the carbonyl group of the enone system. Consequently, the ring opening is apparently more facile than in our examples (the sulfur atoms can be replaced by oxygen atoms and the lithium salts, themselves, rearrange), and the ring closure may be more properly described as a six-electron electrocyclic process.

A preliminary experiment (last entry in Table I)[11] indicates that acid catalyzed ring expansion of the same types of substrates will provide five-membered rings. This type of rearrangement, which undoubtedly proceeds by protonation of the unsaturated side chain followed by a pinacol type rearrangement, is well-known in the 1-vinylcyclopropanol series[12] but, without the sulfur substituent, it is sluggish in the 1-vinylcyclobutanol series.[13]

Experimental Section

All reactions were performed under argon. Flash chromatography[14] was performed with 40–63-μm silica gel 60 (E. Merck). Thin layer chromatograms (TLC) were run on glass supported silica gel 60 plates (0.25 mm layer, F-254, E. Merck).

Alkylation of 2-(Phenylthio)cyclobutanone (1). 2-Allyl-2-(phenylthio)cyclobutanone (19). To a slurry of potassium *tert*-butoxide (0.251 g, 2.24 mmol) in DMF (8 mL) was added a solution of ketone 1 (0.379 g, 2.13 mmol) in DMF (2 mL) dropwise at −40 °C. The mixture was stirred at −40 °C for another 0.5 h after the addition and then stirred at 25 °C for 6 h. After having been quenched with saturated aqueous ammonium chloride, the mixture was partitioned between ether and water, and the aqueous phase was extracted with ether. All ethereal layers were combined, were washed with water and then with brine, and were dried over anhydrous magnesium sulfate. Concentration and flash chromatography gave some recovered **1** and 0.276 g (59%) of 2-allyl-2-(phenylthio)cyclobutanone (**19**): ^{1}H NMR δ 1.89–1.98 (m, 1 H), 2.17–2.26 (m, 1 H), 2.37–2.53 (m, 2 H), 2.81–2.92 (m, 1 H), 3.04–3.16 (m, 1 H), 5.10–5.19 (m, 2 H, $=CH_2$), 5.74–5.88 (m, 1 H, $CH=CH_2$), 7.27–7.39 (m, 3 H, Ph), 7.52–7.56 (m, 2 H, Ph); IR (neat) 1775 (CO), 1630 (C=C) cm^{-1}; mass spectrum (15 eV), m/e (relative intensity) 218 ($M^+ - CH_2CO$, 100), 110 ($PhSH^+$, 15); exact mass calcd for $C_{13}H_{14}OS$ 218.0765, found 218.0766.

2-Benzyl-2-(phenylthio)cyclobutanone was obtained in 60% yield by the same procedure: ^{1}H NMR δ 1.85–1.94 (m, 1 H), 2.17–2.27 (m, 1 H), 2.41–2.52 (m, 1 H), 2.89–3.05 (m, overlapping a doublet at δ 2.91, J = 13.95 Hz, 2 H), 3.17 (d, J = 13.95 Hz, 1 H, benzylic), 7.14–7.58 (m, 5 H, Ph); IR (neat) 1780 (CO) cm^{-1}; mass spectrum (15 eV), m/e (relative intensity) 268 (M^+, 4), 226 ($M^+ - CH_2CO$, 100); exact mass calcd for $C_{17}H_{16}OS$ 268.0922, found 268.0922.

2-(Benzyl)cyclobutanone. To a reaction vessel containing lithium (30 mg, 4.3 mmol) in THF (10 mL) was added 0.64 mL (3.9 mmol) of 1-(dimethylamino)naphthalene at −50 °C (hexyl alcohol–dry ice bath) under argon. The dark blue solution was stirred at −50 °C for 3.5 h. A solution of 2-benzyl-2-(phenylthio)cyclobutanone (386 mg, 1.44 mmol) in THF (2 mL) was added dropwise. The mixture was stirred at −50 °C for 1 h and was quenched with saturated aqueous ammonium chloride. The mixture was partitioned between ether and water, and the aqueous layer was extracted with ether. All ethereal extracts were washed with 3% hydrochloric acid and then with 5% aqueous sodium hydroxide solution. The dried and concentrated residue was purified by flash chromatography to give 139 mg (60%) of 2-(benzyl)cyclobutanone: ^{1}H NMR δ 1.71–1.81 (m, 1 H), 2.10–2.22 (m, 1 H), 2.77–2.92 (m, 2 H), 2.97–3.10 (m, 2 H), 3.57–3.64 (m, 1 H), 7.18–7.33 (m, 5 H); IR (neat) 1780 (CO) cm^{-1}; mass spectrum (15 eV), m/e (relative intensity) 160 (M^+, 83), 132 ($M^+ - CH_2{=}CH_2$, 24), 128 ($M^+ - CH_2CO$, 100); exact mass calcd for $C_{11}H_{12}O$ 160.0888, found 160.0889.

1-Methylbicyclo[4.2.0]octan-7-one (4). A solution of 1-methyl-8,8-dichlorobicyclo[4.2.0]octan-7-one[4] (5.0 g, 24 mmol) and α,α-azobisisobutyronitrile (36 mg) in cyclohexane (5 mL) was added over a period of 2 h to a solution of tri-*n*-butyltin hydride (14 mL, 52 mmol) in cyclohexane (25 mL) at reflux. The mixture was heated at reflux for 3 h after the addition. The cooled, concentrated mixture was chromatographed to give 2.5 g (75%) of **4**: ^{1}H NMR δ 1.10–1.69 (m, overlapping a singlet at δ 1.40, 9 H), 1.78–1.99 (m, 2 H), 2.60 (dd, J = 15.56, 1.42 Hz, 1 H), 2.81 (dd, J = ~15.6, ~2.3 Hz, 1 H), 2.91 (m, 1 H); IR (neat) 1782 (CO) cm^{-1}; mass spectrum (15 eV), m/e (relative intensity) 138 (M^+, 8), 96 ($M^+ - CH_2CO$, 100); exact mass calcd for $C_9H_{14}O$ 138.1045, found 138.1045.

6-Methyl-8-[(trimethylsilyl)oxy]bicyclo[4.2.0]oct-8-ene (5). The procedure used is due to Miller and McKean.[15] To a solution of cyclobutanone **4** (1.36 g, 9.9 mmol) and hexamethyldisilazane (2.5 mL, 12 mmol) in pentane (150 mL) at −20 °C was added iodotrimethylsilane (1.5 mL, 11 mmol). The reaction mixture was stirred at −20 °C for 20 min, allowed to warm to 25 °C, and maintained at that temperature for 10 h. The solid was removed by centrifugation. The pentane layer was washed with cold

(7) Trost, B. M.; Preckel, M. *J. Am. Chem. Soc.* **1973**, *95*, 7862. For related reactions, see: Conia, J. M.; Robson, M. J. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 473. Trost, B. M.; Rigby, J. H. *J. Org. Chem.* **1976**, *41*, 3217. Trost, B. M.; Preckel, M.; Leichter, L. M. *J. Am. Chem. Soc.* **1975**, *97*, 2224. Cossement, E.; Biname, R.; Ghosez, L. *Tetrahedron Lett.* **1974**, 997.

(8) Sano, T.; Toda, J.; Tsuda, Y. *Chem. Pharm. Bull.* **1984**, *31*, 2960. Sano, T.; Toda, J. *Heterocycles* **1983**, *21*, 702.

(9) Wilson, S. R.; Misra, R. N.; Georgiadis, G. M. *J. Org. Chem.* **1980**, *45*, 2460.

(10) Spangler, L. A.; Swenton, J. S. *J. Org. Chem.* **1984**, *49*, 1800 and references cited therein.

(11) There is no significance to the use of the silyl ether rather than the alcohol; this experiment was performed at the time that we were carrying out preliminary experiments on the thermal rearrangement of silyl ethers such as **22**.

(12) Wasserman, H. H.; Cochoy, R. E.; Baird, M. S. *J. Am. Chem. Soc.* **1969**, *91*, 2375. Girard, C.; Amice, P.; Barnier, J. P.; Conia, J. M. *Tetrahedron Lett.* **1974**, 3329.

(13) Johnson, C. R.; Herr, R. W. *J. Org. Chem.* **1973**, *38*, 3153.

(14) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.

(15) Miller, R. D.; McKean, D. R. *Synthesis* **1979**, 730.

saturated aqueous sodium bicarbonate and dried over magnesium sulfate. Distillation of the concentrated residue gave 1.57 g (76%) of **5**, bp 90 °C (5 mm): ^{1}H NMR δ 0.20 (s, 9 H, $SiMe_3$), 1.05–1.80 (m, overlapping a singlet at δ 1.08, 9 H), 2.18–2.29 (m, 4 H); IR (neat), 1620 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 210 (M^+, 21), 195 ($M^+ - CH_3$, 14), 75 ($C_2H_7SiO^+$, 100); exact mass calcd for $C_{12}H_{22}OSi$ 210.1440, found 210.1437.

1-Methyl-6-(phenylthio)bicyclo[4.1.0]octan-7-one (6). A solution of benzenethiol (1.1 g, 10 mmol) in methylene chloride (5 mL) was added slowly to a vigorously stirred mixture of trichloroisocyanuric acid (790 mg, 3.4 mmol) in methylene chloride (5 mL) at 25 °C. After the completion of the addition, the mixture was stirred for 10 min and cooled to −78 °C, and **5** (1.25 g, 5.95 mmol) was added. The resulting mixture was allowed to warm to 25 °C. The concentrated filtrate was dissolved in carbon tetrachloride, filtered, and concentrated. Medium pressure liquid chromatography gave 1.23 g (84%) of **6**, mp 49.5–50.5 °C: ^{1}H NMR δ 1.15–1.93 (m, overlapping a singlet at δ 1.42, 11 H), 2.83 (d, J = 15.76 Hz, 1 H, CH_2CO), 3.37 (d, J = 15.76 Hz, 1 H, CH_2CO), 7.26–7.58 (m, 5 H, Ph); IR (neat) 1773 (CO) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 246 (M^+, 2), 204 ($M^+ - CH_2CO$, 100), 109 (PhS^+, 8); exact mass calcd for $C_{15}H_{18}OS$ 246.1078, found 246.1078.

Addition of Vinyl Grignard Reagent to 2-Substituted Cyclobutanones. 2-(Phenylthio)-1-vinylcyclobutanol (2). To a solution of 2-(phenylthio)cyclobutanone (1.21 g, 6.80 mmol) in THF (40 mL) was added vinylmagnesium bromide (20 mL of 1.1 M solution in THF, 22 mmol), at −78 °C under argon. The mixture was allowed to warm to 25 °C over a period of 5 h, and it was quenched with saturated aqueous ammonium chloride at −40 °C. The same workup procedure as described for 2-allyl-2-(phenylthio)cyclobutanone (**19**) and column chromatography gave 0.050 g (4%) of starting material 1 and 1.15 g (82%) of **2**: ^{1}H NMR δ 1.91–2.00 (m, 1 H), 2.09–2.34 (m, 3 H), 3.13 (s, 1 H, OH), 3.90 (t, J = 4.90 Hz, 1 H, HCSPh), 5.11 (dd, J = 10.71, 1.12 Hz, 1 H, RCH=CH_2 (cis to H)), 5.34 (dd, J = 17.18, 1.12 Hz, 1 H, RCH=CH_2 (trans to H)), 6.03 (dd, J = 17.18, 10.71 Hz, 1 H, RC*H*=CH_2), 7.15–7.32 (m, 5 H, Ph); IR (neat) 3450 (OH), 1640 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 206 (M^+, 9), 178 ($M^+ - CH_2CH_2$, 6), 136 (CH=CHSPh$^+$, 100); exact mass calcd for $C_{12}H_{14}OS$ 206.0765, found 206.0766.

Compounds **12** and **20** were prepared by the same procedure.

2-Benzyl-1-vinylcyclobutanol (12): ^{1}H NMR δ 1.73–1.87 (m, overlapping a singlet at δ 1.75, 3 H), 2.01–2.20 (m, 2 H), 2.56–2.66 (m, 1 H), 2.74 (dd, J = 13.74, 9.30 Hz, 1 H, benzylic), 2.92 (dd, J = 13.74, 6.47 Hz, 1 H, benzylic), 5.00 (dd, J = 10.71, 1.21 Hz, 1 H, RCH=CH_2 (cis to H)), 5.16 (dd, J = 17.38, 1.21 Hz, 1 H, RCH=CH_2 (trans to H)), 6.02 (dd, J = 17.38, 10.71 Hz, 1 H, RC*H*=CH_2), 7.15–7.20 (m, 3 H, Ph), 7.24–7.29 (m, 2 H, Ph); IR (neat) 3403 (OH), 1638 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 188 (M^+, 11), 170 ($M^+ - H_2O$, 45), 160 ($M^+ - CH_2CH_2$, 28), 118 ($PhCH_2CHCH_2^+$, 95), 70 ($M^+ - CH_2CHCH_2Ph$, 100); exact mass calcd for $C_{13}H_{16}O$ 188.1201, found 188.1202.

1-Methyl-6-(phenylthio)-7-vinylbicyclo[4.2.0]octan-7-ol (20): mp 58–61 °C; ^{1}H NMR δ 1.20–1.83 (m, overlapping a singlet at δ 1.39, 11 H), 1.85 (d, J = 12.13 Hz, 1 H, CH_2COH), 2.33 (d, J = 12.13 Hz, 1 H, (CH_2COH), 4.17 (s, 1 H, OH), 5.12 (dd, J = 10.51, 1.62 Hz, 1 H, RCH=CH_2 (cis to H)), 5.34 (dd, J = 17.18, 1.62 Hz, 1 H, RCH=CH_2 (trans to H)), 5.82 (dd, J = 17.18, 10.51 Hz, 1 H, RC*H*=CH_2) 7.23–7.54 (m, 5 H, Ph); IR (neat) 3390 (OH), 1584 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 274 (M^+, 1), 204 ($M^+ - CH_2C(OH)(CH=CH_2)$, 100), 109 (PhS^+, 4); exact mass calcd for $C_{17}H_{22}OS$ 274.1391, found 274.1391.

Addition of Vinyllithiums to 2-Substituted Cyclobutanones. 2-Allyl-2-(phenylthio)-1-(1-cyclohexenyl)-cyclobutanol (10). *tert*-Butyllithium (0.53 mL of 1.77 M solution in pentane, 0.93 mmol) was added to a solution of 1-bromocyclohexene[16] (75 mg, 0.47 mmol) in anhydrous diethyl ether (2 mL) at −78 °C under argon. The solution was stirred at −78 °C for 0.5 h and then at 0 °C for 20 min. To this solution was introduced dropwise a solution of 2-allyl-2-(phenylthio)cyclobutanone (**19**, 85 mg, 0.39 mmol) in dry ether (1.5 mL). The resulting solution was allowed to warm to 25 °C over a period of 5 h and was quenched with saturated aqueous ammonium chloride. The same workup procedure as described above and flash chromatography provided 58 mg (49%) of **10** and a mixture of two diastereomers of what appears to be the aldol condensation product of the ketone **19** in 26% and 16% yield, respectively. **10**: ^{1}H NMR δ 1.48–1.95 (m, 8 H), 2.08–2.48 (m, 6 H), 3.96 (s, 1 H, OH), 4.99 (dd, J = 17.2, 1.1 Hz, 1 H, RCH=CH_2 (cis to H)), 5.11–5.19 (m, 1 H, vinyl), 5.73 (br s, 1 H, vinyl), 5.87–5.98 (m, 1 H, vinyl), 7.26–7.35 (m, 3 H, Ph), 7.53–7.58 (m, 2 H, Ph); IR (neat) 3430 (OH), 1635 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 259 ($M^+ - CH_2CH=CH_2$, 8), 191 ($M^+ - PhS$, 100); exact mass calcd for $C_{16}H_{19}OS$ ($M^+ - CH_2CH=CH_2$) 259.1157, found 259.1158. Aldol (major): ^{1}H NMR δ 1.26–3.96 (m, 12 H), 4.86–5.21 (m, 4 H), 5.73–6.20 (m, 2 H), 7.19–7.64 (m, 10 H); IR (neat) 3500 (OH), 1770 (CO), 1635 (C=C) cm^{-1}; mass spectrum (70 eV), *m/e* (relative intensity) 436 (M^+, 1), 327 ($M^+ - PhS$, 4), 299 ($M^+ - PhS - CO$, 100); exact mass calcd for $C_{20}H_{23}O_2S$ ($M^+ - PhS$) 327.1419, found 327.1422. Aldol (minor): ^{1}H NMR δ 1.60–2.91 (m, 12 H), 4.19 (t, J = 9.4 Hz, 1 H), 4.96–5.17 (m, 4 H, vinyl), 5.80–6.04 (m, 2 H), 7.26–7.34 (m, 8 H, Ph), 7.53–7.54 (m, 2 H, Ph); IR (neat) 3500 (OH), 1765 (CO), 1630 (C=C) cm^{-1}; mass spctrum (15 eV), *m/e* (relative intensity) 436 (M^+, 1), 327 ($M^+ - PhS$, 5), 299 ($M^+ - PhS - CO$, 100); exact mass calcd for $C_{20}H_{23}O_2S$ ($M^+ - PhS$) 327.1419, found 327.1422.

(*Z*)-2-(Phenylthio)-1-(1-cyclohexenyl)cyclobutanol (7) was preared by the same procedure: ^{1}H NMR δ 1.49–1.61 (m, 4 H), 2.00–2.07 (m, 6 H), 2.19–2.32 (m, 2 H), 2.95 (s, 1 H, OH), 3.99 (br t, J = ~6 Hz, 1 H, HSPh), 5.71 (br s, 1 H, vinyl), 7.16–7.28 (m, 3 H, Ph), 7.33–7.37 (m, 2 H, Ph); IR (neat) 3460 (OH), 1660 (C=C) cm^{-1}; mass spectrum (70 eV), *m/e* (relative intensity) 260 (M^+, 3%), 151 ($M^+ - PhS$, 32%), 150 ($M^+ - PhSH$, 26%), 136 (CH_2=CHSPh$^+$, 100%); exact mass calcd for $C_{16}H_{20}OS$ 260.1235, found 260.1234.

(*Z*)-2-(Phenylthio)-1-isopropenylcyclobutanol (13) was prepared by the procedure described above using 2-bromopropene: ^{1}H NMR δ 1.71 (s, 3 H), 1.92–2.11 (m, 2 H), 2.21–2.36 (m, 2 H), 3.08 (s, 1 H, OH), 2.95–3.70 (m, 1 H, CHSPh), 4.85 (br s, 1 H, vinyl), 4.95 (br s, 1 H, vinyl), 7.15–7.38 (m, 5 H, Ph); IR (neat) 3450 (OH), 1630 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 220 (M^+, 8), 192 ($M^+ - CH_2$=CH_2, 4), 136 (CH_2=CHSPh$^+$, 100), 111 ($M^+ - PhS$, 65), 110 ($PhSH^+$, 31); exact mass calcd for $C_{13}H_{16}OS$ 220.0922, found 220.0920.

(*Z*)-2-(Phenylthio)-1-isopropenyl-1-[(trimethylsilyl)-oxy]cyclobutane (22) were prepared by the same procedure except that the reaction was quenched with chlorotrimethylsilane (1 mL), instead of ammonium chloride, and was stirred at 25 °C for 15 h. All volatile components were removed in vacuo: ^{1}H NMR δ 0.13 (s, 9 H, $SiMe_3$), 1.78 (s, 3 H, allylic CH_3), 1.88–1.95 (m, 1 H), 2.14–2.21 (m, 1 H), 2.38–2.46 (m, 2 H), 3.75 (m, 1 H, HCSPh), 4.90 (br s, 1 H, vinyl), 5.02 (s, 1 H, vinyl), 7.12–7.32 (m, 5 H, Ph); IR (neat) 1643 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 292 (M^+, 31), 264 ($M^+ - CH_2$=CH_2, 10), 183 ($M^+ - PhS$, 100), 182 ($M^+ - PhSH$, 52), 136 (CH_2=CHSPh$^+$, 55); exact mass calcd for $C_{16}H_{24}OSSi$ 292.1317, found 292.1318.

Rearrangement of 1-Vinylcyclobutanols Accelerated by Potassium Hydride. Rearrangement of 2-(Phenylthio)-1-vinylcyclobutanol (2). Potassium hydride (22.2% in oil) was washed with dry pentane 3 times under argon and was dried under vaccum. To this potassium hydride (1.60 g, 40 mmol) were added THF (10 mL), hexamethylphoshoric triamide (HMPA, 8 mL), and a solution of **2** (150 mg, 0.73 mmol) in THF (3.5 mL) at −11 °C (ethylene glycol–dry ice bath). The cloudy, yellow mixture was stirred at −11 °C for 1 h, at 0 °C for another 1 h, and then at 25 °C for 1.5 h. It was injected into a mixture of glacial acetic acid–water (1:2) dropwise. The resulting solution was partitioned between pentane and 5% aqueous sodium hydroxide. The organic layer was washed with the latter until the washing became basic, and it was then washed with water. Flash chromatography of the dried (magnesium sulfate) and concentration residue gave 90 mg (60%) of 4-(phenylthio)-1-cyclohexane (**3**): ^{1}H NMR δ 1.72–1.99 (m, 2 H), 2.18–2.39 (m, 4 H), 2.54–2.62 (m, 2 H), 3.55 (quintet, J = ~4 Hz, 1 H, HCSPh), 7.26–7.36 (m, 3 H, Ph), 7.44–7.48 (m, 2 H, Ph): ^{13}C NMR δ 32.16 (t, C-3), 39.47 (t, C-2), 44.26 (d, C-4), 127.60 (d, *p*-Ph), 129.12 (d, *o*-Ph), 132.81 (d, *m*-Ph), 134.24 (s, SC of Ph), 209.72 (s, CO); IR (neat) 1706 (CO) cm^{-1}; mass spectrum

(16) Stevens, C. L.; Valicenti, J. A. *J. Am. Chem. Soc.* **1965**, *87*, 838.

(70 eV), *m/e* (relative intensity) 206 (M^+, 100), 110 ($PhSH^+$, 100), 97 (M^+ – PhS, 43); exact mass calcd for $C_{12}H_{14}OS$ 206.0765, found 206.0766.

Rearrangement of (*Z*)-2-(Phenylthio)-1-isopropenylcyclobutanol (13). The above procedure was used. Medium pressure liquid chromatography of the concentrated residue gave 186 mg (69%) of 2-methyl-4-(phenylthio)cyclohexanone (**15**) in two diasteriomeric forms (cis:trans, 5:1). Pure samples of each diasteriomer could be obtained from the first and last fractions of the chromatogram. Cis: mp 80.5–81.5 °C; ^1H NMR δ 1.01 (d, J = 6.57 Hz, 3 H, CH_3), 1.46–1.59 (m, 1 H), 1.67–1.85 (m, 1 H), 2.28–2.55 (m, 5 H), 3.51 (tt, J = 12.86, 3.43 Hz, 1 H, HCSPh), 7.26–7.48 (m, 5 H, Ph); IR (Nujol) 1712 (CO) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 220 (M^+, 100), 111 (M^+ – PhS, 22), 110 (M^+ – PhSH or $PhSH^+$, 25); exact mass calcd for $C_{13}H_{16}OS$ 220.0922, found 220.0924. Trans: mp 29.5–30.5 °C; ^1H NMR δ 1.04 (d, J = 6.67 Hz, 3 H, CH_3), 1.79–1.89 (m, 1 H), 2.07–2.35 (m, 4 H), 2.76–2.94 (m, 2 H), 3.73 (t, J = 3.64 Hz, 1 H, HCSPh), 7.25–7.48 (m, 5 H, Ph); IR (Nujol) 1709 (CO) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 220 (M^+, 100), 192 (M^+ – CO, 8), 111 (M^+ – PhS, 20), 110 (M^+ – PhSH or $PhSH^+$, 30); exact mass calcd for $C_{13}H_{16}OS$ 220.0922, found 220.0924.

In a similar experiment except that 18-crown-6 was used instead of HMPA, the reaction gave the cis and trans isomers of **15** in 36% and 18% yields, respectively, and epimerized cyclobutanol **14** in 18% yield. **14**: mp 70–71 °C; ^1H NMR δ 1.56–1.71 (m, 1 H), 1.91 (d, J = 0.61 Hz, 3 H, CH_3), 2.04–2.18 (m, 2 H), 2.25–2.36 (m, 1 H), 2.55–2.63 (m, 1 H), 3.93 (t, J = 9.30 Hz, 1 H, HCSPh), 5.09 (br s, 2 H, vinyl), 7.11–7.38 (m, 5 H, Ph); IR (CCl_4) 3586 (OH), 1641 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 220 (M^+, 16), 203 (M^+ – OH, 1), 192 (M^+ – CH_2=CH_2, 2), 111 (M^+ – PhS, 100), 110 ($PhSH^+$ or M^+ – PhSH, 74); exact mass calcd for $C_{13}H_{16}OS$ 220.0922, found 220.0922.

Rearrangement of 2-(Phenylthio)-1-(1-cyclohexenyl)cyclobutanol (7). The reaction, which was performed using HMPA, gave *trans*-4-(phenylthio)-*trans*-decahydro-1-naphthalenone (**8a**), *cis*-4-(phenylthio)-*trans*-decahydro-1-naphthalenone (**8b**), and a mixture of a 4-(phenylthio)-*cis*-decahydro-1-naphthalenone (**8c**) and 1-(1-cyclohexenyl)-4-(phenylthio)-1-butanone (**9**) in 65%, 10%, and 10% yield, respectively. **8a**: ^1H NMR δ 1.12–1.29 (m, 4 H), 1.44 (br q, J = 11.0 Hz, HC-4a), 1.68–1.86 (m, 3 H), 2.00–2.12 (m, 2 H), 2.27–2.41 (m, 3 H), 2.52–2.55 (m, 1 H), 3.13 (td, J = 11.0, 3.0 Hz, 1 H, HCSPh), 7.27–7.34 (m, 3 H, Ph), 7.43–7.46 (m, 2 H, Ph) (When the peaks at δ 3.13 and 1.44 were irradiated, respectively, those at δ 1.44 and 3.13 became a broad triplet, J = 11.0 Hz, and a broad doublet, J = 11.1 Hz, respectively.); IR (neat) 1703 (CO) cm^{-1}; mass spectrum (70 eV), *m/e* (relative intensity) 260 (M^+, 100), 151 (M^+ – PhS, 52), 150 (M^+ – PhSH, 9), 110 ($PhSH^+$, 28), 109 (PhS^+, 14); exact mass calcd for $C_{16}H_{20}OS$ 260.1235, found 260.1234. **8b**: ^1H NMR δ 1.12–2.42 (m, 13 H), 2.98 (td, J = 13.8, 5.6 Hz, 1 H, HC-8a), 3.54 (br s, 1 H, *H*CSPh), 7.27–7.34 (m, 3 H, Ph), 7.46–7.48 (m, 2 H, Ph); IR (neat) 1705 (CO) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 260 (M^+, 100), 151 (M^+ – PhS, 61), 150 (M^+ – PhSH, 11), 110 ($PhSH^+$, 16), 109 (PhS^+, 3); exact mass calcd for $C_{16}H_{20}OS$ 260.1235, found 260.1235.

The diagnostic peak in the NMR spectrum of **8c** was that at δ 3.47 (br s, HCSPh); the diagnostic peaks in the ^1H NMR spectrum of **9** were those at δ 2.80 (t, J = 7.06 Hz) and 2.97 (t, J = 6.87 Hz); IR (neat) 1706 (CO for **8c**), 1663 (CO for **9**), 1640 (C=C for **9**); mass spectrum (15 eV), *m/e* (relative intensity) 260 (M^+, 95), 151 (M^+ – PhS, 100), 150 (M^+ – PhSH, 56), 110 ($PhSH^+$, 39), 109 (PhS^+, 6).

Rearrangement of 2-(Phenylthio)-2-allyl-1-(1-cyclohexenyl)cyclobutanol (10). The reaction in the presence of HMPA gave a mixture of 4-(phenylthio)-4-allyl-*trans*-decahydro-1-naphthalenones (**11**) in 44% yield in which the isomer possessing the axial phenylthio group (**11a**) predominates (2:1) over that in which the phenylthio group is equatorial (**11b**). **11**: ^1H NMR δ 1.05–3.24 (m, overlapping a td at δ 3.18, J = 13.8, 6.0 Hz, HC-8a of **11a**, 16 H), 4.98–5.26 (m, 2 H, =CH_2), 5.56–5.67 (m), 6.07–6.19 (m, the ratio of the last two peaks is 2:1, total 1 H for the last two peaks, C*H*=CH_2), 7.27–7.57 (m, 5 H, Ph); ^{13}C NMR δ 25.20, 25.75, 25.92, 26.05, 26.21, 26.63, 27.60, 28.47, 34.52, 37.75, 35.53, 38.31, 38.01, 44.07, 48.89, 49.37, 50.25, 50.44, 54.87, 56.10, 118.29, 119.03, 128.83, 128.93, 129.25, 129.42, 130.87, 132.94, 133.94, 137.41, 137.89, 138.15, 210.30, 211.50; IR (neat) 1705 (CO) 1638 (C=C) cm^{-1}; mass spectrum (15 eV), *m/e* 300 (relative intensity) (M^+, 17), 259 (M^+ – CH_2=$CHCH_2$, 12), 191 (M^+ – PhS, 100), 190 (M^+ – PhS, 59); exact mass calcd for $C_{19}H_{24}SO$ 300.1548, found 300.1545.

Rearrangement of 1-Methyl-6-(phenylthio)-7-vinylbicyclo[4.2.0]octan-7-ol (20). The reaction in the presence of HMPA provided 8-methyl-4-(phenylthio)decahydro-2-naphthalenone (**20**) in 45% yield: ^1H NMR δ 1.05–3.25 (m, overlapping a singlet at δ 1.27, 17 H), 7.27–7.54 (m, 5 H, Ph); IR (neat) 1720 (CO) cm^{-1}; mass spectrum (15 eV), *m/e* (relative intensity) 274 (M^+, 12), 259 (M^+ – CH_3, 1), 165 (M^+ – PhS, 100), 110 ($PhSH^+$, 63); exact mass calcd for $C_{17}H_{22}OS$ 274.1391, found 274.1391.

Acid Induced Rearrangement of (*Z*)-2-(Phenylthio)-1-isopropenyl-1-[(trimethylsilyl)oxy]cyclobutane (22). A solution of **22** (80 mg, 0.28 mmol) and *p*-toluenesulfonic acid (105 mg, 0.55 mmol) in toluene (19 mL) was heated at reflux for 1.5 h. The cooled reaction mixture was partitioned between ether and saturated aqueous sodium bicarbonate and the aqueous phase was extracted with ether. All ethereal extracts were washed with water and then brine and were dried over magnesium sulfate. Flash chromatography of the concentrated residue gave 38 mg (62%) of 3-(phenylthio)-2,2-(dimethyl)cyclopentanone (**23**): ^1H NMR δ 1.07 (s, 3 H, CH_3), 1.10 (s, 3 H, CH_3), 1.89–2.01 (m, 1 H), 2.11–2.26 (m, 1 H), 2.31–2.40 (m, 1 H), 2.45–2.56 (m, 1 H), 3.42 (dd, J = 9.90, 6.06 Hz, 1 H, HCSPh), 7.25–7.33 (m, 3 H, Ph), 7.45–7.48 (m, 2 H, Ph); IR (neat) 1718 (CO); mass spectrum (15 eV), *m/e* (relative intensity) 220 (M^+, 100), 192 (M^+ – CO, 1), 111 (M^+ – PhS, 62); exact mass calcd for $C_{13}H_{16}OS$ 220.0922, found 220.0913.

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Registry No. **1**, 60603-14-7; **2**, 98678-05-8; **3**, 34259-60-4; **4**, 39778-69-3; **5**, 98678-06-9; **6**, 98678-07-0; **7**, 98678-08-1; **8a**, 98678-09-2; **8b**, 98678-17-2; **8c**, 98678-18-3; **9**, 98678-10-5; **10**, 98678-11-6; **11a**, 98678-12-7; **11b**, 98678-19-4; **12**, 98678-13-8; **13**, 98678-14-9; **14**, 98678-15-0; *cis*-**15**, 98678-16-1; *trans*-**15**, 98678-27-4; **19**, 98678-20-7; **20**, 98678-21-8; **21**, 98678-22-9; **22**, 98678-23-0; **23**, 98678-24-1; 2-benzyl-2-(phenylthio)cyclobutanone, 98678-25-2; 2-benzylcyclobutanone, 98678-26-3; 1-methyl-8,8-dichlorobicyclo[4.2.0]octan-7-one, 68212-48-6; 1-(dimethylamino)-naphthalene, 86-56-6; iodotrimethylsilane, 16029-98-4; benzenethiol, 108-98-5; vinyl bromide, 593-60-2; 1-bromocyclohexene, 2044-08-8; 2-bromopropene, 557-93-7; 18-crown-6, 17455-13-9.