Intramolecular Sulfur Ylide Additions to Ketones[1a,2]

Jack K. Crandall,* H. Steve Magaha, Mark A. Henderson,[1b] Rexford K. Widener, and Gregg A. Tharp

Department of Chemistry, Indiana University, Bloomington, Indiana 47405

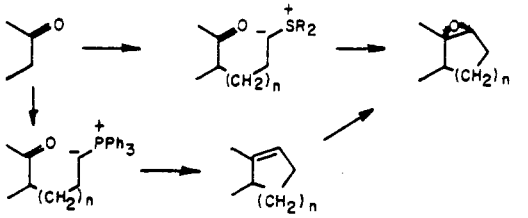
Received April 13, 1982

Methodology is described for the annulation of five-membered carboxylic rings onto cycloalkanones, using an intramolecular sulfur ylide reaction. Epoxybicyclo[x.3.0]alkanes (x = 3, 4, 5, 6) were obtained from cycloalkanones via the corresponding 2-[3-(phenylthio)propyl]cycloalkanones (**2a–d**, **7**, **11**), which were reacted successively with triethyloxonium tetrafluoroborate and potassium *tert*-butylate. An analogous annulation to give a six-membered ring epoxide from **14** also proceeds smoothly, whereas attempted seven-membered ring formation from **17** was unsuccessful. The stereochemistry of the various annulations was determined and compared with the stereochemistry of the epoxidations of the corresponding olefins (**33a–d**, **35**, **38**, **40**). These olefins were obtained by intramolecular Wittig reactions. Mechanisms for the ylide cyclizations are discussed.

The reaction of sulfur ylides with aldehydes and ketones constitutes an important general method for the synthesis of epoxides in which a new carbon–carbon bond is generated.[3] Intramolecular versions of this reaction are potentially useful for the construction of carbocyclic systems bearing the synthetically versatile epoxide function, although examples of this type of conversion are sparse.[4] In this contribution we describe a new cyclopentane annulation scheme that utilizes such an intramolecular sulfur ylide addition to an appropriately situated ketone group as the key transformation (Scheme I).[5] In addition, analogous intramolecular Wittig reactions[6] have been studied for comparison purposes. Since the stereochemistry of the sulfur ylide cyclization is an important consideration for applications to the synthesis of complex organic molecules, the stereoselectivity of these reactions was examined in detail and compared with the epoxidation of the related olefins obtained from the Wittig cyclization.

Starting Materials. The 2-allylcycloalkanones can be obtained by alkylation of the corresponding cycloalkanones or, more conveniently, by an adaptation of the Claisen rearrangement performed by heating the ketone with allyl alcohol and 2,2-dimethoxypropane in the presence of an acid catalyst.[7,8] This results in the in situ generation and thermal rearrangement of an allyl vinyl ether intermediate. The regioselective addition of thiophenol to the allylcycloalkenones under free-radical conditions[9] proceeded smoothly to give the corresponding 2-[3-(phenylthio)propyl]cycloalkanones that served as starting materials for the sulfur ylide cyclizations. The 2-allylcycloalkanones were also used as precursors for the 2-(3-bromopropyl)cycloalkanones that were produced by the free-radical addition of hydrogen bromide.[10] Sulfides **14** and **17** were obtained by reaction of bromides **39** and **41** with the sodium salts of ethane- and benzenethiol, respectively.

Scheme I



Sulfur Ylide Reactions. Treatment of the various sulfides with triethyloxonium tetrafluoroborate in CH_2Cl_2 gave the corresponding sulfonium salts that were reacted directly with potassium *tert*-butylate in THF to yield bicyclic epoxides (Scheme II). The crude product mixtures were analyzed by GC to determine the relative amounts of the isomeric epoxides, which were subsequently isolated by column chromatography. These cyclopentane annulations proceeded in moderate to good yields, typically giving a mixture of epoxides. The size of the preformed cycloalkanone ring has a significant effect on the stereoselectivity of the reaction. Thus, the annulation sequence gave only the cis epoxide **4a** when applied to cyclopentanone, a 94:6 ratio of cis and trans epoxides **4b** and **5b** with cyclohexanone, essentially no stereoselectivity (47:53 ratio) in the conversion of cycloheptanone to epoxides **4c** and **5c**, and, interestingly, a 20:80 mixture of **4d** and **5d** from the more flexible cyclooctanone.

The substituted cyclohexanones **7** and **11** were examined to provide further information on the cyclization stereochemistry. The isomeric 4-*tert*-butylcyclohexanone derivatives **7c** and **7t** were each converted by the standard sequence into an 85:15 ratio of cis and trans epoxides **8** and **9**. This indicates that epimerization via enolate formation interconverts the two sulfonium salts faster than epoxide is formed.[11,12] Interestingly, the tetramethylcyclohexanone **11** was converted to a 57:43 mixture of epoxides **12** and **13**. Thus, even symmetrical substitution on the cyclohexanone system has a substantial effect on the stereoselectivity of the ylide cyclization.

A cyclohexane annulation was achieved with cyclohexanone **14**, which yields cis and trans epoxides **15** and **16** an 8:92 ratio.[13] The significant preference for a trans ring fusion in this case contrasts with the cyclopentane

(1) (a) Support from Indiana University in the form of a Grant-in-Aid of Research is gratefully acknowledged. (b) Indiana University Honors Division Summer Research Award and Dow Chemical Company Scholarship grantee, Summer 1981.

(2) For a preliminary account, see: Crandall, J. K.; Magaha, H. S.; Widener, R. K.; Tharp, G. A. *Tetrahedron Lett.* **1980**, 4807.

(3) For reviews, see: (a) Trost, B. M.; Melvin, L. S. "Sulfur Ylides—Emerging Synthetic Intermediates"; Academic Press: New York, 1975. (b) Block, E. "Reactions of Organosulfur Compounds"; Academic Press: New York, 1977.

(4) Newman, M. S.; Lee, L. F. *J. Org. Chem.* **1974**, *39*, 1446. Cazeau, P.; Muckerstrum, B. *Tetrahedron Lett.* **1977**, 1493. Garst, M. E. *J. Org. Chem.* **1979**, *44*, 1578.

(5) After completion of this work we learned of a related study: Garst, M. E.; Johnson, A. T. *Tetrahedron Lett.* **1980**, 4811.

(6) Becker, K. B. *Tetrahedron* **1980**, *36*, 1717.

(7) Lorette, N. B.; Howard, W. L. *J. Org. Chem.* **1961**, *26*, 3112.

(8) Fleming, I.; Kemp-Jones, A. V.; Long, W. E.; Thomas, E. J. *J. Chem. Soc., Perkin Trans. 2* **1976**, 7.

(9) Bakuzis, P.; Campos, O. O. S.; Bakuzis, M. L. F. *J. Org. Chem.* **1976**, *41*, 3261.

(10) House, H. O.; Chu, C. Y.; Phillips, W. V.; Sayer, T. S. B.; Yau, C. C. *J. Org. Chem.* **1977**, *42*, 1709.

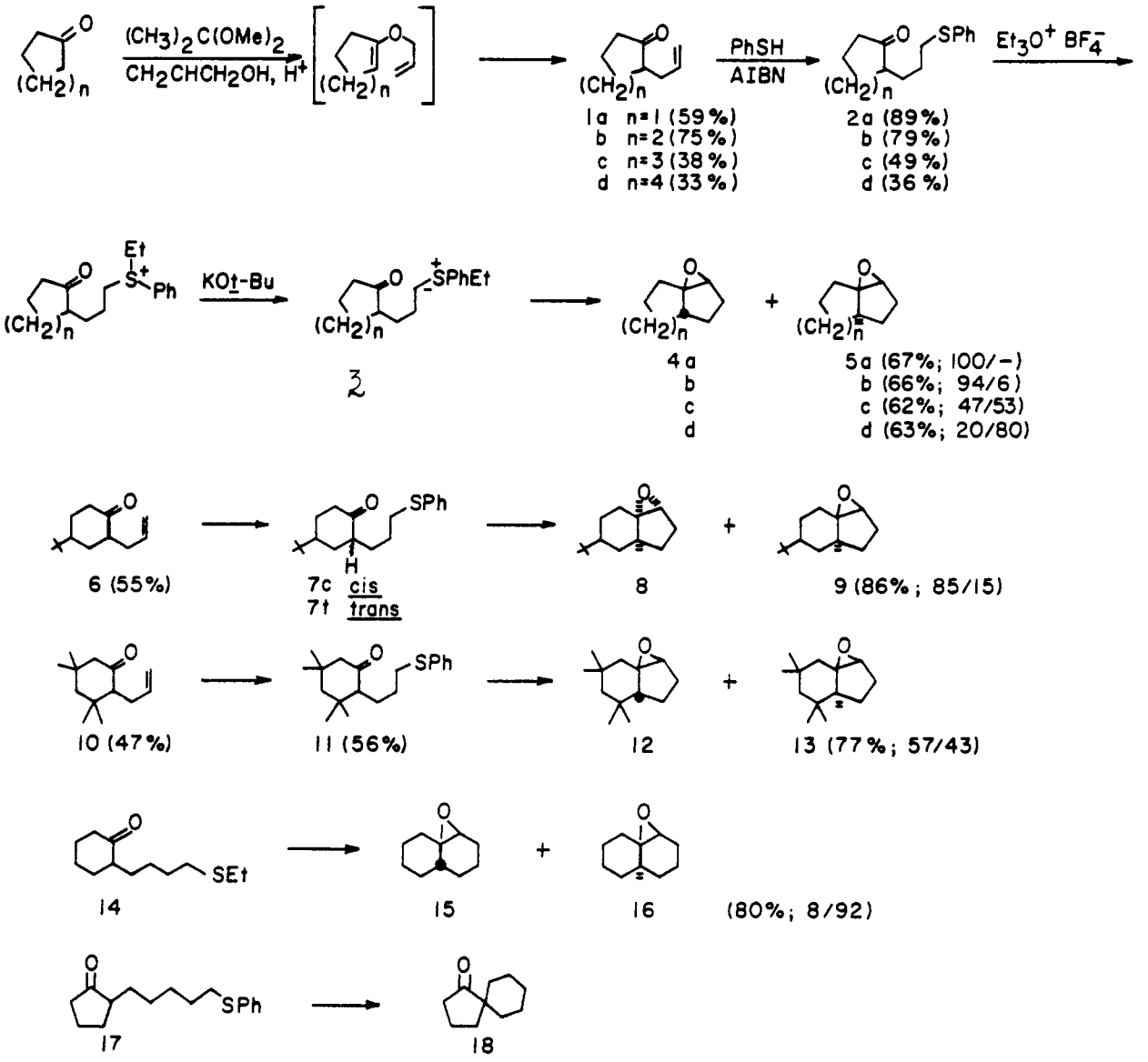
(11) The epimerization of 2,6-dimethylcyclohexanone has been found to be competitive with the bimolecular reaction with a substituted ylide: Trost, B. M.; Preckel, M. *J. Am. Chem. Soc.* **1973**, *95*, 7862.

(12) Epimerization of the intermediate sulfonium salt is also possible.

(13) Garst and Johnson have reported other cyclohexane annulations.[5]

0022-3263/82/1947-5372$01.25/0

Scheme II



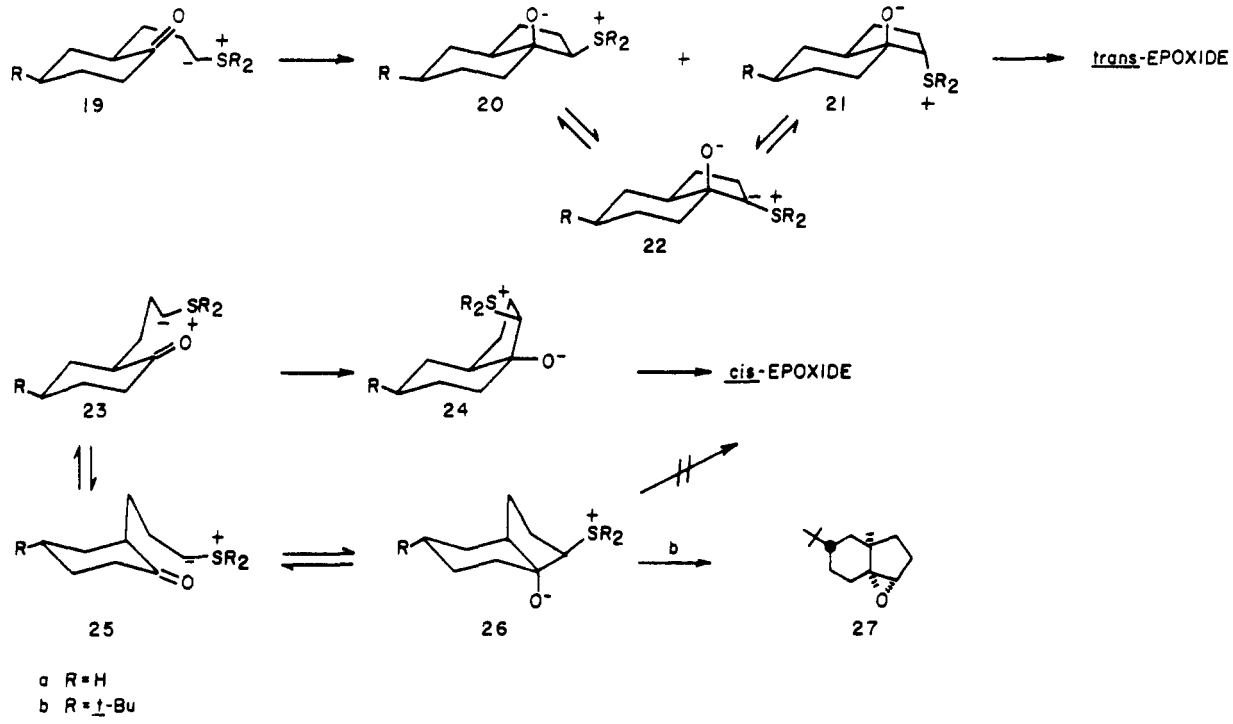
annulations. Finally, cyclopentanone **17**, designed to give cyclization to a seven-membered ring, was found to yield spiro ketone **18** as the only important volatile product. This conversion is an unexceptional example of an intramolecular enolate alkylation that has ample precedence. In fact, it is noteworthy that similar reactions were not observed to compete with the ylide cyclizations described above.

Although many of the mechanistic questions concerning these sulfur ylide cyclizations remain to be answered definitively, it is instructive to consider the most likely possibilities. There are three chair conformations **19a**, **23a**, and **25a** of the cyclohexanone ylide **3b** through which the initial sulfur ylide attack on the carbonyl group can take place (Scheme III). Reaction via either **23a** and **25a** leads to a cis-fused hydrindane, whereas **19a** gives a trans-fused derivative. In fact, there are two cyclic betaines for either hydrindane series that differ only in the stereochemistry of the sulfonium group. This is illustrated for the trans system in which the alkoxide and sulfonium functions are cis (**20a**) or trans (**21a**). Their formation depends on the orientation of the ylide moiety during the cyclization process. Little information appears to be available concerning the preferred geometry for sulfur ylide attack on a carbonyl group. Assuming that the last step of the reaction leading to epoxides requires backside nucleophilic displacement of neutral R_2S by the alkoxide group,[14] only betaine **21a** with trans disposed functions is capable of epoxide formation. However, interconversion of the epimeric betaines **20a** and **21a** is possible under the basic reaction conditions, either by equilibration involving reversal of the cyclization step or via common sulfur ylide **22**.[15] A similar situation exists for the *cis*-hydrindane betaine, although this is not detailed for the sake of brevity. Finally, stereoelectronic considerations require that the final, epoxide-forming step proceed by way of a conformation in which the alkoxide and sulfonium groups approximate an anti, coplanar arrangement. This is the case with **21a**, the only important conformer in the *trans*-hydridane system, and also with conformer **24a** in the *cis*-hydrindane system. Conformer **26a** cannot result in direct formation of epoxide **4b**, but in the unsubstituted series **24a** and **26a** are readily equilibrated by chair–chair interconversion.

(14) Johnson, C. R.; Schroeck, C. W.; Shanklin, J. R. *J. Am. Chem. Soc.* **1973**, *95*, 7424. Durst, T.; Viaw, R.; Van Der Elzen, R.; Nguyen, C. H. *J. Chem. Soc., Chem. Commun.* **1971**, 1334. Townsend, J. M.; Sharpless, K. B. *Tetrahedron Lett.* **1972**, 3313.

(15) In conformationally unrestricted systems, epoxide formation is normally faster than epimerization of the sulfonium group.[14] However, epimerization has been invoked to explain the slight loss of stereospecificity in the closure of diasteriomeric betaines.

Scheme III



The ratio of cis and trans epoxides formed in this and related sulfur ylide cyclizations is determined by the relative rates of the competing reaction sequences. Two extreme situations can be visualized. In the first of these, the initial cyclization step to give the betaines is irreversible and the product ratio simply reflects the relative rates of cyclization of the ylide to the cis and trans cyclic betaines. Alternatively, the initial cyclization step is an equilibrium process and the epoxide ratio is determined by the relative rates of the final step. Of course, intermediate scenarios in which both rates influence the product ratios are possible.

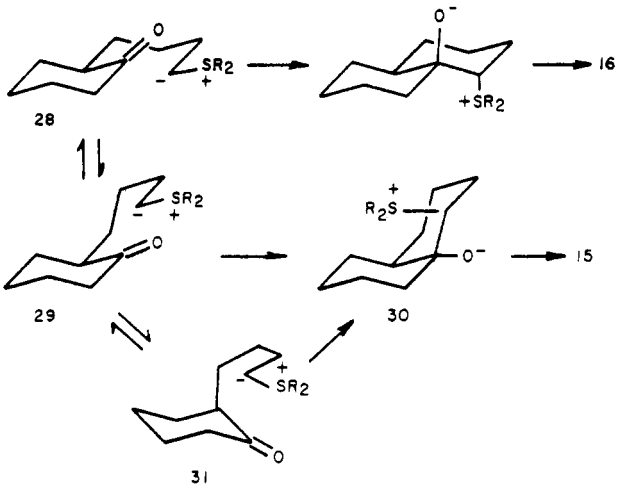
It is known that the bimolecular reaction of dimethylsulfonium methylide with cyclohexanones involves irreversible attack of the reagent.[3] Although extrapolation of this result to more complicated systems is not necessarily warranted, the present intramolecular analogues can be rationalized in terms of product determination by irreversible cyclization to isomeric betaines. According to this view, cyclopentane annulation onto a preexisting cyclohexanone occurs predominantly with the cis stereochemistry because of the relative difficulty in achieving reaction of ylide **3b** via conformation **19a** to give trans betaine. This is attributed to the inability of the ylide carbon of the equatorial side chain to approach the carbonyl carbon along a route perpendicular to this group without significant bond-angle distortions. This type of stereoelectronically favored attack is more facile from conformers **23a** and **25a**, which lead to cis betaine. The related reaction of cyclopentanone ylide **3a** is completely biased in favor of cis cyclization, whereas the conformational flexibility of the cycloalkanone rings of **3c** and **3d** allows for reasonably facile approach of the ylide side chain from either side of the carbonyl group.

Ylide cyclization of tetramethylcyclohexanone **11** shows a much lower stereoselectivity for the cis epoxide. This is understandable in terms of destabilization of the cyclization mode analogous to **23** owing to the severe 1,3-diaxial interactions between the methyl substituents and the ylide center during cyclization. This allows trans attack via a conformation analogous to **19** to become more competitive. In fact, it is likely that most of the cis cyclization of **11** takes place by a pathway analogous to **25** in which an axial side chain makes an equatorial approach to the carbonyl group, since methyl substitution is expected to increase the proportion of this conformer.

The situation with the *tert*-butyl compound **7** is more complicated. In this case, the derived ylide can exist in two diasteriomeric forms. The experimental results indicate that these isomers are interconverted under the reaction conditions, since either epimer yields the same product mixture. In fact, only epoxides **8** and **9**, both resulting from the ylide related to **7c**, are observed. The lower stereoselectivity for the cis epoxide **8** may be a result of the limitation to a single viable route to **8** with this substituted case. The lack of epoxide product from trans ylide **25b** under conditions where this species should be present in significant concentrations implies some problem in its conversion to epoxide. While it is conceivable that cyclization of **25b** to betaine **26b** is strongly disfavored by some inherent feature of the process involving equatorial attack of an axially disposed side chain, it is difficult to appreciate the underlying cause for such a restriction. It appears more likely that the epoxide-forming step is particularly inefficient. This is reasonable in view of the fact that **26b** does not provide the requisite ring-closure stereochemistry in its favored chair conformation but would have to react by way of a nonchair conformation in order to form epoxide **27**. Furthermore, these epoxides are also forced to adopt a less stable, nonchair conformation of the cyclohexane ring. These features can be expected to be reflected in a relatively high activation energy for epoxide formation from **26b**. Thus, reversible formation of betaine **26b** is postulated in this unique situation where further conversion to epoxide is especially difficult. As a consequence, the facile epimerization of the side chain leads to funneling of all reactions through the cis ylide (**19b** $\rightleftarrows$ **23b**).

The modest preference for the trans-fused epoxide **5d** in the cyclization of cyclooctanone **2d** is more difficult to rationalize owing to the more complicated conformational situation. However, it appears that ring closure to the cis

Scheme IV



epoxide **4d** suffers from steric interactions between the cyclooctane and developing cyclopentane rings.

The clear difference in the stereoselectivity for the cyclohexane annulation of **14**, which strongly favors the trans epoxide **16**, is attributed to a more favorable stereoelectronic situation for equatorial attack on the carbonyl group by the longer side chain via conformation **28** (Scheme IV). In the absence of the stereoelectronic limitations that control the cyclopentane annulations, the cyclohexane annulation proceeds dominantly in this manner since both axial attack by an equatorial side chain (**29**) and equatorial approach by an axial side chain (**31**) are destabilized by 1,3-diaxial interactions not present in **28**.[16]

Although the mechanistic rationale just detailed fits the available information quite well, we cannot exclude an alternate description involving the facile equilibration of all intermediates prior to the final, irreversible ring closure to epoxide. Under these circumstances, the product ratios would depend on the relative rates of the competing epoxide-forming reactions. While it is difficult to assess with confidence the controlling features of these competitions, the activation parameters for the reactions involved are expected to reflect the stabilities of the epoxide products and of the immediate betaine precursors. It is likely that the cis epoxides are more stable in the hydrindane series, whereas the opposite is anticipated for the decalin system. On the other hand **30**, the betaine precursor of the cis epoxide **15** in the decalin series, experiences more severe steric destabilization than its hydrindane analogue **24a** owing to nonbonded interactions between the sulfonium group and the preformed cyclohexane ring. These considerations are consistent with the observed variation in stereochemical preference for the two systems. The lower selectivity for cis epoxide **12** from tetramethylcyclohexanone **11** could also be attributed to steric interactions, in this case those between the methyl substituents and the sulfonium group in the betaine precursor to the *cis* epoxide. Finally, the importance of the epoxide-forming step has already been pointed out for the *tert*-butylcyclohexanone system discussed above.

Phosphorus Ylide Reactions. Several intramolecular Wittig reactions were also conducted. In addition to providing bicyclic olefins of general structure **33** for use in epoxidation study (vide infra), these transformations were of interest for comparison with the sulfur ylide cyclizations. The bromides were converted to the phosphonium salts by reaction with triphenylphosphine, usually after halogen exchange with iodide. Treatment of the crude phosphonium salts with potassium *tert*-butylate, or in the case of **32b** with the sodium salt of dimethyl sulfoxide, resulted in the formation of bicyclic olefins as summarized in Scheme V. The mediocre yields of these conversions were not optimized, but they are comparable with those reported in a recent related study.[17]

Two interesting differences between these cyclizations and those of the analogous sulfur ylides are noteworthy. Thus, cyclization to the seven-membered cyclic olefin **42** was successful with the phosphorus ylide, whereas only intramolecular enolate alkylation was observed with the corresponding sulfur system. Two factors are probably responsible for this difference in reaction mode. Thus, the greater acidity of the phosphonium salt over the sulfonium salt should result in a more favorable competition between ylide and enolate formation in the phosphorus system.[18] Furthermore, the decreased effectiveness of the phosphonium substituent as a leaving group relative to the sulfonium group is expected to retard intramolecular alkylation of the phosphorus compound.[3b]

A second difference of the Wittig cyclizations is seen in the formation of isomeric olefins **35** and **36** from the triphenylphosphonium derivative of bromide **34**. The latter product obviously arises from attack of an axial side-chain ylide on the carbonyl group. Interestingly, the **35**/**36** ratio is close to that anticipated for the equatorial to axial composition of the ylide.[19] This suggests that, unlike the sulfur ylide analogues, these intramolecular Wittig reactions take place faster than side-chain equilibration. The greater acidity of phosphonium salts is undoubtedly also important here.

Bicycloalkene Epoxidations. Several of the olefins available from the intramolecular Wittig reactions were subjected to peracid oxidation in order to obtain information regarding the stereoselectivity of epoxidation for comparison with the sulfur ylide cyclizations. These reactions were performed with *m*-chloroperbenzoic acid (MCPBA) in a buffered, two-phase solvent system consisting of methylene chloride and aqueous sodium bicarbonate. The results are summarized in Scheme V.

The olefin epoxidations show poor stereoselectivity usually with a slight preference for the trans ring-fused product. This corresponds to preferred axial attack of the peracid on the double bond exocyclic to the cyclohexyl ring in **33b**, **35**, and **40**. These results are in good agreement with prior experience on the epoxidation of related systems.[20] The seven-membered ring analogue **33c** behaves similarly, whereas the cyclooctyl derivatives **33d** yields essentially equivalent amounts of cis and trans epoxides. In contrast to the above trends, tetramethyl olefin **38** is converted to a single epoxide assigned the cis structure **12**. In this case the axial methyl groups shield the axial face of the double bond forcing equatorial approach of the peracid. Ample precedence for such steric control is also available.[20] Thus, while the epoxidation route may be useful as a selective route to epoxides in certain circumstances, the sulfur ylide cyclization process is, in general, the more selective method.

Stereochemical Assignments. The assignment of the cis structure to the tetramethyl epoxide obtained from the

(16) Although the bimolecular addition of dimethylsulfonium ylide to cyclohexanones prefers axial attack, substitution of the ylide reverses this tendency.[3]

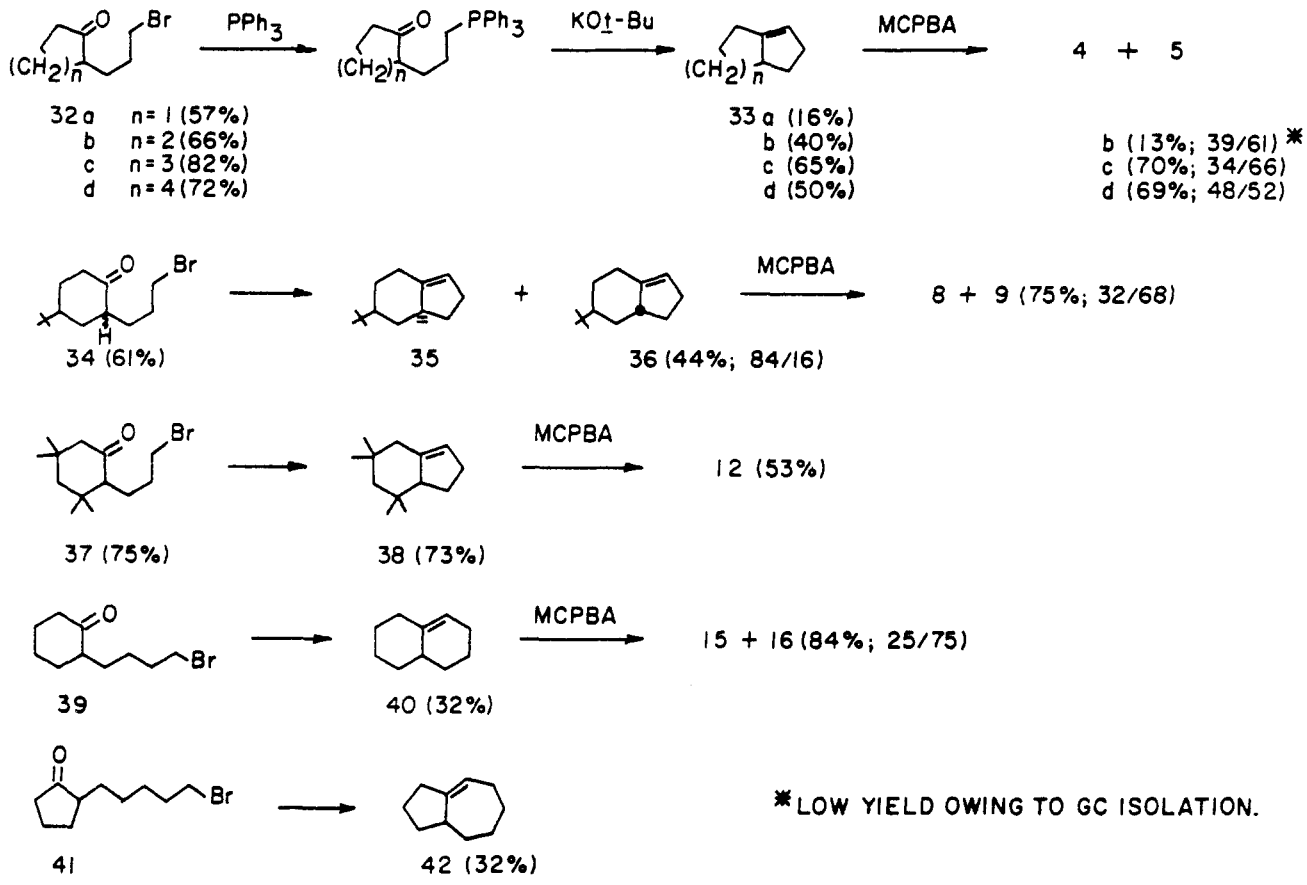
(17) Becker, K. B.; Boschung, A. T.; Grob, C. A. *Helv. Chim. Acta* **1973**, *56*, 2733.

(18) Johnson, A. W.; Amel, R. T. *Can. J. Chem.* **1968**, *46*, 461.

(19) This should be similar to the 85:15 ratio observed for the allyl compound **6**.[8]

(20) Berti, G. *Topics Stereochem.* **1973**, *7*, 93.

Scheme V



epoxidation route secures the trans structure for the isomeric epoxide produced in the sulfur ylide cyclization. The stereochemistry of epoxide pairs **4b** and **5b**, **4c** and **5c**, **15** and **16**, and cis epoxide **4a** were determined by $LiAlH_4$ reduction to the corresponding bridgehead alcohols of general structure **43** and **44** and comparison with authentic samples or literature data.

Although alcohol **44c** was obtained from the hydride reduction of trans epoxide **5c**, the major product from this reaction was a secondary alcohol assigned structure **45** on the basis of comparisons with published melting point and IR data.[21] The unexpected reduction of **5c** by hydride delivery at the tertiary center probably involves catalysis by a Lewis acid. Similar hydride reductions with inversion of configuration at the tertiary center have been documented with 5,6-epoxycoprostanes.[22]

The stereochemistry of the *tert*-butyl epoxides **8** and **9** is based on several observations. The proton NMR of the 85:15 mixture of epoxides obtained from ylide cyclization showed the epoxide hydrogens as singlets at 3.19 and 3.37 ppm for the major and minor component, respectively. These values correspond closely with the chemical shifts of the epoxide protons of the unsubstituted cis and trans epoxides **4b** and **5b**, which appear at 3.25 and 3.40 ppm, respectively. The mixture of epoxides was reduced by $LiAlH_4$ to a mixture of bridgehead alcohols. The ^{13}C NMR of this mixture showed a signal for the carbinyl carbon of the major isomer at 80.7 ppm and one for the minor isomer at 76.9 ppm. These values compare well with those of *cis*- and *trans*-bicyclo[4.3.0]nonan-1-ol (80.0 and 77.3 ppm, respectively).[23] These data serve to distinguish between epoxides **8** and **9** provided that the isomeric structures **27** can be excluded as possibilities. Epoxidation of an 85:15 mixture of olefins **35** and **36** gave a 75% yield of an epoxide mixture of the same two components obtained in the ylide reaction as indicated by proton NMR. In this instance, however, the epoxide ratio was reversed to 32:68. This ratio is in agreement with expectations for equatorial to axial attack of peracid on olefin **35**.[20] The relative amounts of the two epoxides obtained in good yield requires that both be derived from **35**, the major olefin in the mixture. No evidence for epoxides derived from minor olefin **36** was apparent from the NMR spectrum of the mixture. These materials may not have survived the reaction conditions owing to their strained nature.

A mixture of epoxides **4d** and **5d** were reduced with $LiAlH_4$ to the alcohols **43d** and **44d**. An authentic sample of **43d** was obtained from the hydroboration of the tetrasubstituted olefin **48**. This olefin was secured by an acid-catalyzed isomerization of olefin **33d**.

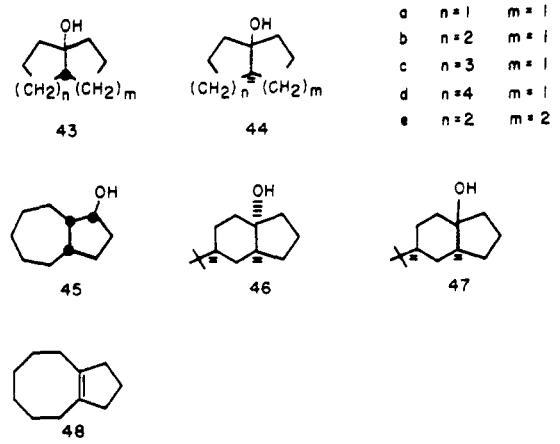
Experimental Section

General Procedures. Melting points were determined on a Thomas-Hoover Unimelt apparatus. Unless otherwise indicated, infrared (IR) spectra were determined as thin films between NaCl plates with a Perkin-Elmer Model 467 grating spectrometer. Nuclear magnetic resonance (NMR) spectra were obtained with Varian T-60 and HR-220 spectrometers for proton spectra and a Varian XL-100-12 instrument for ^{13}C spectra. Proton NMR spectra were routinely recorded at 60 MHz on $CDCl_3$ solutions. Unless otherwise indicated ^{13}C data were obtained on CCl_4 solutions and are reported in parts per million relative to Me_4Si. Gas Chromatography (GC) was performed on a Varian Aerograph 600D equipped with a flame-ionization detector. Preparative GC separations utilized a Varian A-700 instrument. Mass spectra were recorded on a Varian-MAT CH-7 spectrometer. Exact mass

(21) Kovats, E.; Furst, A.; Günthard, H. *Helv. Chim. Acta* **1954**, *37*, 534.

(22) Hallsworth, A.; Henbest, H. B. *J. Chem. Soc.* **1957**, 4604. Plattner, P. A.; Heusser, H.; Feurer, M. *Helv. Chim. Acta* **1949**, *32*, 587.

(23) Crandall, J. K.; Magaha, H. S., preceding paper in this issue.



determinations were made on a Varian-MAT CH-5DF instrument at the Michigan State University–NIH Mass Spectrometry Facility. Elemental analyses were performed by Midwest Microlabs.

Tetrahydrofuran (THF) was dried over lithium aluminum hydride and distilled immediately before use. Dimethyl sulfoxide and dimethylformamide (DMF) were dried over and distilled from calcium hydride. Anhydrous magnesium sulfate was routinely used as a drying agent. Potassium carbonate was added in drying operations and in distillations involving the epoxides and alcohols described herein. A rotary evaporator was employed to remove solvent unless otherwise indicated.

2-Allylcyclohexanone (**1b**),[7] 2-allylcyclopentanone (**1a**),[7] 4-*tert*-butyl-2-allylcyclohexanone (**6**),[8] 2-(4-bromobutyl)cyclohexanone (**39**),[24] and 2-(5-bromopentyl)cyclopentanone (**41**)[25] were prepared according to published procedures.

2-Allylcycloheptanone (1c). A solution of 37.0 g (0.33 mol) of cycloheptanone, 42.3 g (0.73 mol) of allyl alcohol, 37.4 g (0.36 mol) of 2,2-dimethoxypropane, 0.03 g of *p*-toluenesulfonic acid, and 165 mL of benzene was heated in a flask equipped with a 50-cM column of glass helices and a distillation head. The head temperature was maintained at 55–60 °C until ca. 150 mL of distillate has been collected. After the solution cooled, 100 mL of toluene was added to the flask and distillation was continued until the head temperature reached 100 °C. The reaction mixture was cooled, stirred with anhydrous potassium carbonate, and filtered. Distillation through a spinning-band column afforded 19.3 g (38%) of **1c**:[26] bp 86–87 °C (5 torr); IR 3.27, 5.90, 6.11, 10.1, 11.0 μM; NMR δ 1.0–2.9 (m, 13), 4.8–5.2 (m, 2), 5.4–6.1 (m, 1).

2-Allylcyclooctanone (1d). The reaction was performed as described above, using 40 g (0.32 mol) of cyclooctanone, 50 g (0.48 mol) of dimethoxypropane, 43 g (0.75 mol) of allyl alcohol, 0.03 g of *p*-toluenesulfonic acid, 100 mL of benzene, and 75 mL of toluene. Distillation gave, in addition to recovered cyclooctanone, 17.7 g (33%) of **1d**:[27] bp 107–110 °C (10 torr); IR 3.3, 5.90, 10.1, 11.0 μM; NMR (CCl_4) δ 1.0–2.8 (m, 15), 4.7–5.2 (m, 2), 5.2–6.0 (m, 1).

2-Allyl-3,3,5,5-tetramethylcyclohexanone (10). A. The reaction was performed in the same manner as above, using 10.0 g (64.9 mmol) of 3,3,5,5-tetramethylcyclohexanone,[28] 9.1 g (156 mmol) of allyl alcohol, 7.50 g (72 mmol) of dimethoxypropane, 0.01 g of *p*-toluenesulfonic acid, 30 mL of benzene, and 30 mL of toluene. After workup and distillation, 5.9 g (47%) of **10** was obtained.

B. A solution of 10.0 g (64.9 mmol) of 3,3,5,5-tetramethylcyclohexanone was added dropwise to a stirred slurry of 3.22 g (80 mmol) of potassium hydride in 250 mL of THF. After the mixture was stirred for 3 h at 25 °C, 20 mL of HMPA was added and the solution was cooled to −78 °C. Allyl bromide (31.5 g, 260 mmol) was added and the mixture was stirred for 1 h. After warming to 25 °C, the reaction mixture was stirred overnight. The resulting suspension was diluted with 200 mL of pentane and filtered through Celite. Solvent was removed by distillation and the residue was heated at 170 °C for 30 min. After cooling, the residue was dissolved in pentane and the resulting solution was washed with water and dried. After evaporation of solvent, the residue was distilled to give 7.26 g (58%) of **10**: bp 100–102 °C (20 torr); IR 5.85 μM; NMR δ 0.85 (s, 3), 1.00 (s, 3), 1.05 (s, 3), 1.08 (s, 3), 1.4–2.6 (m, 7), 5.3–6.1 (m, 1); exact mass calcd for $C_{13}H_{22}O$ 194.1672, found 194.167.

General Procedure for the Preparation of 2-[3-(Phenylthio)propyl]cycloalkanones. A solution of the 2-allylcycloalkanone (1 equiv), thiophenol (2 equiv), and a few milligrams of azobis(isobutyronitrile) in hexane was refluxed until NMR analysis indicated that all of the allyl ketone had been consumed (typically 24 h). Ether was added and the resulting solution was washed with 10% NaOH solution and water and dried. After concentration, the residue typically was distilled to give the sulfide.

2-[3-(Phenylthio)propyl]cyclohexanone (2b). 2-Allylcyclohexanone (**1b**) (34.6 g, 250 mmol) was converted to 49.2 g (79%) of **2b**: bp 137–139 °C (0.03 torr); IR 5.85, 9.72, 12.4, 14.4 μM; NMR δ 1.2–2.4 (m, 13), 2.83 (m, 2), 7.30 (m, 5); mass spectrum, **m/z** (relative intensity) 249 (4), 248 (39), 218 (45), 139 (100), 123 (21), 110 (81), 109 (76), 69 (40), 55 (35), 41 (58).

Anal. Calcd for $C_{15}H_{20}OS$: C, 72.52; H, 8.13; S, 12.91. Found: C, 72.44; H, 7.85; S, 12.76.

***cis*- and *trans*-4-*tert*-Butyl-2-[3-(phenylthio)propyl]cyclohexanones (7c and 7t).** 2-Allyl-4-*tert*-butylcyclohexanone (**6**; 10.0 g, 51.5 mmol) gave, after column chromatography on silica gel with 5% ether–hexane and distillation, 13.0 g (83%) of a mixture of **7c** and **7t**: bp 148–152 °C (0.01 torr).

Anal. Calcd for $C_{19}H_{28}OS$: C, 74.95; H, 9.27; S, 10.33. Found: C, 74.81; H, 9.24; S, 10.41.

Careful rechromatography afforded separation of **7c** and **7t**. The cis isomer **7c** shows the following: IR 5.86, 6.32, 13.4, 14.6 μM; NMR (220 MHz) δ 0.87 (s, 9), 1.2–2.6 (m, 12), 2.85 (m, 2), 7.0–7.3 (m, 5); ^{13}C NMR δ 26.7, 27.5, 28.3, 28.8, 32.3, 33.4, 34.9, 41.0, 46.9, 48.8, 125.0, 128.2, 176.0.

The minor isomer **7t** shows the following: IR 5.87, 6.32, 13.5, 14.5 μM; NMR (220 MHz) δ 0.88 (s, 9), 1.2–2.6 (m, 12), 2.56 (t, 2, J = 6), 7.0–7.3 (m, 5).

2-[3-(Phenylthio)propyl]-3,3,5,5-tetramethylcyclohexanone (11). The crude product from reaction of 2-allyl-3,3,5,5-tetramethylcyclohexanone (4.90 g, 25.2 mmol) was triturated with pentane to give 4.22 g (56%) of **11** as white crystals: mp 70–72 °C; NMR δ 0.83 (s, 6), 1.00 (s, 3), 1.05 (br s, 6), 1.22–2.20 (m, 9), 2.90 (t, 2), 7.35 (m, 5).

Anal. Calcd for $C_{19}H_{28}OS$: C, 74.95; H, 9.27; S, 10.53. Found: C, 75.3; H, 9.6; S, 10.2.

2-[3-(Phenylthio)propyl]cyclopentanone (2a). The product from 10.0 g (80 mmol) of 2-allylcyclopentanone was distilled to give 16.7 g (89%) of **2a**, which solidified upon cooling. Recrystallization from pentane afforded white crystals of **2a**: mp 36–37 °C; bp 112–115 °C (0.03 torr); IR 3.3, 5.77, 6.33, 13.6, 14.5 μM; NMR δ 1.0–2.4 (m, 11), 2.85 (t, 2), 6.9–7.4 (m, 5).

Anal. Calcd for $C_{14}H_{18}OS$: C, 71.75; H, 7.74; S, 13.68. Found: C, 72.10; H, 7.69; S, 13.45.

2-[3-(Phenylthio)propyl]cycloheptanone (2c). 2-Allylcycloheptanone (**1c**; 10.0 g, 66 mmol) yielded 8.6 g (49%) of **2c**: bp 140–142 °C (0.02 torr); IR 3.29, 5.88, 6.30, 13.6, 14.6 μM; NMR δ 1.2–2.1 (m, 12), 2.2–2.6 (m, 3), 2.7–3.0 (m, 2), 6.9–7.3 (m, 5).

Anal. Calcd for $C_{15}H_{20}OS$: C, 72.67; H, 8.40; S, 12.12. Found: C, 72.63; H, 8.30; S, 12.34.

2-[3-(Phenylthio)propyl]cyclooctanone (2d). 2-Allylcyclooctanone (**1d**) (10 g, 60 mmol) yielded in the normal fashion after column chromatography on alumina, using 5% ether–hexane, 7.2 g (36%) of **2d**: IR 3.25, 5.90, 6.32, 12.8, 14.5 μM; NMR δ 1.0–2.6 (m, 17), 2.83 (m, 2), 7.18 (m, 5).

Anal. Calcd for $C_{17}H_{24}OS$: C, 73.86; H, 8.75; S, 11.60. Found: C, 73.86; H, 8.59; S, 11.43.

2-[4-(Ethylthio)butyl]cyclohexanone (14). Ethanethiol (1.24 g, 20.0 mmol) was slowly added to a suspension of 0.43 g (18.0 mmol) of sodium hydride in 25 mL of DMF. After hydrogen evolution had ceased, 3.23 g (13.9 mmol) of bromide **39** was added and the resulting mixture was stirred for 3 h. The solution was diluted with water and extracted with ether. The ether extract was washed with 10% NaOH solution and water and dried. After evaporation of the ether, the residue was distilled to give 2.37 g

(24) Becker, K. B. *Helv. Chim. Acta* **1977**, *60*, 68.
(25) Porkorny, J. *Z. Chem.* **1973**, *13*, 382.
(26) Araújo, H. C.; Mahajan, J. R. *Synthesis* **1978**, *228*.
(27) Saharia, G. S.; Tyagi, M. P. *J. Indian Chem. Soc.* **1972**, *49*, 611.
(28) Kharasch, M. S.; Tawney, P. O. *J. Am. Chem. Soc.* **1941**, *63*, 2308.

(80%) of 14: bp 94–96 °C (0.03 torr); IR 5.88 μM; NMR δ 1.0–2.8.

Anal. Calcd for $C_{12}H_{22}OS$: C, 67.23; H, 10.35; S, 14.96. Found: C, 67.25; H, 10.26; S, 14.88.

2-[5-(Phenylthio)pentyl]cyclopentanone (17). Bromide 41 (11.8 g, 50.6 mmol) was added to a solution of sodium thiophenoxide, prepared from 1.32 g (55 mmol) of sodium hydride and 6.61 g (60 mmol) of thiophenol in 100 mL of DMF, and the mixture was stirred for 3 h. Following the usual workup, distillation afforded 12.6 g (95%) of 17: bp 136–138 °C (0.02 torr); IR 5.74, 6.30, 13.4, 14.3 μM; NMR δ 1.2–2.4 (m, 17), 2.90 (t, 2), 7.23 (m, 5).

Anal. Calcd for $C_{16}H_{22}OS$: C, 73.23; H, 8.45; S, 12.22. Found: C, 72.97; H, 8.21; S, 12.34.

2-(3-Bromopropyl)cyclohexanone (32b). A mixture of 20.4 g (150 mmol) of allylcyclohexanone (**1b**), 1 g of benzoyl peroxide, and 1500 mL of pentane was stirred while being irridated by a sunlamp (275 W, General Electric Model RS). Dry HBr gas was bubbled through the solution for 1 h after which the reaction vessel was purged with nitrogen. The reaction mixture was washed with saturated $NaHCO_3$ solution and water and dried. After removal of the solvent by distillation, the residue was distilled to give 21.2 g (66%) of **32b**:[10] bp 76–77 °C (0.03 torr); IR 5.87 μM; NMR δ 1.0–2.25 (m, 13), 3.33 (t, 2, J = 7 Hz).

2-(3-Bromopropyl)-4-*tert*-butylcyclohexanone (34). In a similar fashion to the preceding experiment, 6 yielded 8.69 g (61%) of 34: bp 122–124 °C (0.04 torr); IR 5.85 μM; NMR (220 MHz) δ 0.85, 0.90 (2 s, 9), 1.0–2.39 (m, 12), 3.36 (m, 2).

Anal. Calcd for $C_{13}H_{23}OBr$: C, 56.73; H, 8.42; Br, 29.03. Found: C, 56.77; H, 8.26; Br, 29.30.

2-(3-Bromopropyl)-3,3,5,5-tetramethylcyclohexanone (37). In the same manner as the preceding experiments, 2.20 g (11.3 mmol) of **10** was treated with HBr to afford 2.33 g (75%) of **37**: bp 94–96 °C (0.04 torr); IR 5.88 μM; NMR δ 0.82 (s, 3), 1.00 (s, 3), 1.07 (s, 3), 1.10 (s, 3), 1.2–2.4 (m, 9), 3.40 (t, 2).

Anal. Calcd for $C_{13}H_{23}OBr$: C, 56.73; H, 8.42; Br, 29.03. Found: C, 56.87; H, 8.10; Br, 29.30.

2-(3-Bromopropyl)cyclopentanone (32a). In the same manner, 15.0 g (121 mmol) of **1a** was treated with HBr to give 14.1 g (57%) of **32a**:[29] bp 89–90 °C (0.1 torr); IR 5.78 μM; NMR δ 1.2–2.4 (m, 11), 3.42 (t, 2, J = 6 Hz).

2-(3-Bromopropyl)cycloheptanone (32c). Reaction of 6.0 g (39.4 mmol) of **1c** as described above afforded 7.5 g (82%) of **32c**: bp 89–91 °C (0.02 torr); IR 5.89 μM; NMR δ 1.2–2.2 (m, 12), 2.2–2.8 (m, 3), 3.42 (t, 2).

Anal. Calcd for $C_{10}H_{17}OBr$: C, 51.52; H, 7.35; Br, 34.27. Found: C, 51.80; H, 7.15; Br, 34.19.

2-(3-Bromopropyl)cyclooctanone (32d). In the same fashion 2.0 g (12 mmol) of **1d** was converted to 2.1 g (72%) of **32d**: bp 108–109 °C (0.05 torr); IR 5.95, 8.05 μM; NMR (CCl_4) δ 0.8–2.8 (m, 17), 3.35 (t, 2).

Anal. Calcd for $C_{11}H_{19}BrO$: C, 53.45; H, 7.75; Br, 32.33. Found: C, 53.18; H, 7.77; Br, 32.54.

6,7-Epoxybicyclo[4.3.0]nonanes (4b and 5b). A solution of 6.22 g (32.7 mmol) of triethyloxonium tetrafluoroborate[30] and 7.33 g (29.5 mmol) of sulfide **2b** in 100 mL of CH_2Cl_2 was stirred overnight. Evaporation of solvent gave the sulfonium salt as an oil that refused to crystallize after repeated washing with pentane. The sulfonium salt was dissolved in 60 mL of THF and the resulting solution was added to a solution of potassium *tert*-butylate [prepared from 6.12 g (71 mmol) of *tert*-butyl alcohol and 1.40 g (35.8 mmol) of potassium in 100 mL of THF] at 0 °C over a period of 1 h. The resulting mixture was heated to 25 °C and stirred for 3 h. Water was added and the mixture was extracted with ether. GC analysis showed a 94:6 mixture of epoxides **4b** and **5b**. After evaporation of solvent, the residue was purified by column chromatography on silica gel, eluting with 5% ether–hexane, to afford 2.71 g (66%) of a mixture of **4b** and **5b**: IR 3.32, 10.1, 10.7, 10.8, 11.3, 11.5, 11.8, 11.9, 12.6, 12.8, 13.9 μM; NMR δ 0.8–2.0 (m, 13), 3.25 and 3.40 (2 s, 1); mass spectrum, **m/z** (relative intensity) 139 (4), 137 (14), 110 (50), 94 (80), 81 (76), 79 (100).

Anal. Calcd for $C_9H_{14}O$: C, 78.21; H, 10.21. Found: C, 77.79; H, 10.00.

2,2,4,4-Tetramethyl-6,7-epoxybicyclo[4.3.0]nonanes (12 and 13). In a similar fashion, 4.09 g (13.4 mmol) of sulfide 11 was treated with 2.93 g (15.4 mmol) of triethyloxonium tetrafluoroborate to give the sulfonium salt. Subsequent reaction with potassium *tert*-butylate in THF followed by column chromatography on silica gel with 2% ether–hexane gave 0.86 g (33%) of **13** and 1.14 g (44%) of **12**.

Epoxide **13** showed the following: IR 3.33, 11.0, 11.8, 8.05 μM; NMR (220 MHz) δ 0.87 (s,3), 0.93 (s, 3), 1.03 (s, 3), 1.10 (s, 3), 1.12–1.98 (m, 9), 3.05 (s, 1); ^{13}C NMR δ 21.5, 23.6, 28.3, 32.0, 33.4, 34.6, 35.1, 41.5, 48.4, 53.2, 63.6.

Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.67; H, 11.15.

Epoxide **12** showed the following: IR 3.33, 10.5, 11.2, 11.9, 12.8, 13.2 μM; NMR (220 MHz) δ 0.87 (s, 6), 0.93 (s, 3), 1.10 (s, 3), 1.20–1.95 (m, 9), 3.34 (s, 1); ^{13}C NMR δ 19.0, 23.0, 26.7, 27.6, 33.2, 33.6, 35.0, 41.2, 49.0, 55.1, 56.3, 65.3.

Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.24; H, 11.24.

3-*tert*-Butyl-6,7-epoxybicyclo[4.3.0]nonanes (8 and 9). Sulfide **7c** (2.33 g, 7.65 mmol) was treated with triethyloxonium tetrafluoroborate and the resulting sulfonium salt reacted with potassium *tert*-butylate to afford a mixture of two epoxides. GC analysis indicated an 85:15 mixture of epoxides **8** and **9**, respectively. Column chromatography on silica gel with 2% ether–hexane gave 0.56 g (38%) of a 75:25 mixture of **8** and **9** and 0.72 g (48%) of **8**: IR 3.32, 10.1, 10.6, 10.8, 11.0, 11.6, 11.8, 12.5, 13.7 μM; NMR (220 MHz) δ 0.85 (s, 9), 1.1–1.4 (m, 5), 1.6–2.1 (m, 7), 3.19 (s, 1); ^{13}C NMR δ 26.0, 26.3, 26.8, 27.6, 28.6, 32.3, 39.7, 46.9, 61.6, 67.8. NMR (220 MHz) of the epoxide mixture showed resonances at δ 3.19 and 3.37 for the epoxide protons of **8** and **9**, respectively.

Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.34; H, 11.26.

In the same manner, 0.36 g (1.19 mmol) of sulfide **7t** was converted into 0.20 g (87%) of a mixture of epoxides containing 85% of **8** and 15% of **9** by GC analysis.

1,2-Epoxy-*cis*-bicyclo[3.3.0]octane (4a). In the same manner 3.00 g (12.8 mmol) of sulfide **2a** was converted into 1.07 g (67%) of **4a**: bp 92–93 °C (50 torr); IR 3.32, 10.5, 11.2, 11.7 μM; NMR δ 1.0–2.2 (m, 11), 3.27 (s, 1).

Anal. Calcd for $C_8H_{12}O$: C, 77.38; H, 9.74. Found: C, 77.39; H, 9.81.

7,8-Epoxybicyclo[5.3.0]decanes (4c and 5c). Sulfide **2c** (1.99 g, 7.58 mmol) was treated as above with triethyloxonium tetrafluoroborate and subsequently with potassium *tert*-butylate. After the usual workup a mixture of 47% of **4c** and 53% of **5c** was obtained as determined by GC analysis. Column chromatography on Activity II alumina gave 0.49 g (42%) of **5c** and 0.23 g (20%) of **4c**. The major isomer was identified as **5c**: IR 3.32, 9.63, 10.4, 10.8, 11.1, 12.3, 12.7 μM; NMR (220 MHz) δ 1.0–2.0 (m, 15) and 3.00 (s, 1); ^{13}C NMR δ 24.6, 27.3, 27.8, 28.1, 28.3, 30.0, 31.4, 42.3, 63.6, 67.7.

Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 78.90; H, 10.38.

The minor epoxide **4c** showed the following: IR 3.32, 9.9, 10.2, 10.4, 10.8, 11.2, 11.6, 11.7, 11.8 μM; NMR (220 MHz) δ 1.0–2.0 (m, 16), 3.02 (s, 1); ^{13}C NMR δ 24.6, 26.6, 27.6, 29.6, 30.3, 31.9, 32.1, 43.2, 62.7, 69.8; exact mass calcd for $C_{10}H_{16}O$ 152.1201, found 152.120.

8,9-Epoxybicyclo[6.3.0]undecanes (4d and 5d). Sulfide **2d** (3.47 g, 12.5 mmol) was converted by the same procedure into a 20:80 mixture of **4d** and **5d** as indicated by GC. Column chromatography on alumina using 5% ether–hexane yielded 2.50 g (63%) of a mixture of **4d** and **5d**: IR 3.35, 11.5 μM; NMR (CCl_4) δ 0.8–2.5 (m, 17) and singlets at 2.95 and 3.13 for a total of one proton.

Anal. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.91. Found: C, 79.09; H, 10.32.

1,2-Epoxybicyclo[4.4.0]decanes (15 and 16). Sulfide **14** (1.16 g, 4.88 mmol) was treated with 1.03 g (5.42 mmol) of triethyloxonium tetrafluoroborate. The resulting sulfonium salt was reacted with potassium *tert*-butylate and the mixture was worked up in the usual manner. GC analysis showed a 92:8 mixture of

(29) White, J. D.; Lodwig, S. N.; Trammell, G. L.; Fleming, M. P. *Tetrahedron Lett.* **1974**, 3263.

(30) Meerwein, H. "Organic Syntheses"; Wiley: New York, 1973; Collect. Vol. V, p 1080.

16 to 15. Solvent and diethyl sulfide were removed by distillation at reduced pressure and the residue was vacuum transferred to afford 0.59 g (80%) of a mixture of 15 and 16: IR 10.7, 10.9, 11.2, 11.4, 12.0, 12.1, 12.2, 13.2 μM; NMR (220 MHz) δ 1.1–2.0 (m, 15), 2.89 (m, 1).

Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 78.71; H, 10.41.

Spiro[4.5]decan-1-one (18). Sulfide 17 (2.09 g, 7.96 mmol) was added to a solution of 1.68 g (8.84 mmol) of triethyloxonium tetrafluoroborate in 25 mL of CH_2Cl_2 and the mixture was stirred for 5 h. The crude sulfonium salt was isolated after evaporation of solvent. A solution of the sulfonium salt in 5 mL of THF was added to a solution of potassium *tert*-butylate [prepared from 0.63 g (16.0 mmol) of potassium and 2.37 g (32.0 mmol) of *tert*-butyl alcohol in 25 mL of THF] at 0 °C over a 30-min period. The reaction mixture was processed as usual and chromatographed on silica gel with 5% ether–hexane. Vacuum transfer yielded 0.41 g (34%) of 18:[31] IR 5.74 μM; ^{13}C NMR δ 18.8, 22.1 (2 C), 25.7, 32.0 (2 C), 34.3, 36.9, 48.4, 218.6.

In a similar fashion to the above experiment, 1.29 g (4.92 mmol) of sulfide 17 was reacted with 1.04 g (5.47 mmol) of triethyloxonium tetrafluoroborate. The resulting sulfonium salt was added to a solution of lithium diisopropylamide (5.50 mmol) in 25 mL of THF at −78 °C. The mixture was allowed to warm to 25 °C overnight. Water was added and the resulting mixture was extracted with ether. After washing the ether extract with 5% HCl solution and saturated $NaHCO_3$ solution, it was dried and concentrated. Column chromatography on silica gel with 5% ether–hexane, followed by vacuum transfer gave 40 mg (5%) of 18.

Bicyclo[4.3.0]non-6-ene (33b). A solution of 5.00 g (22.8 mmol) of bromide **32b** and 12.1 g (46 mmol) of triphenylphosphine in 60 mL of benzene was refluxed for 18 h. The solvent was decanted, and the residue was washed with benzene and dried under vacuum to give the crude phosphonium salt. Without purification the phosphonium salt was added to a solution of dimsylsodium, prepared from 0.58 g (24.0 mmol) of NaH and 100 mL of dimethyl sulfoxide. The resulting solution was heated at 70 °C for 12 h. After cooling, the reaction mixture was extracted with pentane and the extract was washed with water and dried. Distillation afforded 1.11 g (40%) of **33b**:[17,24] bp 102–105 °C (132 torr); NMR δ 1.0–2.6 (m, 13), 5.23 (s, 1); IR 3.27, 6.03, 6.90, 10.0, 12.5 μM.

2,2,4,4-Tetramethylbicyclo[4.3.0]non-6-ene (38). Reflux of a mixture of 2.33 g (8.50 mmol) of bromide **37** and 4.5 g (17 mmol) of triphenylphosphine in 50 mL of benzene for 24 h afforded the phosphonium salt. A solution in 20 mL of HMPA was added to a solution of potassium *tert*-butylate prepared from 0.43 g (11 mmol) of potassium and 1.85 (25 mmol) of *tert*-butyl alchol in 30 mL of THF. The mixture was refluxed for 18 h. After cooling, the mixture was dissolved in pentane and the resulting solution washed with water and dried. After filtration through a short column of silica gel, the pentane was evaporated and the residue distilled to give 1.11 g (73%) of **38**: bp 41–42 °C (0.04 torr); NMR (220 MHz) δ 0.77 (s, 3), 0.85 (s, 3), 0.88 (s, 3), 0.90 (s, 3), 1.22 (s, 2), 1.6–2.3 (m, 7), 5.23 (m, 1); IR 3.28, 6.04, 10.2, 11.2, 12.3, 12.4, 13.1 μM; exact mass calcd for $C_{13}H_{22}$ 178.1722, found 178.172.

3-*tert*-Butylbicyclo[4.3.0]non-6-enes (35 and 36). Bromide **34** (4.40 g, 16.0 mmol) was stirred with 4.8 g (32 mmol) of sodium iodide in 50 mL of acetone for 2 h. The resulting slurry was concentrated and partitioned between ether and water. The ether extract was washed with 10% $NaHSO_3$ solution and water and dried. The solvent was evaporated to give the crude iodide, which was added to a solution of 8.39 g (32 mmol) of triphenylphosphine in 50 mL of benzene and 50 mL of hexane. After this mixture was refluxed for 24 h, the phosphonium salt was isolated as in the preceding experiment and reacted with excess potassium *tert*-butylate in a mixture of HMPA and THF. After workup, distillation afforded 1.25 g (44%) of a mixture of **35** and **36**: bp 35–36 °C (0.05 torr); IR 3.29, 6.03, 7.30, 10.1, 12.5 μM; NMR (220 MHz) δ 0.87 (s, 9), 0.9–2.7 (m, 12), and singlets at 5.15 and 5.20 in a ratio of 84:16 accounting for 1 proton; exact mass calcd for $C_{13}H_{22}$ 178.1722, found 178.172.

Bicyclo[3.3.0]oct-1-ene (33a). Bromide **32a** (7.68 g, 32.4 mmol) was converted into the iodide by reaction with NaI in acetone in the same manner as above and reacted with triphenylphosphine. Crude phosphonium salt was treated with potassium *tert*-butylate in THF. Workup and distillation gave 0.56 g (16%) of **33a**:[24] bp 85–87 °C (140 torr); NMR 1.2–3.0 (m, 11), 5.23 (m, 1).

Bicyclo[5.3.0]dec-7-ene (33c). In the same fashion 7.50 g (32.2 mmol) of bromide **32c** was converted into the iodide. Reaction with 17.1 g (65 mmol) of triphenylphosphine in 100 mL of benzene and 50 mL of hexane gave the phosphonium salt. Subsequent reaction with potassium *tert*-butylate followed by workup and distillation afforded 2.85 g (65%) of **33c**:[24] bp 94–96 °C (32 torr); IR 3.31, 6.10, 12.6, 12.8 μM; NMR δ 1.0–3.0 (m, 15), 5.33 (br s, 1).

Bicyclo[4.4.0]dec-1-ene (40). Following the procedure of the preceding experiment, 5.07 g (21.7 mmol) of bromide **39** was converted into the iodide. Subsequent reaction with 11.5 g (44 mmol) of triphenylphosphine in 50 mL of benzene and 50 mL of hexane gave the phosphonium salt. A solution in HMPA was treated with 2 equiv of potassium *tert*-butylate in THF and the resulting mixture was refluxed overnight. After workup, distillation afforded 0.96 g (32%) of **40**:[24] bp 85–86 °C (20 torr); IR 3.29, 7.70, 10.8, 11.6, 11.9, 12.4, 12.5 μM; NMR δ 1.2–2.6 (m, 15), 5.40 (m, 1).

Bicyclo[5.3.0]dec-1-ene (42). In the same manner 6.00 g (25.7 mmol) of bromide **41** was converted into the iodide and subsequently into the phosphonium salt. Reaction with potassium *tert*-butylate gave 1.11 g (32%) of **42**:[24] bp 88–90 °C (27 torr); IR 3.29, 5.99, 10.4, 10.7, 12.1, 12.4 μM; NMR δ 1.02–2.8 (m, 15), 5.6–6.0 (m, 1).

Anal. Calcd for $C_{10}H_{16}$: C, 88.16; H, 11.84. Found: C, 87.72; H, 11.99.

Bicyclo[6.3.0]undec-8-ene (33d). In a similar manner 7.6 g (30.8 mmol) of **32d** was converted to the iodide and reacted with triphenylphosphine. The crude phosphonium salt was treated with potassium *tert*-butylate in THF to give, after vacuum transfer, 2.3 g (50%) of **33d**: IR 3.30 μM; NMR δ 0.9–2.6 (m, 17), 5.32 (s, 1); exact mass calcd for $C_{11}H_{18}$ 150.1409, found 150.141.

Epoxidation of 33b. A heterogeneous mixture of 1.10 g (9.0 mmol) of **33b** in 80 mL of CH_2Cl_2 and 80 mL of 15% $NaHCO_3$ solution was cooled to 0 °C. MCPBA (2.6 g, 15.0 mmol) was added and the mixture was stirred for 3 h. The two-phase mixture was separated and the organic phase was washed with 10% $NaHSO_3$ solution, saturated $NaHCO_3$ solution, and water and dried. GC analysis of this solution showed a 39:61 mixture of **4b** and **5b**. Evaporation of solvent and preparative GC gave 0.09 g (7%) of **4b** and 0.08 g (6%) of **5b**.

Epoxidation of 38. Following the same procedure, 0.24 g (1.33 mmol) of **38** was treated with MCPBA to afford a single epoxide. Column chromatography on silica gel with 5% ether–hexane gave 0.14 g (53%) of **12**, identical with the major product from sulfur ylide cyclization by TLC and NMR analysis.

Epoxidation of 35. To a solution of 172 mg (0.96 mmol) of an 84:16 mixture of **35** and **36** in 13 mL of CH_2Cl_2 and 20 mL of aqueous $NaHCO_3$ solution at 0 °C was added 250 mg (1.2 mmol) of MCPBA. Processing in the usual fashion after 3 h gave 140 mg (75%) of a crude epoxide mixture of **15** and **16** in a 32:68 ratio as determined by signals at δ 3.19 and 3.36 in the 220-MHz NMR. All of the olefin was consumed but no spectroscopic indication of other epoxides was present. Weak IR bands indicated small amounts of OH and C=O impurities.

Epoxidation of 33c. Olefin **33c** (0.75 g, 5.51 mmol) was treated with MCPBA (1.90 g, 11 mmol) as above. GC analysis showed a 34:66 mixture of epoxides **4c** and **5c**. Column chromatography on activity II alumina with 2% ether–hexane gave 0.21 g (25%) of **4c** and 0.38 g (45%) of **5c**.

Epoxidation of 33d. In a similar fashion 50 mg (0.33 mmol) of **33d** in 3 mL of CH_2Cl_2 was treated with 120 mg (0.7 mmol) of MCPBA. Workup gave a crude yield of 38 mg (69%) of **4d** and **5d** in a 48:52 ratio as determined by NMR.

Epoxidation of 40. A heterogeneous mixture of 208 mg (1.53 mmol) of **40** in 10 mL of CH_2Cl_2 and 10 mL of 10% $NaHCO_3$ solution was stirred at 0 °C. MCPBA (517 mg, 3.00 mmol) was added and the resulting mixture was stirred for 12 h. The two-

(31) Tinker, J. F. *J. Org. Chem.* **1951**, *16*, 1417. Zimmermann, D.; Ottinger, R.; Reisse, J.; Christol, H.; Bugidou, J. *Org. Magn. Reson.* **1974**, *6*, 346.

phase mixture was separated and the organic phase was washed with 10% NaOH solution and dried. GC analysis showed a 25:75 mixture of **15** and **16**. After evaporation of solvent, vacuum transfer of the residue afforded 197 mg (84%) of a mixture of **15** and **16**.

Reduction of 4b and 5b. A 94:6 mixture of epoxides **4b** and **5b** (100 mg, 0.7 mmol) was refluxed with 20 mg (0.04 mmol) of $LiAlH_4$ in 20 mL of THF for 12 h. Careful quenching of the resulting slurry with 10% NaOH solution gave a clear liquid and a white precipitate. The solution was filtered and the solvent was evaporated. Vacuum transfer of the residue afforded 70 mg (73%) of a 95:5 mixture of **43b** and **44b**, identified by GC comparison with authentic samples.[17]

Reduction of 8 and 9. An 85:15 mixture of epoxides **8** and **9** (0.61 g, 3.14 mmol) was reacted with 0.15 g (4.0 mmol) of $LiAlH_4$ in refluxing THF for 24 h. After the usual workup, the crude product was sublimed to yield 0.52 g (84%) of an 89:11 mixture of **46** and **47** as indicated by GC analysis. ^{13}C NMR showed signals for **46** at 21.1, 25.1, 27.7, 30.9, 32.1, 32.7, 34.4, 36.7, 47.2, 47.7, and 80.7 ppm and for the minor isomer **47** at 48.2, 48.3, and 76.9 ppm.

Anal. Calcd for $C_{13}H_{24}O$: C, 79.53; H, 12.32. Found: C, 79.35; H, 12.14.

Reduction of 4a. A mixture of 0.20 g (1.61 mmol) of **4a**, 0.08 g (2.0 mmol) of $LiAlH_4$, and 10 mL of THF was heated at reflux for 12 h. After the usual workup, the crude product was sublimed to give 0.12 g (59%) of **43a**: mp 43–45 °C (lit.[32] mp 46 °C); IR 2.8–3.1, 3.40, 3.49, 8.3, 9.95, 10.2 μM; NMR δ 1.0–2.2 (m, 13), 3.33 (s, 1); ^{13}C NMR δ 90.5, 51.5, 41.6, 33.2, 25.6.

Reduction of 4c. In the same manner, 0.22 g (1.45 mmol) of epoxide **4c** was reacted with 0.12 g (3.2 mmol) of $LiAlH_4$. After workup and column chromatography on silica gel with 20% ether–hexane, sublimination gave 0.11 g (49%) of **43c**: mp 44–46 °C (lit.[33] mp 53 °C); IR (CCl_4) 2.78, 6.89, 8.28, 9.55, 10.2, 10.4, 10.8 μM; ^{13}C NMR δ 23.4, 23.9, 29.7, 31.3, 34.2, 35.2, 40.0, 43.6, 51.4, 83.5.

Reduction of 5c. A mixture of 120 mg (0.76 mmol) of epoxide **5c**, 120 mg (3.2 mmol) of $LiAlH_4$, and 10 mL of THF was refluxed for 12 h. The reaction mixture was worked up as usual to yield a mixture of two products, which were separated by preparative GC. The major product (19 mg, 16%) was assigned as **45**: mp 42–43 °C (lit.[21] mp 41 °C); IR 2.77, 8.05, 9.36, 9.50, 10.2 μM; NMR (220 MHz) δ 0.9–1.8 (m, 17), 3.94 (m, 1); mass spectrum, *m/z* (relative intensity) 154 (1), 136 (59), 121 (53), 95 (65), 94 (52), 81 (83), 67 (91), 55 (100). The minor product was shown to be **44c** by IR comparison.[21]

Reduction of 15 and 16. A 75:25 mixture of trans and cis epoxides **16** and **15** (197 mg, 1.29 mmol) and 100 mg (2.5 mmol) of $LiAlH_4$ in 10 mL of THF was refluxed for 12 h. Workup, column chromatography on silica gel with 10% ether–hexane, and vacuum sublimation gave 65 mg (33%) of trans alcohol **44e** and 32 mg (16%) of cis alcohol **43e**. Alcohol **44e** was compared by GC with an authentic sample and showed: mp 53–55 °C (lit.[34] mp 54 °C); IR (CCl_4) 2.78, 8.60, 10.3, 10.5, 11.0 μM; ^{13}C NMR δ 21.5, 26.3, 28.4, 39.9, 44.3, 69.3. Alcohol **43e** showed the following: mp 56–58 °C (lit.[34] mp 65 °C); IR (CCl_4) 2.78, 9.80, 10.2, 10.6, 10.8 μM; NMR δ 1.0–2.0 (m). Its assignment is based on published IR data.[34]

Reduction of 4d and 5d. In a similar manner a 20:80 mixture of **4d** and **5d** (0.15 g, 0.9 mmol) was reduced with 0.1 g of $LiAlH_4$. The crude product was isolated by GC to give 20 mg (12%) of a 20:80 mixture of **43d**/**44d**: IR 3.0, 10.5 μM; NMR δ 1.0–2.5 (m).

Anal. Calcd for $C_{11}H_{20}O$: C, 78.51; H, 11.98. Found: C, 78.29; H, 12.07.

Bicyclo[6.3.0]undec-1(8)-ene (48). To a solution of 0.50 g (3.3 mmol) of **33d** in 20 mL of CH_2Cl_2 was added 4 drops of methanesulfonic acid. After being stirred overnight at room temperature, the solution was washed with $NaHCO_3$ solution and water and dried. Removal of the solvent gave 0.47 g (94%) of **48**: NMR δ 1.3–2.5 (m); a pure sample was isolated by GC; exact mass calcd for $C_{11}H_{18}$ 150.1409, found 150.140.

***cis*-Bicyclo[6.3.0]undecan-1-ol (43d).** To a solution of 0.15 g (1 mmol) of **48** in 5 mL of THF was added 5 mL of 1 M borane in THF (5 mmol). After the mixture was stirred for 1 h at room temperature, 5 mL of 3 N NaOH was added, followed by 5 mL of 30% hydrogen peroxide. After an hour, pentane was added and the organic layer was washed with water, dried, and concentrated to yield 0.14 g (91%) of **43d**: IR 3.0, 10.5 μM; NMR δ 1.0–2.5 (m). This material corresponds to the minor component of the alcohol mixture obtained from the reduction of epoxides **4d** and **5d**.

Registry No. **1a**, 30079-93-7; **1b**, 94-66-6; **1c**, 58105-24-1; **1d**, 38931-77-0; **2a**, 77516-32-6; **2b**, 77516-33-7; **2c**, 77516-34-8; **2d**, 83587-20-6; **4a**, 77505-25-0; **4b**, 77550-59-5; **4c**, 77550-61-9; **4d**, 83587-21-7; **5b**, 77550-60-8; **5c**, 77550-65-3; **5d**, 83648-25-3; **6**, 4861-78-3; **7c**, 77516-41-7; **7t**, 77516-46-2; **8**, 77516-42-8; **9**, 77550-62-0; **10**, 83587-22-8; **11**, 77516-43-9; **12**, 77516-44-0; **13**, 77550-63-1; **14**, 77505-23-8; **15**, 77550-64-2; **16**, 77550-66-4; **17**, 77516-45-1; **18**, 4728-91-0; **32a**, 10468-38-9; **32b**, 10468-37-8; **32c**, 62547-86-8; **32d**, 83587-23-9; **33a**, 694-73-5; **33b**, 16189-41-6; **33c**, 62548-00-9; **33d**, 83587-24-0; **34**, 83587-25-1; **35**, 83587-26-2; **36**, 83587-27-3; **37**, 83587-28-4; **38**, 83587-29-5; **39**, 51953-08-3; **40**, 1194-95-2; **41**, 51566-66-6; **42**, 62547-99-3; **43a**, 52318-93-1; **43b**, 13366-92-2; **43c**, 27935-18-8; **43d**, 83587-30-8; **43e**, 3574-58-1; **44b**, 13366-91-1; **44c**, 27935-17-7; **44d**, 83587-31-9; **44e**, 1654-87-1; **45**, 83587-32-0; **46**, 83587-33-1; **47**, 83587-34-2; **48**, 25107-10-2; cycloheptanone, 502-42-1; allyl alcohol, 107-18-6; cyclooctanone, 502-49-8; 3,3,5,5-tetramethylcyclohexanone, 14376-79-5; thiophenol, 108-98-5; ethanethiol, 75-08-1.

(32) Cope, A. C.; Grisar, J. M.; Peterson, P. E. *J. Am. Chem. Soc.* **1960**, *82*, 4299.

(33) Bessiere, J. M.; Christol, H. *Bull. Soc. Chim. Fr.* **1969**, 4063.

(34) Huckel, W.; Maucher, D.; Fechtig, O.; Kurz, J.; Heinzel, M.; Hubele, A. *Justus Liebigs Ann. Chem.* **1961**, *645*, 115.