to be bery pure. The oil solidified: mp 79–80 °C; ^{1}H NMR δ 0.27 (s, 9.1 H), 3.72 and 3.80 (both s, 9.0 total H), 6.07 (s, 1.8 H); IR (KBr pellet) 1599 (14), 1578 (16), 1398 (19), 1220 (8), 1207 (13), 1155 (23), 1123 (11), 1092 (18), 848 (19), 809 (21); MS 240 (M^+, 15), 225 (35), 202 (20), 165 (100), 121 (20), 95 (14), 93 (34), 73 (13), 59 (23). Anal. Calcd for $C_{12}H_{20}O_3Si$: C, 59.96; H, 8.39. Found: C, 59.95; H, 8.43.

2,4-Bis(trimethylsilyl)-1,3,5-trimethoxybenzene (26) was obtained as a solid, mp 95–97 °C, from the double bromine/lithium exchange with 2,4-dibromo-1,3,5-trimethoxybenzene, **35**, followed by silylation: ^{1}H NMR δ 0.28 (s, 18.0 H), 3.49 (s, 3.0 H), 3.74 (s, 6.0 H), 6.16 (s, 1.0); IR (KBr pellet) 1572 (4), 1348 (3), 1246 (11), 1241 (12), 1202 (7), 1120 (5), 1099 (5), 1092 (7), 855 (7), 840 (5); MS 312 (M^+, 22), 267 (33), 259 (16), 237 (100), 199 (24), 193 (38), 141 (18), 133 (19), 95 (30), 93 (75), 89 (32), 75 (18), 73 (64), 59 (53). Anal. Calcd for $C_{15}H_{28}O_3Si_2$: C, 57.64; H, 9.03. Found: C, 57.79; H, 9.09.

Bromo Derivatives of Methoxybenzenes. The bromo derivatives used in the bromine/lithium exchanges were prepared following standard procedures which used 1 or 2 equiv of Br_2 in either chloroform, carbon tetrachloride, or acetic acid.

1,5-Dibromo-2,3,4-trimethoxybenzene (34) was obtained as an oil: bp 100–110 °C (0.5 mm) (lit.[10] bp 157–161 °C (12 mm)); ^{1}H NMR δ 3.85 and 3.89 (both s, 9.1 total H), 7.43 (s, 0.94 H); IR (liquid film) 2938 (19), 1459 (0.07), 1412 (0.1) 1398 (0.08), 1272 (18), 1218 (4), 1066 (2), 1004 (0.7), 873 (19), 726 (16); MS 328 (M^+, 45), 326 (100), 324 (48), 313 (16), 311 (35), 309 (18), 270 (16), 268 (32), 266 (20), 204 (26), 202 (33), 77 (40), 53 (37).

2,4-Dibromo-1,3,5-trimethoxybenzene (35) was obtained as a solid: mp 131–132 °C (lit.[21] mp 132 °C; ^{1}H NMR δ 3.93 and 3.95 (both s, 9.03 total H), 6.32 (s, 0.97 H); IR (KBr pellet) 1573 (32), 1468 (47),1458 (48), 1429 (42), 1387 (36), 1340 (42), 1211 (25), 1107 (21), 1098 (42), 691 (49); MS 328 (M^+, 42), 326 (100), 324 (50), 217 (50), 215 (51), 189 (22), 187 (30), 166 (35), 138 (24).

5-Bromo-1,2,4-trimethoxybenzene (19) was obtained as a solid: mp 52–55 °C (lit.[15] mp 54–55.5 °C); ^{1}H NMR δ 3.75, 3.78, and 3.80 (all s, 8.8 total H), 6.47 (s, 1.1 H), 6.95 (s, 1.1 H); ^{1}H NMR (lit.[15]) δ 3.75 (s, 3 H), 3.78 (s, 6 H), 6.43 (s, 1 H), 6.93 (s, 1 H); IR (KBr pellet) 1507 (26), 1472 (49), 1452 (48), 1439 (44), 1379 (44), 1280 (52), 1213 (20), 1169 (45), 1025 (34), 801 (44). MS: 248 (M^+, 79), 246 (84), 233 (58), 231 (70), 205 (55), 203 (47), 159 (23), 124 (100), 109 (44), 53 (46).

1-Bromo-2,3,5-trimethoxybenzene was obtained by following the procedure of Dorn:[16] ^{1}H NMR δ 3.74, 3.78 and 3.82 (all s, 9.08 total H), 6.31 (d, J = 2.6 Hz, 0.97 H), 6.61 (d, J = 2.6 Hz, 0.95 H); ^{1}H NMR (lit.[15]) δ 3.60, 3.67, and 3.68 (all s), 6.22 (d, J = 2.8 Hz), 6.42 (d, J = 2.8 Hz).

2,3-Dibromo-1,4,5-trimethoxybenzene (22) was obtained by following the procedure of Dorn,[16] who incorrectly assigned the structure: ^{1}H NMR δ 3.75 (s, 2.9 H), 3.85 (s, 6.2 H), 6.5 (s, 0.96 H) [lit.[15] ^{1}H NMR δ 3.70 (s, 3 H), 3.78 (s, 3 H), 3.79 (s, 3 H), 6.38 (s, 1 H)]; IR (KBr pellet) 1582 (46), 1478 (44), 1430 (30), 1373 (27), 1320 (39), 1226 (32), 1205 (32), 1032 (25), 1009 (39), 818 (41); MS 328 (M^+, 35), 326 (76), 324 (45), 313 (45), 311 (100), 309 (49), 259 (33), 189 (35), 187 (39).

General Bromine/Lithium Exchange Conditions. The best results were obtained by following a procedure similar to that used by Worden.[10] The intermediate aryllithium derivatives were allowed to form for 1 min at 0 °C in diethyl ether and then quenched with chlorotrimethylsilane/*tertiary* amine solution.

(2,4,5-Trimethoxyphenyl)trimethylsilane (20) was obtained by distillation as an oil (bp 83–84 °C (0.1 mm)) from bromine/lithium exchange and silylation of 5-bromo-1,2,4-trimethoxybenzene, **19**. The oil solidified: mp 40.5–43 °C; ^{1}H NMR δ 0.26 (s, 8.84 H), 3.74, 3.80, and 3.84 (all s, 9.14 total H), 6.45 (s, 1.01 H), 6.84 (s, 1.01 H); IR (KBr pellet) 1371 (62), 1239 (56), 1211 (51), 1100 (37), 1077 (60), 1034 (58), 936 (38), 903 (25), 853 (63), 838 (59). MS: 240 (M^+, 52), 225 (22), 195 (100), 151 (69), 105 (10), 89 (12), 75 (11), 59 (19).

Carbonation Experiments. The lithiation reaction mixture (heterogeneous suspension) was poured onto solid dry ice and the mixture opened to the atmosphere and allowed to evaporate overnite. The reaction mixture was then acidified. In the case of 2,3-dimethoxyterephthalic acid (from 1,2-dimethoxybenzene), the acid was extracted into ether and then into $NaHCO_3$ solution, from which it was reextracted after acidification. The solvent was evaporated to yield crude product which was washed with cold benzene and dried to give 2,3-dimethoxyterephthalic acid, mp 214 °C dec (lit.[22] mp 219 °C. In the case of 2,5-dimethoxyterephthalic acid (from 1,4-dimethoxybenzene), the crude product was obtained by filtering the acidified reaction mixture then recrystallized from hot water, mp 265 °C, lit.[23] mp 263–264 °C.

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Registry No. 1, 100-66-3; 2, 877-68-9; 3, 92669-90-4; 4, 91-16-7; 5, 92669-91-5; 6, 92669-92-6; 7, 151-10-0; 8, 92669-93-7; 9, 92669-94-8; 10, 150-78-7; 11, 72054-75-2; 12, 92669-95-9; 13, 634-36-6; 14, 92669-96-0; 15, 92669-97-1; 16, 135-77-3; 17, 92669-98-2; 18, 92669-99-3; 19, 20129-11-7; 20, 92670-00-3; 21, 92670-01-4; 22, 23149-34-0; 23, 92670-02-5; 24, 621-23-8; 25, 36086-05-2; 26, 92670-03-6; 27, 92670-04-7; 28, 92670-05-8; 29, 92670-06-9; 30, 92670-07-0; 31, 92670-08-1; 34, 92670-09-2; 35, 5876-90-4; 1-bromo-2,3,5-trimethoxybenzene, 23030-39-9; 2,3-dimethoxyterephthalic acid, 7168-95-8; 2,5-dimethoxyterephthalic acid, 21004-11-5.

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Synthesis of Cis Vicinally Disubstituted Cyclopentanes by Fragmentation of Bicyclo[3.2.0]heptan-6-ols. Total Synthesis of (±)-Multifidene[1a]

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A fragmentation–olefination process has been developed for the conversion of bicyclo[3.2.0]heptan-6-ols bearing anion stabilizing functions at C-7 into cyclopentanes with vicinal and functionalized methyl substituents. Under appropriate conditions reasonable stereoselectivity in favor of the cis isomers can be achieved as in the **3** → **4c** and **16** → **17c** transformations. This methodology is applied to a total synthesis of (±)-multifidene (**1c**), the gamete-attracting substance of the brown algae *Cutleria multifida*.

Several years ago we became interested in methodology for the stereoselective synthesis of cis-1,2-disubstituted cyclopentanes. Existing methods for the construction of vicinally substituted cyclopentanes have arisen primarily

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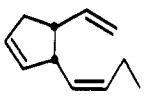
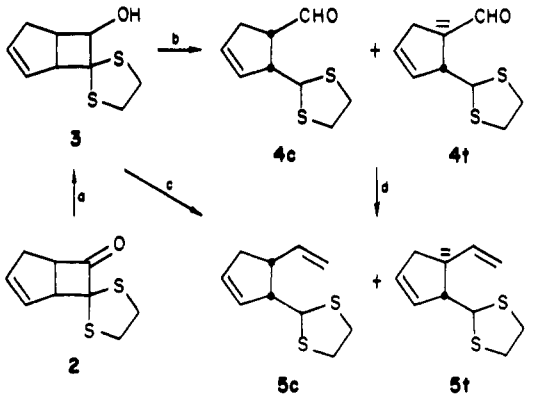
in conjunction with synthetic approaches to prostaglandins and attention has accordingly been focused on the trans stereochemistry common to these molecules.[2] The growing number of cyclopentanoid natural products which possess either a cis ring fusion or cis vicinal side chains,[3] as well as increased attention to theoretically interesting cyclopentanoid structures,[4] has provided impetus for the development of approaches to cis-1,2-disubstituted cyclopentanes.

An attractive route to these types of molecules takes advantage of the ready accessibility of bicyclo[3.2.0]heptan-6-ones, which are available in quantity from the in situ cycloaddition of ketenes to cyclopentenes.[5] The facility for cyclobutane ring opening inherent to these bicyclic systems provides a pathway to the desired monocyclic structures. Since the first demonstration of the cleavage of cyclobutanones possessing carbanion-stabilizing groups at the α-carbon,[6] a number of examples of this transformation have appeared.[7-9] These reactions have, with a few exceptions, involved ring opening of appropriately functionalized cyclobutanones with scant attention being directed toward ring fission of the corresponding cyclobutanols.[8b,e,9c,d] The aldehyde function potentially available upon application of the latter process to secondary cyclobutanols is an attractive feature for subsequent synthetic transformations which we explore herein. The methodology developed is subsequently utilized in a total synthesis of (±)-multifidene (**1c**),[10,11] the gamete attractant of the brown algae *Cutleria multifida*.[12]



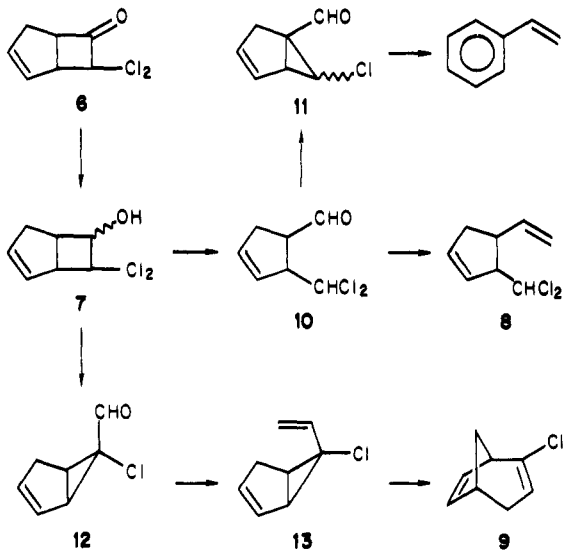
1c

Scheme I[a]



[a] (a) $LiAlH_4$; (b) *t*-BuOK; (c) *t*-BuOK, Ph_3PCH_3Br; (d) Ph_3PCH_3Br, BuLi.

Scheme II



Results and Discussion

The known[9b] dithiolane-substituted bicycloheptenone **2** was readily reduced to the corresponding alcohol **3** (Scheme I). Upon treatment of this alcohol with potassium *tert*-butoxide in THF there was obtained a mixture of aldehydes **4c** and **4t** in a 1:2 ratio. The formation of two aldehydes was clearly indicated by the presence of a pair of doublets at δ 9.6 and 9.8 in the NMR spectrum of the product. Thus, facile epimerization of the aldehyde group under the conditions required for ring opening of **3** was signaled as a major concern from the onset. This threat to the preservation of the cis stereochemistry of the bicyclic precursor proved to be a general one.

An acceptable solution to this problem was achieved by devising reaction conditions such that the aldehyde group was trapped in an inactive form by a process whose rate was faster than the objectionable epimerization. In view of our long range synthetic objectives, a Wittig reagent was utilized as a convenient trapping agent. A preliminary experiment involving reaction of **3** with 2 equiv of potassium *tert*-butoxide in the presence of 2 equiv of methyltriphenylphosphonium bromide in THF at 60 °C afforded the vinylcyclopentenes **5c** and **5t** with the cis isomer preferred by a 2:1 ratio. The same two products, but in a 1:2 ratio, were generated when the above mixture of aldehydes **4c** and **4t** was subjected to Wittig conditions.

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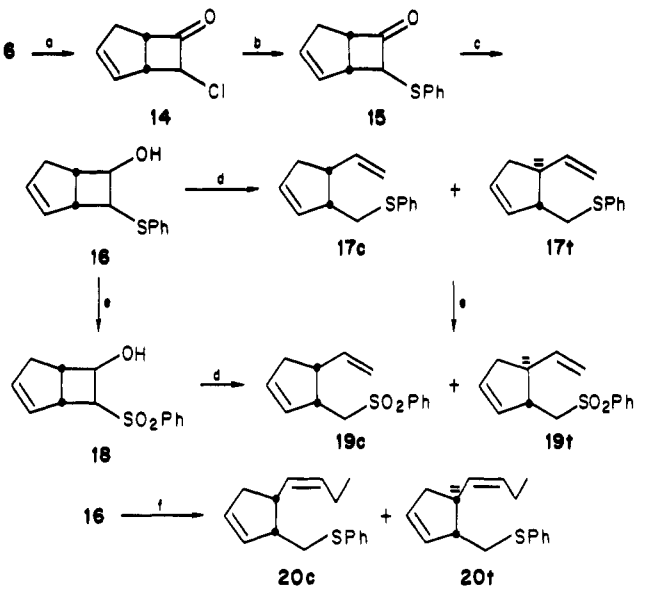
The variation in the **5c:5t** ratio according to application of a one-step or a two-step fragmentation–olefination process provides a basis for the stereochemical assignments in view of the anticipated thermodynamic advantage of the trans isomers.[7b]

Subsequent studies revealed that the **5c:5t** ratio was highly dependent on the concentrations of reagents in the fragmentation–olefination reaction, with high reactant concentrations favoring more efficient trapping of the cis aldehyde. Optimum reaction conditions employed 2 equiv each of potassium *tert*-butoxide and the phosphonium salt in THF solution which was ca. 0.1 M in **3**. These conditions provided a 9:1 mixture of cis- and trans-vinylcyclopentenes **5c** and **5t** in 83% yield. Interestingly, a large excess of the phosphonium salt did not improve the isomeric ratio. Attempts to induce reaction with an excess of preformed methylenetriphenylphosphorane as both base and trapping reagent produced no reaction. Likewise, reaction was not induced by the addition of **3** to a solution of the Wittig reagent and sodium dimsylate in Me_2SO.[13]

The readily available bicyclic ketone **6**, which itself fragments under basic conditions without complication, was converted to alcohol **7**.[14,15] Fragmentation-olefination of **7** gave a complex mixture containing three major components assigned as styrene, **8**, and **9** on the basis of spectral examination (Scheme II). The least abundant product of the three was the anticipated vinylcyclopentene **8**. Although GC and proton NMR data indicate that this material is stereochemically homogeneous, its stereochemistry was not unequivocally demonstrated. Aldehyde **10** is, of course, the presumed precursor of **8**. Styrene is also thought to be derived from **10**. Thus, enolate formation followed by intramolecular alkylation would lead to aldehyde **11**. Dehydrohalogenation with electronic reorganization and Wittig olefination (not necessarily in that order) provide a plausible pathway from **11** to styrene. The third product is tentatively assigned as bicyclic diene **9** mainly on the basis of its mass spectrum, which evidences a single chlorine in its molecular formula, and a consistent NMR spectrum, which shows three different olefinic protons among other characteristic features. Bicyclic diene **9** is envisioned as being derived from the cyclopropylcarboxaldehyde **12** by Wittig olefination and subsequent Cope rearrangement[16] of bicyclic diene **13**. The ring contraction of **7** to **12** finds precedence in a related study.[14] The chemistry of **7** points out some of the potential complications associated with the availability of good leaving groups appropriately situated in the cyclobutanol ring of fragmentation substrates.

A second sulfur-substituted system proved to be more useful from a synthetic point of view as illustrated in Scheme III. Thus, reduction of **6** with tri-*n*-butyltin hydride afforded the monochloro ketone **14** which was smoothly transformed into 7-(phenylthio)bicyclo[3.2.0]-hept-2-en-6-one (**15**)[17] by reaction with sodium thiophenolate. Compound **15** was a 4:1 mixture of endo and exo isomers which could be separated by fractional crystallization. Stereochemical assignments are based on the chemical shifts and coupling constants of the C-7 methine proton.[5c] Bicycloheptenone **15**, typically as a mixture of

Scheme III[a]



[a] (a) Bu_3SnH, (b) PhSNa; (c) $LiAlH_4$; (d) *t*-BuOK, Ph_3PCH_3Br; (e) MCPBA; (f) *t*-BuOK, $Ph_3PCH_2CH_2CH_3Br$.

isomers, was converted by lithium aluminum hydride to a mixture of diastereomeric alcohols of general structure **16**. This product was used directly in fragmentation studies.

Treatment of **16** (ca. 0.3 M in THF) with 2 equiv of potassium *tert*-butoxide in the presence of 2 equiv of methyltriphenylphosphonium bromide gave a 9:1 mixture of vinylcyclopentenes **17c** and **17t** in 75% yield. These isomers were resolvable by analytical GC, were readily distinguishable by ^{13}C NMR, but were inseparable on a preparative scale. The stereochemical assignments for **17** are based on a combination of chemical and spectroscopic evidence. By decreasing the reactant concentrations (ca. 0.06 M in **16** in THF) the product ratio of **17c** to **17t** was reversed to 1:9, consistent with the behavior of the analogous compound **3**. Analysis of the mixture of isomers by ^{13}C NMR clearly revealed two sets of signals. Each of the sp^3 carbons in the cis isomer appears upfield with respect to the corresponding carbon of the trans isomer as anticipated.[18] Furthermore, **17c** shows its terminal olefinic carbon markedly downfield from that of **17t** (115.3 vs. 113.8 ppm), whereas the associated substituted olefinic carbon of **17c** is upfield of its counterpart in **17t** (138.3 vs. 141.1 ppm).

The related fragmentation system **18** with an α-phenylsulfonyl substituent was prepared by peracid oxidation of **16** and found to ring open under the usual conditions to give vinylcylcopentenes **19c** and **19t** in good yield.[19] Structural assignment of these compounds was based on an alternate synthesis by peracid oxidation of **17c** and **17t**.

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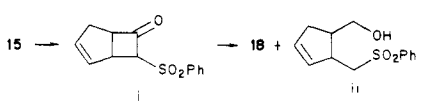
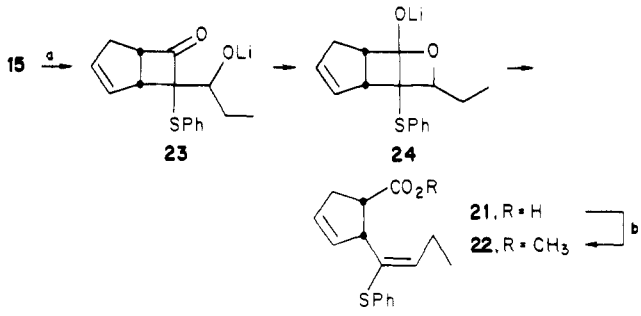
(19) Attempts to prepare sulfone **18** by the sequence of MCPBA oxidation of sulfide **15** followed by lithium aluminum hydride or sodium borohydride reduction of ketone **i** gave mixtures of the desired bicycloheptanol **18** and the ring opened hydroxymethyl cyclopentene **ii**.



i ii

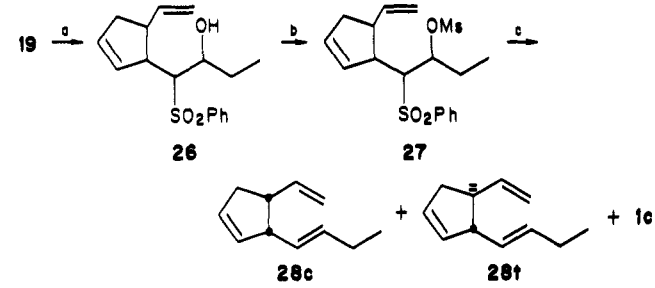
For a related reaction see: Baldwin, S. W.; Crimmins, M. T. *Tetrahedron Lett.* **1978**, 4197.

Scheme IV[a]



[a] (a) LDA, CH_3CH_2CHO; (b) CH_2N_2.

Scheme V[a]



[a] (a) BuLi; CH_3CH_2CHO; (b) MsCl, pyridine; (c) Na(Hg), Na_2HPO_4, MeOH.

The fragmentation–olefination of sulfone **18** is not as selective as that of the corresponding sulfide **16**, since a 2:3 ratio of **19c**:**19t** was observed under conditions which strongly favored cis product from **16**. Apparently the relative rates of the epimerization and the Wittig reaction are less favorable with the sulfone substrate.

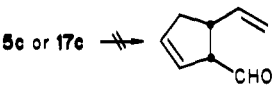
The fragmentation–olefination process was also studied with a substituted Wittig reagent. In this instance, reaction of **16** with 2 equiv each of potassium *tert*-butoxide and *n*-propyltriphenylphosphonium bromide under the optimum conditions developed for the unsubstituted Wittig reagent resulted in a 1:1 mixture of **20c** and **20t**. The lower selectivity here undoubtedly reflects the slower reaction of the substituted phosphorous ylide with the intermediate aldehydes. The stereochemistry of the newly formed double bond was at least 90% cis[20] as judged by the absence of the characteristic band for a trans double bond at 980 cm^{-1} in the IR spectrum of the crude product mixture.

During the course of this investigation, an attempted crossed aldol condensation of the lithium enolate of **15** with propionaldehyde was performed in THF containing an equivalent of HMPA at −78 °C (Scheme IV). This resulted in the formation of carboxylic acid **21** in 65% yield. Attempts to trap an intermediate adduct by low-temperature quenching with water or trimethylsilyl chloride were unsuccessful. Omission of HMPA in this reaction led to the recovery of starting material. Acid **21** was converted to its methyl ester **22** by diazomethane. The observation of a clean triplet (J = 7 Hz) for the olefinic proton of the vinyl sulfide moiety at ca. 6 ppm in the NMR spectra of **21** and **22** suggests that these compounds are stereochemically homogeneous. However, this data does not allow unambiguous assignment of configuration to the vinyl sulfide group. A satisfactory rationalization for the formation of **21** invokes cyclization of the enolate adduct **23** to give an intermediate **24** which subsequently fragments to the observed carboxylic acid.[21] The cis relationship of the side chains should be preserved in the product.

The results described above outline the potential and some of the limitations of the stereoselective synthesis of cis-1,2-disubstituted cyclopentanes by the base-induced fragmentations of bicyclo[3.2.0]heptanols in the presence of phosphorus ylides. The use of other trapping agents remains to be explored, although hydride reagents have been observed to function in this capacity.[19]

Synthesis of Multifidene. The fragmentation–olefination reaction discussed above was developed in conjunction with a planned synthesis of multifidene (**1c**). As envisioned this reaction would afford regio- and stereochemical control in the elaboration of the vicinal side chains of **1c** from an appropriate bicyclic precursor. In principle, this approach could be modified to permit the stereoselective synthesis of the stereoisomers of **1c**.

Vinylcyclopentenes **5c** and **17c** were considered as potential intermediates on the way to **1c**, since either of these ring opened materials require only the elaboration of the sulfur-functionalized side chain into a *cis*-butenyl moiety to complete the synthesis. The obvious route involving conversion to aldehyde **25** for subsequent stereoselective olefination was explored first. Although numerous methods have been developed for the transformation of thioacetal[22] and primary aryl thioether groups[23] into aldehydes, a variety of attempted conversions of **5c** and **17c** to the β,γ-unsaturated aldehyde **25** were unsuccessful. Typically



25

a mixture of **25** and its α,β-unsaturated isomer was obtained in low yield. Since the facile isomerization of **25** to its conjugated isomer would almost certainly compromise the projected Wittig reaction of this aldehyde as well, this direct route was put aside in favor of approaches which circumvent this problem.

The construction of the butenyl side chain using sulfur-stabilized carbanions was a logical next choice. Attempted metalation of **17** with *tert*-butyllithium followed by the addition of propionaldehyde gave only recovered starting material.[24] Consequently sulfone **19** was used in order to facilitate metalation. Thus, treatment of **19** (4:1 ratio of **19c**:**19t**) with *n*-butyllithium in THF at 0 °C,[25] followed by the addition of propionaldehyde at −78 °C afforded the desired β-hydroxy sulfone **26** as a mixture of diastereomers. It remained only to introduce a double bond with the appropriate cis stereochemistry between the two functionalized carbons to reach **1c**.

The first approach to this task applied the reductive elimination procedure of Julia[26] to the β-mesyloxy sulfone **27**. Although the stereochemical aspects of this reaction had not been delineated at the time, subsequent reports indicate that predominately trans olefin is formed re-

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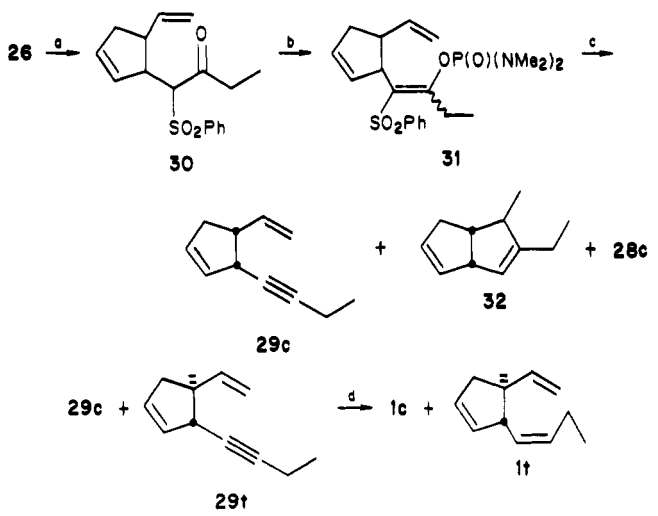
Scheme VI[a]



[a] (a) H_2CrO_4; (b) KH, $(Me_2N)_2POCl$; (c) Na(Hg), Na_2HPO_4, MeOH, (d) H_2, $Pd/CaCO_3$.

gardless of the stereochemistry of the two functional groups.[27] In the actual event, treatment of the above sample of **26** with methanesulfonyl chloride followed by reaction of the crude mesylate with 6% sodium amalgam in buffered methanol[28] gave three major products as a 5:1:1 mixture as indicated by analytical GC. This product was separated into two fractions by preparative GC.

The major fraction was identified as a 5:1 mixture of *cis*- and *trans*-3-(*trans*-1-butenyl)-4-vinylcyclopentene (**28c** and **28t**). Of the three diastereomers of multifidene, only the trans,trans isomer **28t** has not been described previously. Further separation of this mixture was not achieved on a preparative scale, but the isomeric nature of the two components was indicated by GC–mass spectral analysis. The 220-MHz NMR of the mixture was largely in agreement with the data reported for the cis, trans isomer **28c**.[10,29] A broad multiplet at δ 3.26 and an additional triplet centered at δ 0.95 were the most discernible evidence for the trans,trans isomer. However, the ^{13}C NMR spectrum of the mixture revealed two sets of signals in roughly a 5:1 ratio of intensities with chemical shifts consistent with the indicated structural assignments. Compound **28t** must arise from the trans isomer present in the starting material.

The second fraction isolated by GC in 5% yield was identified as (±)-multifidene (**1c**) on the basis of comparison of spectral data for authentic material.[10,29] The relatively large proportion of cis olefin formed in the reductive elimination reaction is noteworthy.[27]

A more selective approach to elaboration of the *cis*-butenyl side chain hinged on the use of alkyne **29c** as a key intermediate. This compound was derived from hydroxysulfone **26** by the route shown in Scheme VI.

Thus, chromic acid oxidation of the complex mixture of diasteromers of structure **26** gave keto sulfone **30** as an oily mixture of diasteromers. In an attempt to obtain a product from which one of the pure stereoisomers could be isolated as a crystalline solid, keto sulfone **30** was reduced with lithium aluminum hydride to give **26** as an altered mixture of diasteromers. Since this material also resisted crystallization, it was chromatographed over silica gel. In this fashion an oily chromatographic fraction was obtained which proved to be free of isomers with trans side chains. Reoxidation of this sample gave keto sulfone **30c** as a 3.5:1 mixture of isomers that are epimeric at the phenylsulfonyl center. Sequential treatment of **30c** with potassium hydride in THF–HMPA and *N,N,N',N'*-tetramethylphosphordiamidic chloride gave enolic derivative **31c** as a mixture of *E* and *Z* isomers.[30]

Reduction of **31c** with sodium amalgam in methanol buffered with disodium hydrogen phosphate[28] resulted in a 73:17:5:5 mixture of four volatile hydrocarbons. The major component was the desired acetylene **29c** which was isolated in 36% yield. The 220-MHz proton and ^{13}C NMR spectra of **29c** indicated that it was a single isomer.

The second product is a $C_{11}H_{16}$ hydrocarbon which is assigned as bicyclo[3.3.0]octadiene **32**.[31] This is based on the 220-MHz NMR spectrum of **32** which shows three-proton signals assigned to methyl groups attached to saturated carbon at δ 0.99 (t, J = 7.5 Hz) and 1.01 (d, J = 7 Hz), a one-proton multiplet at δ 3.52 attributed to the doubly allylic bridehead proton, and three vinyl protons.

One of the minor components was identified as **28c**, one of the multifidene isomers.[10,29] The remaining product was not obtained in sufficient quantity for characterization.

The final step in the total synthesis of **1c** was performed on a sample of **29** which was a 4:1 mixture of **29c** and **29t**. Careful hydrogenation of this sample over Lindlar's catalyst[32] gave a product which was resolved into two components by preparative GC. The major component, obtained in 45% isolated yield, was pure (±)-multifidene (**1c**) as shown by comparison of proton NMR, ^{13}C NMR, IR, and mass spectra with the reported data.[10,29]

The second GC fraction was predominately **1t**, the trans,cis isomer of multifidene, contaminated with some over reduction product.[10,29] The **1t** undoubtedly was formed from the **29t** present in the starting material.

Experimental Section

General Methods. Melting points were determined on a Thomas-Hoover Unimelt apparatus and are uncorrected. Infrared (IR) spectra were obtained with a Perkin-Elmer Model 467 infrared grating spectrophotometer as liquid films between NaCl plates unless otherwise stated. Nuclear magnetic resonance spectra (NMR) were recorded with Varian EM-360, T-60, and HR-220 spectrometers for ^1H measurements and a Varian XL-100-12 for ^{13}C determinations; ^1H NMR data are given for CCl_4 solutions at 60 MHz unless otherwise indicated; ^{13}C chemical shifts are reported in ppm relative to internal Me_4Si for CCl_4 solutions. Low-resolution mass spectra were obtained with a Varian-MAT-CH-7 mass spectrometer. GC–MS determinations were performed on an HP-5992A gas chromatograph mass spectrometer with analytical columns of either 2% OV-101 plus 0.2% Carbowax 20M on Chromosorb W-HP or 10% Carbowax on Chromosorb W. Gas chromatography utilized Varian Aerograph 600D (flame-ionization detector) and Varian Aerograph A-700 (thermal-conductivity detector) instruments. Elemental analyses were determined by Midwest Microlabs, Inc. Exact mass determina-

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(29) We thank Professor Jaenicke and Dr. Boland for kindly providing us with NMR spectra of synthetic **1c**, **1t**, and **28**.

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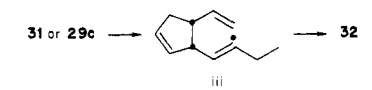
(31) This product is thought to be formed by cyclization of an intermediate radical of type iii which arises by reduction of either **31** or **29c**.



iii

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tions were performed on a Varian MAT CH-5DF mass spectrometer courtesy of the MSU-NIH Mass Spectrometry Facility.

Ether and tetrahydrofuran were dried over lithium aluminum hydride and freshly distilled prior to use. All air-sensitive reactions were performed under a nitrogen atmosphere. Anhydrous magnesium sulfate was used for all drying operations. Solutions were generally concentrated by rotary evaporation unless the volatility of the expected product required solvent removal by distillation through a fractionating column.

7-Hydroxyspiro{bicyclo[3.2.0]hept-3-ene-6,2′-[1,3]dithiolane} (3). To an ice-cold, stirred slurry of 0.48 g (13 mmol) of lithium aluminum hydride in 100 mL of dry ether was added 5.0 g (25 mmol) of **2**[9b] in 25 mL of ether. The reaction mixture was stirred at 0 °C for 1.5 h, after which 2 mL of water was carefully added to destroy the excess hydride. The precipitate was removed by filtration and washed with several portions of ether. The combined filtrate was dried and concentrated. Vacuum transfer gave 4.4 g (87%) of **3**: NMR δ 2.2–2.7 (m, 3), 2.7–3.4 (m, 5), 3.4–3.7 (m, 1), 3.9–4.3 (m, 1), 5.6–6.0 (m, 2); IR 3440, 1610, 1110, 720 cm^{-1}; exact mass, *m/e* 200.034, calcd for $C_9H_{12}OS_2$ 200.0330.

2-(1,3-Dithiolan-2-yl)-3-cyclopentenecarboxaldehyde (4c and 4t). To a stirred slurry of 0.15 g (3.8 mmol) of potassium hydride in 10 mL of dry THF under a nitrogen atmosphere was added 0.56 g (7.5 mmol) of *tert*-butyl alcohol in 5 mL of THF. After stirring for 30 min, 0.75 g (3.8 mmol) of **3** in 2 mL of THF was added. The mixture was stirred for 4 h at 25 °C, poured into 50 mL of 5% aqueous HCl solution, and extracted with ether. The extract was washed with brine and dried. Concentration followed by vacuum transfer gave 0.4 g (53%) of **4** as a 1:2 mixture of cis and trans isomers (determined by NMR integration of the pair of doublets assigned to the aldehyde proton): NMR δ 2.4–3.7 (m, 8, including br s at 3.2), 4.55 (d, *J* = 7 Hz) and 4.60 (d, *J* = 8 Hz) (total of 1 H, SCHS), 5.4–6.0 (m, 2), 9.6 (d, *J* = 2 Hz, 0.67 H) and 9.8 (d, *J* = 2 Hz, 0.33 H) (total of 1 H, CHO); IR 3060, 2930, 2850, 2720, 1725, 1620 cm^{-1}.

3-(1,3-Dithiolan-2-yl)-4-vinylcyclopentene (5c and 5t). To a stirred slurry of 0.25 g (6.3 mmol) of potassium hydride in 15 mL of dry THF under a nitrogen atmosphere was added 1.0 g (13 mmol) of *tert*-butyl alcohol in 8 mL of THF. The resulting solution was transferred via syringe to a flask containing a stirred slurry of 2.4 g (6.6 mmol) of methyltriphenylphosphonium bromide in 10 mL of THF. After stirring for 15 min, 0.66 g (3.3 mmol) of **3** in 2 mL of THF was added. The mixture was heated at 60 °C overnight. The cooled reaction mixture was filtered and the precipitate was thoroughly washed with ether. The filtrate was concentrated to give a dark, viscous residue which was dissolved in pentane and filtered through an 8-cm column of silica gel. Concentration followed by vacuum transfer of the residue gave 0.54 g (83%) of **5** as a 9:1 mixture of cis and trans isomers (determined by integration of a pair of doublets in the NMR spectrum assigned to the methine proton of the dithiolane group). An analytical sample was obtained by preparative GC: NMR ($CDCl_3$) δ 2.2–3.3 (m, 6, including br s at 3.17), 4.46 (d, *J* = 8 Hz, cis isomer) and 4.54 (d, *J* = 6 Hz, trans isomer) (total 1 H, SCHS), 4.8–5.2 (m, 2), 5.6–6.1 (m, 3); IR 3070, 3000, 2980, 2950, 2850, 1640, 1615, 1000, 915 cm^{-1}; exact mass, *m/e* 198.055, calcd for $C_{10}H_{14}S_2$ 198.0538.

Wittig Olefination of 4. To a stirred suspension of 0.9 g (2.5 mmol) of methyltriphenylphosphonium bromide in 10 mL of dry THF was added 2 mL of 1.2 M *n*-butyllithium in hexane followed by 0.25 g (1.25 mmol) of **4** (ca. 2:1 mixture of trans and cis isomers) in 1 mL of THF. After stirring overnight at 25 °C, the solvent was removed by distillation through a short Vigreaux column. The residue was diluted with ether and filtered. The filtrate was concentrated, diluted with pentane, and filtered through an 8-cm column of silica gel. Concentration followed by vacuum transfer of the residue gave 0.16 g (65%) of **5** as a 2:1 mixture of trans and cis isomers. The spectra of this material were identical with those reported above with the following exceptions. The NMR spectrum ($CDCl_3$) shows a pair of singlets at δ 3.17 and 3.20, and the ratio of the pair of doublets at δ 4.46 and 4.54 is 1:2, respectively.

Ring Opening and Olefination of 7,7-Dichlorobicyclo[3.2.0]hept-2-en-6-ol (7). To a stirred slurry of 0.23 g (5.8 mmol) of potassium hydride in 20 mL of THF was added 0.83 g (11.2 mmol) of *tert*-butyl alcohol in 5 mL of THF followed by 2.0 g (5.6 mmol) of methyltriphenylphosphonium bromide in one portion. After stirring for 15 min, 0.5 g (2.8 mmol) of **7**[14] in 5 mL of THF was added. The mixture was stirred for 24 h at 25 °C followed by refluxing for 8 h. THF was removed by distillation through a short Vigreaux column. The residue was diluted with ether and filtered. The filtrate was concentrated and the residue was vacuum transferred to afford 0.56 g of volatile products as a 1:1.8:1.4 mixture of **8**, **9**, and styrene. The three products were separated by preparative GC. 3-(Dichloromethyl)-4-vinylcyclopentene (**8**): NMR (220 MHz) δ 2.2–2.6 (m, 2), 3.01 (q, 1, *J* = 7 Hz), 3.36 (m, 1), 4.9–5.2 (m, 2, C=CH_2), 5.58 (d, 1, *J* = 6 Hz, $CHCl_2$), 5.7–6.0 (m, 3); IR 3080, 2980, 2930, 2850, 1640, 1620, 1000, 920, 765, 735, 675 cm^{-1}; mass spectrum, *m/e* (relative intensity) 176 (M, 1.2), 105 (20), 93 (100), 91 (30), 77 (38); exact mass, *m/e* 176.016, calcd for $C_8H_{10}Cl_2$ 176.0159.

2-Chlorobicyclo[3.2.1]octa-2,6-diene (**9**): NMR (360 MHz) δ 1.85–1.95 (m, 2), 2.03 (d of t, 1, *J* = 9.8, 4.7 Hz), 2.42 (d of d of d, 1, *J* = 18.1, 4.9, 3.4 Hz), 2.72 (br s, 1), 2.81 (br s, 1), 5.30 (br s, 1), 5.83 (d of d, 1, *J* = 5.5, 2.9 Hz), 6.38 (d of d, 1, *J* = 5.5, 2.7 Hz);[34] IR 3070, 2950, 2890, 2830, 1635, 1590, 1325, 1020, 970, 725 cm^{-1}; mass spectrum, *m/e* (relative intensity) 142 (M + 2, 7.5), 140 (M, 21), 105 (100), 79 (21), 77 (21); exact mass, *m/e* 140.039, calcd for C_8H_9Cl 140.0393.

The proton NMR spectrum of the third product was identical with that of styrene.

7-(Phenylthio)bicyclo[3.2.0]hept-2-en-6-one (15).[9b,17] To a stirred slurry of 1.1 g (45 mmol) of sodium hydride in 50 mL of dry DMF was added 5.4 g (49 mmol) of thiophenol. To the resulting solution was added 5.9 g (41 mmol) of **14**.[33] A voluminous precipitate of NaCl appeared within 5 min. The mixture was stirred overnight, poured into 50 mL of 10% aqueous HCl solution, and extracted with ether. The extract was washed with Na_2CO_3 solution and dried. Concentration at reduced pressure gave a crude crystalline product, which was recrystallized from ether to afford 6.6 g (74%) of pure *endo*-**15**. Concentration of the mother liquors left 1.5 g of *exo*-**15** as a pale yellow oil which solidified upon standing. The endo isomer: mp 85–87 °C; NMR δ 2.3–3.0 (m, 2), 3.6–4.0 (m, 2), 4.56 (m, 1, C*H*SPh), 5.82 (d, 2), 6.9–7.3 (m, 5); IR (CCl_4) 3060, 1785 cm^{-1}; mass spectrum, *m/e* (relative intensity) 216 (M, 19), 123 (100), 109 (20), 107 (63), 93 (73), 91 (80), 77 (60).

Anal. Calcd for $C_{13}H_{12}OS$: C, 72.18; H, 5.59; S, 14.82. Found: C, 72.3; H, 5.7; S, 14.5.

The exo isomer: mp 56–60 °C; NMR δ 2.3–2.5 (m, 1), 2.6–2.7 (d, 1) 3.0–3.4 (m, 1), 3.6–3.9 (m, 2), 5.8 (m, 2), 7.0–7.5 (m, 5); mass spectrum, *m/e* (relative intensity) 216 (M, 18), 110 (44), 105 (33), 79 (100), 77 (61).

7-(Phenylthio)bicyclo[3.2.0]hept-2-en-6-ol (16). To an ice-cold, stirred slurry of 0.18 g (4.7 mmol) of lithium aluminum hydride in 30 mL of ether was added 1.0 g (4.6 mmol) of **15** in 30 mL of ether. The reaction mixture was stirred for 2 h at 0 °C, after which 1 mL of water was carefully added. The precipitate was removed by filtration through a short pad of magnesium sulfate. Concentration of the filtrate gave 0.96 g of crude alcohol which crystallized upon standing. Recrystallization from ether gave 0.7 g (70%) of pure **16**: mp 47–49 °C; NMR δ 1.8–3.8 (m, 6), 4.2 (m, 1), 5.8 (m, 2), 7.2 (br s, 5); IR 3440, 3050, 1580, 1480, 1440, 1110, 740, 725, 690 cm^{-1}; mass spectrum, *m/e* (relative intensity) 218 (M, 1.5), 152 (100), 123 (19); exact mass, *m/e* 218.076, calcd for $C_{13}H_{14}S$ 218.0766.

***trans*-3-[(Phenylthio)methyl]-4-vinylcyclopentene (17t).** To a stirred slurry of 0.18 g (4.6 mmol) of potassium hydride in 10 mL of THF was added 0.68 g (4.6 mmol) of *tert*-butyl alcohol in 5 mL of THF. The resulting solution was transferred via syringe to a flask containing a stirred slurry of 1.64 g (4.6 mmol) of methyltriphenylphosphonium bromide in 20 mL of THF. After stirring for 15 min, 0.5 g (2.3 mmol) of **16** in 6 mL of THF was added. The reaction mixture was stirred at 25 °C for 3 h and then heated at 60 °C overnight. The cooled reaction mixture was filtered and the precipitate was thoroughly washed with ether.

(33) Brady, W. T.; Hoff, E. F.; Roe, R.; Perry, F. H. *J. Am. Chem. Soc.* **1969**, *91*, 5679.

(34) For model *J* values and leading references, see: Cahill, R.; Cookson, R. C.; Crabb, T. A. *Tetrahedron* **1969**, *25*, 4711.

The filtrate was concentrated to give a dark, viscous residue which was dissolved in hexane and filtered through an 8-cm column of silica gel. Concentration followed by vacuum transfer gave 0.38 g (76%) of **17** as a 1:9 mixture of cis and trans isomers. The isomeric ratio was determined by GC analysis: NMR δ 2.2–3.2 (m, 6), 4.7–5.2 (m, 2), 5.4–5.8 (m, including a singlet at 5.72, total of 3 H), 7.1 (m, 5); IR 3060, 1640, 1610, 1580, 1480, 1440, 1030, 1000, 915, 740, 720, 690 cm^{-1}; ^{13}C NMR δ 37.7, 38.6, 48.6, 50.9, 113.8, 125.1, 128.2, 128.7, 129.8, 132.4, 137.0, 141.1.

Anal. Calcd for $C_{14}H_{16}S$: C, 77.72; H, 7.45; S, 14.82. Found: C, 77.9; H, 7.5; S, 14.9.

***cis*-3-[(Phenylthio)methyl]-4-vinylcyclopentene (17c).** A solution of potassium *tert*-butoxide was prepared by adding 3.8 g (40 mmol) of *tert*-butyl alcohol to 0.8 g (20 mmol) of potassium in 25 mL of THF. The resulting solution was transferred by syringe to a flask containing 7.14 g (20 mmol) of methyltriphenylphosphonium bromide. After stirring for 15 min, 2.18 g (10 mmol) of **16** in 4 mL of THF was added. The mixture was stirred for 24 h at 25 °C, filtered, and concentrated. The residue was dissolved in pentane and filtered through a 12-cm column of silica gel. Concentration of the filtrate followed by vacuum transfer gave 1.63 g (75%) of pure **17** as a 9:1 mixture of cis and trans isomers (determined by GC analysis): NMR δ 2.2–3.2 (m, 6), 4.8–5.2 (m, 2), 5.6–6.0 (m, including a br s at 5.77, total of 3 H), 7.1 (m, 5); ^{13}C NMR δ 35.2, 37.7, 45.9, 47.7, 115.3, 125.2, 128.3, 130.0, 133.4, 137.0, 138.3.

3-[(Phenylsulfonyl)methyl]-4-vinylcyclopentene (19). To a stirred solution of 1.78 g (8.2 mmol) of **16** in 75 mL of methylene chloride at −78 °C was added 1.5 g (8.5 mmol) of MCPBA in a single portion. After stirring for 30 min at −78 °C, an additional 1.5 g of MCPBA was added. The mixture was slowly warmed to 25 °C and stirred for 2 h. The resulting mixture was washed with 10% aqueous Na_2SO_3 solution, saturated $NaHCO_3$ solution, and brine. Drying and concentration gave 2.12 g of sulfone **18** as a semisolid material: IR ($CHCl_3$) 3500 (OH), 1305 and 1140 cm^{-1} (SO_2). Sulfone **18** was used in the following reaction without further purification.

To a stirred slurry of 0.5 g (12.5 mmol) of potassium hydride in 5 mL of dry THF was added 1.6 g (21 mmol) of *tert*-butyl alcohol. The solution was transferred by syringe to a flask containing 4.5 g (12.5 mmol) of methyltriphenylphosphonium bromide. After stirring for 15 min, 1.2 g (5 mmol) of **18** in 1.5 mL of THF was added. The mixture was stirred for 8 h, poured into water, and extracted with ether. The extract was washed with water and brine, dried, and concentrated. The residue was chromatographed on silica gel with 15% ethyl acetate–hexane as eluant to give 0.91 g (76%) of **19** as a 3:2 mixture of trans and cis isomers (determined by ^{13}C NMR): IR 3060, 1635, 1610, 1300, 1140, 995, 915 cm^{-1}; NMR (220 MHz) δ 2.07 (m, 1), 2.27–3.20 (m, 5), 4.80–4.95 (m, 2), 5.43–5.77 (m, 3), 7.48–7.77 (m, 5); ^{13}C NMR trans isomer δ 37.6, 45.2, 49.1, 59.3, 114.7, 127.7, 128.8, 130.5, 131.6, 132.8, 139.8, 140.3; ^{13}C NMR cis isomer δ 36.9, 42.0, 45.8, 57.3, 116.1, 127.6, 128.7, 130.2, 132.4, 132.8, 137.6, 140.3.

Anal. Calcd for $C_{14}H_{16}O_2S$: C, 67.71; H, 6.49; S, 12.91. Found: C, 67.8; H, 6.4; S, 12.8.

MCPBA Oxidation of 17. To a stirred solution of 2.16 g (10 mmol) of **17** (9:1 mixture of cis and trans isomers) in 100 mL of CH_2Cl_2 at −78 °C was added in one portion 2.0 g of 85% MCPBA. The mixture was stirred at −78 °C for 30 min, and an additional 2.0 g of 85% MCPBA was added. After slowly warming to 25 °C and stirring for 7 h, the mixture was filtered, and the filtrate concentrated. The residue was dissolved in ether and washed with 10% aqueous Na_2SO_3 solution and saturated $NaHCO_3$ solution. Drying and concentration gave 2.34 g of crude sulfone **19**. Chromatography on silica gel with hexane–ethyl acetate (85:15) as eluant afforded 1.9 g (77%) of pure **19** as a colorless oil. The ^{13}C NMR spectrum of the product showed two sets of signals in a 9:1 ratio assigned to the cis and trans isomers, respectively. Chemical shifts were identical with those reported above.

4-(*cis*-1-Butenyl)-3-[(phenylthio)methyl]cyclopentene (20). A solution of potassium *tert*-butoxide was prepared by adding 0.43 g of *tert*-butyl alcohol to 0.11 g of potassium in 5 mL of THF. The solution was transferred to a flask containing 1.12 g (2.8 mmol) of *n*-propyltriphenylphosphonium bromide. After stirring for 15 min, 0.32 g (1.4 mmol) of **16** in 1 mL of THF was added. The mixture was stirred for 5 h at 25 °C, diluted with ether, filtered, and concentrated. The residue was diluted with pentane and filtered through 10 g of silica gel. Concentration of the filtrate followed by vacuum transfer gave 0.1 g (29%) of **20** as a 1:1 mixture of cis and trans isomers (determined by GC analysis): NMR (220 MHz) δ 0.98 (t, 3), 1.95–2.20 (m, 2), 2.39–3.30 (m, 6), 5.23–5.45 (m, 2), 5.59–5.82 (m, 2), 6.91–7.25 (m, 5); IR 3050, 3000, 2960, 2920, 2870, 2840, 1605, 1580, 1480, 1440, 1025, 730, 685 cm^{-1}; mass spectrum, *m/e* (relative intensity) 244 (M, 38), 135 (52), 123 (93), 121 (68), 105 (49), 93 (49), 91 (57), 79 (100), 77 (54), 41 (62); exact mass, *m/e* 244.126, calcd for $C_{16}H_{20}S$ 244.1285.

2-[1-(Phenylthio)buten-1-yl]-3-cyclopentenecarboxylic Acid (21). A solution of lithium diisopropylamide was prepared by adding 3.4 mL of 1.5 M *n*-butyllithium in heptane to a stirred solution of 0.56 g (5.5 mmol) of diisopropylamine in 25 mL of THF at −20 °C. After stirring for 30 min, the temperature was lowered to −78 °C, and 1.0 g (5.5 mmol) of HMPA was added followed by 1.0 g (4.6 mmol) of **15** in 5 mL of THF. After stirring for 1.5 h, 0.32 g (5.5 mmol) of propionaldehyde was added. The reaction mixture was warmed slowly to 25 °C and after 6 h was poured into saturated NH_4Cl solution and extracted with pentane. The extract was washed with saturated $NaHCO_3$ solution and the basic solution was acidified with concentrated HCl and extracted with ether. The ether extract was dried and concentrated to give 0.83 g (66%) of **21** as a colorless oil: NMR δ 0.97 (t, 3, J = 7 Hz), 2.0–4.0 (m, 6), 5.3–5.9 (m, 2), 5.97 (t, 1, J = 7 Hz), 7.1 (br s, 5), 10.0 (br s, 1); IR 3600–2200, 3070, 1710, 1620, 1585, 1485, 1445, 1295, 1240, 1030, 745, 695 cm^{-1}; mass spectrum, *m/e* (relative intensity) 274 (M, 84), 165 (90), 163 (39), 119 (98), 109 (53), 91 (100), 77 (68); exact mass, *m/e* 274.103, calcd for $C_{16}H_{18}O_2S$ 274.1027.

Methyl 2-[1-(Phenylthio)buten-1-yl]-3-cyclopentenecarboxylate (22). To an ice-cold, stirred solution of 0.83 g of **21** in 30 mL of ether was added an ethereal solution of diazomethane. After stirring for 15 min, the excess diazomethane was destroyed by the addition of acetic acid. The resulting solution was washed with $NaHCO_3$ solution, brine, and dried. After concentration, the residue was vacuum transferred to give 0.73 g (84%) of pure **22**: NMR δ 0.98 (t, 3, J = 7 Hz), 2.0–4.0 (m, 9, including a singlet at 3.6), 5.2–5.9 (m, 3, including a triplet at 5.87, J = 7 Hz), 7.1 (s, 5); IR 3070, 1740, 1620, 1585, 1485, 1445, 1205, 1180, 1030, 745, 695 cm^{-1}; mass spectrum, *m/e* (relative intensity) 288 (M, 14), 179 (52), 163 (100), 125 (15), 119 (99), 109 (19), 91 (50), 77 (23).

3-[2-Oxo-1-(phenylsulfonyl)butyl]-4-vinylcyclopentene (30). To an ice-cold, stirred solution of 3.1 g (12.5 mmol) of **19** (ca. 4:1 mixture of cis and trans isomers) in 25 mL of THF was added 7.5 mL of 2.1 M *n*-butyllithium in hexane. The mixture was stirred for 45 min at 0 °C and cooled to −78 °C, and 1.45 g (25 mmol) of propionaldehyde was added. After stirring for 15 min, the mixture was poured into an ice-cold saturated NH_4Cl solution and extracted with pentane. The extract was washed with water, dried, and concentrated to give crude **26** (IR 3520, 1305, and 1145 cm^{-1}) as a viscous oil.

The crude alcohol was dissolved in 75 mL of acetone and treated with 8 N Jones reagent until a faint red-orange color persisted. The mixture was diluted with water and thoroughly extracted with pentane. The extract was washed with aqueous Na_2SO_3 solution, water, and brine, dried, and concentrated to afford 3.68 g of **30** as a mixture of diastereomers: NMR δ 1.0 (t, 3, J = 7 Hz), 2.0–3.6 (m, 6), 4.2 (d, 0.8, J = 12 Hz) and 4.4 (d, 0.2, J = 6 Hz) (total of 1 H, C*H*SO_2Ph), 4.7–6.0 (m, 5), 7.4–8.0 (m, 5); IR 1720, 1310, 1150, 1000, 920 cm^{-1}.

***cis*-3-[2-Hydroxy-1-(phenylsulfonyl)butyl]-4-vinylcyclopentene (26c).** To an ice-cold, stirred slurry of 0.32 g of lithium aluminum hydride in 20 mL of ether was added 2.56 g of **30** in 10 mL of ether. After 2 h, excess hydride was destroyed by the careful addition of 1 mL of water. The mixture was diluted with 5% aqueous HCl solution and extracted with ether. The extract was washed with 2 N NaOH solution, dried, and concentrated. Column chromatography of the residue with hexane–ether (4:1) as eluant gave four fractions, one of which (0.72 g, 28%) was >95% pure cis-β-hydroxy sulfone **26**. The cis isomer: NMR (220 MHz, $CDCl_3$) δ 0.82 (t, 3, J = 7 Hz), 1.48–1.89 (m, 2), 2.04–2.20 (m, 1), 2.39–2.57 (m, 1), 2.80–3.86 (m, 5), 4.89 (d of d, 1, J = 2, 17 Hz), 5.01 (d of d, 1, J = 2, 10 Hz), 5.58 (d of t, 1, J = 10, 17 Hz), 5.68–5.98 (m, 2), 7.45–7.91 (m, 5); IR 3520, 3060, 2960, 2920, 2870,

2840, 1640, 1570, 1450, 1305, 1145, 1080, 995, 750, 725, 710, 690 cm^{-1}; mass spectrum, *m/e* (relative intensity) 306 (M, not present), 277 (3), 135 (68), 117 (70), 107 (100), 93 (34), 92 (51), 79 (44), 77 (65), 57 (75); chemical-ionization high-resolution mass spectrum, *m/e* 307.136, calcd for $C_{17}H_{23}O_3S$ 307.1367.

***cis*-3-[2-Oxo-1-(phenylsulfonyl)butyl]-4-vinylcyclopentene (30c).** To an ice-cold, stirred solution of 0.72 g (2.4 mmol) of **26c** in 25 mL of acetone was added 8 N Jones reagent until a red-orange color persisted. The mixture was diluted with water and worked up in the usual manner. Concentration gave 0.63 g (87%) of **30c** as a viscous oil: NMR (220 MHz, $CDCl_3$) δ 0.97 (t, 3, J = 7 Hz), 2.06 (m, 1), 2.36–2.73 (m, including a quartet at 2.63, total of 3 H), 2.84–3.18 (m, 1), 3.44 (m, 1), 4.09 (d, J = 12 Hz) and 4.35 (d, J = 6 Hz) (total of 1 H, $CHSO_2Ph$), 4.75–5.09 (m, 2), 5.30–6.25 (m, 3), 7.39–7.93 (m, 5); mass spectrum, *m/e* (relative intensity) 304 (M, not present), 163 (94), 145 (22), 133 (39), 105 (42), 91 (32), 79 (22), 77 (68), 57 (100); chemical-ionization high-resolution mass spectrum, *m/e* 305.123, calcd for $C_{17}H_{21}O_3S$ 305.1211.

***cis*-3-(1-Butynyl)-4-vinylcyclopentene (29c).** To an ice-cold, stirred slurry of 96 mg (2.4 mmol) of potassium hydride in 5 mL of a 4:1 mixture of THF–HMPA was added 0.58 g (1.9 mmol) of **30c** in 1 mL of THF. After the evolution of hydrogen ceased, 1.6 g (9.4 mmol) of *N,N,N',N'*-tetramethylphosphordiamidic chloride was added. The mixture was warmed to 25 °C, stirred for 12 h, poured into 5% aqueous HCl solution, and extracted with ether. The extract was washed with 2 N NaOH solution, water, and brine, dried, and concentrated to give 0.8 g of crude **31**. Column chromatography on silica gel with ethyl acetate–hexane (3:1) as eluant afforded 0.62 g (74%) of **31** as a mixture of *E* and *Z* isomers: NMR (220 MHz, $CDCl_3$) δ 1.22 (t, 3, J = 7 Hz), 2.27–2.84 (m, including a pair of doublets at 2.61 and 2.64, total of 16 H), 3.06 (m, 1), 4.15 (m, 1), 4.75–6.11 (m, 5), 7.27–7.73 (m, 5); IR 3060, 2970, 2920, 2850, 2810, 1600, 1300, 1235, 1175, 1145, 985, 905, 805, 750 cm^{-1}.

To a vigorously stirred solution of 0.62 g (1.4 mmol) of **31** in 15 mL of methanol was added 1.0 g of Na_2HPO_4 and 2.7 g of 6% sodium amalgam. After 1.5 h the mixture was diluted with water and extracted with pentane. The extract was washed with water and brine and dried. Solvent was removed by distillation through a short Vigreaux column. The residue was vacuum transferred to give 0.13 g of volatile product. Preparative GC gave 75 mg (36%) of pure **29c**, 14 mg of bicyclooctadiene **32**, and 6 mg of **28c**.

Vinylcyclopentene **29c**: NMR (220 MHz) δ 1.08 (t, 3, J = 7.5 Hz), 2.08 (d of q, 2, J = 2, 7.5 Hz), 2.16–2.48 (m, 2), 2.80 (m, 1), 3.38 (m, 1), 4.86–5.00 (m, 2), 5.50–5.68 (m, 2), 5.91 (d of d of d, 1, J = 8, 10, 17.5 Hz); ^{13}C δ 12.4, 14.2, 37.4, 40.2, 46.1, 77.6, 84.7, 114.1, 129.7, 131.6, 139.6; IR 3060, 2970, 2920, 2880, 2840, 1640, 1610, 995, 915, 715 cm^{-1}; mass spectrum, *m/e* (relative intensity) 146 (M, 1), 131 (24), 117 (100), 115 (46), 91 (62), 79 (30); exact mass, *m/e* 146.190, calcd for $C_{11}H_{14}$ 146.1905.

Bicyclooctadiene **32**: NMR (220 MHz) δ 0.99 (t, 3, J = 7 Hz), 1.01 (d, 3, J = 7 Hz), 1.68–2.73 (m, 6), 3.52 (m, 1), 5.14 (br s, 1), 5.45 (m, 2); mass spectrum, *m/e* (relative intensity) 148 (M, 60), 133 (44), 119 (100), 105 (44), 91 (59); exact mass, *m/e* 148.125, calcd for $C_{11}H_{16}$ 148.1252.

The IR, NMR, and mass spectral data for **28c** are in agreement with the reported data.[10,29]

A similar reduction of 1.89 g (4.3 mmol) of **31** (prepared from a 4:1 mixture of vinyl sulfides **17c** and **17t** according to the sequence described above) with 8.3 g of 6% sodium amalgam in methanol containing 3.08 g of Na_2HPO_4 was performed in an analogous manner. Preparative GC gave 127 mg (20% yield) of a 4:1 mixture of alkynes **29c** and **29t** as indicated by analytical GC. This material was used in the synthesis of **1c**.

Multifidene (1c). To a mixture of 30 mg of Lindlar catalyst[35] in 25 mL of hexane in a standard low pressure hydrogenation apparatus, was added 10 μL of quinoline followed by 100 mg (0.7 mmol) of **29** (4:1 mixture of cis and trans isomers). Stirring was begun, and the uptake of hydrogen was monitored. After 15.3 mL (1 equiv) of hydrogen was absorbed, the mixture was filtered through Celite, and the solvent was removed by distillation through a short Vigreaux column. Purification of the residue by preparative GC gave two fractions. The first fraction, 17 mg, was identified as **1t**, contaminated by a small amount of over reduction product. The second fraction, 45 mg (45%), was pure multifidene (**1c**). The NMR, ^{13}C NMR, IR, and mass spectral data for the purified (±)-multifidene are in complete accord with the reported data.[10,29]

The NMR and mass spectral data for **1t** are in agreement with the reported values.[10,29]

3-(*trans*-1-Butenyl)-4-vinylcyclopentene (28). To an ice-cold, stirred solution of 1.24 g (5.5 mmol) of **19** (3:1 mixture of cis and trans isomers) in 10 mL of THF was added 3 mL of 2.1 M *n*-butyllithium in hexane. After stirring for 45 min at 0 °C, the mixture was cooled to −78 °C, and 0.58 g (10 mmol) of propionaldehyde was added dropwise. The resulting solution was stirred for 15 min at −78 °C, poured into an ice-cold, saturated NH_4Cl solution, and extracted with pentane. The extract was washed with brine, dried, and concentrated to give 1.85 g of crude alcohol **26** as a mixture of diastereomers: IR 3520 (OH), 1305 and 1145 cm^{-1} (SO_2).

To an ice-cold stirred solution of crude **26** in 25 mL of pyridine was added 1.14 g (10 mmol) of methanesulfonyl chloride. The mixture was stirred overnight at 0 °C, poured into water, and extracted with ether. The extract was thoroughly washed with 5% aqueous HCl solution and brine, dried, and concentrated to afford 1.82 g of crude mesylate **27** as a viscous oil: IR (CCl_4) 3060, 2970, 2870, 2840, 1635, 1445, 1360, 1345, 1320, 1305, 1175, 1145, 990, 915 cm^{-1}.

To a vigorously stirred solution of 1.54 g (4 mmol) of crude mesylate **27** in 40 mL of methanol was added 28.4 g of Na_2HPO_4 and 7.7 g of 6% sodium amalgam. After 2 h the mixture was diluted with water and extracted with pentane. The extract was washed with water and brine, dried, and concentrated by distillation through a short Vigreaux column. Vacuum transfer of the residue afforded 0.41 g of volatile product. Preparative GC of this material gave 158 mg (27%) of a 5:1 mixture of *cis*- and *trans*-3-(*trans*-1-butenyl)-4-vinylcyclopentene **28c** and **28t** and 30 mg of multifidene.[10,29] The ^{13}C NMR spectrum of the mixture of **28c** and **28t**: cis isomer **28c** δ 13.9, 25.3, 37.0, 46.8, 51.5, 113.7, 128.3, 129.4, 131.7, 133.7, 139.7, trans isomer **28t** δ 13.9, 25.3, 38.2, 50.2, 54.3, 113.2, 129.0, 130.9, 131.3, 133.4, 140.9; GC–mass spectrum trans isomer **28t** (R_t 6.8 min), *m/e* (relative intensity) 148 (M, 14), 119 (38), 105 (36), 91 (100), 79 (89), 77 (33), 66 (26), cis isomer **28c** (R_t 7.1 min), *m/e* (relative intensity) 148 (M, 12), 119 (38), 105 (36), 91 (100), 79 (94), 77 (36), 66 (28); exact mass, *m/e* 148.125, calcd for $C_{11}H_{16}$ 148.1252.

(35) Lindlar, H.; Dubuis, R. "Organic Synthesis"; Wiley: New York, 1966; Vol. 46, p 89.