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THE UNIVERSITY OF ALBERTA

FORMATION OF CARBOCYCLES BY FREE RADICAL METHODS

by

TARYN L. B. BOIVIN ©

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled FORMATION OF CARBOCYCLES BY FREE RADICAL METHODS submitted by TARYN L. B. BOIVIN in partial fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY.

Supervisor

Peter Sporns

James D Wuest
External Examiner

Date: 12th December, [illegible]

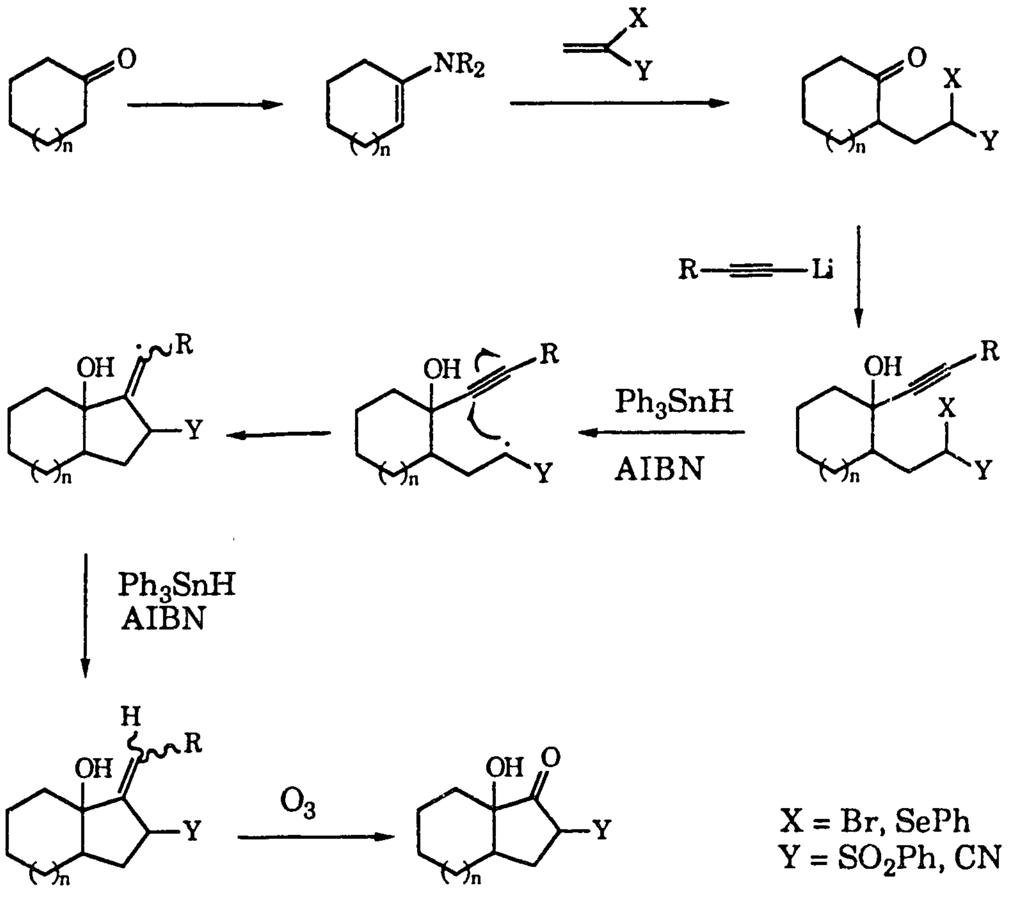
To my parents

Raymond and Eileen Boivin

ABSTRACT

The development of methods using a free radical chain reaction for the production of functionalized carbocycles is presented in this thesis. Three routes are discussed. In the first section a Michael addition - radical cyclization sequence is presented which leads to mixtures of *cis* and *trans* ring-fused carbocycles (Scheme A).

SCHEME A

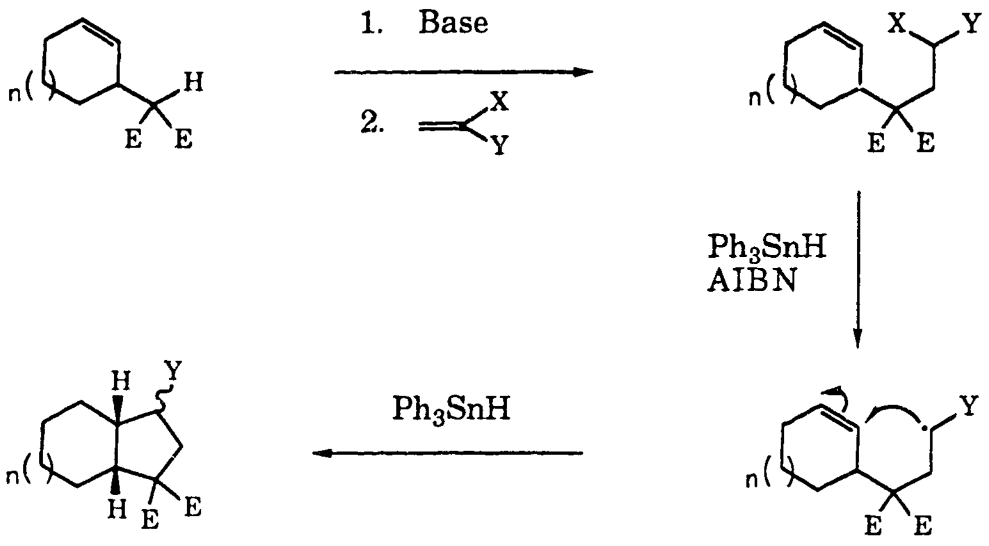


X = Br, SePh
Y = SO_2Ph, CN

The general outline of the Michael - radical method was developed earlier in this laboratory and expansion and refinement of the technique is discussed.

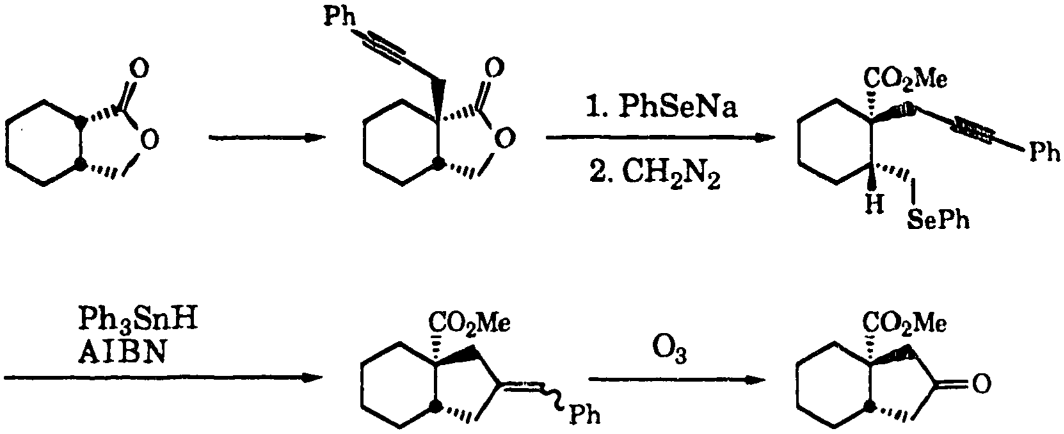
The next two sections deal with the problem of controlling ring-fusion stereochemistry. The first approach is a modification of the Michael - radical route using malonate esters and exclusively *cis* ring-fused materials are obtained as shown in Scheme B.

SCHEME B (E = COOEt)



Trans ring-fused carbocycles are produced by the second approach. Here, *cis*-fused bicyclic lactones are employed as substrates and they are first alkylated and then ring-opened in a manner which leads to formation of *trans* disposed pendants on the original lactone skeleton. The molecule then undergoes radical cyclization to afford only *trans* ring-fused products (Scheme C).

SCHEME C



Ph
O
O
1. PhSeNa
2. CH2N2
CO2Me
Ph
H
SePh
Ph3SnH
AIBN
CO2Me
Ph
O3
CO2Me
O

ACKNOWLEDGEMENTS

I express my sincere gratitude to Professor D. L. J. Clive for his advice and encouragement throughout the course of my studies and gratefully acknowledge his assistance in the preparation of this manuscript.

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I thank my family for their consistent support and encouragement and most importantly I express deep appreciation to my husband David for always being there.

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I. INTRODUCTION

Free radical chain reactions have recently* become the subject of a great deal of interest from synthetic organic chemists. This situation is surprising in view of the fact that pioneering work in the field was done by Julia[1] as early as 1964 - 1968 and examples of the synthetic utility of free radical chain reactions were published by Bakuzis[2] in 1976 and Büchi[3] in 1979. The recent appeal of the subject is due in part to the mild conditions under which free radical reactions take place and to the convenience of avoiding the use of protecting groups that are often required in ionic chemistry. Furthermore, radical reactions can provide routes to sterically congested molecules which cannot be as readily prepared by ionic means.

There are two main processes by which free radical reactions can take place, one is an *inter*molecular course (eq. 1), and the other is an *intra*molecular sequence (eq. 2) which results in a carbocycle. The latter process has attracted the most attention by synthetic chemists since it leads to cyclic products and such structures are abundant in nature.

---

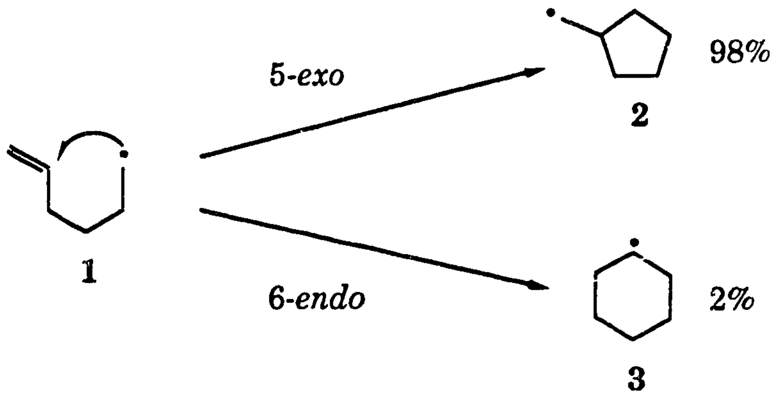
* The degree of interest by the organic chemical community can be roughly gauged by the approximate number of publications on the subject of free radical methods. Considering only those publications which we judge to be relevant to synthesis, there were 86 publications prior to 1980, and 150 between 1980 and 1984. However, since 1985, over 400 have appeared.

eq. 1

eq. 2

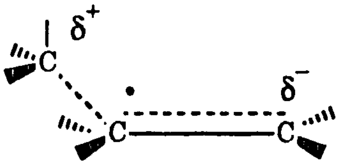
The use of radical cyclization in organic synthesis depends primarily on the design of efficient routes to radical precursors and many of these routes can be placed into general categories. In the following review I have presented the literature from this perspective and limited the discussion to those free radical chain reactions which are *intra*molecular. The first section deals with routes to heterocycles and the second one routes to carbocycles. Many of the subclassifications used in the review are arbitrary and the treatment is intended only to highlight the general approaches. Excellent reviews on the broad subject of free radicals in synthesis have been published.[4] Before proceeding with synthetic details a brief summary of the basic principles involved in free radical cyclizations will be given.

The prototypical reaction is the ring closure of 5-hexenyl radical 1



eq. 3

(eq. 3) which was first generated in solution in 1963.[5] This reaction has since been studied in detail and is widely accepted as a mechanistic probe.[6] Ring closure of **1** affords mostly cyclopentylmethyl radical **2** via a 5-*exo* pathway. An explanation[7a] for this behaviour is that there exists a requirement in the transition structure for efficient overlap between the semi-occupied 2p (SOMO) orbital of the radical with one lobe of the vacant π^* orbital of the olefin. Consequently, the transition structure must have the three participating atoms at the vertices of an obtuse triangle orthogonal to the nodal plane of the π-system (see **4**).

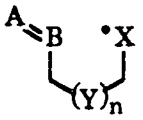


4

Beckwith[7] found that calculations and the inspection of models reveal such a disposition of centers can be much more readily accommodated in the transition complex for 1,5-closure of **1** (leading to **2**) than for 1,6-closure (leading to **3**). Both processes, however, are allowed by Baldwin's rules.[8]

A consequence of this stereoelectronic control is that the less stable primary radical **2** is formed faster than the thermodynamically more stable secondary radical **3**. The following general statement can then be made concerning the regiochemistry of cyclization: The *exo*-ring closure (**1** → **2**) will be kinetically favoured over the *endo* route (**1** →

3) for those radicals where **Y** (see **5**) is in a chain of up to 5 atoms (n≤3). A=B is any double (or triple) bond and **X** represents a C, O, or N center. When the chain is short (n=1, or 2) the transition complex for the *endo* process is very highly strained; however, when the chain is long the system will be more flexible and so the difference in strain energy between the transition structures leading to **6** and **7** will be small. Consequently, in those cases the *degree* of preference for *exo* over *endo* closure will be less marked.



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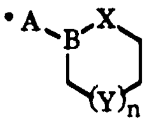

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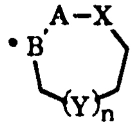

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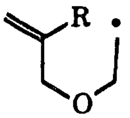
The rate and regioselectivity of ring closure is altered by any structural feature which affects the ability of the unsaturated radical to accommodate the triangular transition structure. For example, the 3-oxa-5-hexenyl systems (**8a** and **8b**) undergo ring closure much more rapidly than their hexenyl analogues and display a greater preference for the 5-*exo* mode.



8a, R = H
8b, R = Me

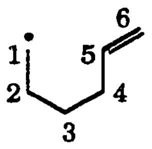
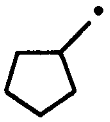
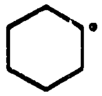
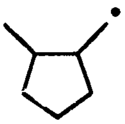
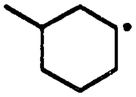
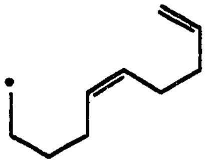
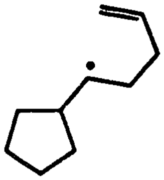
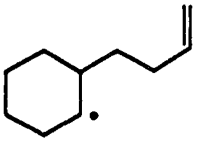
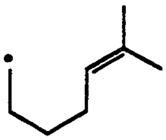
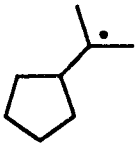
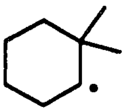
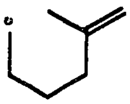
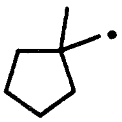
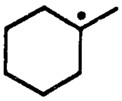
This is due to the fact that the C-O-C bond angle is less than the C-C-C angle and a C-O bond is shorter than a C-C bond so the minimum C1-C5 distance in radical **8a** is less than it is in the 5-hexenyl system, while the C1-C6 distance is greater. Similar conclusions can be made regarding chains which contain a nitrogen atom.

Substituents have an effect on the course of homolytic intramolecular additions, and these effects vary depending on whether substitution is at the reactive center or elsewhere on the chain. On the basis of purely thermochemical grounds one can argue that the rates of reaction of radicals having alkyl substituents at C1 or C6 should reflect the relative stabilities of reactants and products; hence the rate of 1,5-ring closure should be diminished by substitution at C1 and enhanced by substitution at C6. This is found experimentally not to be the case and Beckwith[7] suggests that the following two effects are responsible for the experimental observations: (1) The homolytic addition proceeds through a very early transition state in which the change of configuration at C1 or C6 is small and there is little transfer of spin density. (2) Energy changes in the polar transition state **4** that may result from interaction of the substituents with the free charges at C1 and C6 will be counterbalanced by those changes expected to result from interactions with the free spin.

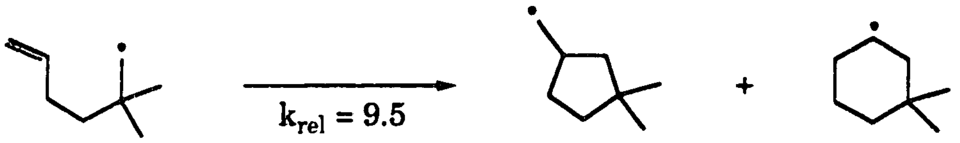
Substitution at C5 in 5-hexenyl type systems has a substantial effect on the regioselectivity of ring closure (Table **1**)[6] resulting in a predominance of *endo* over *exo* products. Kinetic data show that this is probably due to the fact that C5 substitution greatly *reduces* the rate of 1,5-cyclization as opposed to *enhancing* the rate of 1,6-cyclization. The phenomenon is probably steric in origin.

TABLE 1

Relative rate values for $k_{1,5}$ and $k_{1,6}$ at 20°C

Starting Radical	1,5-*exo*	1,6-*endo*	$k_{1,5}$	$k_{1,6}$
			1	0.02
			1.4	0.02
			1.4	0.007
			2.4	0.011
			0.022	0.04

Substituents at C1 alone have only minor effects while those at C2, C3, and C4 enhance the rate of 1,5-closure. For example closure of radical **9** (eq. 4) has a rate constant almost ten times larger than that for the unsubstituted case.



eq. 4

9 >99% <1%

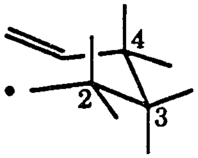
The Thorpe-Ingold or gem-dialkyl effect[9] has been used to explain this observation in the following way: In the ground state, the presence of two methyl substituents in **9** causes considerably more *gauche* interactions than those present in the unsubstituted case. However, there is a smaller difference in the number of gauche interactions between the two cases in the cyclic transition state. The rate of ring closure in the substituted case is thereby enhanced since the free energy of the reactant ground state is raised relative to that of the cyclic transition state in comparison to the unsubstituted one. Therefore, the $\Delta H^\ddagger$ for ring closure is effectively lower when there are substituents at C2, C3, or C4 of the chain.[10] The effect is less pronounced in the case of monosubstitution.

The stereoselectivity that one can expect to observe in intramolecular radical cyclizations of 5-hexenyl and similar systems is summarized in the following two guidelines published by Beckwith:[7]

(1) 1- or 3-Substituted radicals preferentially give *cis*-disubstituted cyclopentyl products.

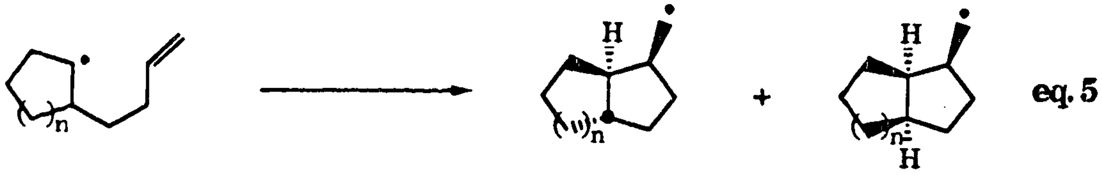
(2) 2- or 4-Substituted radicals give mainly *trans*-disubstituted cyclopentyl products.

The explanation for this behaviour is illustrated in structure **10** which resembles the chair form of cyclohexane and represents one conformation of the 5-hexenyl radical before closure. At C2, C3, and C4 axial and equatorial positions are clearly distinguishable and so the most favourable conformation will be that in which the substituent is equatorial. An equatorial substituent at C3 will then necessarily lead to a *cis* product while one at either C2 or C4 will produce a *trans* compound.



10

The guidelines discussed above cannot be fully applied to systems which afford bicyclic products, but in these cases the observations can usually be explained using the same steric and stereoelectronic arguments on which the guidelines are based. For example, in the ring closure of butenyl cycloalkyl radicals (**11a**, **11b**, eq. 5), which may be regarded as 1,2-substituted hexenyl systems, the *anticipated* major products are **12a** and **12b**, where the newly-formed radical is *cis* to the formal 1-substituent and *trans* to the formal 2-substituent. The actual major products are, however, the all *cis* compounds **13a, 13b**. This observation conflicts with the guidelines but, from inspection of models, Beckwith[7] suggests that efficient overlap between the semi-occupied orbital and the π^* orbital is more readily attained when **11b** reacts through the conformer containing the substituent in a pseudo-axial position.



11a, n = 1
11b, n = 2

12a, 12b

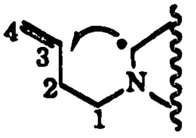
13a, 13b

Use of these general principles for prediction of observed regio- and stereochemistry in *intra*molecular radical cyclizations is extremely valuable for synthetic applications.

(A) Radical Cyclization Routes to Heterocycles

Nitrogen Heterocycles

A unifying theme in syntheses of nitrogen heterocycles by radical means is the method of preparation of the radical precursors. Often they are formed by the attachment of a chain (to the nitrogen atom) which carries either a radical trap as in carbons 1 to 4 of **14**, or a radical precursor as in carbons 1 to 4 of **15**. These routes are illustrated in the following discussion.



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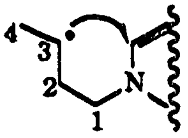
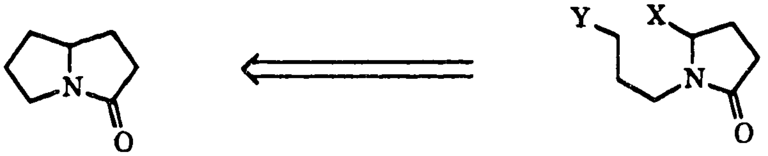


15

The alkaloids are an important class of nitrogen heterocycles and much interest has been directed toward their synthesis. Previously, the key step in most approaches was formation of a C-C bond adjacent to nitrogen (see eq. 6) usually by *ionic* means.



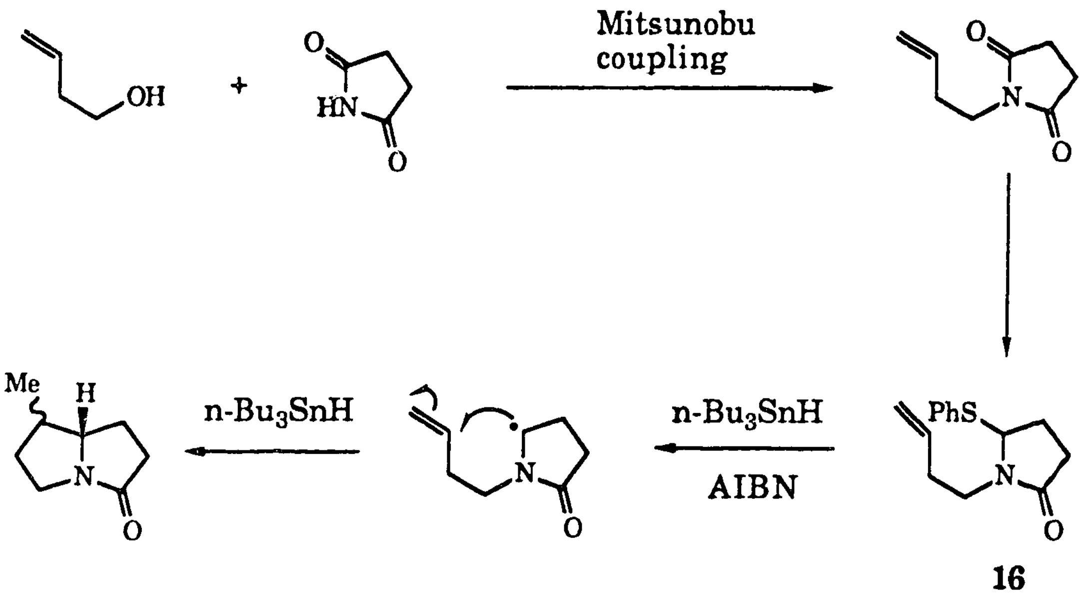
eq. 6

In 1982, Hart and co-workers[11] devised a route using α-acylamino *radicals* for achieving the same bond construction under neutral conditions. Their approach is shown in Scheme 1.

The radical precursor **16** is readily assembled by Mitsunobu coupling of the requisite homoallylic alcohol with succinimide (in order to attach the radical trapping pendant to nitrogen) and then chemical manipulation of one of the carbonyls affords the protected radical functionality and completes the synthesis of **16**. The alkaloid framework is then assembled by homolysis of the C-SPh bond using tributyltin hydride and 5-*exo* closure of the resulting radical onto the olefin.

The authors[11b] were able to adjust the regiochemical course of cyclization to favour either pyrrolizidinone (see **III** and **IV**, Table 2) or indolizidinone (see **V**, Table 2) formation by judicious substitution of the double bond and also by changing the length of the connecting chain between the radical and olefinic center. The ratios of products (Table 2) reflect the kinetic partitioning of the radical between the two cyclization pathways.

SCHEME 1

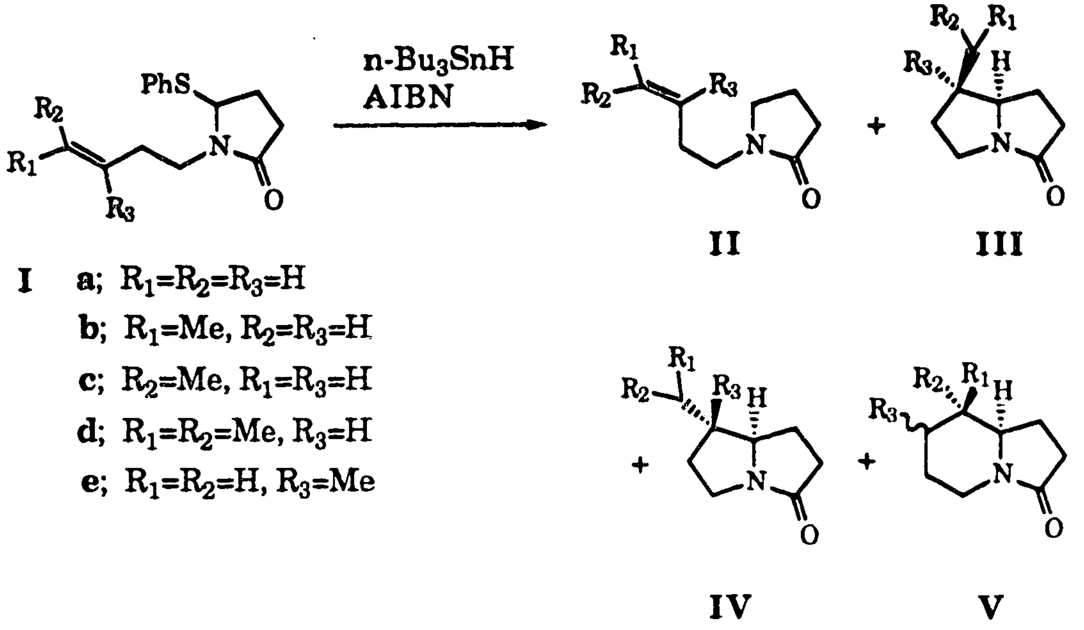


16

Hart and co-workers[11f] also studied the utility of radical closure onto an acetylene (although this was not the first example of the use of acetylenes as radical traps[3]) in similar systems. The result of such closure is an olefin which can be manipulated further. In 1985 this method was used in an enantioselective synthesis of the naturally occurring pyrrolizidine alkaloids (-)-dehydrohastanecine **17** (+)-heilotridine**18**, and (+)-hatanecine **19**.[11a]

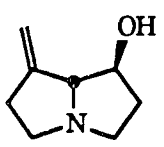
TABLE 2

Cyclization Yields in Formation of Pyrrolizidinones and Indolizidinones



I **a**; $R_1=R_2=R_3=H$
b; $R_1=Me, R_2=R_3=H$
c; $R_2=Me, R_1=R_3=H$
d; $R_1=R_2=Me, R_3=H$
e; $R_1=R_2=H, R_3=Me$

Radical Precursor	% **II**	% **III**	% **IV**	% **V**
Ia	12	45	4	24
Ib	13	42	5	22
Ic	25	45	7	4
Id	12	60	15	0
Ie	12	7	0	63



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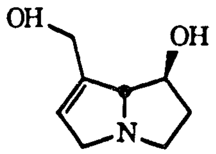

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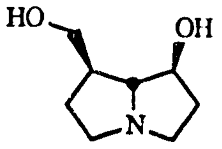
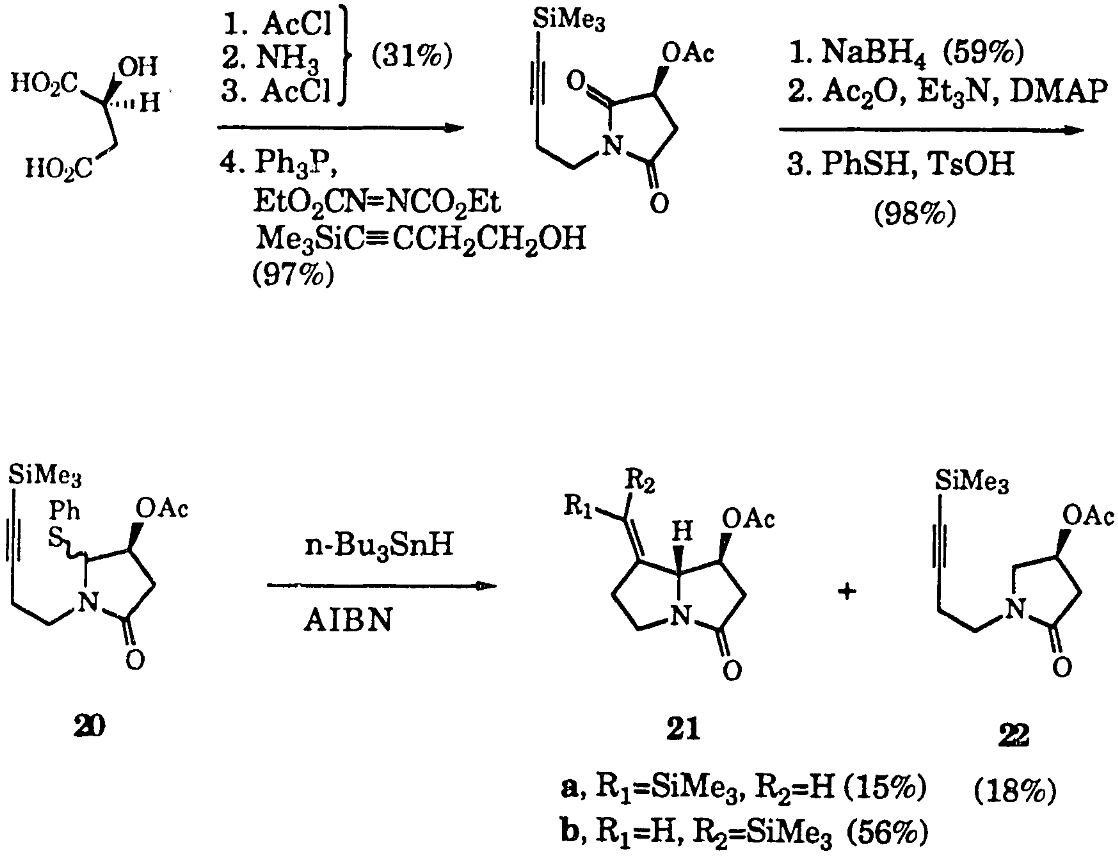


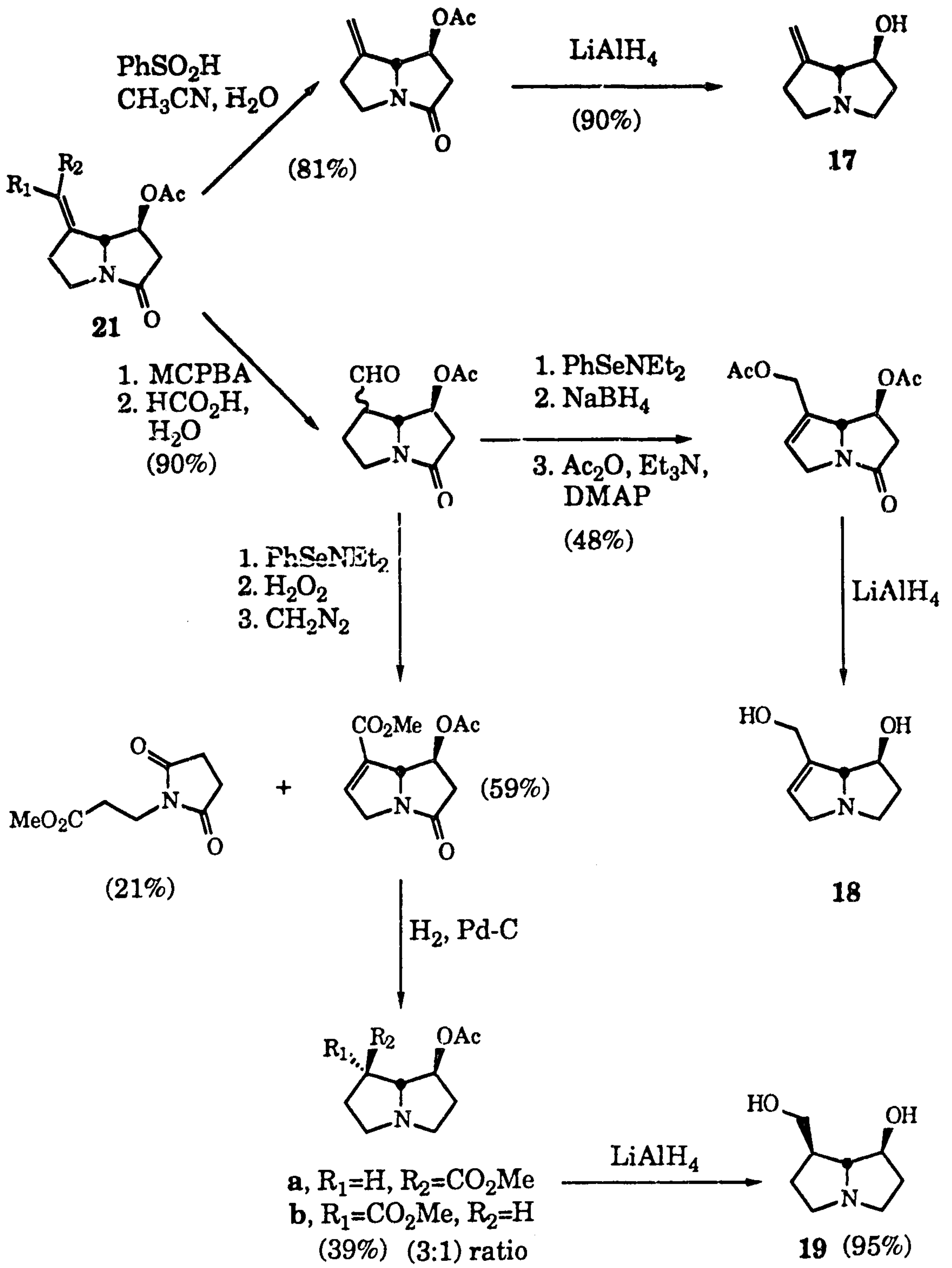
19

Hart's route is based on formation of a pivotal intermediate **21** (Scheme 2) which results from radical cyclization of **20** and leads to each of the three natural products as shown in Scheme 3. The radical precursor **20** was easily prepared from (*S*)-malic acid by sequential treatment with acetyl chloride, ammonia, and acetyl chloride again, followed by Mitsunobu coupling with 4-trimethylsilyl-3-butyn-1-ol. Reduction with sodium borohydride, acetylation, and acetoxy-thiophenoxy exchange gave **20** in good yield. Treatment with tributyltin

SCHEME 2



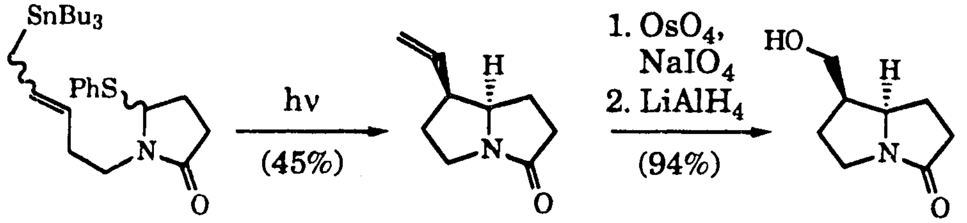
SCHEME 3


PhSO$_2$H
CH$_3$CN, H$_2$O
(81%)
OAc
O
LiAlH$_4$
(90%)
OH
17
R$_2$
R$_1$
OAc
21
O
1. MCPBA
2. HCO$_2$H, H$_2$O
(90%)
CHO
OAc
1. PhSeNEt$_2$
2. NaBH$_4$
3. Ac$_2$O, Et$_3$N, DMAP
(48%)
AcO
OAc
1. PhSeNEt$_2$
2. H$_2$O$_2$
3. CH$_2$N$_2$
LiAlH$_4$
O
MeO$_2$C
(21%)
+
CO$_2$Me
OAc
(59%)
HO
OH
18
H$_2$, Pd-C
R$_1$
R$_2$
OAc
a, R$_1$=H, R$_2$=CO$_2$Me
b, R$_1$=CO$_2$Me, R$_2$=H
(39%) (3:1) ratio
LiAlH$_4$
HO
OH
19 (95%)

hydride and AIBN (azobisisobutyronitrile) in benzene under high dilution conditions afforded the reduction product **22** (18%) together with **21** as a separable mixture of geometric isomers in 71% yield. Manipulation of **21** led to each of the natural products (Scheme 3).

Biotin has also been prepared by radical closure of an acylamino radical onto a triple bond.[12]

Keck and Enholm[13] applied a Mitsunobu technique to the preparation of a radical precursor for synthesis of the pyrrolizidine alkaloid (±)-isoretronecanol **23**. An allylstannane was incorporated as the radical trap in this case (eq. 7) instead of an unsubstituted olefin or acetylene.

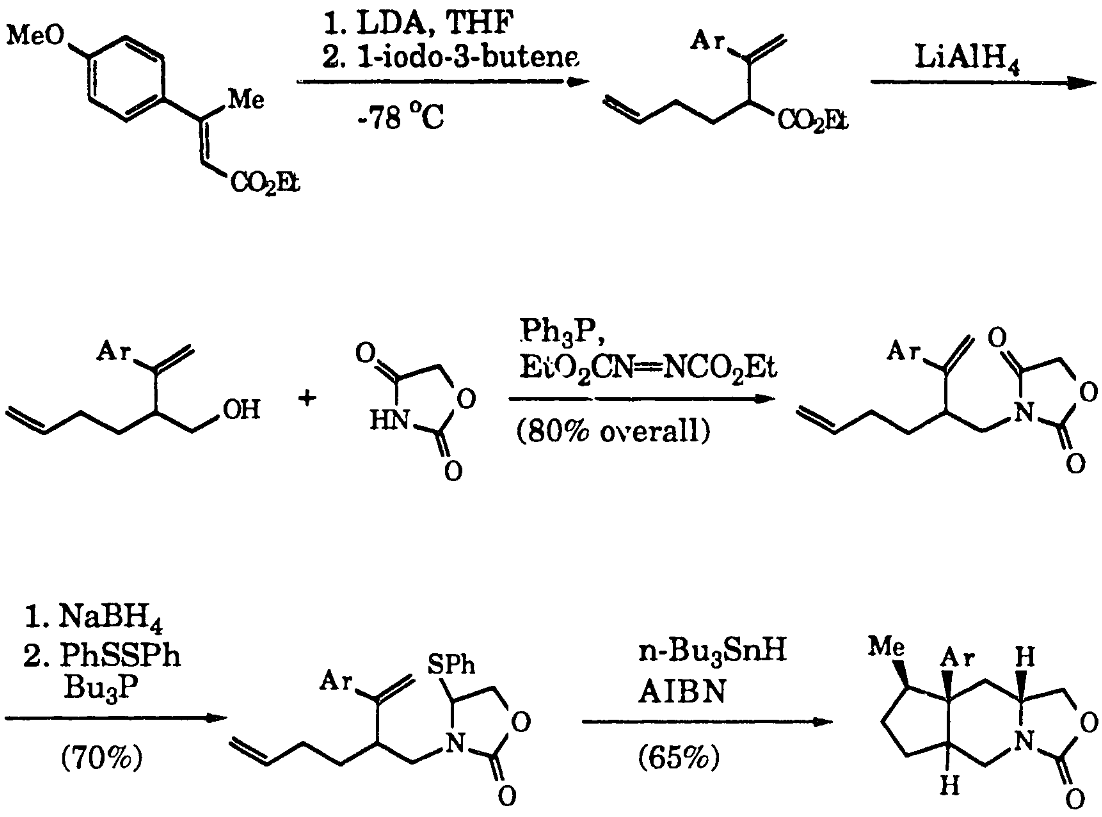


23

eq. 7

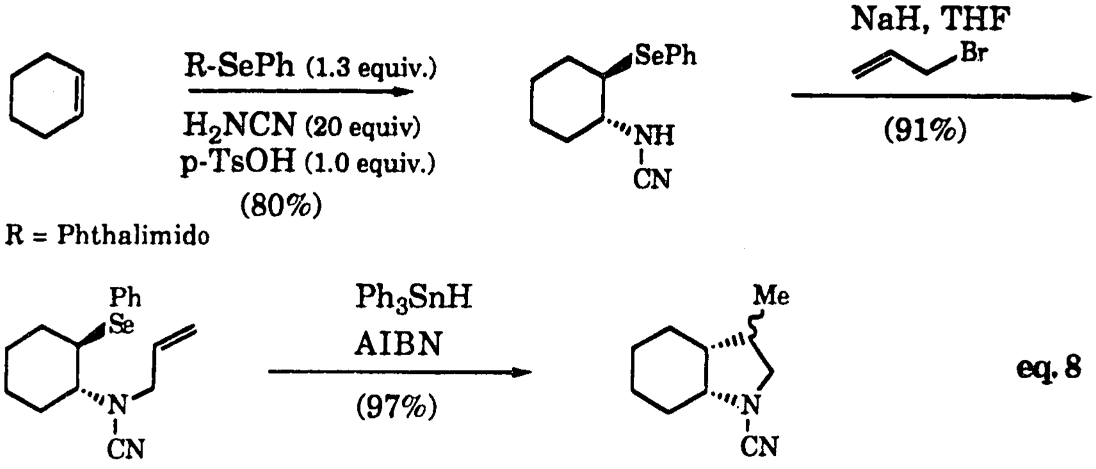
In 1986 Kano and co-workers used the Hart methodology in diastereoselective syntheses of 1- and 5-substituted tetrahydropyrrolo[1,2]oxazole and 1-substituted pyrrolizidine derivatives[14a] and they developed the technique further by applying it[14b] to the tandem radical cyclization shown in Scheme 4. The radical acceptor pendant was prepared by known chemistry and then condensed with oxazolidine-2,4-dione by Mitsunobu coupling. The acceptor then had two sites for radical attack, and reaction with tributyltin hydride led to two successive ring closures and afforded the tricyclic compound **24** in 65% yield.

SCHEME 4



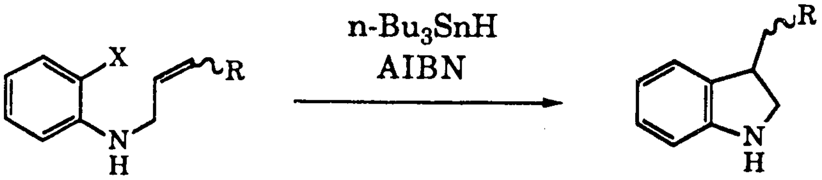
24

Other types of nitrogen heterocycle have received some attention in the radical chemistry literature,[15, 16] including work in this laboratory[16b] on the preparation of substituted pyrrolidines by the general method shown in eq. 8. The protected radical and nitrogen functions are added simultaneously to a cyclic alkene and then a radical trap is attached by ionic chemistry to nitrogen. Radical closure affords *cis*-fused heterocycles.



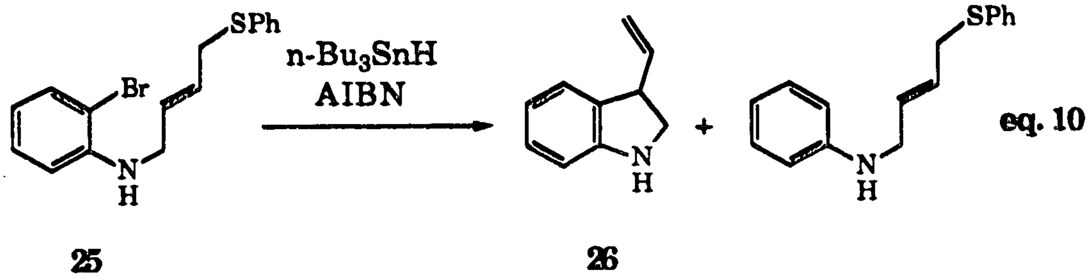
eq. 8

Routes to indole alkaloids have been explored by numerous groups and once again the central theme is attachment of a pendant carrying a radical trap to the nitrogen atom prior to ring closure. The difference here, however, is that the radical is generated from an aryl halide. The procedure is illustrated in eq. 9.

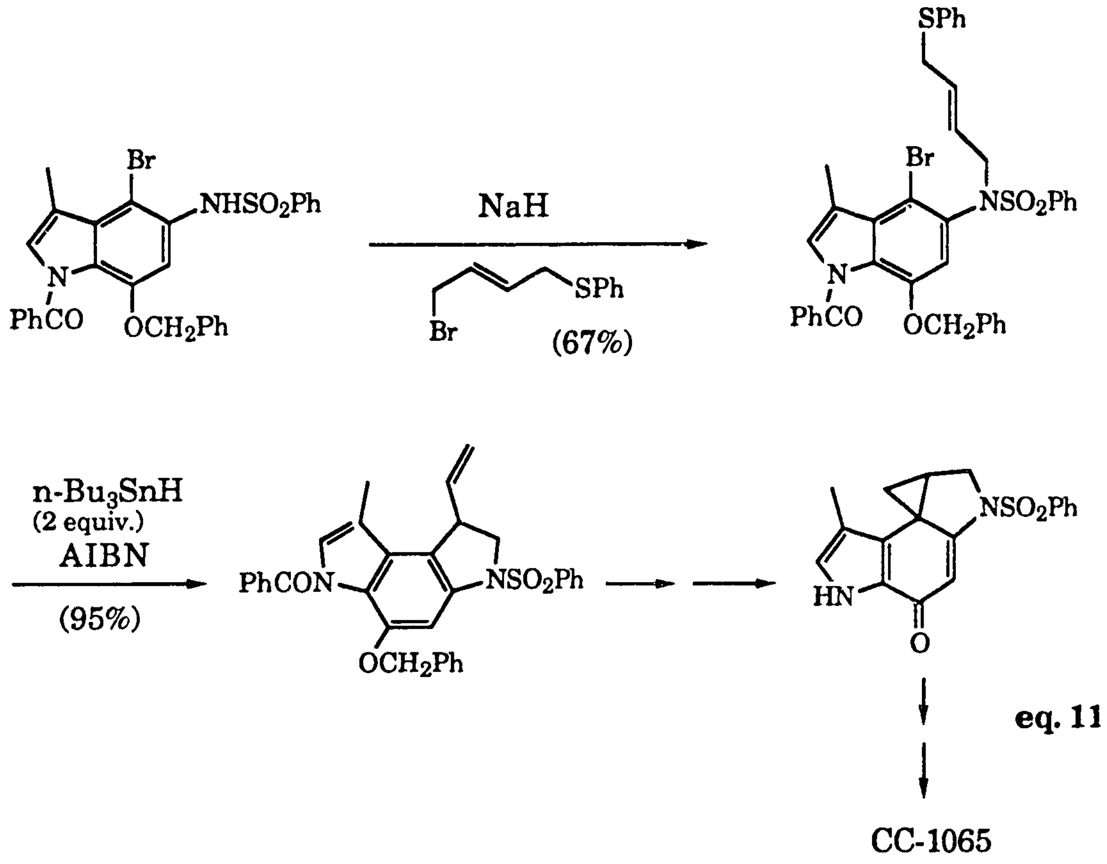


eq. 9

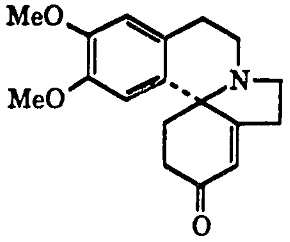
In 1982 Ueno[17] showed that cyclization of **25** to **26** (eq. 10) was highly dependent on the concentration of tributyltin hydride; under high dilution cyclization was favoured; at low dilution simple reduction predominated. Other workers[18] have since explored similar pathways to indole alkaloids.



The antitumor antibiotic CC-1065 has been prepared using Ueno's basic strategy for the left-hand segment of the molecule (eq. 11).[19]



The other general technique in the indole area is attachment, to the nitrogen atom, of a pendant which carries a protected radical. This approach has been applied to preparation of erythrina alkaloids and an illustrative example is Danishefsky's[20] route to (±)-3-demethoxyerythratidinone **27**.

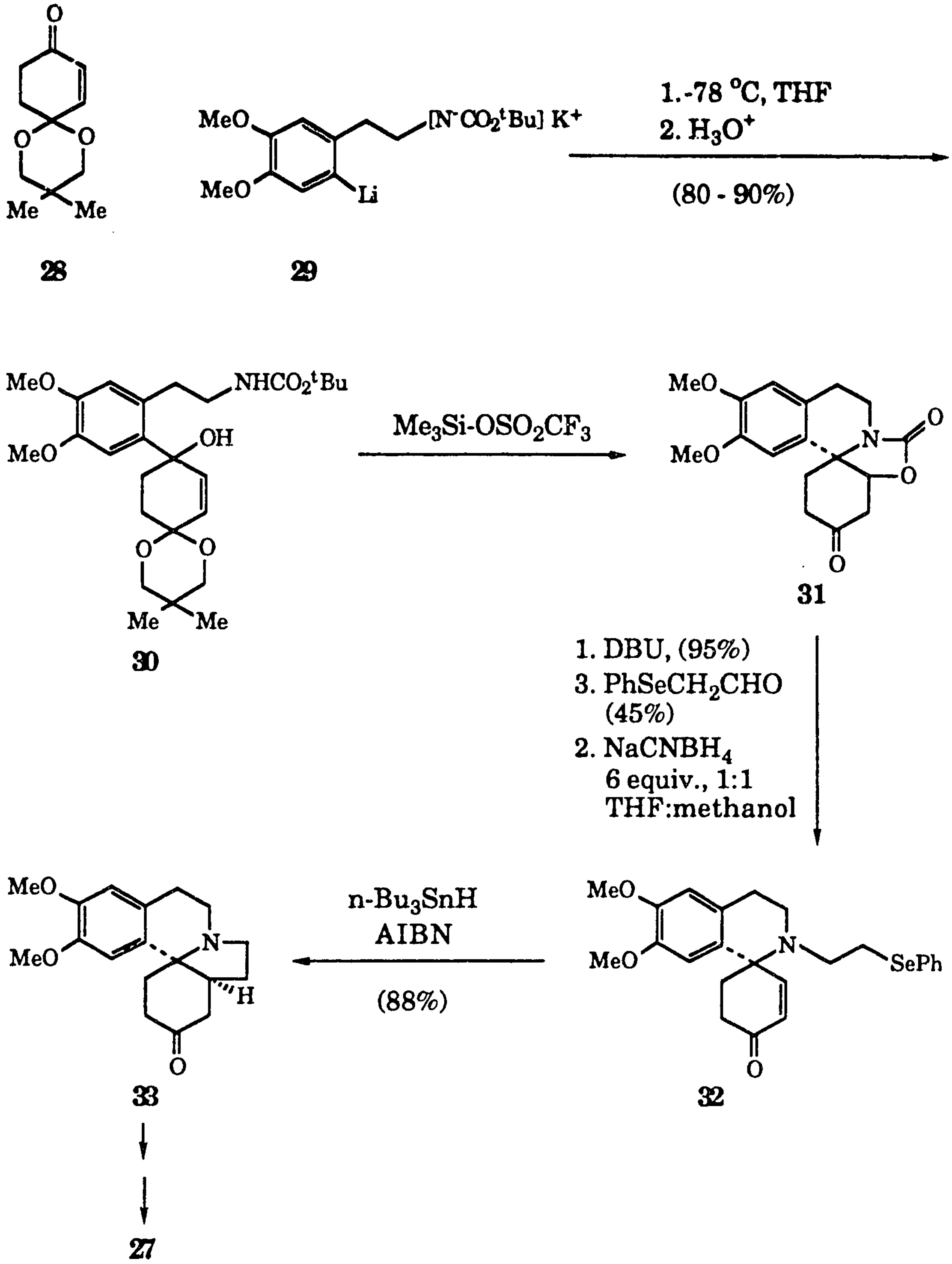


27

Synthesis of the radical precursor **32** (Scheme 5) involved coupling of the two intermediates **28** and **29** to give the tertiary alcohol **30**, followed by formation of the spiro compound **31**. Reductive amination with phenylselenoacetaldehyde served to attach the radical pendant. Treatment with tributyltin hydride and AIBN gave an 88% yield of **33** by an internal, Michael-like, free radical cyclization. Further manipulations of **33** led to the target.

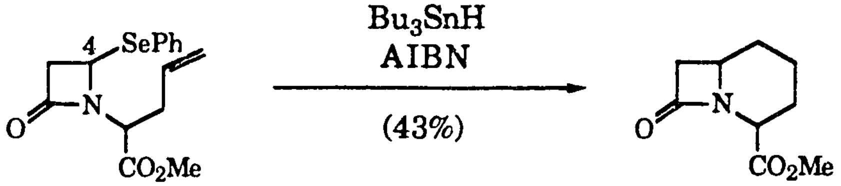
β-Lactam antibiotics constitute another major class of nitrogen heterocycles which has been the focus of numerous synthetic radical studies. As with the alkaloids, construction of a C-C linkage α to nitrogen (C4 of an azetidinone) is central to the main approaches using ionic chemistry. A useful strategy in radical chemistry, as in the studies above, involves attachment of a chain to the nitrogen atom which

SCHEME 5


MeO
MeO
Li
[N⁻CO₂ᵗBu] K⁺
O
Me
Me
28
29
1. -78 °C, THF
2. H₃O⁺
(80 - 90%)
NHCO₂ᵗBu
OH
30
Me₃Si-OSO₂CF₃
N
31
1. DBU, (95%)
3. PhSeCH₂CHO (45%)
2. NaCNBH₄ 6 equiv., 1:1 THF:methanol
SePh
32
n-Bu₃SnH
AIBN
(88%)
H
33
27

again carries either a radical trap or a protected radical.

It became apparent to early researchers in this field that judicious placement of the free radical center on the cyclization precursor would lead to either *exo* or *endo* modes of closure. In particular, when the radical trap is a terminal double bond, exclusive *endo* cyclization appears to be typical of azetidin-2-ones which have the radical either at C4,[21,22] or alpha to N but exocyclic to the ring.[23] Examples are shown in eq. 12[21] and in Table 3.[22]



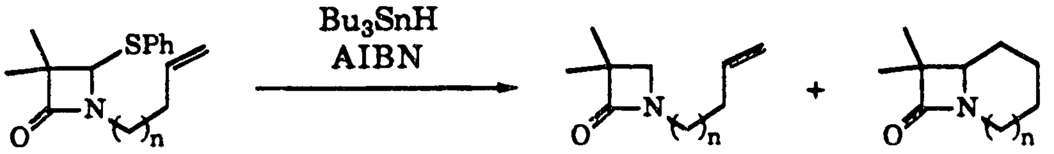
eq. 12

The results presented in the Table[22] indicate that ring closure in these systems goes exclusively in the *endo* mode and the production of **36c** (seven membered ring) appears faster than closure to **36b** (six membered ring). It is believed that this preference for *endo* closure and the relative rates for the reaction leading to **36b** and **36c**, reflect the strain (due to the azetidinonyl ring) in the *exo* transition structures. This effect was exploited by a number of groups in the preparation of carbacepham and carbacephem ring systems.[24]

The preference for *endo*- over *exo*-closure can be reversed by preparing a radical precursor with a substituted double bond[25] and Bachi has found that annelation occurs exclusively through the *exo* mode in the example of eq. 13.

TABLE 3

Radical Cyclization Yields of Azetidin-2-one Derivatives



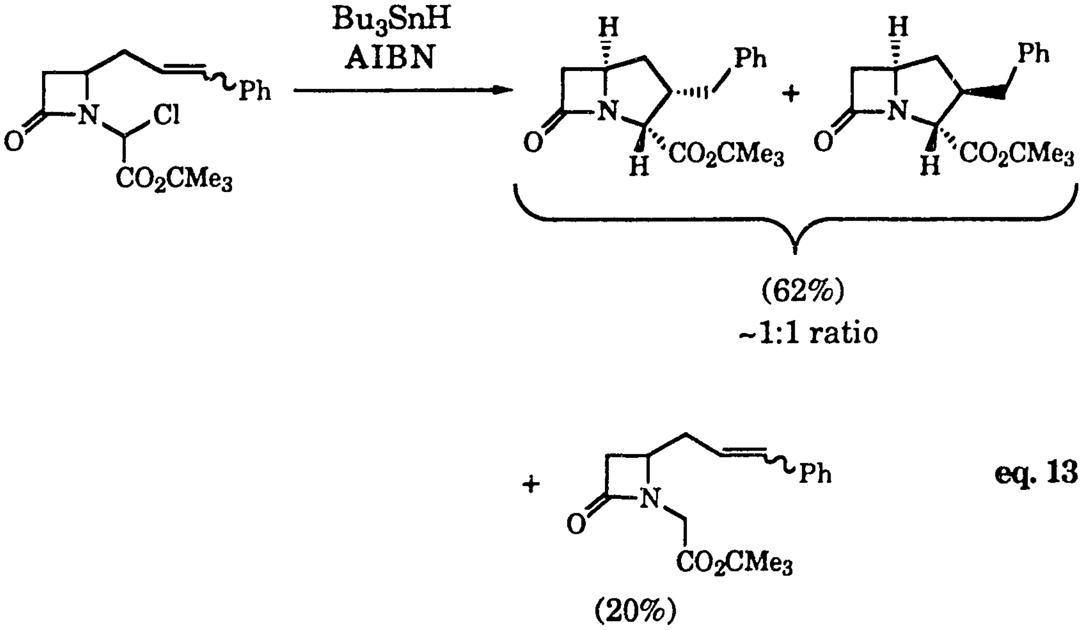
34 **a**, n=0
b, n=1
c, n=2

35

36 **a**, n=0
b, n=1
c, n=2

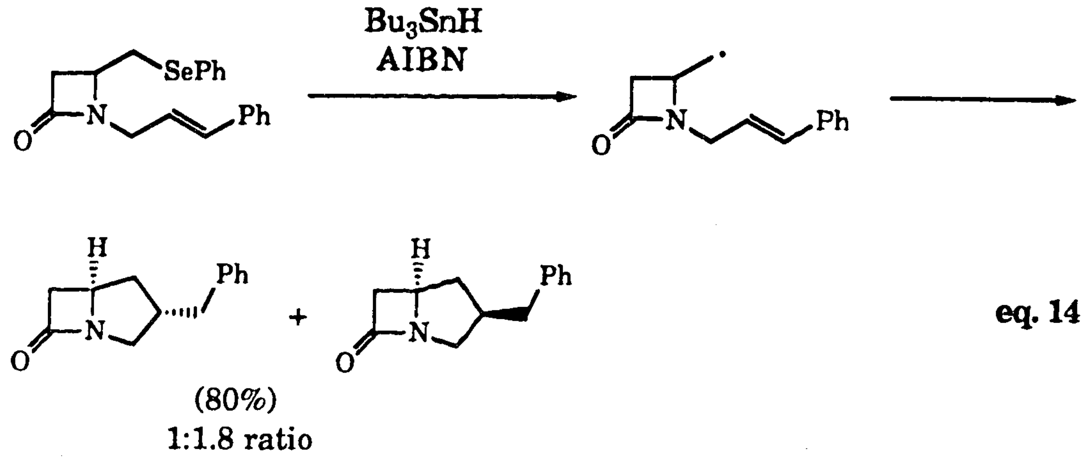
Starting Material	Products (% yield)			
	35	**36a**	**36b**	**36c**
34a	-[a]	-	-	-
b	48%	-	26%	-
c	25%	-	-	55%

[a] The authors indicate only that no *cyclized* material was isolated.



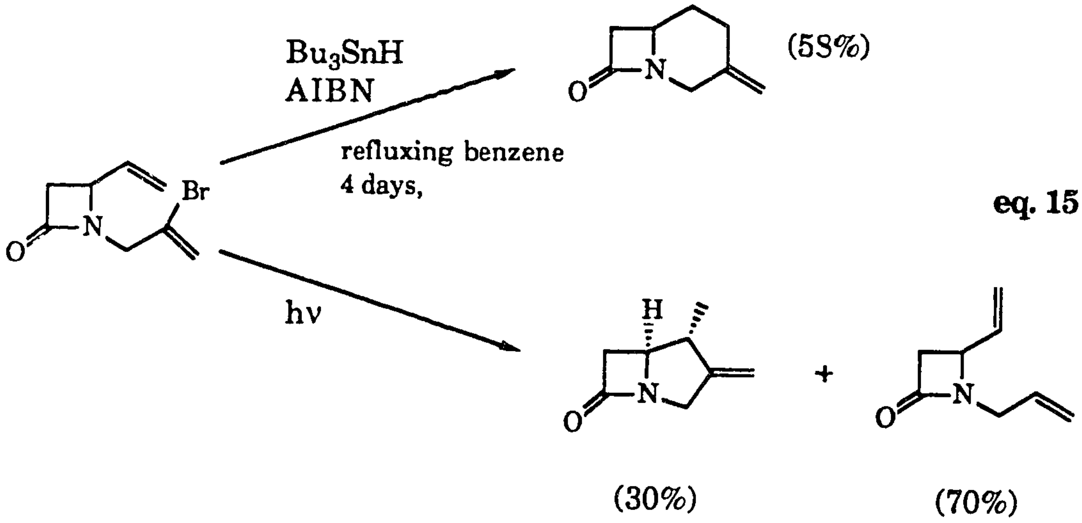
eq. 13

An even better route (eq. 14), in which the acceptor pendant is now placed on the ring nitrogen but the radical is one carbon away from the four-membered ring, was also described by Bachi.



eq. 14

Parsons et al.[24b] have employed vinyl radicals (which are more reactive than alkyl radicals[7, 26a]) in similar work to produce varying amounts of *exo* versus *endo* products (eq. 15).

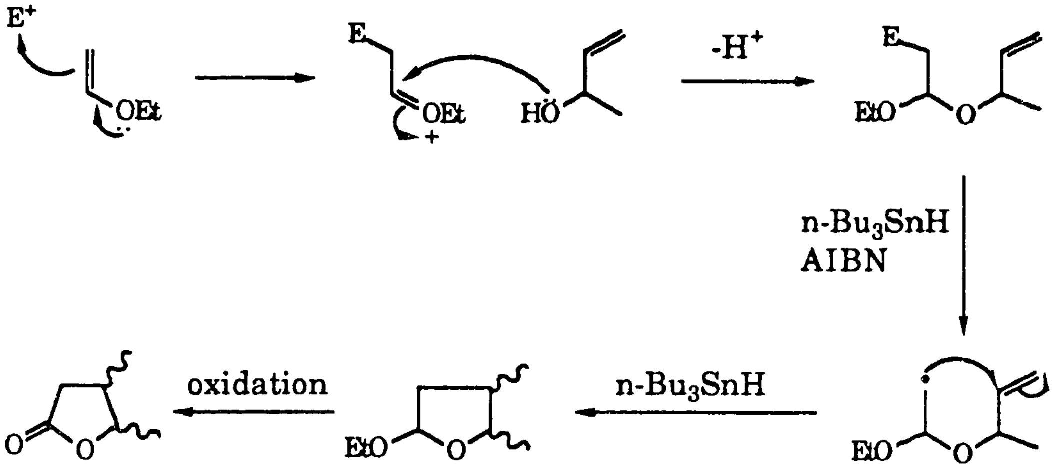


eq. 15

Oxygen Heterocycles

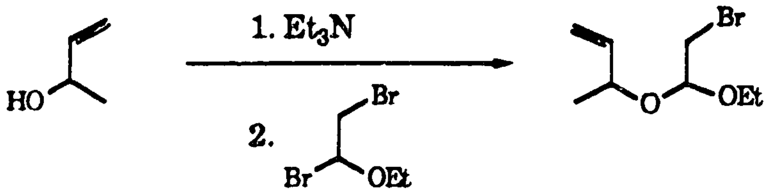
Radical cyclization has been used to make γ-butyrolactones which constitute a very large class of oxygen heterocycles. Usually a bromoacetal is used and there are two methods to obtain these radical precursors. The first one, electrophile-induced attachment of an unsaturated chain (usually an allylic alcohol) to an olefin, is illustrated in Scheme 6.[27, 28]

SCHEME 6



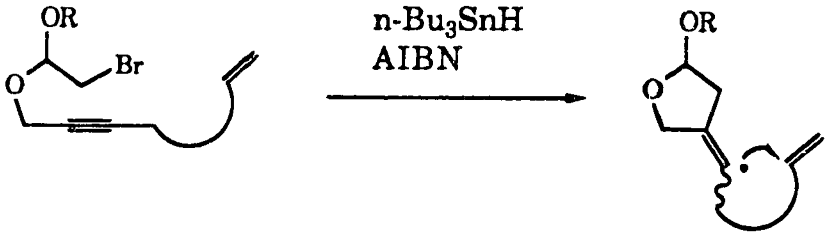
The electrophile (E+, Scheme 6), which is commonly bromine, iodine, or a phenylselenenyl halide, serves a dual purpose: (1) It promotes coupling of the two fragments (the vinyl ether and the oxygen-containing unsaturated chain) and (2) the electrophile, once attached to the substrate, acts as a precursor for the radical.

The second easy route to bromoacetals involves displacement of bromine from 1,2-dibromoethyl ethyl ether by an allyl alcohol (eq. 16).



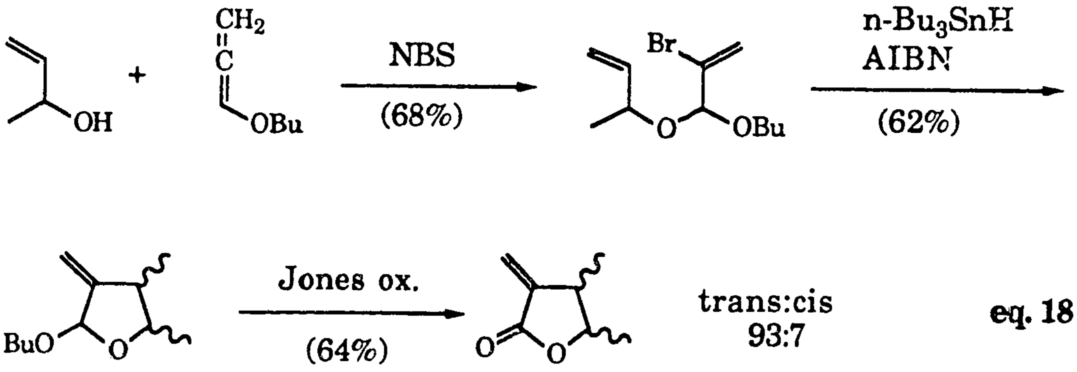
eq. 16

Stork[28] has prepared bromoacetals from ethynyl carbinols. On radical cyclization these produce vinyl radical intermediates (eq. 17) which undergo further cyclization.



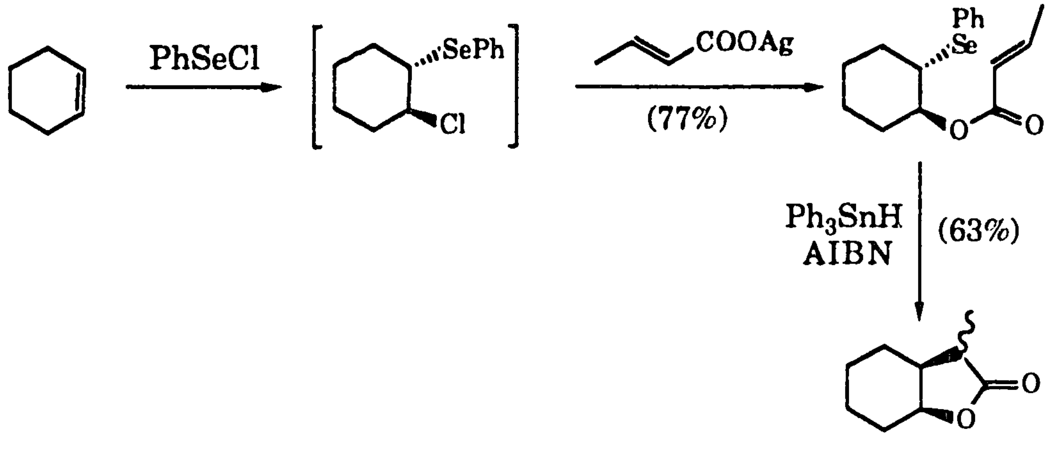
eq. 17

Ueno[29] has employed vinyl bromoacetals as precursors to α- and β-methylene-γ-butyrolactones and he made the starting materials using a method similar to the basic one described above (Scheme 6). However, Ueno used an alkoxy allene rather than a vinyl ether (eq. 18).



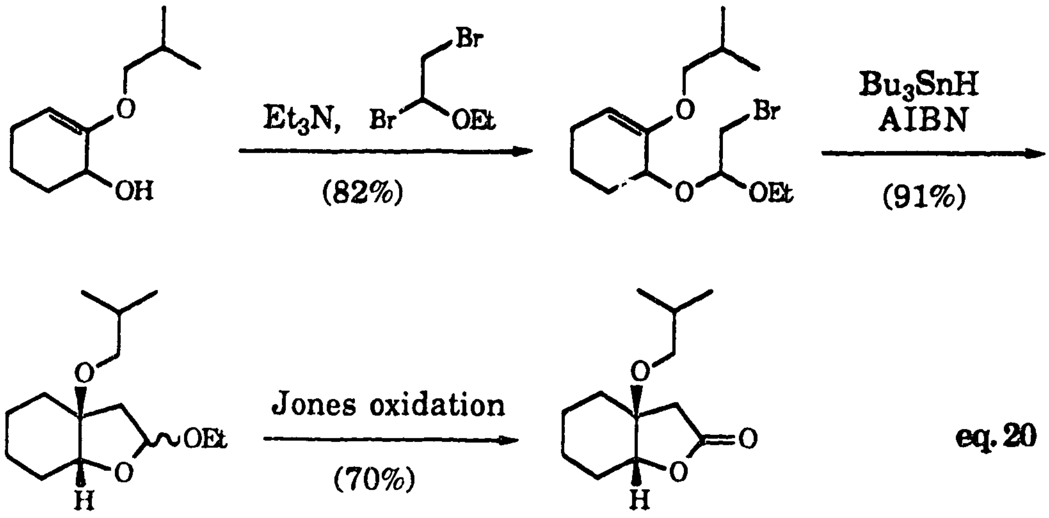
eq. 18

In 1983 a concise route to fused γ-lactones was reported from this laboratory (eq. 19).[30] Readily available cyclic alkenes were coupled with an appropriate unsaturated acid, the process being mediated by phenylselenenyl chloride. Cyclization of the resulting phenylselenide led directly to the lactone as illustrated.



eq. 19

A good deal of work has been done by many other groups in recent years both in total syntheses using the bromoacetal technique and in the development of new methods in which the nature of the radical-trapping pendant is altered.[31, 32] For example, propargyl alcohols, rather than allylic alcohols, have been used since ring closure affords an alkene which can be manipulated further.[31] Pattenden and Ladlow[32a] have provided another variation in which β-oxy-γ-butyrolactones can be elaborated by construction of a cyclization precursor that carries an alkoxy function on the double bond (eq. 20). Pattenden[32b] has also studied several examples of cobalt-mediated radical cyclizations and there has been a report using fluoro-olefinic compounds.[31f]



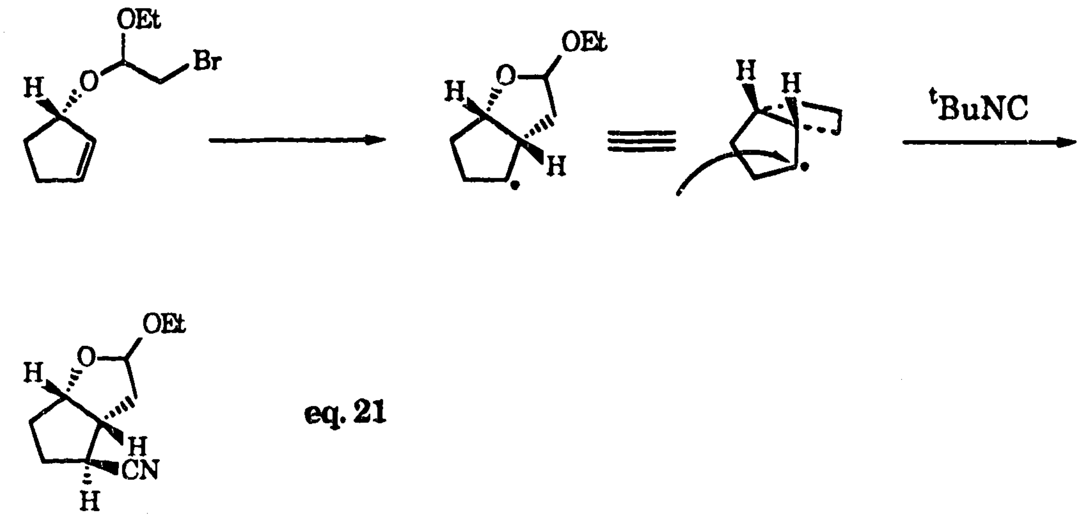
eq. 20

Stork et al.[28, 33] have expanded the bromoacetal cyclization method into a very powerful technique for positioning substituents on adjacent carbons of a ring system. The complete regiochemical and high stereochemical control in this sequence deserves some comment. The technique is based on the fact that when bromoacetal cyclization occurs, the newly-formed *cis*-fused* five-membered ring imposes a cup shape on the bicyclic system and so access to the new radical by a donor molecule

---

* MM2 Force-field calculations show the strain energy of the transition structure for the *cis* ring closures to be markedly less than those for their *trans* counterparts and so *cis* ring-fusion is usually favoured in these cyclizations.[26b]

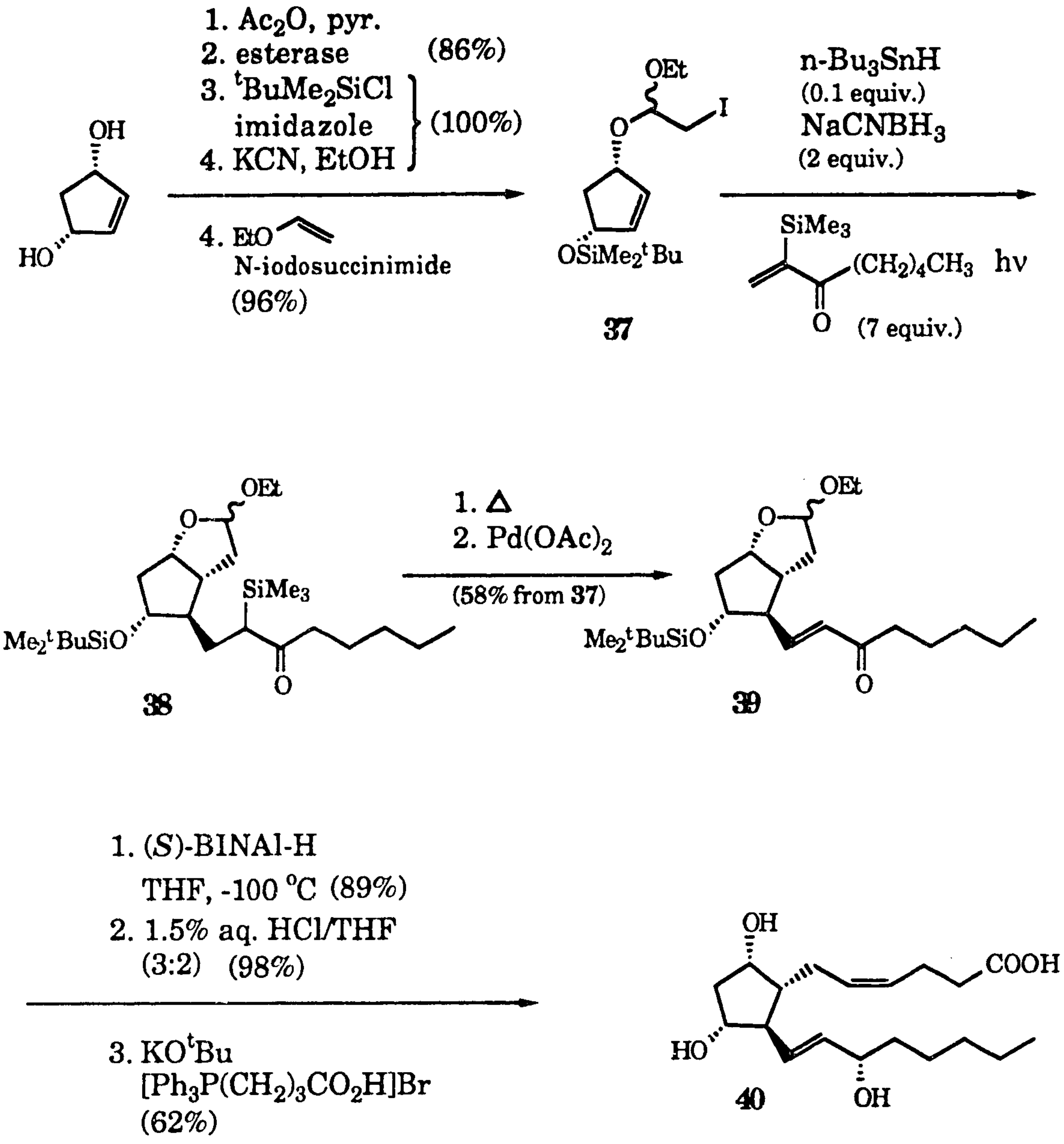
should be largely restricted, for steric reasons, to the convex side of the ring system (eq. 21).



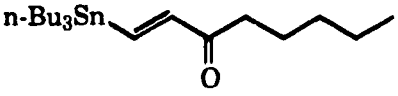
eq. 21

Stork has shown that transfer of a cyano group from *tert*-butyl isocyanide (with tin hydride in low concentration), to the newly formed radical is possible, and that the new functionality will be positioned *trans* to the ring oxygen (because of the steric constraint discussed above) (see eq. 21).[33a,c] In this way two new centers of chirality can be created and their stereochemistries, relative to the initial hydroxyl group, can be predicted. The utility of such a technique is very large and it has led to successful syntheses of prostaglandin $F_{2\alpha}$ **40** by Stork and co-workers[33d] and by Keck and Burnett.[34] Stork's route is illustrated in Scheme 7. The iodoacetal **37** was prepared from *cis*-2-cyclopentene-1,4-diol and then subjected to his cyclization-radical trapping conditions using 2-(trimethylsilyl)-1-octen-3-one as the trapping agent. Trimethylsilyl ketone **38** resulted and led, upon thermal rearrangement, and oxidation, to **39**. The overall yield for the three steps was 58%. Simple chemical manipulations then gave the natural product **40**.

SCHEME 7

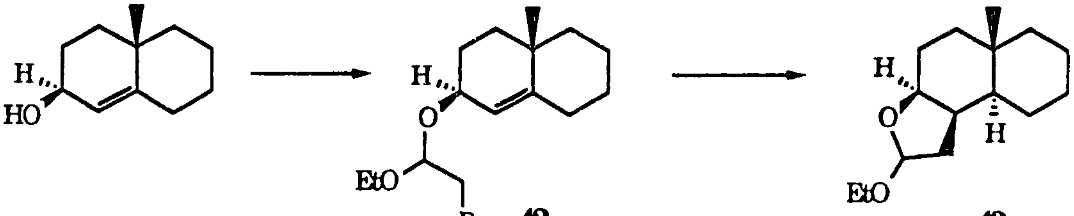


Keck and Burnett's version was similar but involved use of **41** as trapping agent. Cyclization and trapping led directly to Stork's enone **39**.



41

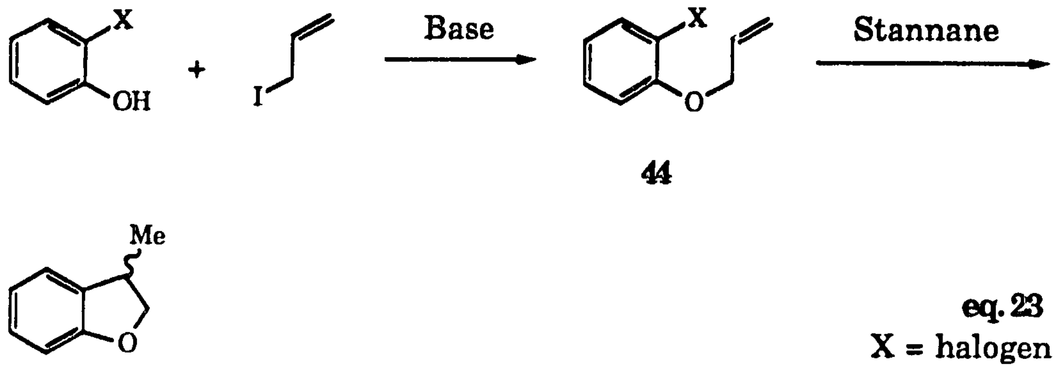
Stork and Kahn have extended the cyclization-trapping sequence so that it can be used for controlling ring junction stereochemistry in decalins (eq. 22).[33b] For example, when the bromoacetal is part of an unsaturated bicyclic system, as in the case of **42**, hydrogen capture results in *trans* ring-fusion in the decalin **43** since the hydrogen is forced to add from the convex face of the molecule. Essentially, the initial hydroxyl group serves to control the stereochemistry of the distal ring junction.



42 **43**

eq. 22

Syntheses of various aromatic oxygen-containing heterocycles by radical methods have been reported in the literature.[35] In most examples the radical cyclization precursor is a β-haloether such as **44** (eq. 23) and it is usually prepared by condensation of a radical acceptor chain with an *ortho*-halophenol. The halogen is attached to the aromatic ring and cyclization leads to benzofurans or benzopyrans.



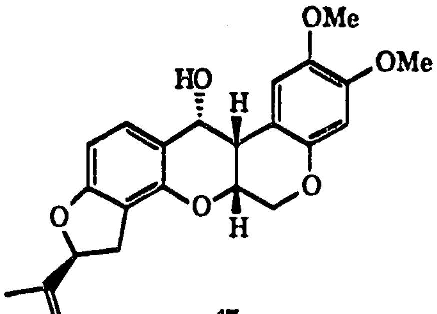
eq. 23
X = halogen

In some cases arene diazonium salts have been employed[35b] and the cyclization precursors were prepared from the corresponding *ortho*-aminophenols. In these examples cupric halides were used to convert the diazonium salts into aryl radicals.

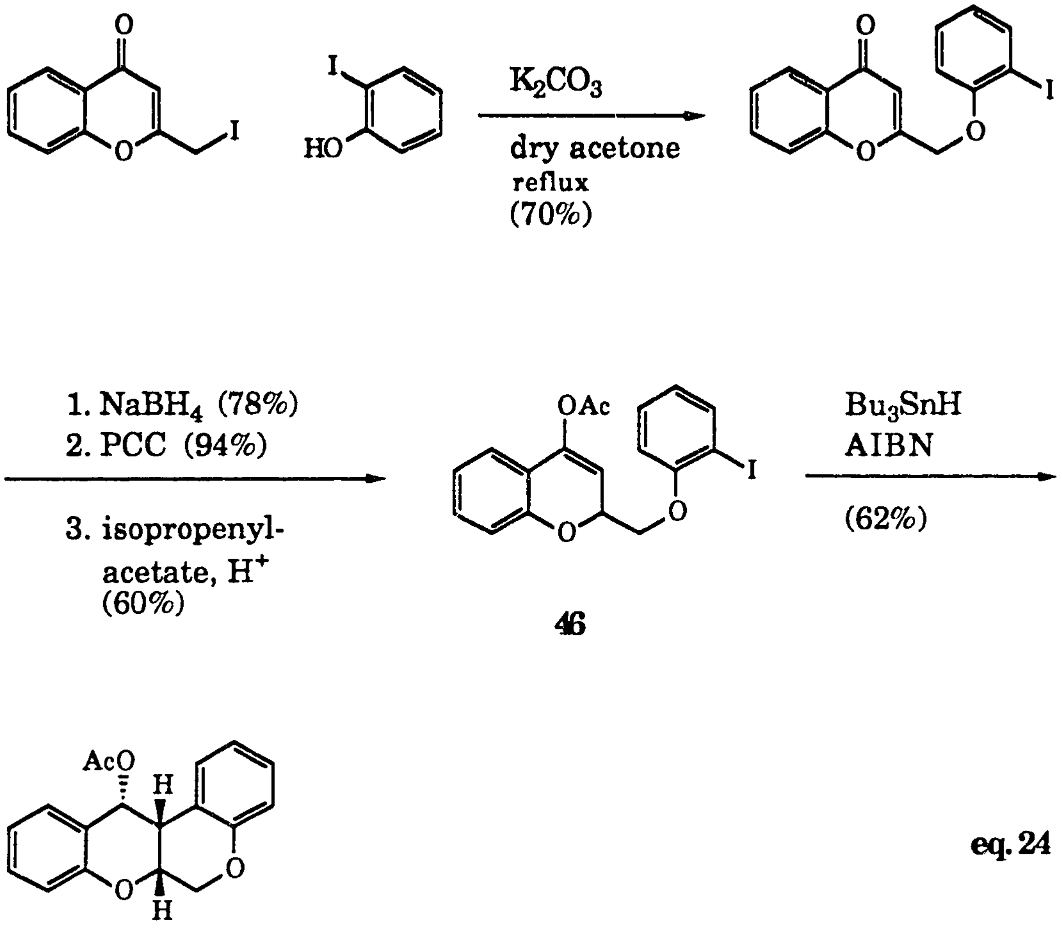
Work with β-haloethers has led to a recent synthesis of the parent ring system of the rotenoid alcohol **45** by Whiting[35c] (eq. 24), the key step being cyclization of **46** to **47** (62% yield).

The pterocarpan skeleton has also been synthesized by radical cyclization[35d] starting with the bromo ether **49** (eq. 25). This was prepared by ring-opening of epoxide **48** with *ortho*-bromophenol followed by dehydration via the tosylate. Cyclization gave **50** in 90% yield.

An example of the use of an aryl β-bromo ether in synthesis is the recent report[35e] of tandem radical cyclization of aryl bromide **51** (eq. 26).



45

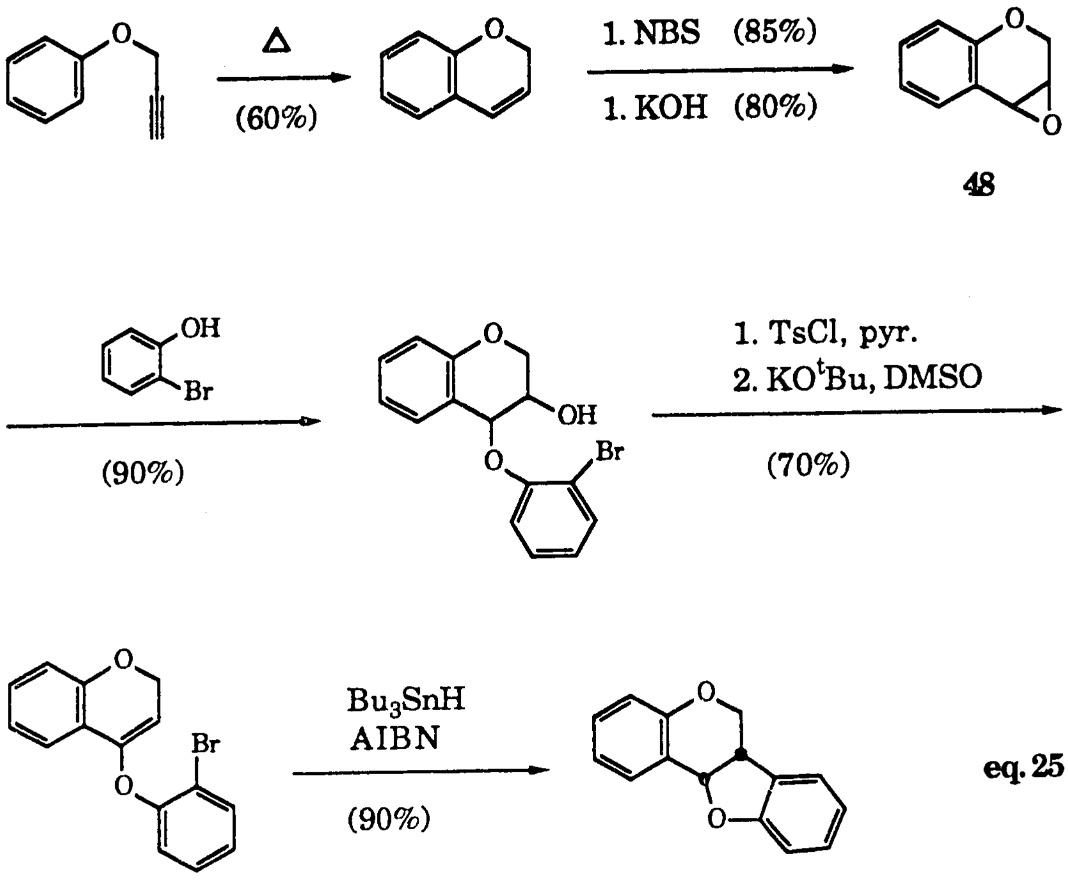


46

47

eq. 24

A *cis* decalin system is formed cleanly without competitive side reactions because of the inherent steric and spatial constraints of the system. The result is a separable mixture of the bridged hydrophenanthrenes **52** and **53** in good yield. The products are close models of the morphine skeleton.



48

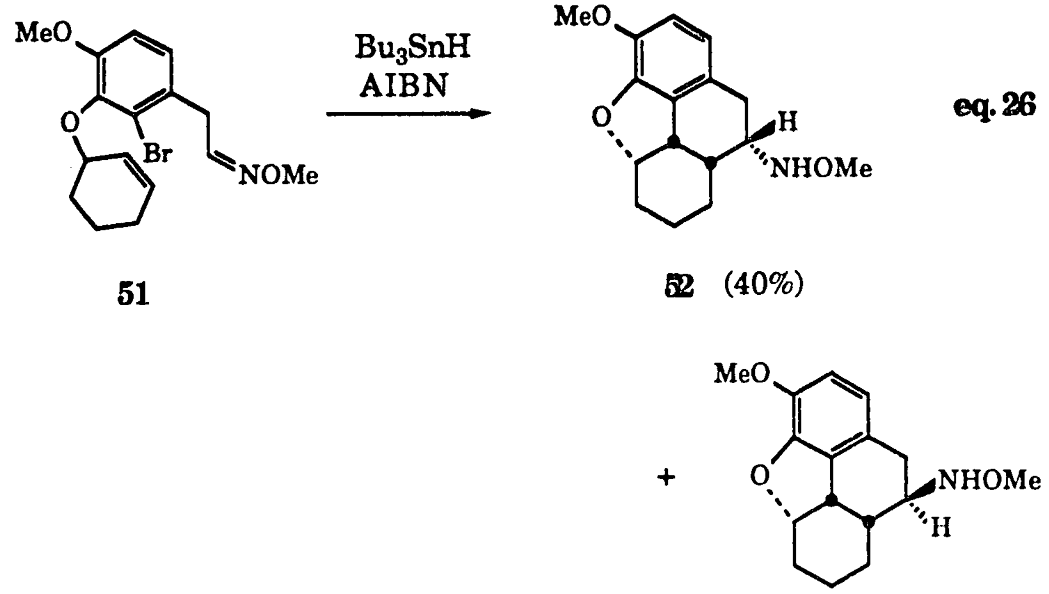
49

50

eq. 25

A β-bromo ether has also been employed by Hanessian and co-workers[35f] in a novel route to a subunit of the avermectins and milbemycins, and a total synthesis of (±)-dihydrocorynantheol was carried out in a similar way by Kametani et al..[35g]

Snieckus[35h, 36] combined the area of directed metallation with radical cyclization. The radical precursors are β-iodoaryl ethers like **54** (eq. 27) which are prepared in 70 - 80% yields as shown. The subsequent radical cyclization produces benzofurans, and in some cases (depending on the precursor) benzopyrans, in 41 - 88% yield.

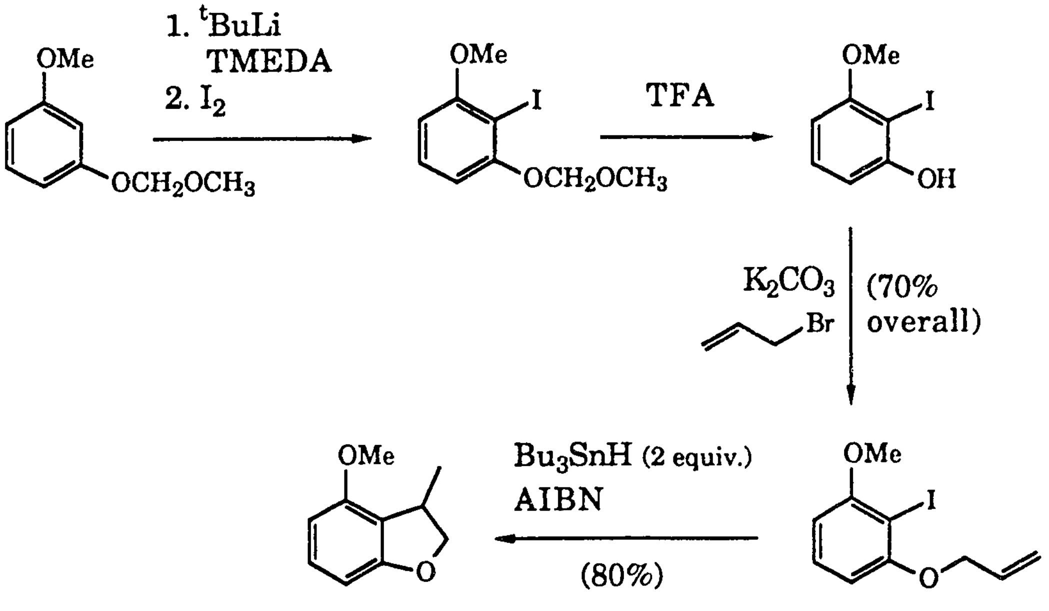


eq. 26

51

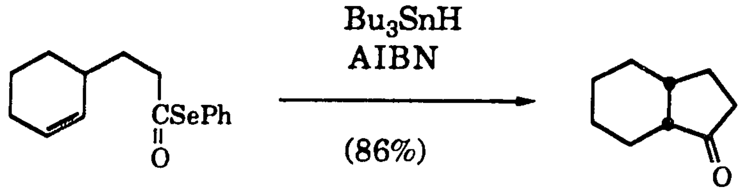
52 (40%)

53 (31%)

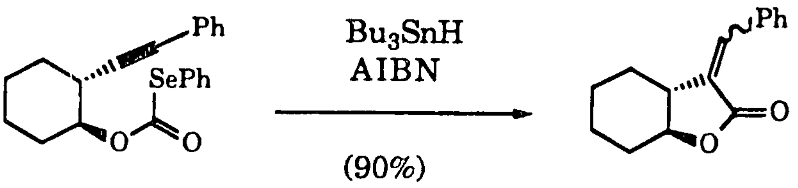


54 **eq. 27**

Some miscellaneous approaches to oxygen heterocycles[37, 38] by methods which do not fit easily into the above categories have been reported including one example of the use of acyl radicals[38a] (see eq. 28) and one involving alkoxycarbonyl radicals[38b] (see eq. 29).

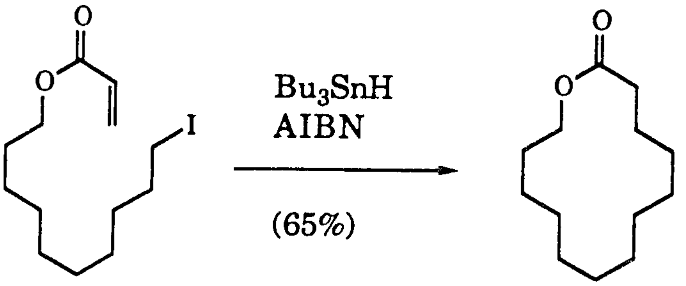


eq. 28



eq. 29

In addition, Porter et al.[39] have developed a route to macrolides via iodo α,β-unsaturated esters (eq. 30).



eq. 30

The various routes to heterocycles discussed above serve to illustrate that radical cyclization is a very powerful method for constructing these molecules. In the area of carbocycle synthesis not as much work has been devoted to the use of radicals and this is perhaps due to the fact that the precursors to heterocyclic molecules are more readily accessible than those needed for carbocycle synthesis. The following is a brief account of the work which has been done on the preparation of carbocycles from appropriate radical precursors.

(B) Radical Cyclization Routes to Carbocycles

The types of carbocycle that have been synthesized by free radical reactions can be classified into three major categories:

(1) Substituted cyclopentanes and cyclohexanes
(2) *Cis* or *trans* ring-fused and spiro carbocycles
(3) Polycyclic carbocycles

Each of these compound groups require different techniques to set up the starting materials for cyclization. A number of special methodologies have been developed for this purpose[40 - 64] and the following discussion will highlight those which appear to be general.

Substituted Cyclopentanes and Cyclohexanes

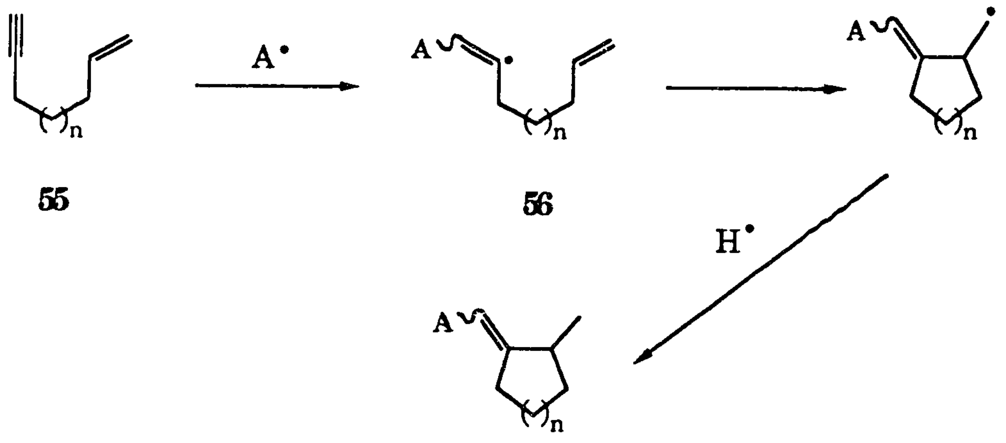
Of the four classes presented above this is by far the largest one, presumably because of the vast number of monocyclic natural products and to the fact that radical cyclization reactions are well suited to their production.

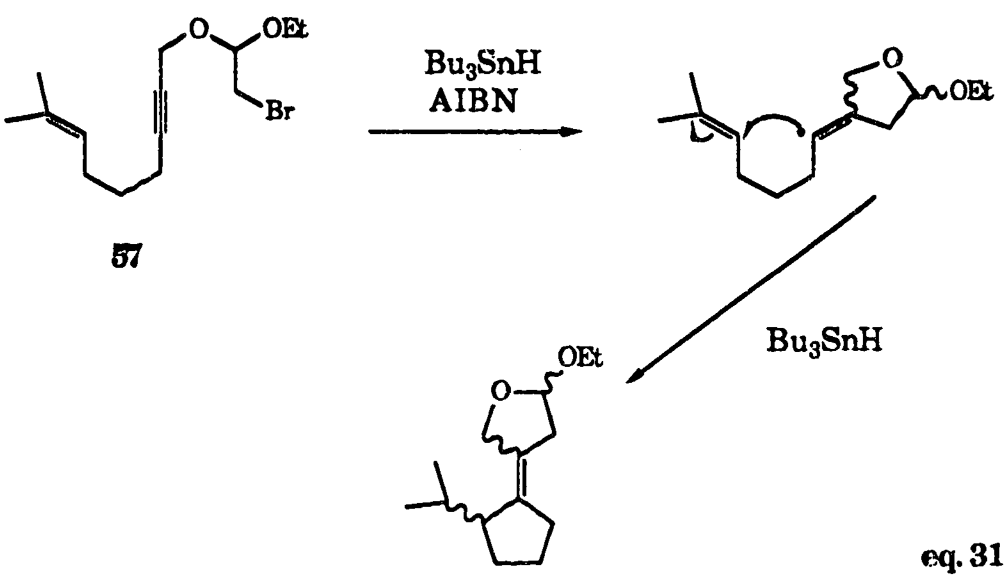
A convenient route to functionalized cyclopentanes or cyclohexanes is via appropriately constituted enynes like **55** (Scheme

8).[40] According to this scheme the radical is produced by selective attack of an external radical **A•** at the triple bond of an enyne which is tethered so as to force closure of the newly-formed vinyl radical **56** onto the double bond. The result is a functionalized carbocycle. This work which was developed by Stork is a natural consequence of one of his earlier studies (eq. 31) in which a vinyl radical is produced by reaction of a bromide, such as, **57** with a stannyl radical.[41]

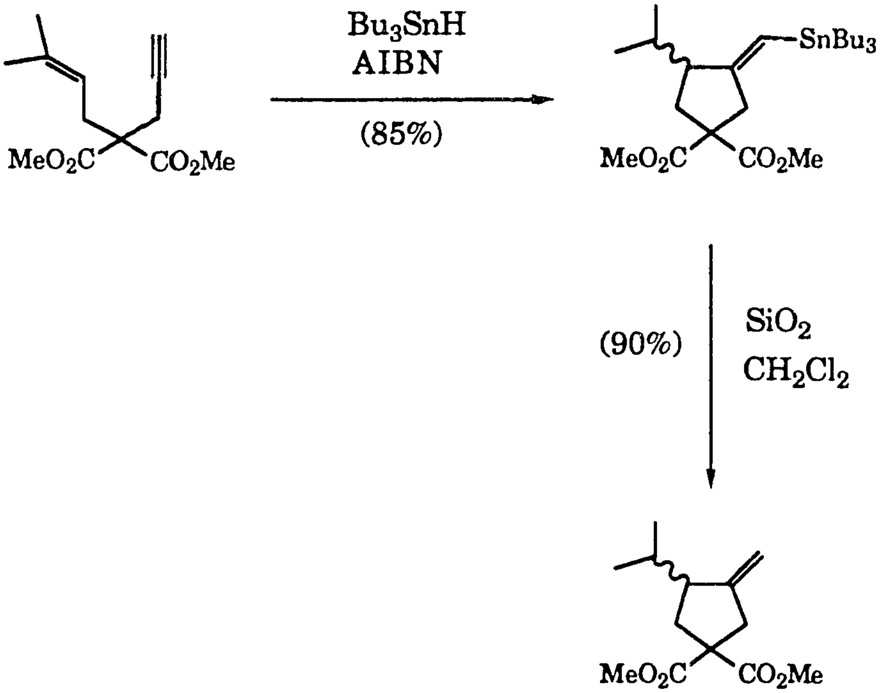
In the former, more general method (Scheme 8), the external radical is also a stannane and an example of the route is illustrated in eq. 32. The tin substituent can be removed easily by stirring the compound with dry silica in methylene chloride.

SCHEME 8



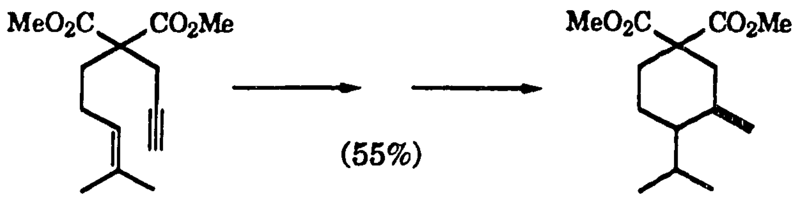


eq. 31

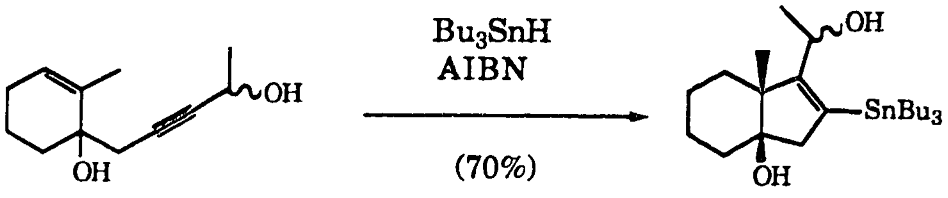


eq. 32

The procedure is amenable to the production of six-membered rings (eq. 33) and also to bicyclic compounds (eq. 34).[40]



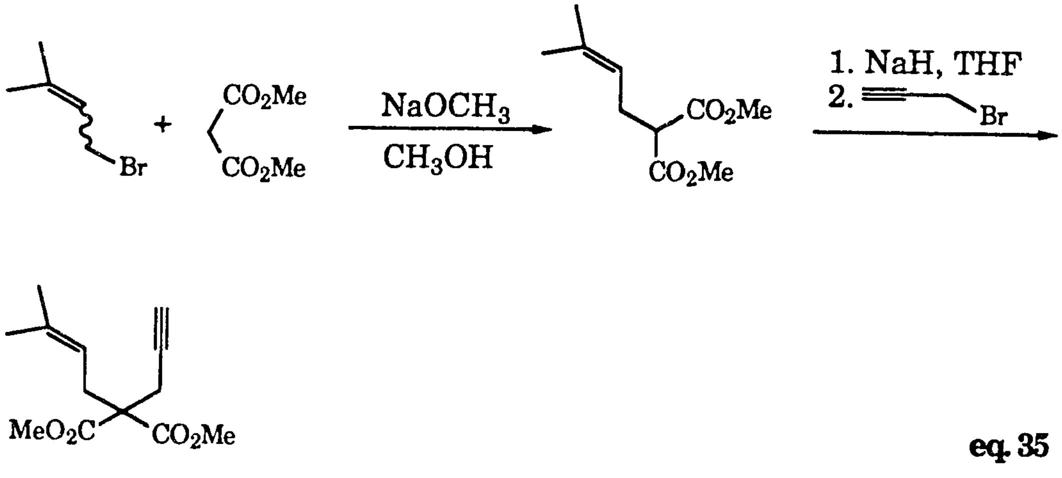
eq. 33



eq. 34

58

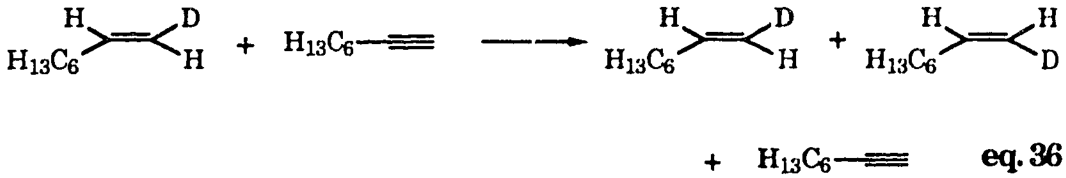
An Organic Syntheses procedure has been published which describes the preparation of the requisite enynes.[42] It involves successive reaction of dimethyl malonate anion first with an allyl bromide and then a propargyl bromide as shown in eq. 35.



eq. 35

Other workers have employed Stork's technique but have used thiophenol as the source of the external radical[43] and in another example a catalytic amount of triethylborane has been used to mediate triphenyltin hydride addition.[44] In the triethylborane method the cyclizations could be conducted at room temperature.

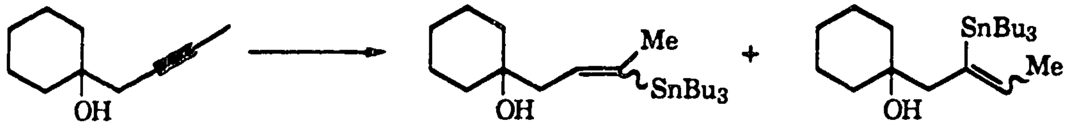
Stork interprets the observed preference of a stannyl radical for a triple over a double bond and the apparent preference for that end of the triple bond which leads to the products just described, as being a result of the reversibility of addition of stannyl radicals to *both* double and triple bonds.[40] His cyclizations are successful because closure is faster, and reversal slower, for vinyl radicals than for similar alkyl ones. Therefore, the cyclization pathway must be via the acetylene-stannyl adduct rather than via the olefin one. Stork proved this with the following experiments. He treated a 1:1 mixture of an olefin and an acetylene with one mole of AIBN and 0.85 equivalents of tributyltin hydride (eq. 36). The result was recovery of a considerable amount of 1-octyne together with (E)- and (Z)-deuterio-1-octene.



eq. 36

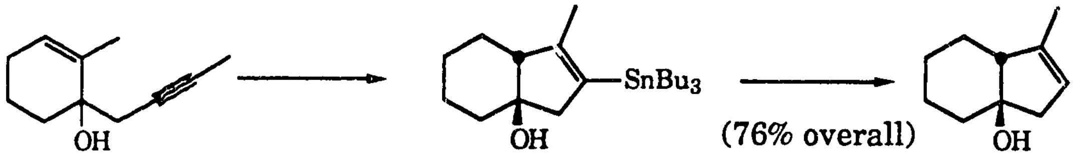
The regioselectivity by the stannane for one end of the triple bond implies reversibility of the acetylene addition and evidence for this was obtained from two other experiments. In one, the ethynylcarbinol **59** (eq.

37) was subjected to Stork's standard cyclization conditions and no addition was observed. When the stannane concentration was increased from 0.02 M to 0.77 M a 1.2:1 mixture of the two possible vinyl stannanes **60** and **61** was obtained in addition to some recovered **59**.



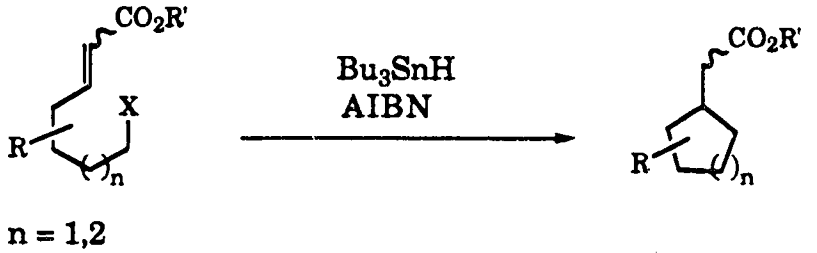
59 **60** **61** **eq. 37**

In the second experiment (eq. 38) **62** was subjected to the standard conditions and it cyclized to **63**. This was subsequently destannylated to **64** in 76% overall yield. The reversibility of addition of stannyl radicals to the triple bonds of **58** and **62** leads to selection of the more rapidly formed ring (five-membered rather than four-membered in these examples) since in the first of the latter two experiments (see eq. 37) both products of stannane addition were formed in similar amounts.



62 **63** **64**
eq. 38

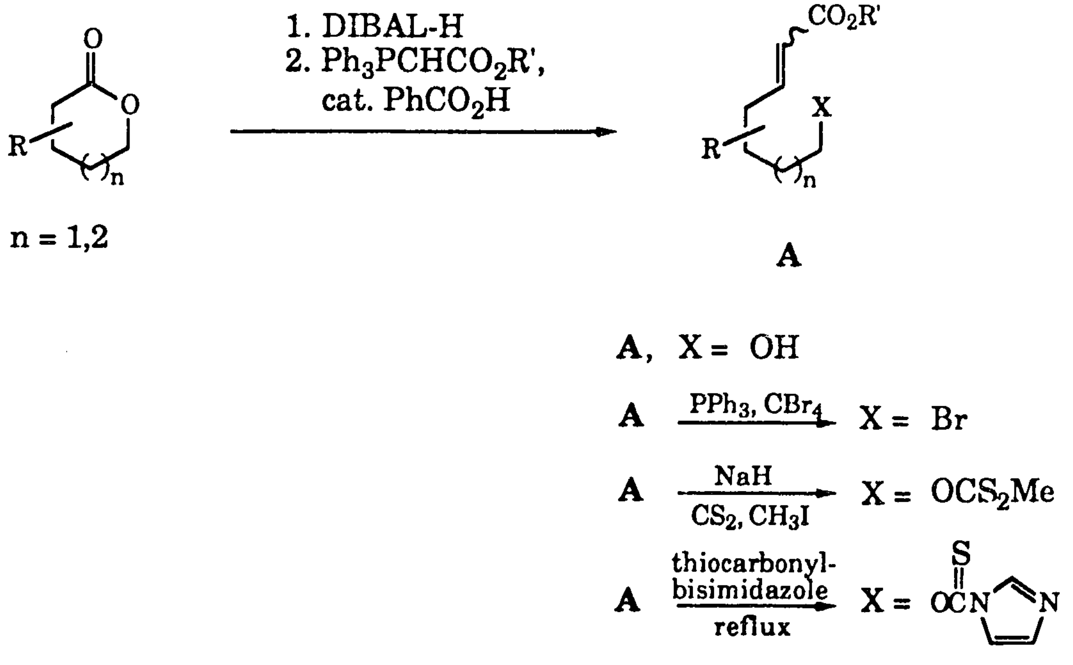
Two groups have prepared functionalized five- and six-membered rings by a different route which involves preparing a radical precursor that, upon reaction with a stannane, will undergo a radical Michael addition process. This is illustrated in eq. 39.[45, 46]

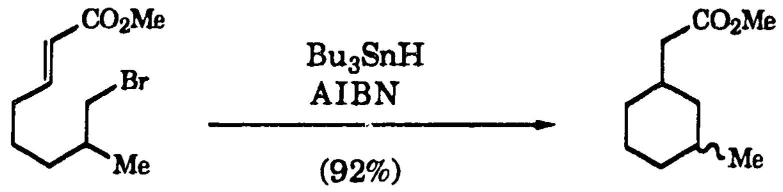


eq. 39

In Hanessian's procedure[45] the radical precursors were prepared from lactones as shown in Scheme 9 and intramolecular radical Michael addition led in high yields to functionalized carbocycles. Both 5- and 6-*exo* modes of ring closure were observed. An example is given in eq 40.

SCHEME 9

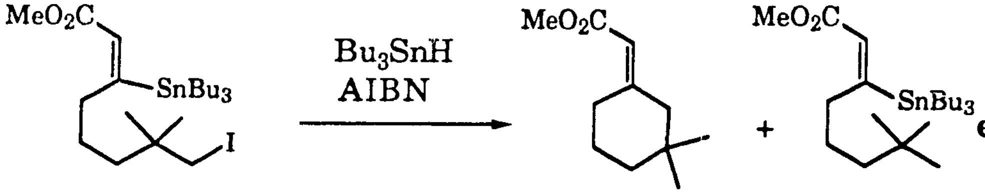




cis:trans
43:57

eq. 40

Harris and Weiler's[46] variation of the radical Michael addition involves use of an olefin which is substituted with a tributyl stannyl group. The radical first cyclizes and then eliminates this unit to afford an exocyclic alkene (eq. 41). The starting iodovinylstannanes were prepared by conjugate addition of tributyltin to a substituted propiolic ester.

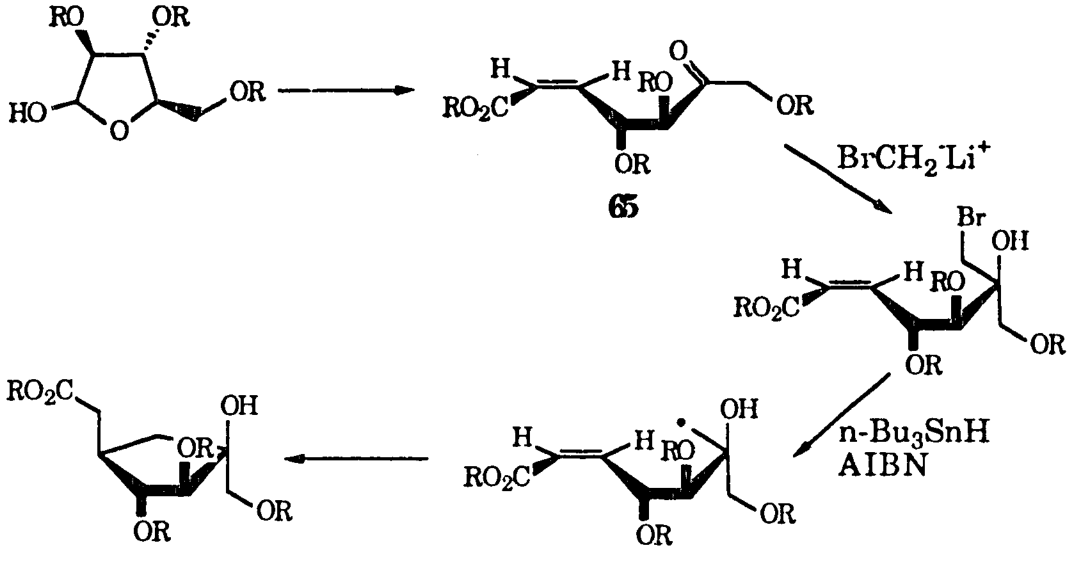


eq. 41

(48%)
E:Z, 77:1

Hydroxylated cyclopentane and cyclohexane derivatives have been produced from carbohydrates and some very interesting methods have been employed to transform these substrates into radical precursors. Examples include the method of Wilcox and co-workers[47] (Scheme 10) in which an aldose is ring-opened by use of a Wittig reagent to give a substituted olefin **65**. Then a one-carbon radical synthon [(bromomethyl)lithium] is added to the ketone functionality which results from oxidation of the alcohol produced in the ring-opening step. This completes the framework of the cyclization precursor **66**. Stannane-induced free radical cyclization affords a carbafuranose in high overall yield.

SCHEME 10

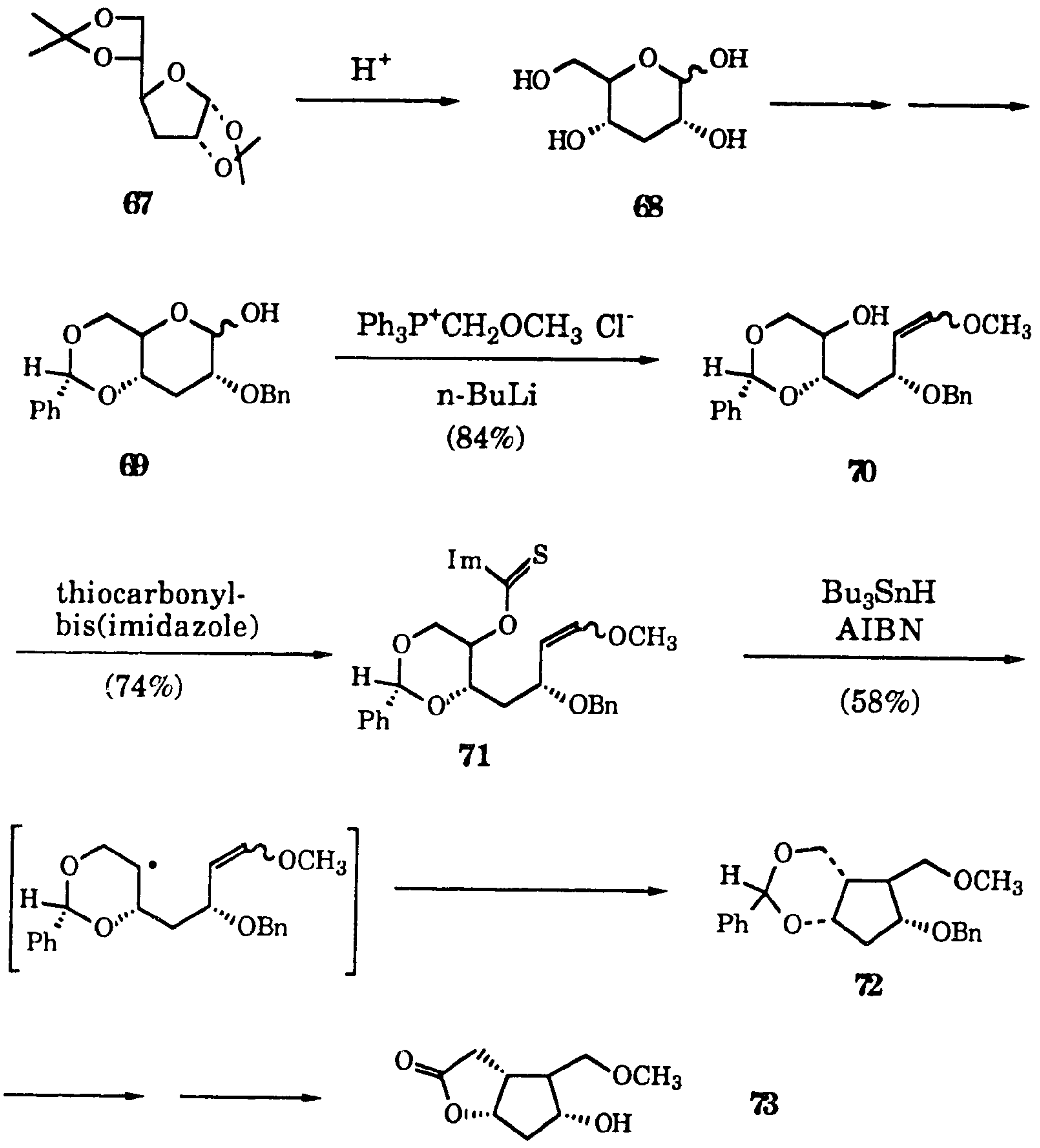


66

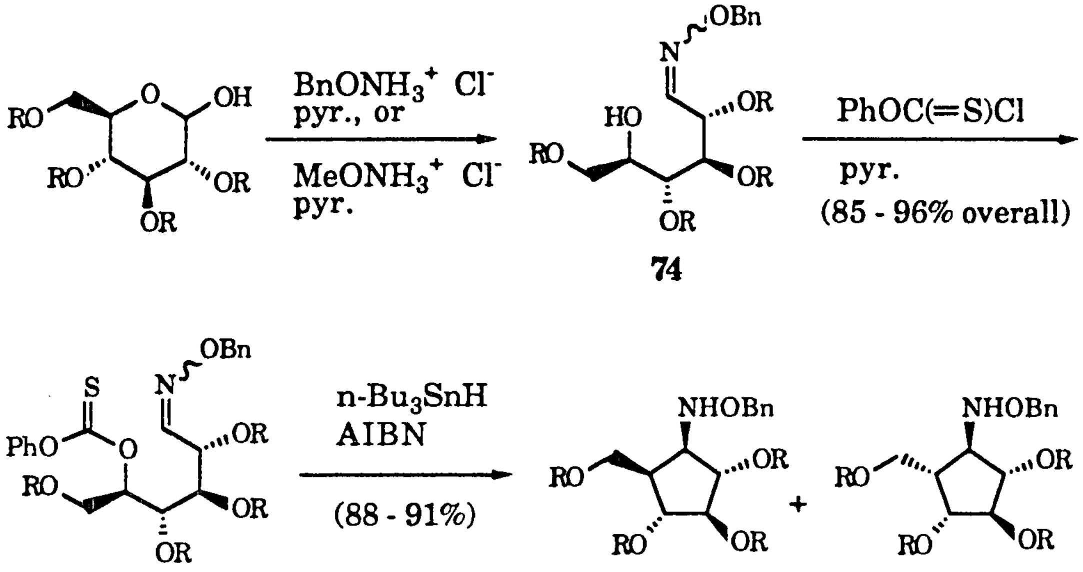
RajanBabu[48] produced the Corey lactone **73**, a well-known prostanoid synthon, by a similar technique (Scheme 11). The method involves acid-catalyzed ring expansion of furanose **67** to pyranose **68**, followed by ring-opening of the protected pyranose **69** using Wittig chemistry. The resulting alcohol **70** is transformed into the protected radical by reaction with thiocarbonylbis(imidazole). Cyclization of **71**, induced by tributyltin hydride, afforded the carbocycle **72** in good yield.

Lactonization by known chemistry gave the Corey lactone **73**. Syntheses of iridoids have been accomplished by Miwa and co-workers[49] using a similar approach.

SCHEME 11

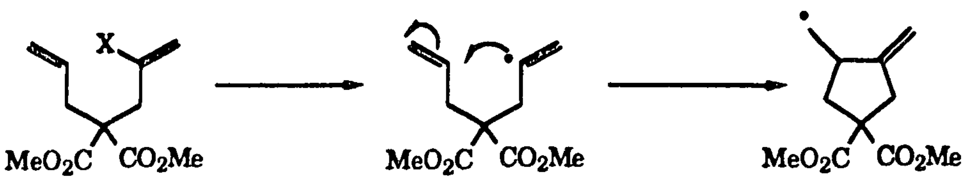


A third variation is Bartlett's[50] very direct route, illustrated in eq. 42, in which O-benzyl oxime ethers **74** are produced directly from pyranose sugars. These give hydroxylated carbocycles upon conversion to an appropriate phenylthiocarbonate or bromide and treatment with a stannane. Bartlett found that the ratio of *cis* to *trans* products varied with the nature of the substituents on the ring.



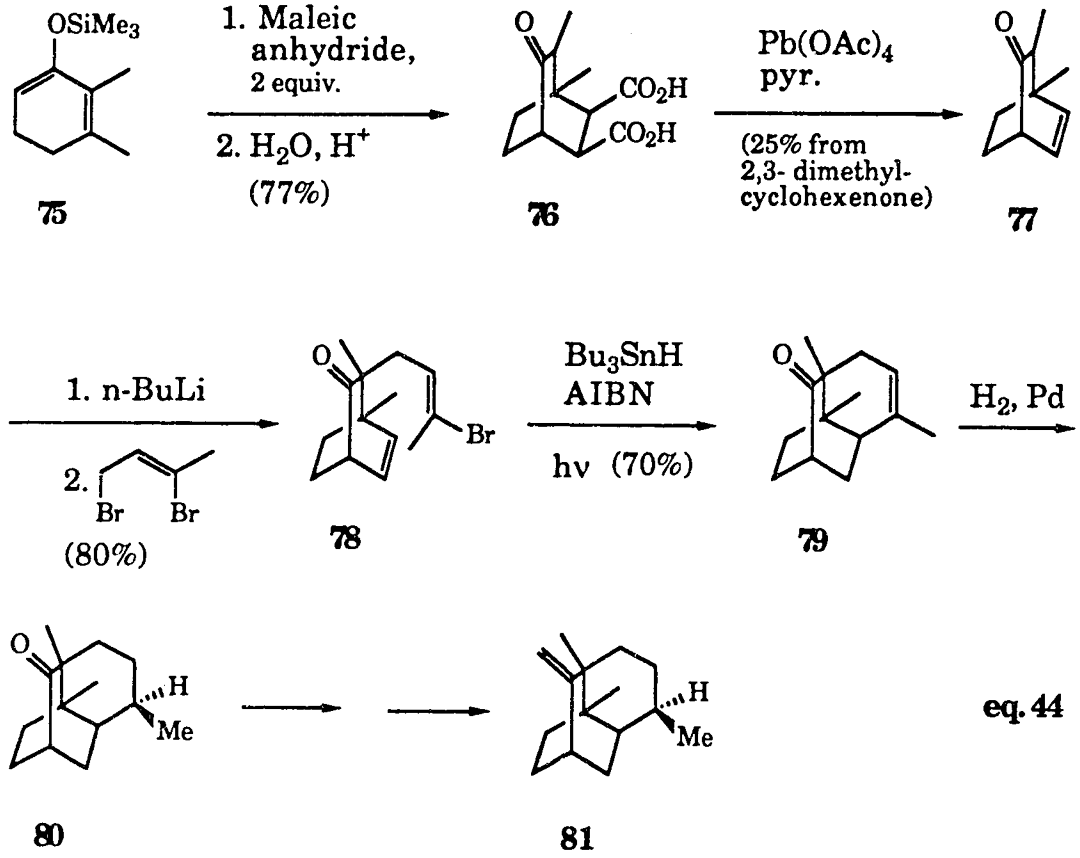
eq. 42

Vinyl halides have been used as precursors for cyclizations that give five- and six-membered carbocycles. The vinyl halides are relatively simple to prepare and an extremely reactive vinyl radical results upon exposure of the halide to a stannane. This readily cyclizes onto a suitably placed olefin or acetylene to produce an alkenyl carbocycle (eq. 43).



eq. 43

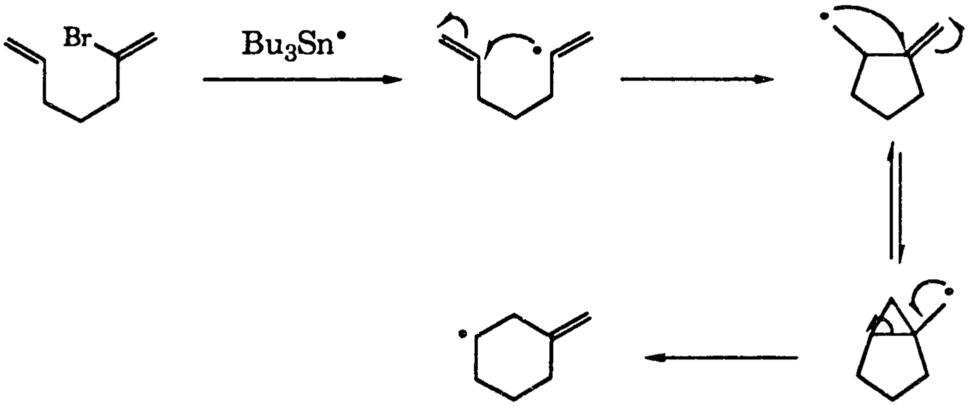
Stork and co-workers[41, 51, 52] introduced this useful method and they have employed it not only in reactions leading to monocyclic compounds but also as a route to bicyclic systems. For example, the sesquiterpene, seychellene **81** (eq. 44) was made in the following way.[52]



eq. 44

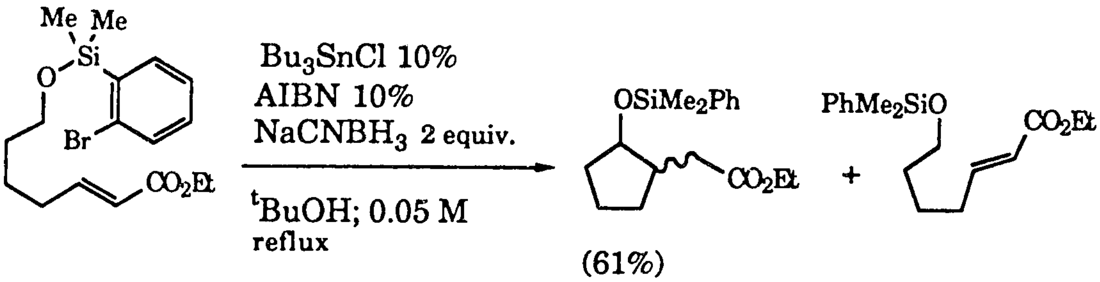
The kinetic lithium enolate of 2,3-dimethylcyclohexenone was trapped as its trimethylsilyl enol ether **75**. Reaction of **75** with two equivalents of maleic anhydride followed by hydrolysis gave the diacid **76**. Oxidative decarboxylation with lead tetraacetate in pyridine provided the bicyclooctenone **77** which was the substrate for alkylation with (*E*)-1,3-dibromo-2-butene. This sequence gave the requisite vinyl bromide **78**, the geometry of which is not significant because the intermediate vinyl radical isomerizes rapidly. The molecule was now set up for vinyl cyclization, and exposure to tributyltin hydride under reflux, with sunlamp irradiation, resulted in a 70% yield of **79**. Simple hydrogenation then led to **80** which previously had been converted into seychellene by other workers.

Beckwith[53] and Marinovic[54] have also studied vinyl radical cyclizations and Beckwith has shown that in some cases (high reaction temperatures and low stannane concentrations) the newly formed radical will undergo rearrangement leading to ring expansion (eq. 45), while Marinovic has determined that bromine is the halogen of choice for vinyl radical formation.



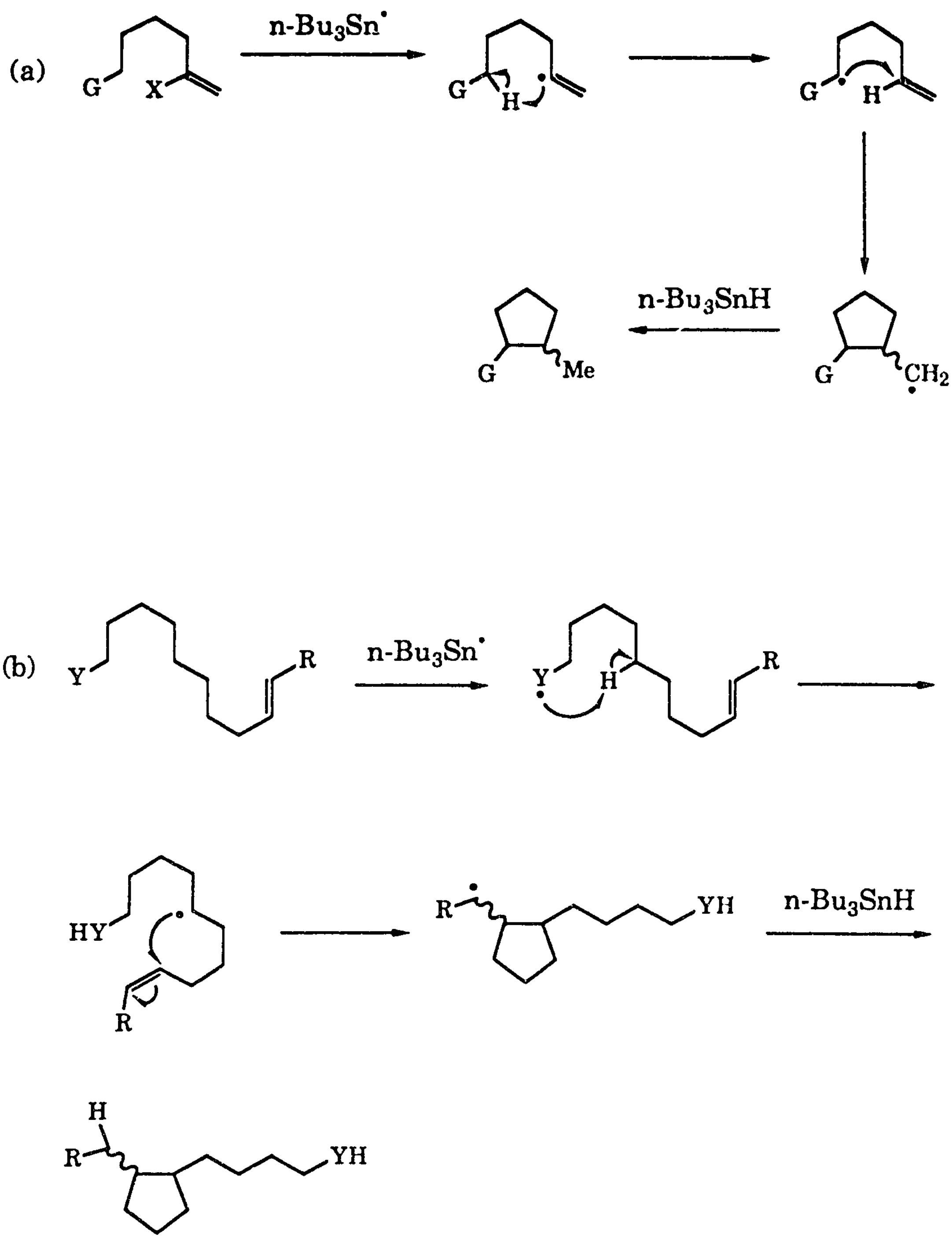
eq. 45

Curran has developed an atom-transfer technique for producing carbocycles in which the free radical is produced indirectly from a C-H bond following the generation of a radical at a remote site.[55] Intramolecular 1,5-hydrogen atom transfer results in translocation of the radical prior to cyclization. There are two variations on this theme (Scheme 12). In method (a), the radical is first generated on a vinyl carbon and then hydrogen abstraction results in formation of an alkyl radical which subsequently closes back onto the double bond. In the second variation, (b), the radical is first generated in a protecting group Y, atom transfer then translocates the radical, and closure onto a suitably located double bond follows. The starting materials for these atom-transfer reactions can be either vinyl halides or protected δ-hydroxy olefins. Such compounds are readily prepared by standard methods. An example of the latter type of cyclization is illustrated in eq. 46.



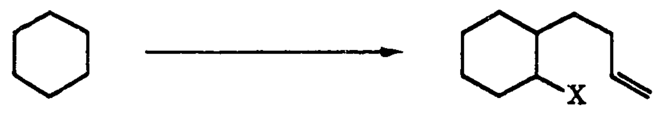
eq. 46

SCHEME 12

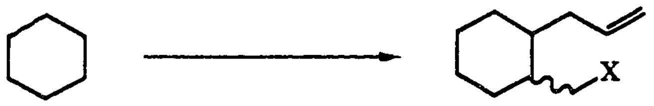


Cis or *Trans* Ring-Fused and Spiro Carbocycles

The production of a fused or spiro ring system by free radical chemistry depends on the ability to attach appropriate groups onto the original ring system so that a second carbocycle will result upon exposure to a stannane. Two general routes are: (1) Attachment of two pendants α to one another on the ring such that one is a radical precursor and the other carries a radical trap (eq. 47 and eq. 48) and, (2) attachment of a single pendant, carrying a protected radical, to a ring which itself acts as the radical trap (eq. 49).



eq. 47

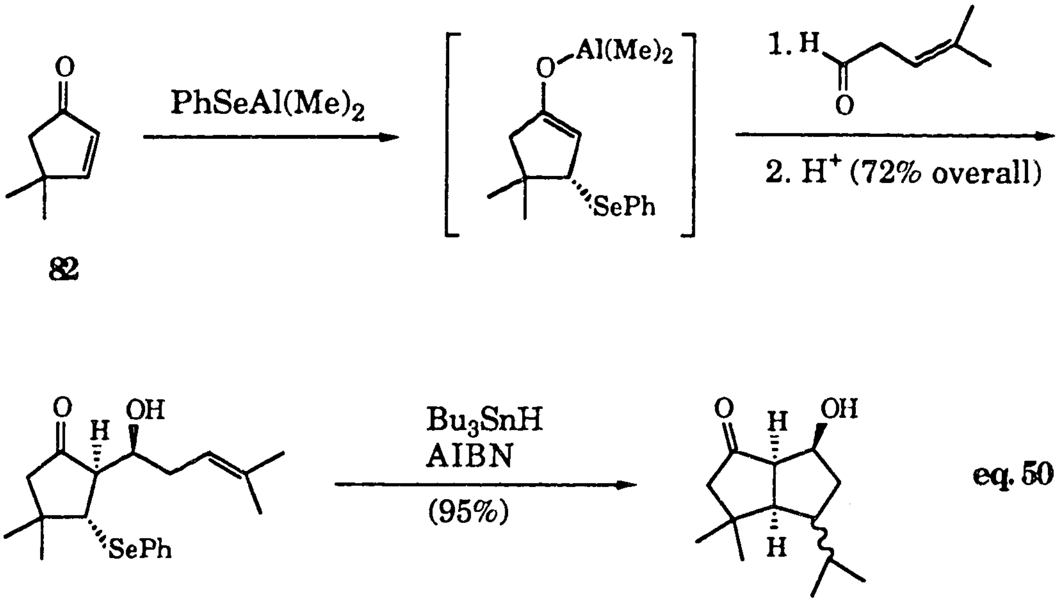


eq. 48

eq. 49

As discussed in more detail later (see p. 55), formation of hydrindanes by the method of eq. 47 or eq. 49 leads to *cis* ring-fusion but, where both the radical and the acceptor are located in pendant groups (eq. 48), the ring-fusion stereochemistry is set by the relative orientation of the chains. Only very recently has the control of ring fusion stereochemistry in bicyclic systems been addressed.[56]

Aldol chemistry was used by Leonard and Livinghouse[57] to produce the 5,5 system illustrated in eq. 50. The radical precursor, a phenylseleno group, and the trapping pendant were attached sequentially to the starting enone by exposure of **82** to (phenylseleno)dimethylalane and then reaction with 4-methylpent-3-en-1-al (to attach the radical trap). The result was predominantly (>20:1) the *trans* erythro-β-(phenylseleno)ketol **83** in 72% yield. The molecule was thereby appropriately constituted to undergo radical cyclization, and exposure to tributyltin hydride at reflux gave the bicyclic ketol **84** in 95% yield.



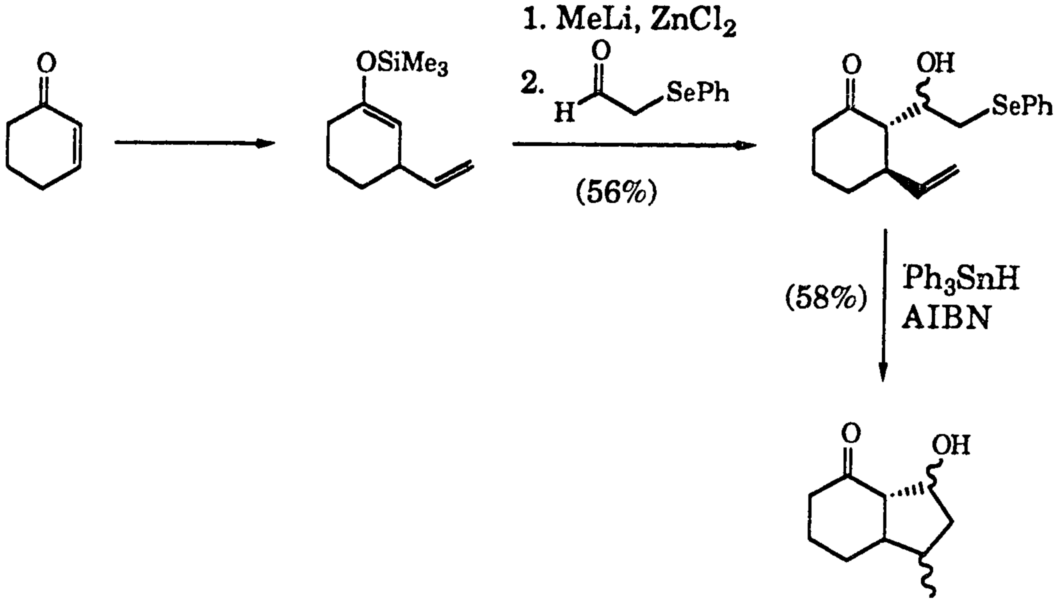
82

83

84

eq. 50

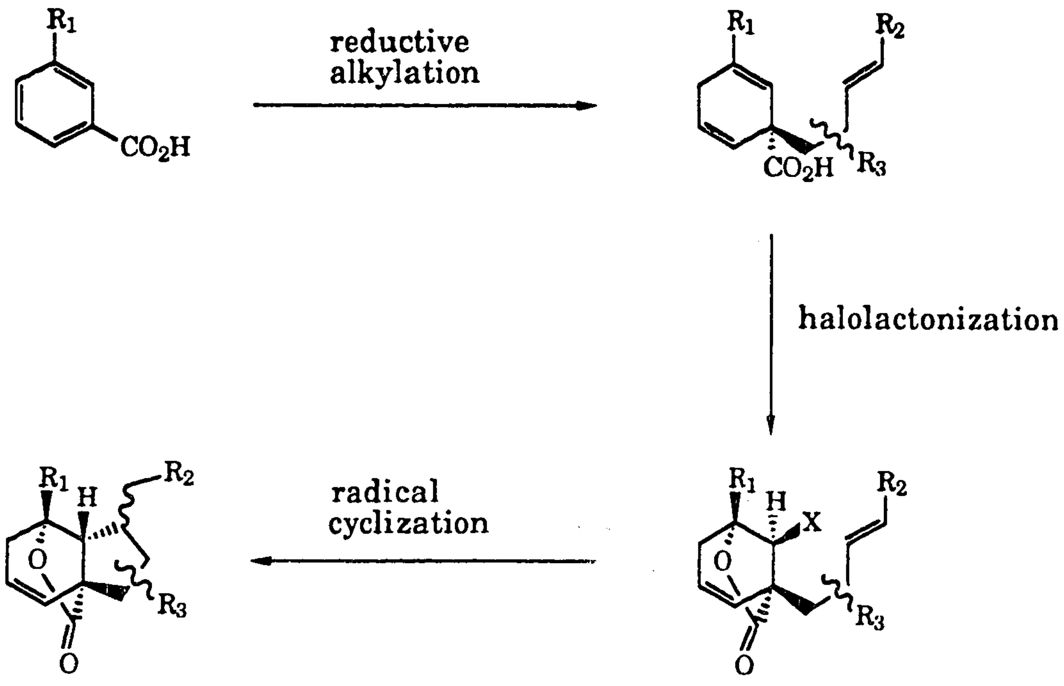
In 1987 work in this laboratory[56a] employed aldol chemistry to produce specifically *trans* ring-fused 6,5 systems by exploiting the preference for di-equatorial placement of large groups onto six-membered rings. The sequence shown schematically in eq. 51 results in formation of a compound which has *trans* disposed pendants and so it undergoes stannane-induced ring closure to give only *trans* bicyclic materials **85**.



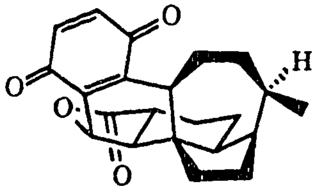
85 eq. 51

Hart and co-workers[56b,c] have done a great deal of work in the refinement of a reductive alkylation-halolactonization sequence to produce molecules suitable for cyclization to *trans* perhydroindans **86**. Their general route is presented in Scheme 13. The trapping pendant is attached in the reductive alkylation step and then halolactonization places the protected radical at a site on the ring suitable for subsequent radical cyclization. *Trans* perhydronaphthalenes are also accessible by this route if the double bond is suitably functionalized so as to favour six-membered ring formation over five. The route has been applied to the total synthesis of the antitumor antibiotic (±)-pleurotin 87.[56c]

SCHEME 13

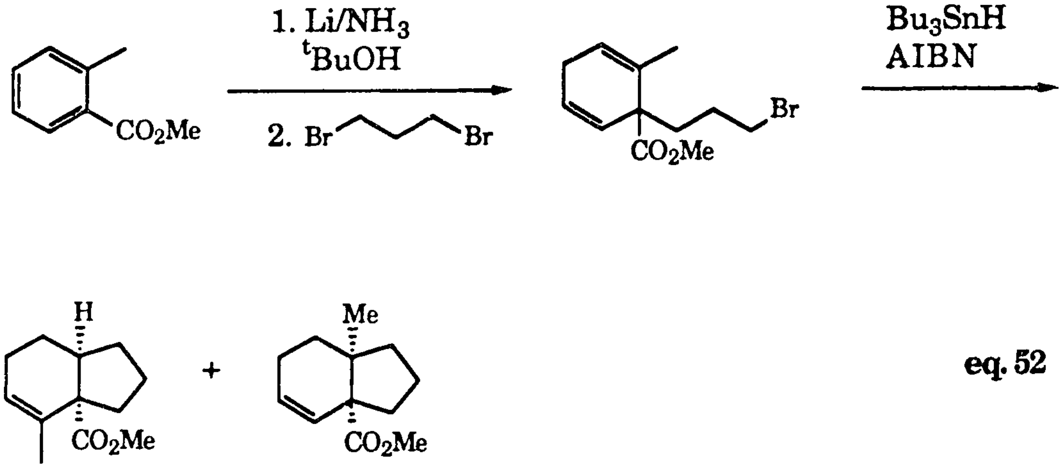


86



87

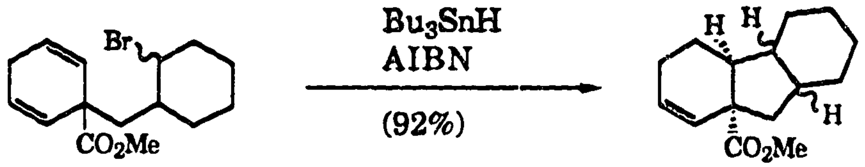
Beckwith and Roberts[56d] have shown that a similar Birch reductive alkylation of suitable aromatic esters (eq. 52) followed directly by radical cyclization leads to *cis*-fused indans. The essential difference between this route and Hart's is that in the previous work the halolactonization step (which Beckwith omits) results in the sterically preferred *cis* ring-fused lactone substructure which then forces the radical cyclization to proceed in a *trans* fashion. In the present work the radical precursor is already attached to the pendant and so cyclization onto the ring results in the favoured *cis* ring-fused products.



(97 : 3)
(85% total yield)

eq. 52

Beckwith applied his strategy to a number of examples including the tricyclic one of eq. 53.

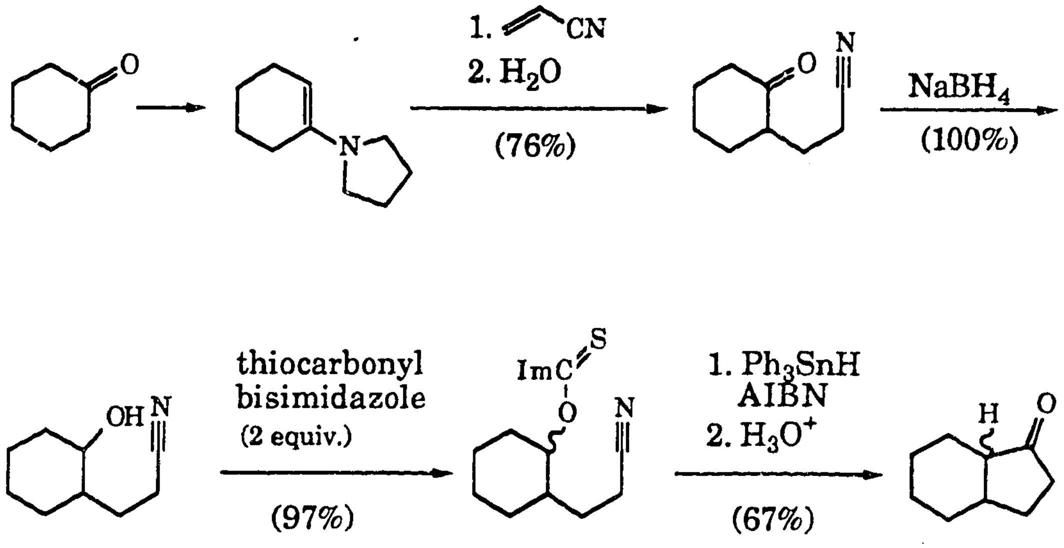


eq. 53

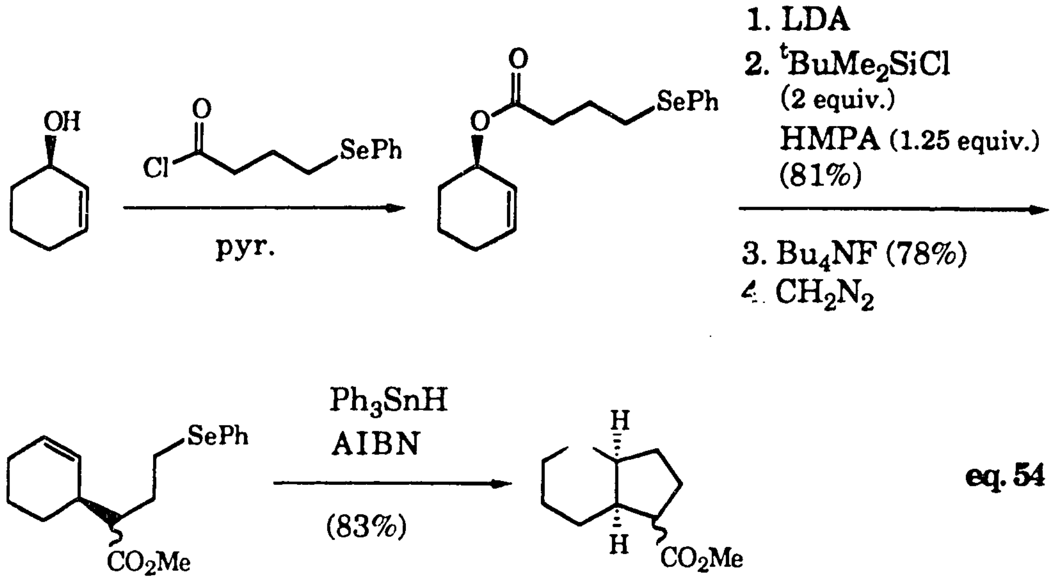
cis, anti, cis : 60%
cis, syn, cis : 24%
cis, anti, trans : 16%

Early routes to bicyclics studied in this laboratory[56e] include the addition of a pendant chain to the starting cyclic compound by enamine chemistry (Scheme 14). Conversion of the ketone to a radical source, as shown, then results in ring closure to yield *cis* and *trans* ring-fused products. Another route[56f] involved the attachment of a pendant chain to the starting ring by Ireland-Claisen rearrangement which serves to deliver the chain to the β carbon stereospecifically.

SCHEME 14



In one of the Ireland-Claisen routes (eq. 54) the chain already contains the radical precursor and so cyclization takes place directly to afford *cis* ring-fused products. In the second case the resulting acid is first converted to the α-keto selenide before ring closure (Scheme 15).

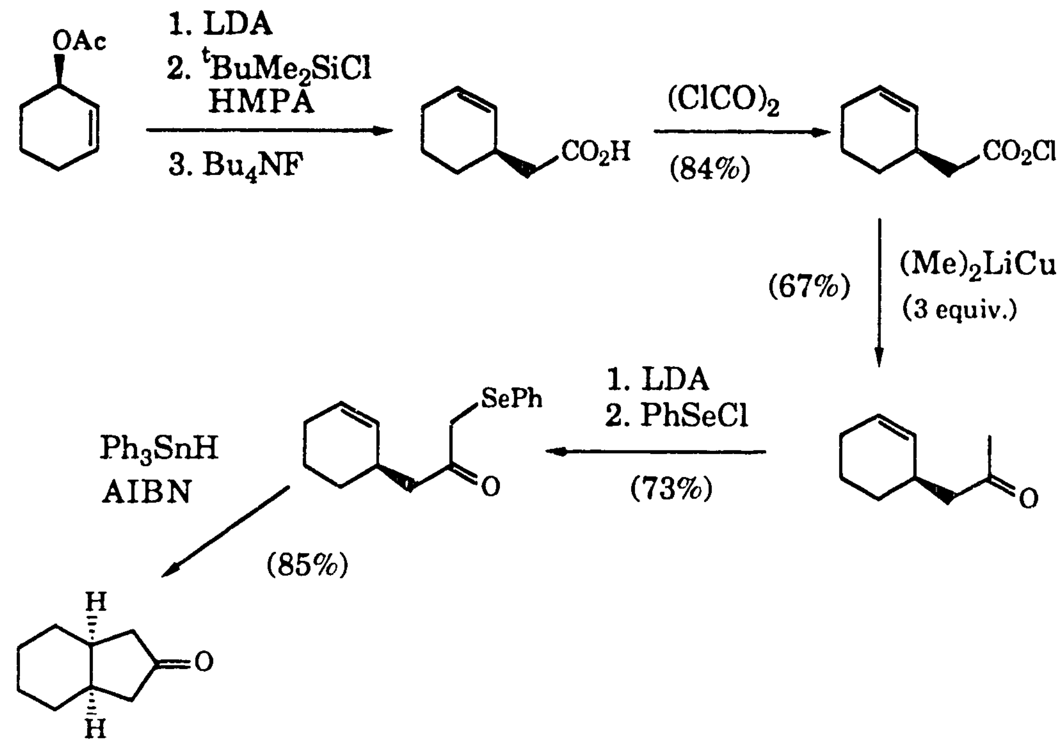


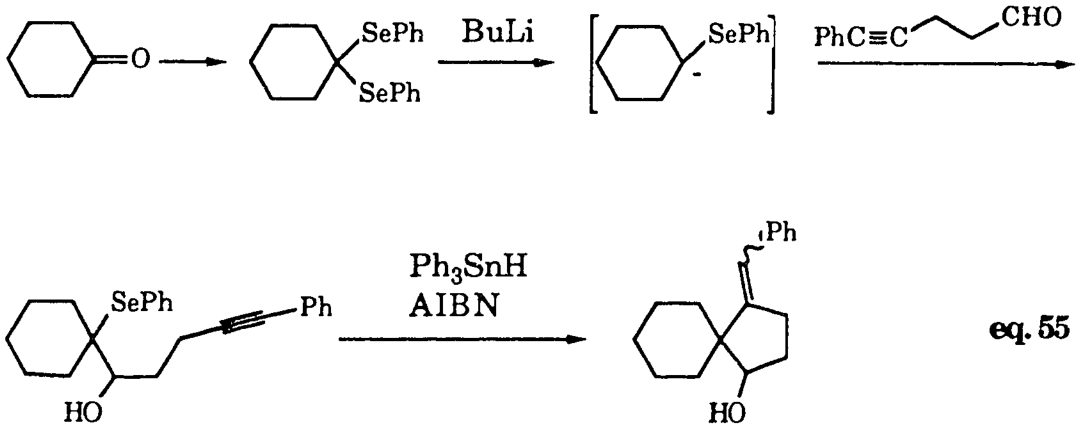
eq. 54

A Michael addition-radical cyclization route to mixtures of *cis* and *trans* ring-fused bicyclics[56g] and specifically to *cis* ring-fused systems[56h] will be presented in the discussion section of this thesis. In addition a route to *trans* ring-fused carbocycles will also be described.

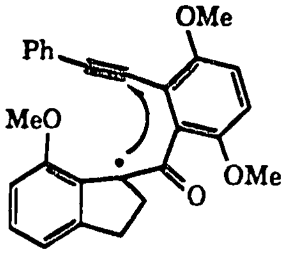
Only a few radical-based methods have been published for the preparation of spiro compounds[58] and these include a methodology developed in this laboratory. The basis of the route[58a] is the method of attachment of both the radical precursor and the trapping pendant to the same carbon of the original carbocycle. This is illustrated in eq. 55. An acetylene is used as the radical trap so as to provide functionality on the spiro system after ring formation. The route was used (see 88) to prepare a model for the top portion of Fredricamycin in this laboratory.[58b]

SCHEME 15





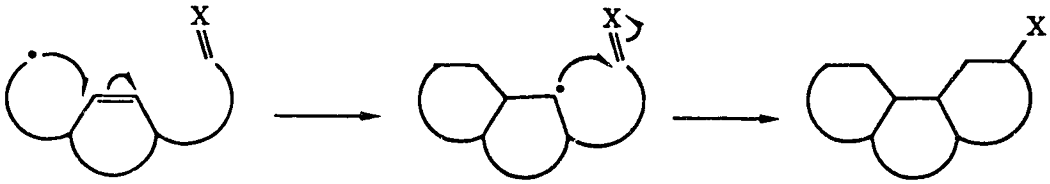
eq. 55



88

Polycyclic Carbocycles

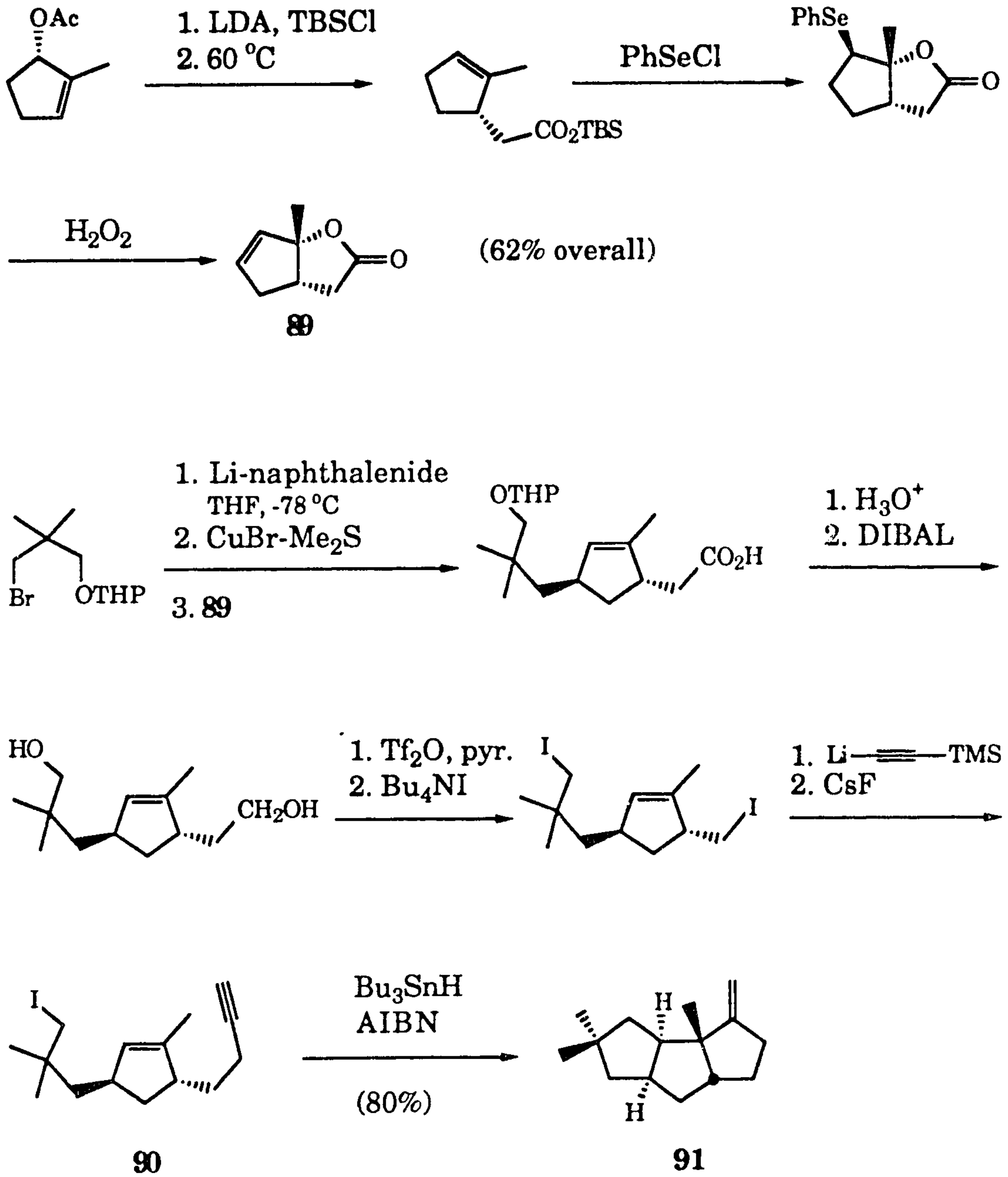
The preparation of tricyclic carbocycles could, in theory, follow directly from work described in the previous two sections. One would simply repeat the cyclization a second time after setting up the newly formed carbocycle for closure. A more efficient strategy, however, is to set up the original uncyclized molecule such that when the radical is generated it closes onto a suitably placed radical trap and, rather than capturing a hydrogen at that stage, the newly formed radical immediately closes onto a second acceptor. In this way three rings can be produced from monocyclic or even acyclic precursors (eq. 56).



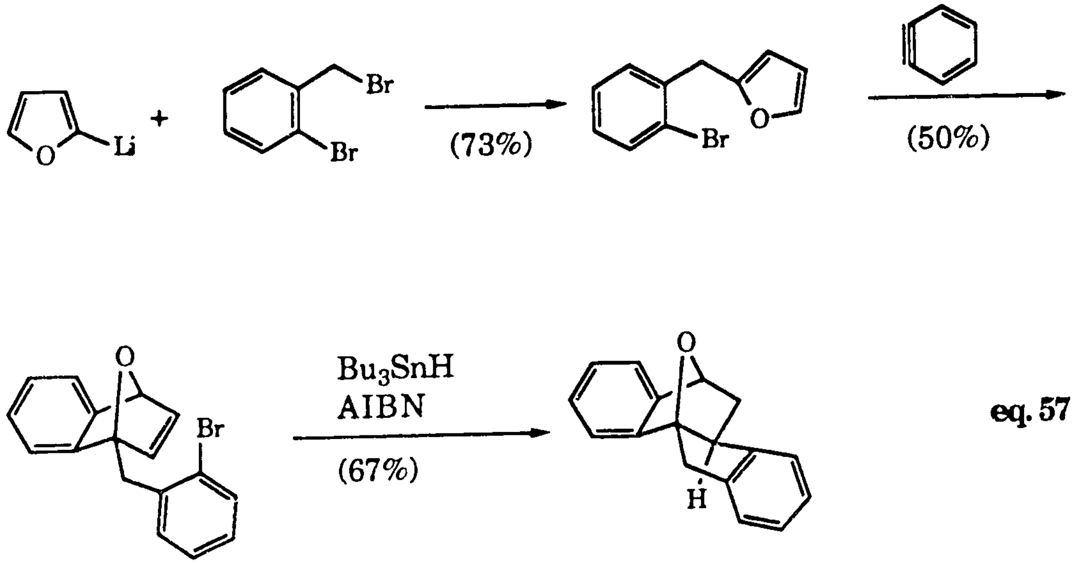
eq. 56

Curran and co-workers[59] pioneered such a route and have applied it to very short syntheses of a number of linear triquinanes such as (±)-hirsutene **91** (Scheme 16). In that example the radical precursor **90** was prepared from the vinyl lactone **89** and then tandem cyclization of **90**, induced by reaction with tributyltin hydride and AIBN, afforded in 80% yield a single substance corresponding to hirsutene **91**.

SCHEME 16



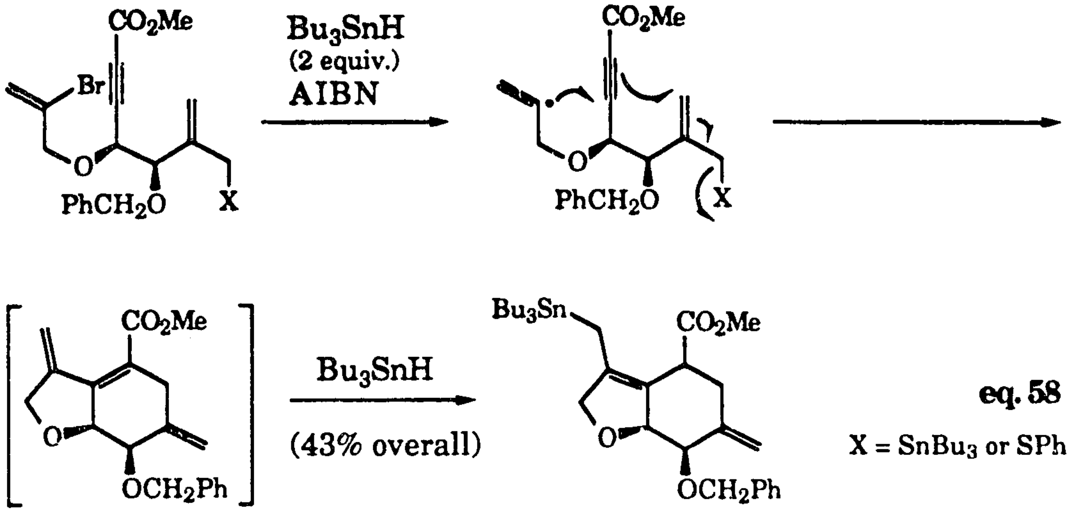
Recently, Hart[60] has shown that polycyclic systems can be obtained by a different route in which a diene that carries an appropriately protected radical is treated successively with a dienophile and a radical source. An example is illustrated in eq. 57.



eq. 57

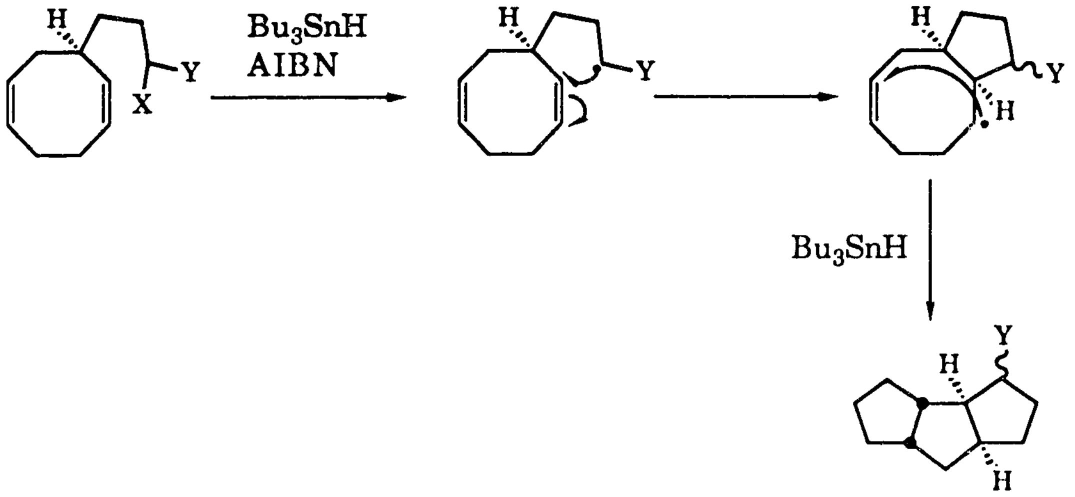
Parsons[61] has utilized a completely acyclic substrate in a sequential radical cyclization to afford the hexahydrobenzofuran skeleton of the avermectins (eq. 58) and Fraser-Reid[62] has employed pyranosides as precursors for similar transformations.

A novel transannular radical cyclization to give linear triquinanes was developed by Winkler.[63] The general strategy is outlined in eq. 59 and it should be pointed out that in this reaction a single stereocenter in the starting material is translated into four contiguous chiral centers in the product.



eq. 58

X = $SnBu_3$ or SPh



eq. 59

It is obvious from the above discussion that the use of free radicals in organic synthesis is becoming widely applicable.[64] There still remains, however, the need for more work in the development of new methodologies for setting up the starting materials for use in radical cyclizations. This is especially true in carbocycle chemistry.

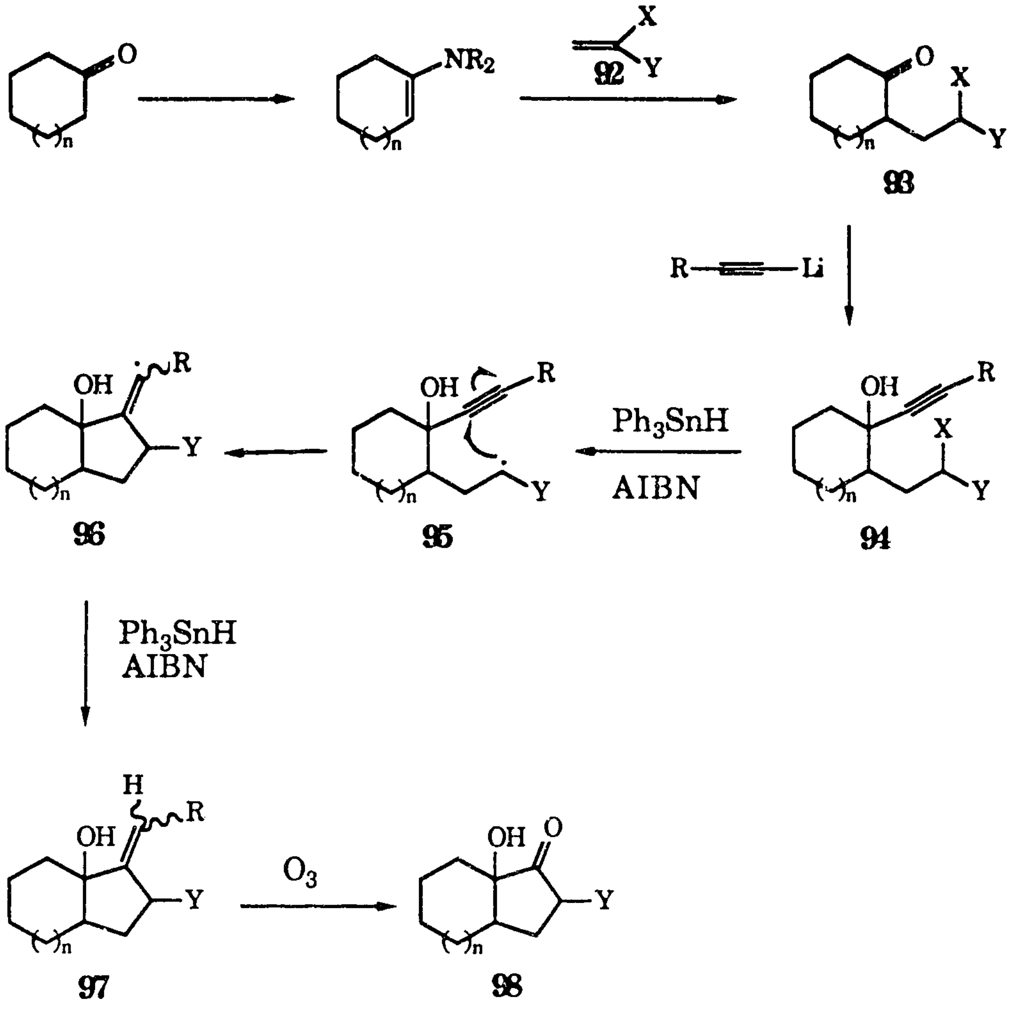
II RESULTS AND DISCUSSION

The widespread use of radical cyclization methodology in organic synthesis depends on the development of new routes for assembling appropriate radical precursors from the types of compounds normally encountered in synthetic work. The methods should be relatively simple, yet general, and they should involve the use of inexpensive and readily available starting materials. To this end we have developed the following routes to *cis* and *trans* ring-fused carbocycles starting from simple carbonyl compounds.

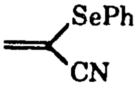
(A) Preparation of *Cis* and *Trans* Ring-Fused Carbocycles

Previous work[65] in this laboratory indicated the potential of a process for making five-membered carbocycles from ketones using a sequence that involves Michael addition and radical cyclization (Scheme 17). A five-membered ring is produced since the radical closure follows a 5-*exo* pathway. In the first step of the sequence a ketone is converted into its enamine, which is then allowed to react with a Michael acceptor **92** carrying groups **X** and **Y** that are chosen on the basis of criteria described below. Treatment of the adduct **93** with a lithium acetylide produces an acetylene. The triple bond is then suitably located to capture the radical (see **95**) produced by treatment with a stannane. Ring closure (**94** → **95** → **96**) affords material that can be cleaved by ozonolysis to a cyclopentanone (**97** → **98**). The ozonolysis step also serves to prove the regiochemistry of the cyclization since a 5-membered ring is produced and this can only come about if the radical closure is 5-*exo*.

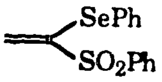
SCHEME 17



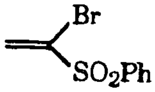
The requirements of the groups **X** and **Y** on the Michael acceptor are that **X** should be of such a nature that the **C-X** bond undergoes homolysis on treatment with a stannyl radical, and that **Y** should be useful as a starting point for further manipulation of the cyclopentanone. Most importantly, however, the Michael acceptor should react in the desired sense with enamines.[66] In preliminary work done on this reaction sequence, the Michael acceptor **99**[67] was used and the results of these examples will be discussed for completeness, although the experimental details are reported elsewhere.[65b] My own work involved elaboration of the method with use of the two phenyl vinyl sulfone derivatives **100**[68] and **101**.[69] These compounds were readily prepared in two steps. Reaction of benzeneselenenyl bromide with phenyl vinyl sulfone followed by base-induced elimination of hydrogen bromide from the product gave **100**, while the successive action of bromine and base on phenyl vinyl sulfone gave **101**.



99



100



101

Each of the three Michael acceptors **99**, **100**, and **101** was found to be quite satisfactory in classical[70] Michael reactions with enamines. For convenience we chose to prepare pyrrolidine enamines derived from common, readily available ketones. The condensations with the Michael acceptors were done simply by adding the Michael acceptor to the crude enamine in THF and stirring the solution at room temperature for a few hours. Mild aqueous hydrolysis then gave ketones (see Table 4), carrying as a radical precursor a bromo or phenylseleno pendant. As expected, each Michael adduct was obtained as a mixture of diastereomers, four in the case of **111a**[71] and two in each of the other

TABLE 4[a]
Carbocycles by Michael Addition - Radical Cyclization

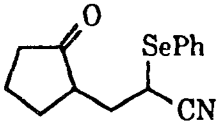
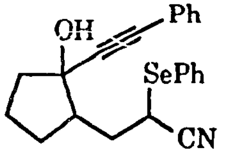
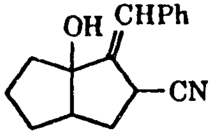
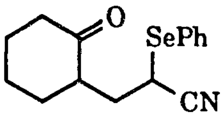
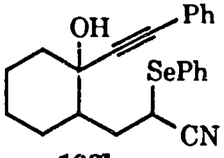
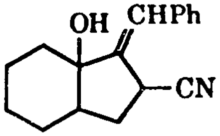
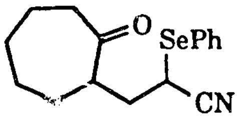
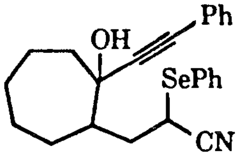
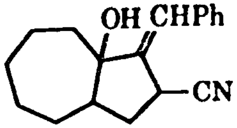
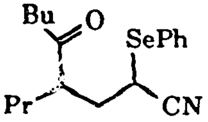
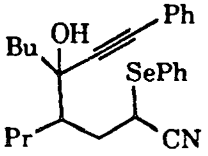
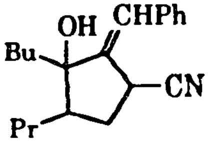
Ketone[b] (% Yield)		**Cyclization Precursor** (% Yield)		**Cyclization Product** [Slow (S) or Fast (F) Addition]	
 **102a**	(~94)[c]	 **102b**	(68)[d]	 **102c**	(S; 89)[e]
 **103a**	(91)[f]	 **103b**	(94)[g]	 **103c**	(S; 91)[h]
 **104a**	(75)[i]	 **104b**	(94)[j]	 **104c**	(S; 91)[k]
 **105a**	(77)[l]	 **105b**	(80)[m]	 **105c**	(S; 79)[n]

TABLE 4 Cont'd[a]

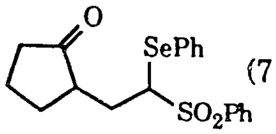
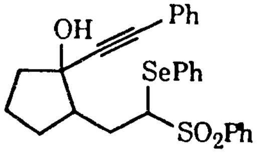
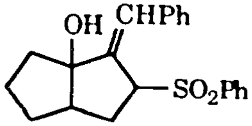
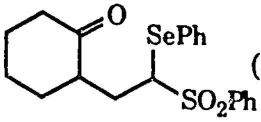
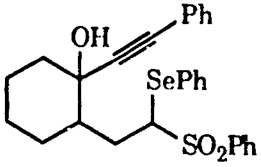
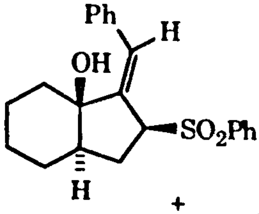
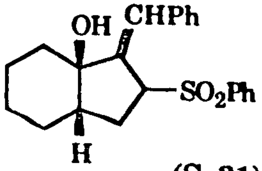
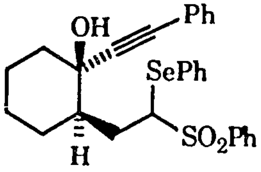
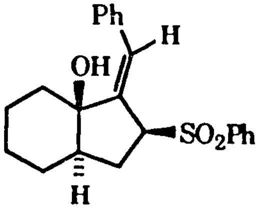
Ketone[b] (% Yield)	**Cyclization Precursor** (% Yield)	**Cyclization Product** [Slow (S) or Fast (F) Addition]
 **106a** (71)[o]	 **106b** (79)[p] (100)[q]	 **106c** (F; 30)[r]
 **107a** (73)[s]	 **107b** (76)[t]	 **107c** (S; 38) +  **107c'** (S; 31)[u]
108a (=107a)	 **108b** (24)[v]	 **108c (=107c)** (F; 55) (90)[q]

TABLE 4 Cont'd[a]

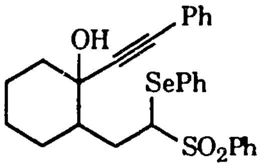
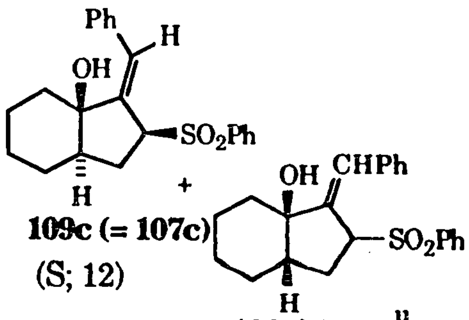
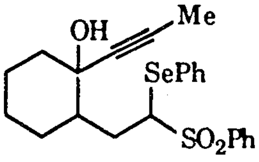
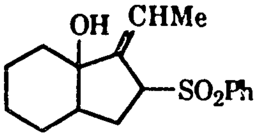
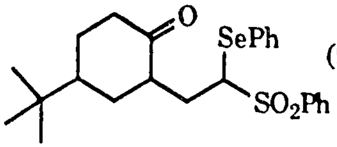
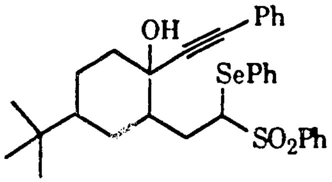
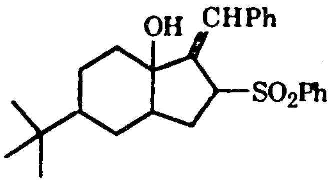
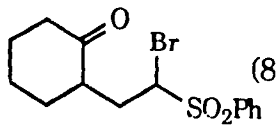
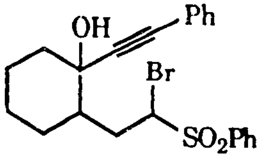
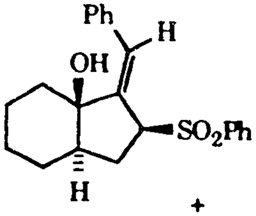
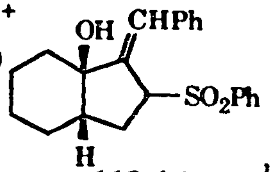
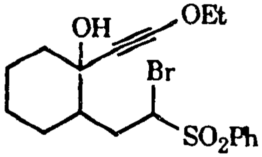
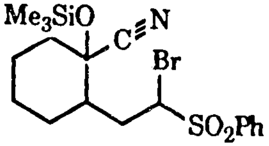
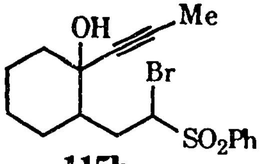
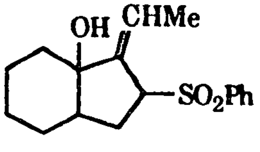
Ketone[b] (% Yield)	**Cyclization Precursor** (% Yield)	**Cyclization Product** [Slow (S) or Fast (F) Addition]
109a (= 107a)	 (16)[w] **109b (=107b)**	 **109c (= 107c)** (S; 12) + **109c' (=107c')**[u] (S; 63)
110a (= 107a)	 (89)[x] **110b**	 (F; 46)[y] **110c**
 (98)[z] **111a**	 (79)[aa] **111b**	 (F; 65)[bb] **111c**

TABLE 4 Cont'd[a]

Ketone[b] (% Yield)	**Cyclization Precursor** (% Yield)	**Cyclization Product** [Slow (S) or Fast (F) Addition]
 (80)[cc] **112a**	 (97)[dd] **112b**	 (F; 92)[ee] **112c (= 107c)** +  **112c' (= 107c')**[ll]
113a (= 112a)	 (96)[ff] **113b**	— [gg]
114a (= 112a)	 (95)[hh] **114b**	0[gg]
115a (= 112a)	 (94)[ii] **115b**	 (F; 90)[jj] **115c (=110c)**

Footnotes to Table 4;

[a] Except where indicated, yields refer to isolated products. [b] Ketones were prepared from the corresponding pyrrolidine enamines. [c] Slight impurities. Two isomers (1:1.1). [d] 68% from enamine. Two isomers (~ 1:1). [e] At least three isomers. [f] Two isomers (1:1). [g] Four isomers (~ 2.2:1.9:1.6:1). [h] At least six isomers. [i] Two isomers (~ 1:1.4). [j] Two main isomers (~ 1:1.1); less than 7.5% of two other isomers. [k] At least three isomers. [l] Two isomers (~ 1:2). [m] Two isomers (1:1); trace of other isomers. [n] At least six isomers. [o] Two isomers (1:1) separated into two fractions: higher R_f (21% yield) corresponding to one isomer; lower R_f (50% yield) corresponding to a mixture of both isomers. [p] Four isomers (1:2.3:3.7:4.3). [q] Corrected for recovered starting material. [r] Mainly one isomer; yield *before* correction for recovered starting material, 25%. [s] Two isomers (1:). [t] Four isomers (2.5:2.75:2.5:1). [u] One isomer. [v] One crystalline isomer obtained in 32% yield from **107b** (24% from **107a**). [w] Three isomers (3.8:1.8:1) obtained in 67% yield by evaporation of mother liquors from crystallization of **107b** (51% from **107a**). [x] Three isomers; the two major components being in a ratio of 1:1.4. [y] Obtained as two fractions: higher R_f (13% yield) was a mixture of two isomers (1:1); lower R_f (23% yield) was a mixture of two other isomers (1:1.6). [z] Four isomers (6.3:4.9:2.1:1). [aa] Four isomers (2.7:1.3:2:1). [bb] Three isomers (3:2:1). [dd] Four isomers (3:2:2.3:1). [ee] Combined yield of **112c** and **112c'**. Ratios of **112c** to **112c'** 2.3:1. [ff] Four isomers (4.8:3.9:4.7:1). [gg] See the text. [hh] Three main isomers (4.3:2.5:1); trace of a fourth isomer. [ii] Three isomers (2:1:1.3). Material that was largely one isomer was obtained by crystallization. [jj] Four isomers (1:1.6:2.2:4.2) identical with **110c**.

examples. The isomer ratios which are different for each case, are indicated in the experimental section.

The individual Michael adducts were then treated with lithium phenylacetylide at low temperature in order to attach the acceptor arm of the molecule required for radical cyclization (see Scheme 17). The yields in the ketone - acetylide reactions were usually quite high and we did not experience any problems due to deprotonation either α to the carbonyl or at the other acidic center.

We chose to use an acetylene instead of a vinyl unit for the acceptor pendant based on the fact that when a double bond captures a radical, in the cyclization process, functionality is lost. In the case of an acetylene the result is a double bond which can be manipulated easily, for example, by ozonolysis.[72] Furthermore, our choice of the *type* of acetylenic unit was based on the fact that the acetylene should be optimally constituted to facilitate the ring closure (see Scheme 17), and since disubstituted acetylenes undergo radical cyclization appreciably faster than terminal acetylenes,* we did not examine the use of acetylene itself (for production of compounds of type **94**, Scheme 17, R = H). In two cases **110b** and **115b**, (see Table 4) the Michael adducts were treated with

---

*The rates of cyclization for the two acetylenes **116** and **117**, have been published in the literature.[73] Compound **116** cyclizes 39 times as fast as compound **117**.

116

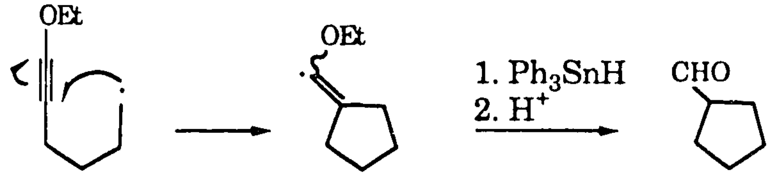
117

the lithium salt of propyne **118** and in one case (**113b**) we examined use of ethoxyacetylene (**119**).

$\mathrm{Me}{-}{\equiv}{-}\mathrm{H}$ $\mathrm{EtO}{-}{\equiv}{-}\mathrm{H}$

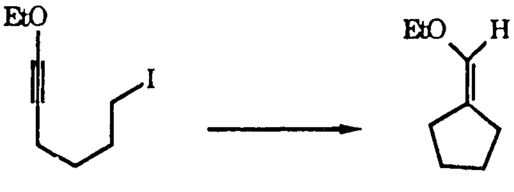
118 **119**

We did this with the specific aim of developing an aldehyde synthesis along the lines of eq 60.



eq. 60

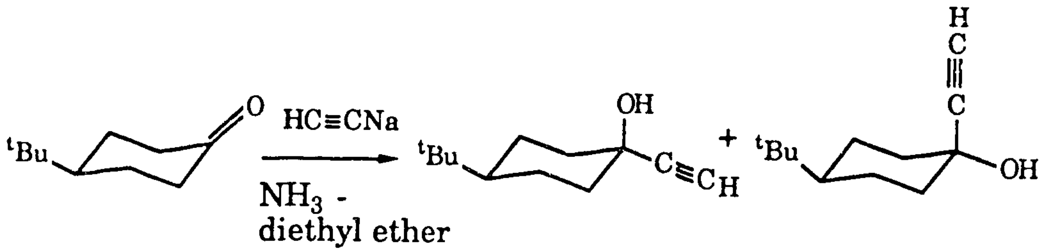
Although Simamura et al.[74] have used radical cyclization onto an ethoxyacetylene unit (eq. 61), our attempts to carry out the cyclization with compound **113b** (see Table 4) were unpromising and gave complex mixtures.



eq. 61

Table 4 lists the hydroxy acetylenes that we prepared as well as one example of a protected hydroxy nitrile (compound **114b**) that was also anticipated[56e] to be suitable for our purposes. Our intention with this example was to obtain a bicyclic ketone in one step rather than in two, as in the acetylene cases, since closure onto a C≡N triple bond would afford an imine which could then be hydrolysed directly to a ketone. In this way the ozonolysis step is avoided. The ease with which ketones form protected cyanohydrins with trimethylsilyl cyanide[75] was also an attractive feature of this route. In the event, however, **114b** did not undergo cyclization although it is known that 5-*exo* closure of a radical onto a nitrile is only slightly slower than onto a terminal acetylene.[76]

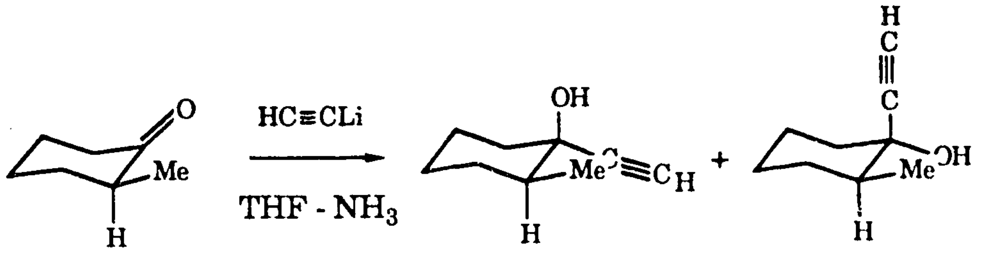
In all cases the hydroxy compounds (Table 4) were obtained as isomer mixtures in the yields given. Except for one case (**108b**, see later), we did not establish the relative stereochemistry of the two pendant groups attached to the original ketone skeleton. Some stereoselectivity was observed, as shown by the isomer ratios. The stereochemistry of the major isomers could not be predicted with confidence from information available[77] on the geometric course of nucleophilic addition of acetylides to α-substituted cycloalkanones. The reason is that although there is an inherent preference for axial attack by an acetylide on a cyclohexanone carbonyl[77, 78] (see eq. 62), this



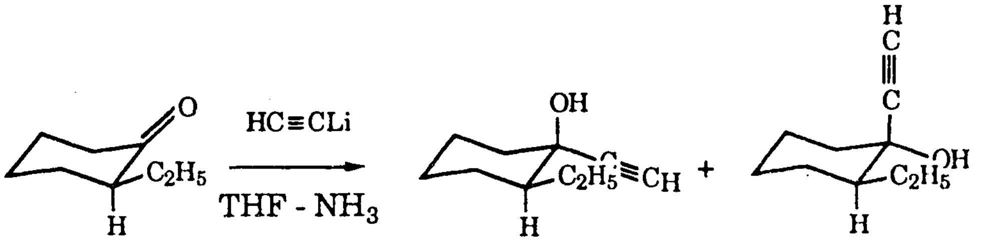
12 : 88

eq. 62

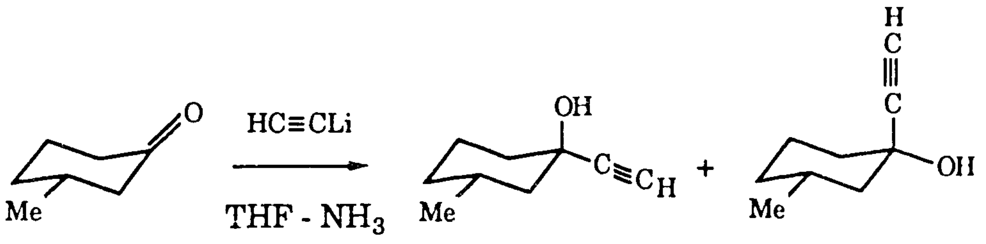
selectivity is easily modified by steric factors and, as the examples of equations 63, 64, and 65 show, seemingly small modifications to the ketone can produce large changes in the selectivity.[77]



45 : 55 **eq. 63**



53 : 47 **eq. 64**



18 : 82 **eq. 65**

In **102b** (Table 4) the pendant chains are probably *cis*; the reason for this tentative assignment is that the yield for the cyclization **102b** → **102c** is high (89%) and material with *trans*-disposed pendants would not be expected[79] to undergo the radical closure effectively.

When the hydroxy acetylenes **107b** were dissolved in a mixture of dichloromethane and hexane, one isomer, **108b**, with the partial stereostructure shown (Table 4), was obtained crystalline in an amount corresponding to 32% of the original mixture. The structure of **108b** followed from an X-ray crystallographic analysis (fig. 1) of its radical cyclization product **108c** (Table 4). The mother liquors from the crystallization of **107b** contained three isomers (**109b**) in a 3.8:1.8:1 ratio. The majority of the species present in this material had *cis* stereochemistry.*

With the hydroxy acetylenes in hand, we next examined the radical cyclization (**94** → **97**, Scheme 17). Two experimental procedures were adopted. In the first of these (slow addition), separate, dilute benzene solutions of triphenyltin hydride and of AIBN were injected simultaneously over about 8 hours into a refluxing solution of the selenide or bromide in the same solvent. The second method (fast addition), which was tried only with the sulfones, involved adding all of the stannane and AIBN in one portion at the beginning of the

---

*This was deduced by radical cyclization to **109c** (=**107c**) (12%) and **109c'** (=**107c'**) (63%). Ozonolysis of the major product **109c'** from this reaction gave two isomeric ketones (see Table 5, **107c''**) that were different from those produced by ozonolysis of compound **108c** for which the X-ray crystal structure had been obtained (fig. 1). It follows that the stereochemistry of the major species in the mother liquors is as shown.

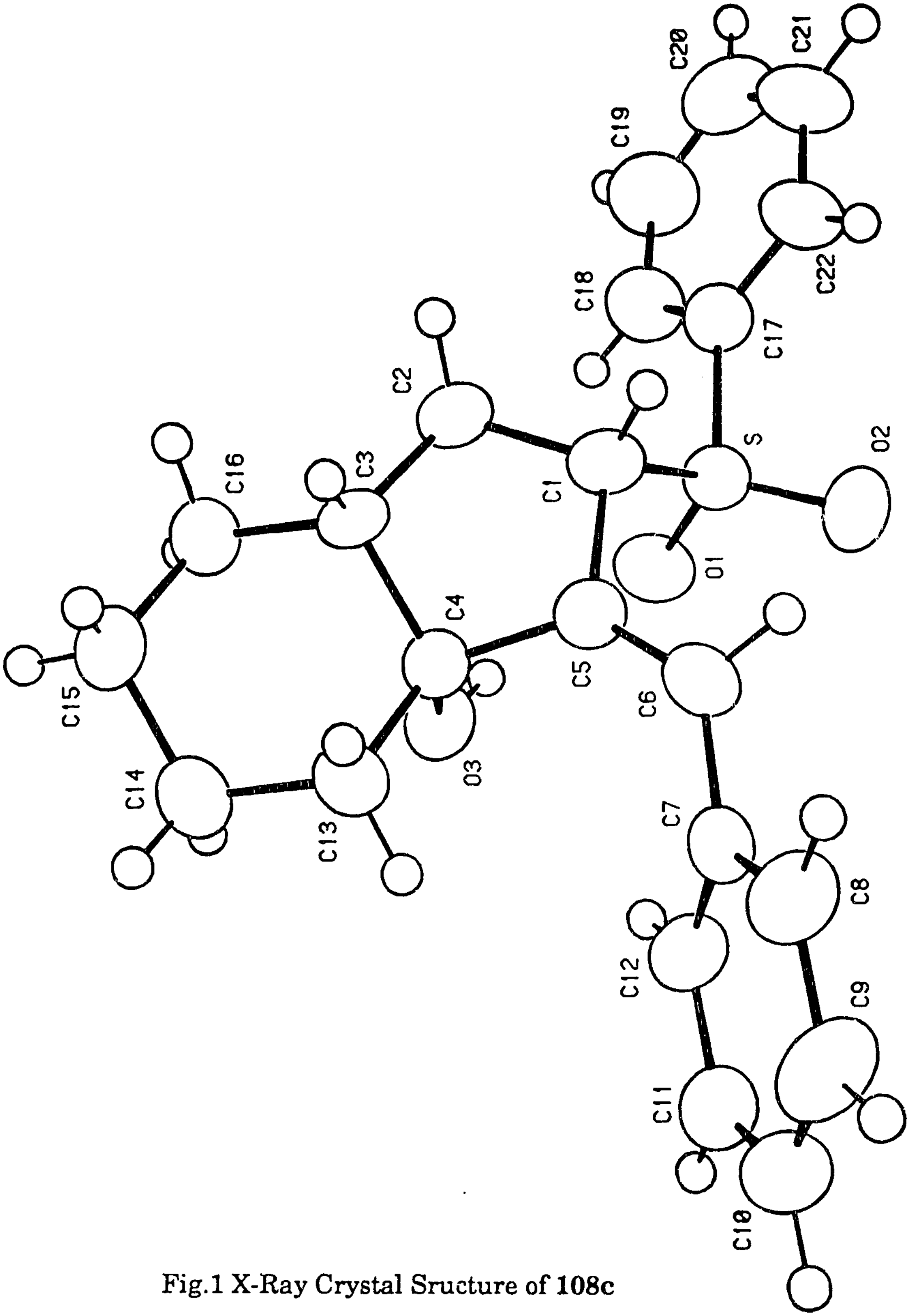
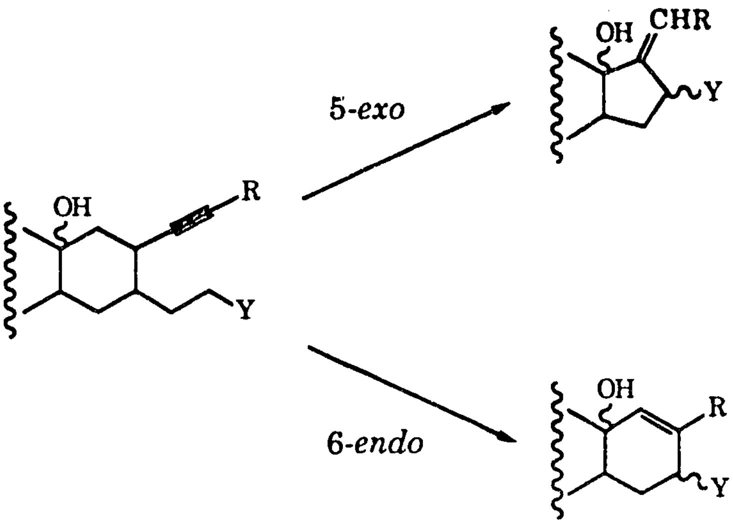


Fig.1 X-Ray Crystal Sructure of **108c**

experiment. Our results are shown in Table 4 (**102c** – **115c**). We observed no real advantage other than that of convenience in the fast addition route for cyclization. In no case did we detect products arising from hydrogen abstraction from the stannane rather than cyclization even in the fast addition examples. The fact that this experimentally convenient technique is successful shows that α-sulfonyl carbon radicals cyclize onto the substituted triple bond faster than they abstract hydrogen from the stannane (even at the initial prevailing concentration of *ca.* 0.2 M of stannane).

Our use of triphenyl- as opposed to tributyltin hydride was made on the following basis: When the stannane reduction of selenides was developed in this laboratory,[80] most of the examples were such that the reaction products did not contain any aromatic hydrogens. Consequently, use of triphenyltin hydride offered a convenient spectroscopic method for proving the absence of organotin compounds in the cyclization products, since the low-field region of the ^{1}H NMR spectrum was devoid of signals if the material was pure. We continued to use triphenyltin hydride because it had proved satisfactory in the earlier work. The aromatic stannane is also less volatile than its aliphatic analogue and this can be an advantage, though a minor one.

During the course of this work we were concerned with the regiochemistry of the cyclization, as both 5-*exo* (which was observed) and 6-*endo* closure are allowed (eq. 66) by Baldwin's rules.[8]

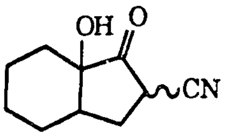
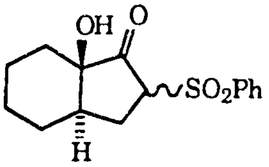
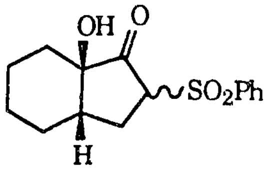


eq. 66

Compound **108c** (Table 4) was obtained crystalline and its structure was determined by X-ray diffraction analysis (fig. 1), as mentioned earlier but, in order to be certain that we were not seeing any 6-*endo* products, we did the following experiments. Compounds **103c**, **108c**, and a mixture of **107c** and **107c'** were ozonized on an appropriate scale to allow isolation of the products (Table 5). These were easily identified as cyclopentanones by IR absorption in the range 1744 - 1750 cm^{-1}. In these cases (Table 5), the major cyclization pathway, if not all of it, must have been 5-*exo*. The ozonolysis experiments also serve to show that the radical cyclization products are synthetically equivalent to ketones.

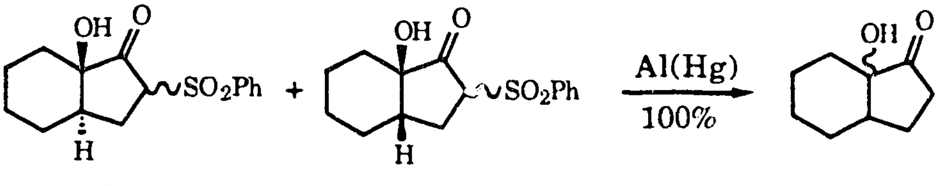
Additional evidence for 5-*exo* closure is apparent in compounds **110c** and **115c** (Table 4) which must have the structures indicated, since the vinyl signals of the products had coupling constants (*ca.* 7 Hz) that defined the presence of ethylidene groups. The chemical shifts of the vinylic signals of **102c**, **104c**, **105c**, **106c**, and **111c** (Table 4) were all similar to those of the compounds for which structures were determined by ozonolysis or X-ray analysis, and the structural assignments shown are based on this fact.[81]

TABLE 5
Hydroxy Ketones

Cyclization Product	Ozonolysis Product	(% Yield)[a]
103c	 **103d**	(79)
108c	 **108d**	(71)[b]
107c + 107c'	**107d (= 108d)** (27)[b] +  **107d'**	(40)[c]

[a] Yields refer to isolated material. [b] Two isomers (1:1.1).
[c] Two isomers.

The sulfone functionality of the cyclization products is available for further manipulation, or it can be removed.[82] Desulfonylation was carried out in one case: A mixture of isomers corresponding to **107c** and **107c'** was ozonized and the resulting ketones (**107d** and **107d'**) were treated with aluminum amalgam. *Cis* and *trans* ring-fused ketones **107e** (eq. 67) were produced in quantitative yield.



107d **107d'** **107e**

eq. 67

The Michael addition - radical cyclization sequence which has been presented in this section is a simple method for construction of five-membered rings which, on ozonolysis, give cyclopentanones. The products are mixtures of both *cis* and *trans* ring-fused carbocycles. In the next section the problem of controlling ring-fusion stereochemistry will be addressed.

(B) Preparation of *Cis* Ring-Fused Carbocycles

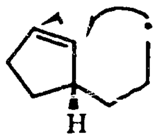
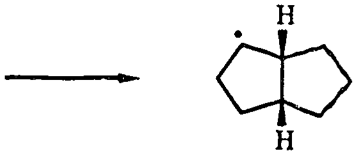
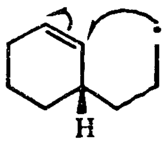
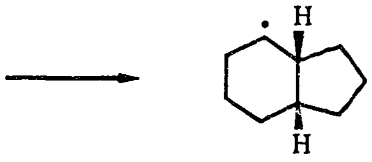
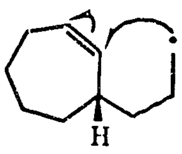
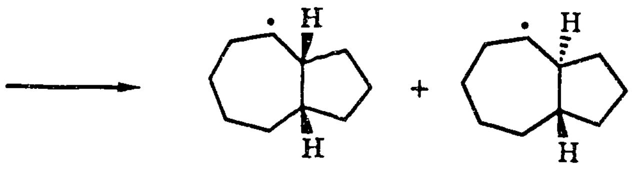
Our approach to the problem of controlling ring-fusion stereochemistry involved modifying the Michael addition - radical cyclization sequence. The basis of our method depends on the following rules. In reactions in which a bicyclic compound is produced by a sequence of the type shown in eq. 68 the stereochemistry of the ring-fusion can be predicted.[56a, 83]

eq. 68

It is useful to introduce a simple nomenclature to discuss this process. The ring closure sequence shown as entry 1 in Table 6 will be described as a 5-*exo*-[*endo*-5] closure. The first part of the name "5-*exo*" has the standard definition and indicates the status of the double bond with respect to the ring being formed; the second part of the name indicates that the double bond is *endocyclic* to a five membered ring.

TABLE 6

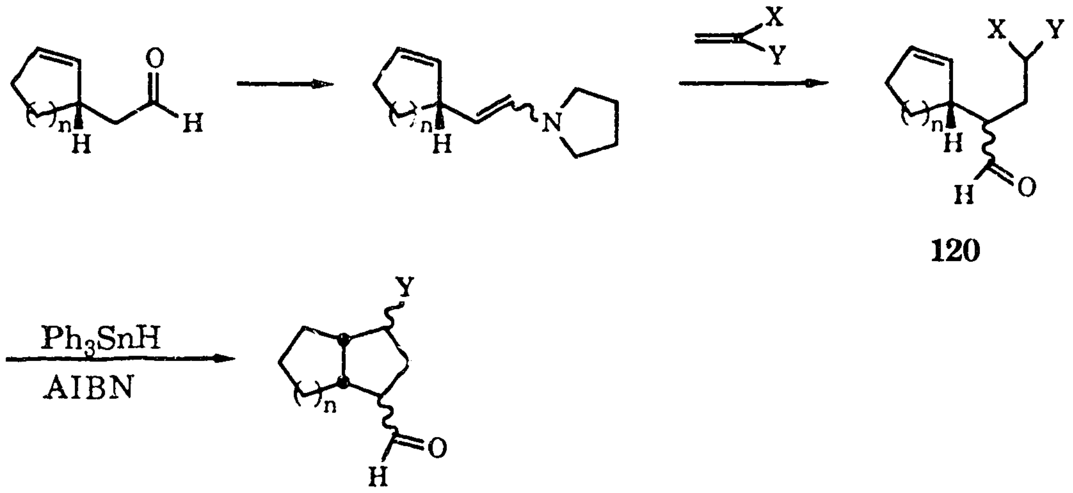
Rules For Ring Fusion Stereochemistry

Entry	Substrate	Product
1		 trans disfavoured
2		 trans disfavoured
3		

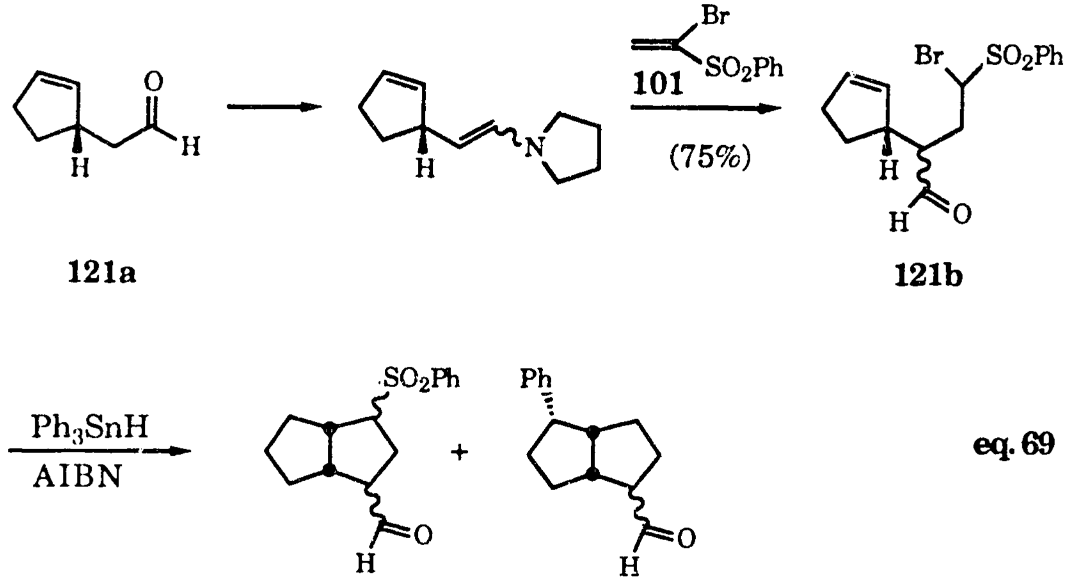
Entry 2 in the table is, correspondingly, a 5-*exo*-[*endo*-6] closure and that shown in entry 3 is a 5-*exo*-[*endo*-7] example. Closures of the types 5-*exo*-[*endo*-5] and 5-*exo*-[*endo*-6] result in *cis*-fused products, i.e., *trans* ring fusion is disfavoured. Both *cis*- and *trans* ring-fused carbocycles are formed in 5-*exo*-[*endo*-7] processes.

With these empirical rules in mind, we envisioned a synthetic procedure (Scheme 18) which involves conversion of an aldehyde into an enamine in the first step. The enamine is then allowed to react with a Michael acceptor carrying groups **X** and **Y** (the required features of these substituents were discussed in part A). Treatment of the adduct **120** with triphenyltin hydride and AIBN results in 5-*exo* closure and leads to a *cis*-fused carbocycle according to the above rules. In addition, the product is suitably functionalized to undergo further manipulation.

SCHEME 18



Our first example began with aldehyde **121a** (eq. 69). We converted it into its pyrrolidine enamine, dissolved it in THF and then allowed it to react with Michael acceptor **101** at room temperature. This gave the adduct **121b** in 75% yield. Normal syringe pump techniques were then used for the cyclization: Separate dilute solutions of triphenyltin hydride and AIBN, each in benzene, were added over several hours to a refluxing solution of the substrate, also in benzene. The *cis* fused material **121c** (40%) was obtained as a mixture of four isomers, together with a complex mixture of byproducts and in addition, compound **121c'** (15%) was isolated.



121a

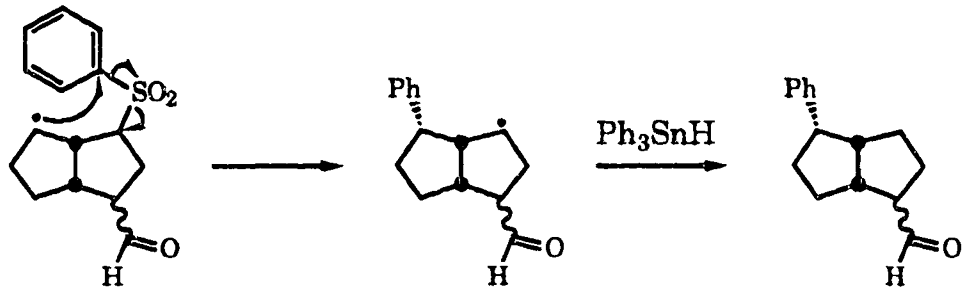
121b

121c
(4 isomers)
(40%)

121c'
(2 isomers)
(15%)

eq. 69

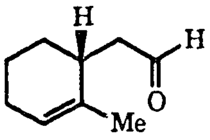
The rearranged material **121c'** presumably arose from attack by the newly formed radical (see **121d**, eq. 70) onto the benzene ring with subsequent elimination of sulfur dioxide. The stereochemistry at the phenyl-bearing carbon of the product is based on the intramolecular mechanism for rearrangement (see later).



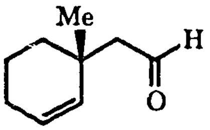
121d

eq. 70

The promising result that we had obtained above led us to extend the methodology to six-membered ring aldehydes and, in particular, to compounds **122** and **123**.



122



123

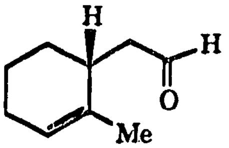
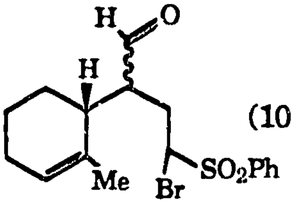
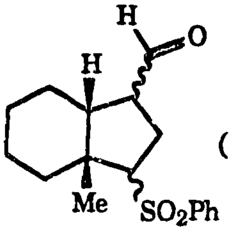
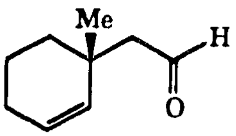
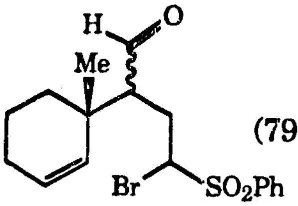
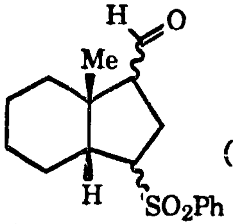
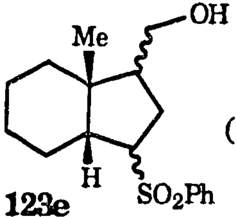
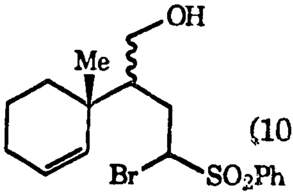
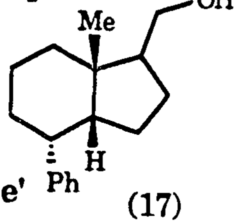
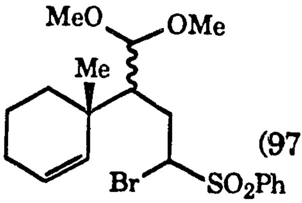
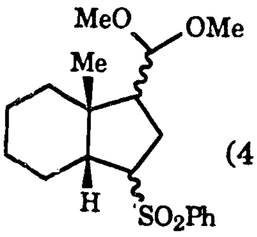
These substrates were chosen because carbocycles which contain angular methyl groups are found among natural products.^{84} When we subjected the two aldehydes to our standard conditions of enamine formation followed by Michael addition, as in the previous example, the Michael reaction went very well. The cyclizations, however, did not go to completion in either case and unreacted starting materials were isolated (see Table 7). A complex mixture of byproducts was also observed by TLC in both examples.

The observation that the starting materials were never completely converted to products and that complex mixtures of byproducts were formed in the above examples may have been due to an interaction of the stannyl radical with the aldehyde group. The stannane reduction of carbonyls is a known process[85] and, based on this fact, we chose to alter the substrate slightly by modifying the aldehyde functionality. We prepared both the alcohol **123d** and the dimethyl acetal **123f** of aldehyde **123b** (see Table 7). When the alcohol was tested in our sequence the desired *cis*-fused product **123e** was obtained in only 36% yield, (41% based on conversion), together with rearranged material **123e'** (15%, 17% based on conversion). Once again unreacted starting material (11%) was isolated. The result was similar in the case of the dimethyl acetal derivative **123f**; cyclization proceeded to compound **123g** in only 39% yield (46% based on conversion) and 16% of the starting material was recovered.

Although the Table shows no products of rearrangement except in the case of alcohol **123e'**, we are not certain that rearrangement did not take place in the other examples. The reason is that if any such material had formed it is likely to have been relatively non-polar and

TABLE 7

Enamines in the Michael Addition - Radical Cyclization Sequence

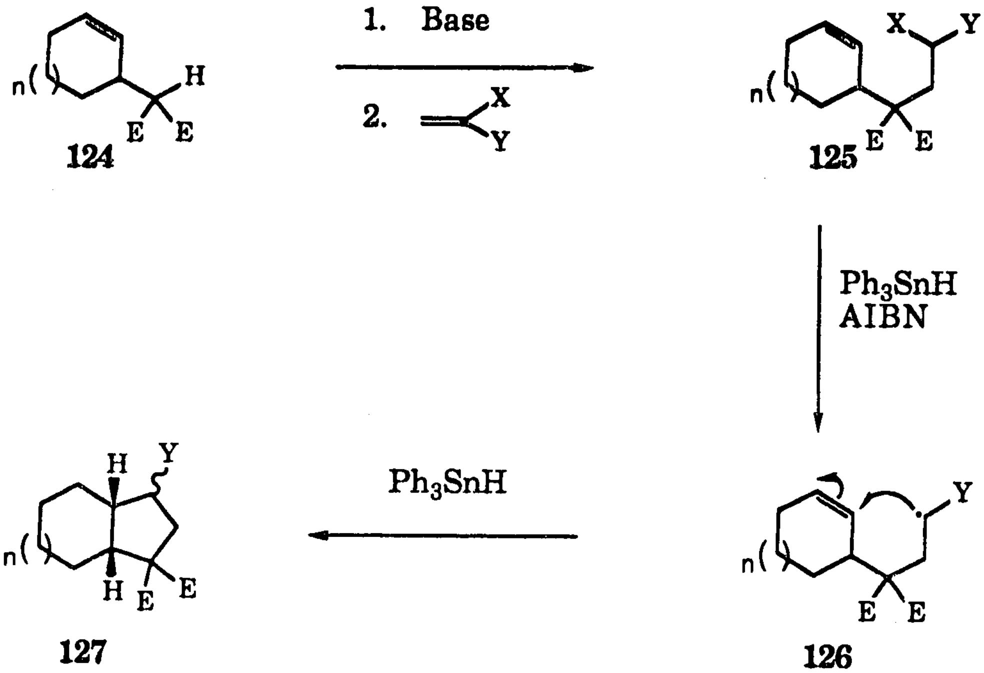
Starting Material	Michael Adduct (% yield)		Cyclization Product (% yields based on conversion)	
 **122a**	 **122b**	(100)	 **122c**	(33) (4 isomers)
 **123a**	 **123b**	(79)	 **123c**	(53) (4 isomers)
			 **123e**	(41) (4 isomers)
	 **123d**	(100)	+	
			 **123e'**	(17) (1 isomer)
	 **123f**	(97)	 **123g**	(46) (4 isomers)

therefore would have been separated chromatographically together with the very complex mixture of non-polar byproducts; these fractions were not examined spectroscopically. The hydroxyl group of **123e'** may have rendered this compound sufficiently more polar than the byproducts and so it was easy to separate by flash column chromatography.

In each of the examples listed in Table 7 a significant excess of stannane was used in the cyclizations and the initiator was added slowly during the course of the reaction. When refluxing toluene was substituted for benzene there was no significant improvement and so, at this point, we elected to make some changes in the nature of the starting materials.

Malonates, in addition to enamines, are known to be useful in Michael reactions.[86] This compound class was therefore chosen to replace the enamines in our Michael - radical sequence. We felt that we could make use of starting materials such as **124** as illustrated in Scheme 19. According to our synthetic plan, deprotonation of the malonate ester **124** followed by reaction with a Michael acceptor would afford the adduct **125** suitable for radical cyclization. The final product in the sequence, **127**, is highly functionalized (as in the enamine route) and this would allow further manipulation of the molecule, if so desired.

SCHEME 19 (E = COOEt)

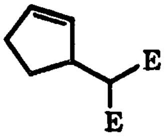


In the first example we prepared the diethyl malonate derivative **128a** (see Table 8) by the literature procedure[87] from 3-bromocyclopentene and diethyl malonate. The Michael addition was effected by deprotonation of this diester using one equivalent of sodium hydride followed by slow addition of the bromo phenyl sulfone Michael acceptor **101** at 0 °C. The desired Michael adduct **128b** was obtained in 72% yield and no unreacted starting material could be detected. It should be noted that there are examples in the literature of Michael reactions using similar reactants in which only a catalytic amount of sodium hydride in THF or sodium ethoxide in absolute ethanol is employed.[88] In addition, there have been reports of the use of catalytic amounts of

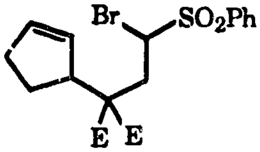
TABLE 8

Malonates in the Michael Addition - Radical Cyclization Sequence

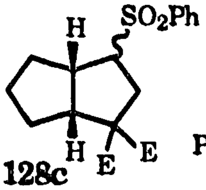
Starting Material | **Michael Adduct** | **Cyclization Products**



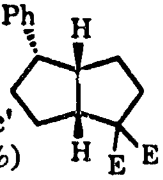
128a



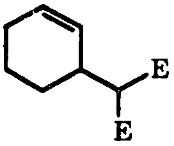
128b (72%)



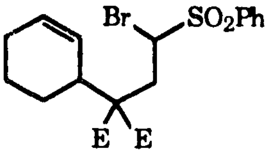
128c (61%)



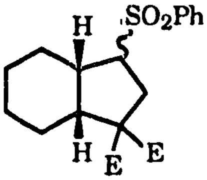
128c' (18%)



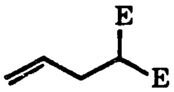
129a



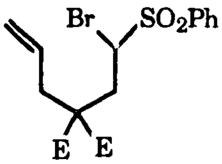
129b (67%)



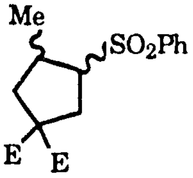
129c (93%)



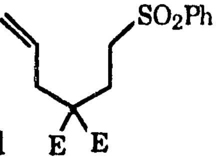
130a



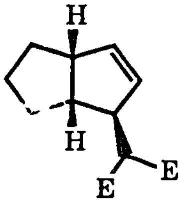
130b (75%)



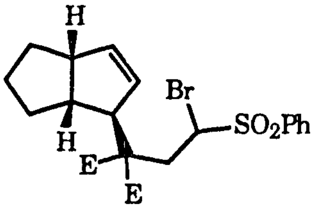
130c (35%)



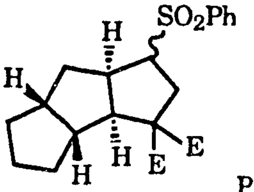
130d (21%)



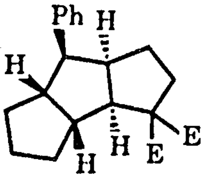
131a
E =CO_2Et



131b (36%) (54% based on conversion)



131c (11%)

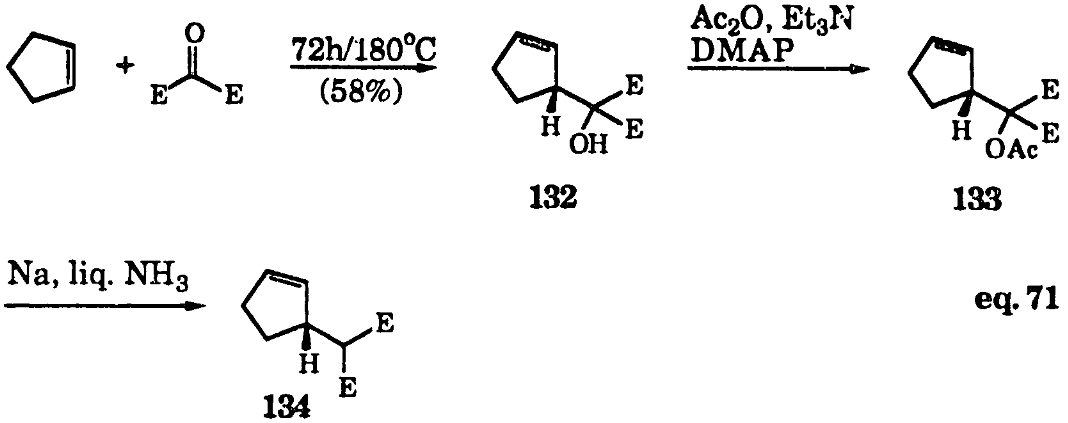


131c' (51%)

tributylphosphine[89] to effect the desired condensation. We tried each of these methods and found the present one to be the most efficient. The general method for radical cyclization, as described previously, was used in the next step of the sequence and this led to a 61% yield of the desired *cis*-fused carbocycle **128c** together with rearranged product **128c'** in 18% yield.

The above result demonstrated that we had a solution to the problem of incomplete conversion of starting material. We still isolated rearranged product in this example but we felt that the yield of cleanly cyclized compound was still encouraging. The methodology was therefore extended to the six-membered analogue **129a** (Table 8). Michael adduct **129b** was prepared by the method described earlier in 67% yield and it cyclized very cleanly (93%) to afford only *one* product (**129c**) which was isolated as a mixture of two isomers. Similarily, the open chain analogue **130a** underwent the Michael reaction in good yield (75%) but, surprisingly, the cyclization was only moderately successful. The closed product **130c** was isolated in 35% yield. We observed in this case, and only in this case, some reduced material (**130d**) which was the result of hydrogen capture at the radical center before closure.

A special feature of this methodology is that the required malonate esters can be generated by an ene reaction, which occurs, in suitable cases, with predictable regio- and stereoselectivity. The ene process for making diesters has been described in the literature (eq. 71):[90] Cyclopentene is heated in a sealed tube at 185 °C for 72 hours with diethyloxomalonate to give the alcohol **132**. Acetylation, followed by reductive elimination using lithium in ammonia, gives material (see **134**) suitable for our Michael - radical methodology.

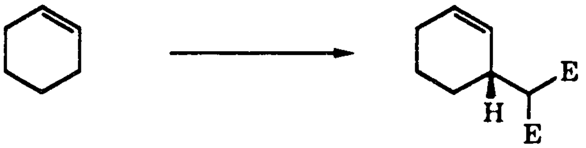


132 **133**

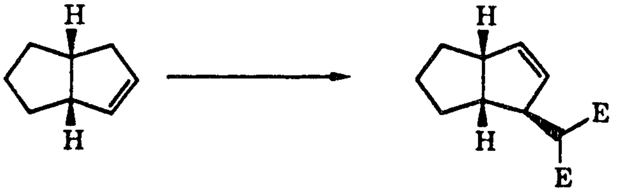
134

eq. 71

The ene procedure can also be applied to cyclohexene (eq. 72) but a more interesting example is that involving the pentalene **135** (eq. 73).



eq. 72

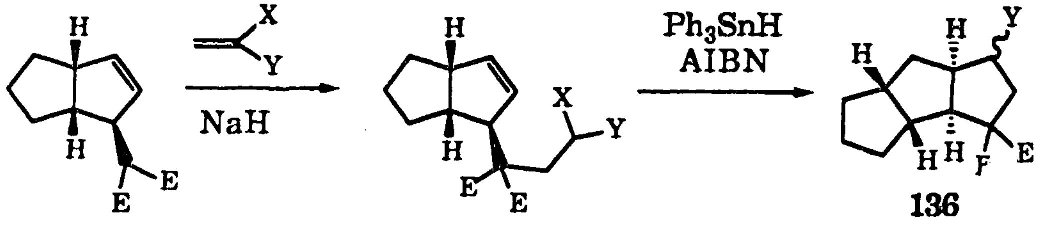


eq. 73

E = CO_2Et

135

We envisioned a route to triquinanes by incorporating this material into our sequence, as shown in eq. 74. The cyclized material **136** bears a close resemblance to the hirsutene family of natural products.[91]



$E = CO_2Et$

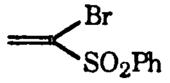
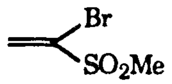
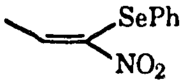
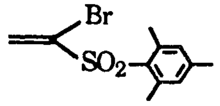
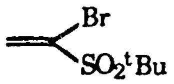
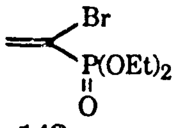
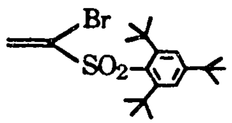
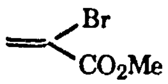
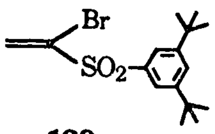
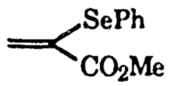
eq. 74

The starting pentalene **131a** (see Table 8, p. 89) was prepared by base-catalyzed isomerization of 1,3-cyclooctadiene[92] followed by ene reaction, as discussed above, with *anhydrous* diethyloxomalonate. Application of the Michael - radical sequence using bromo phenyl sulfone Michael acceptor **101** gave the linear triquinane **131c** in only 11% yield together with a 51% yield of the product **131c'** arising from phenyl migration (Table 8).

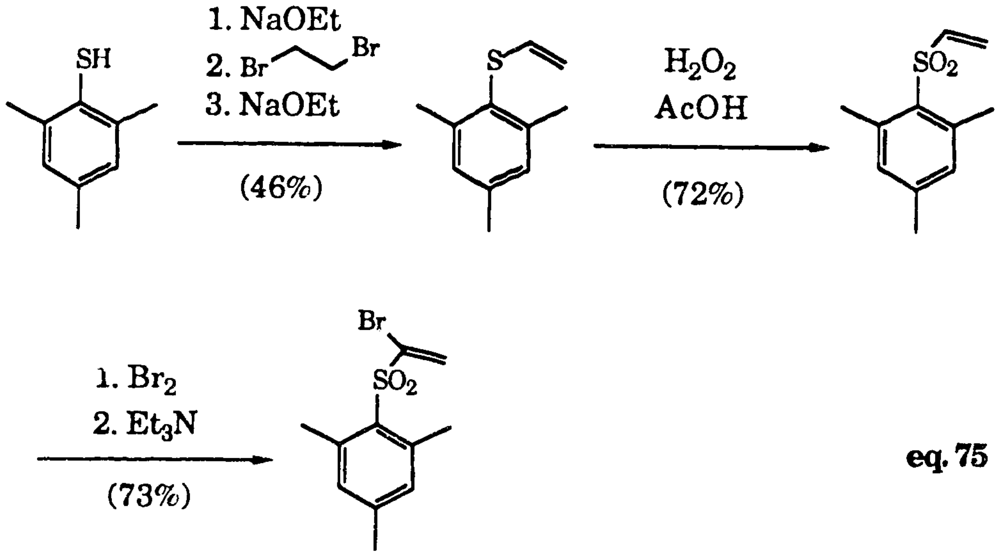
The high degree of rearrangement that resulted in this example indicated that in order for our malonate route to become a useful method in the five-membered series, we would have to search for a different Michael acceptor that would not produce an adduct that could rearrange upon cyclization. We examined a number of possibilities with the following requirements in mind: In order for the acceptor to be useful it must 1) react in the desired sense with malonate esters, 2) it should not rearrange in the cyclization step, 3) it should provide a handle for further manipulation of the final product, and, 4) one should be able to remove residual functionality after cyclization.

Potential Michael acceptors which had not been used in our previous work were examined because we wanted to increase the range of compounds that could be applied in the methodology. The various possibilities that we tested are listed in Table 9. Since the rearrangement was characteristic of the five-membered ring series we tested each possible Michael acceptor on the five-membered ring example first.

TABLE 9
Potential Michael Acceptors

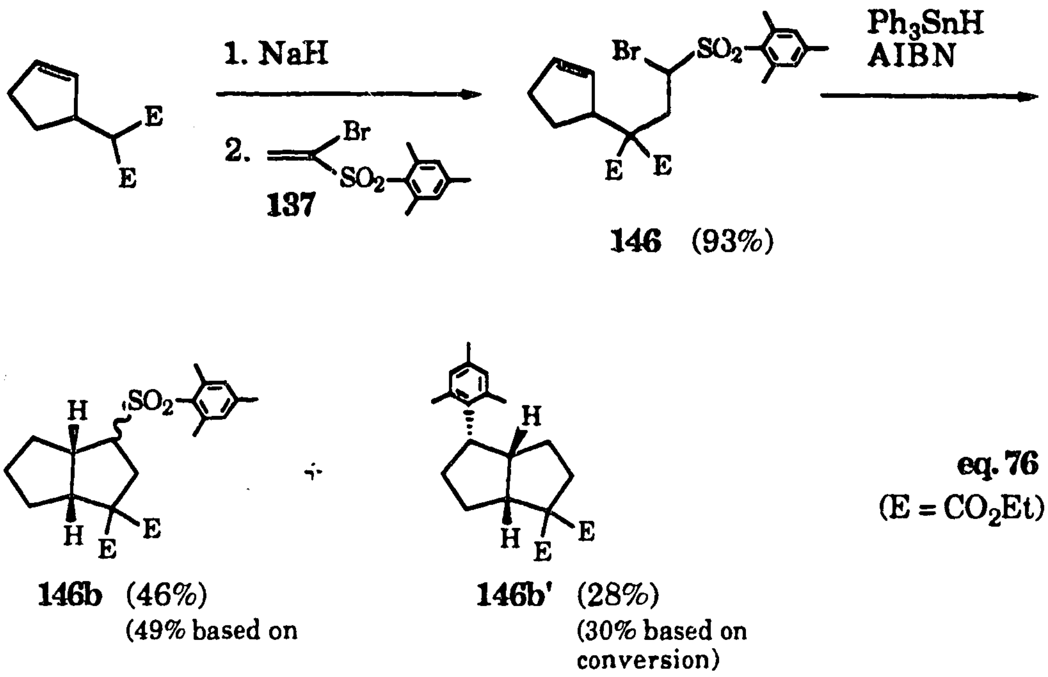
Aryl Sulfones	Alkyl Sulfones	Other Functional Groups
 **101**	 **140**	 **142**
 **137**	 **141**	 **143**
 **138**		 **144**
 **139**		 **145**

Initially, our approach was to try various modifications of the phenyl vinyl sulfone unit **101** since this compound had already worked well in the Michael step and the phenyl sulfone functionality is easily removed after cyclization. We felt that one should be able to slow the phenyl migration in the cyclization step by placing groups on the benzene ring which would create some steric hindrance to rearrangement. In our first attempt at this we prepared the mesityl analogue **137** in three steps from 2-mercaptomesitylene (eq. 75): 1) Alkylation at sulfur using 1,2-dibromo ethane and subsequent dehydrobromination, 3) oxidation of the sulfide to a sulfone, and 4) addition of Br_2 followed by elimination of HBr using triethylamine.



eq. 75

On testing compound **137** in our sequence (eq. 76) we found that the yield in the Michael addition was 93% but, once again, after the cyclization step we isolated a sizeable amount (28%, 30% based on conversion) of rearranged product **146b'**. The desired material **146b** was formed in only 46% yield, (49% based on conversion). In fact, the amount of rearrangement had actually increased over that observed using the unsubstituted phenyl sulfone unit.



137

146 (93%)

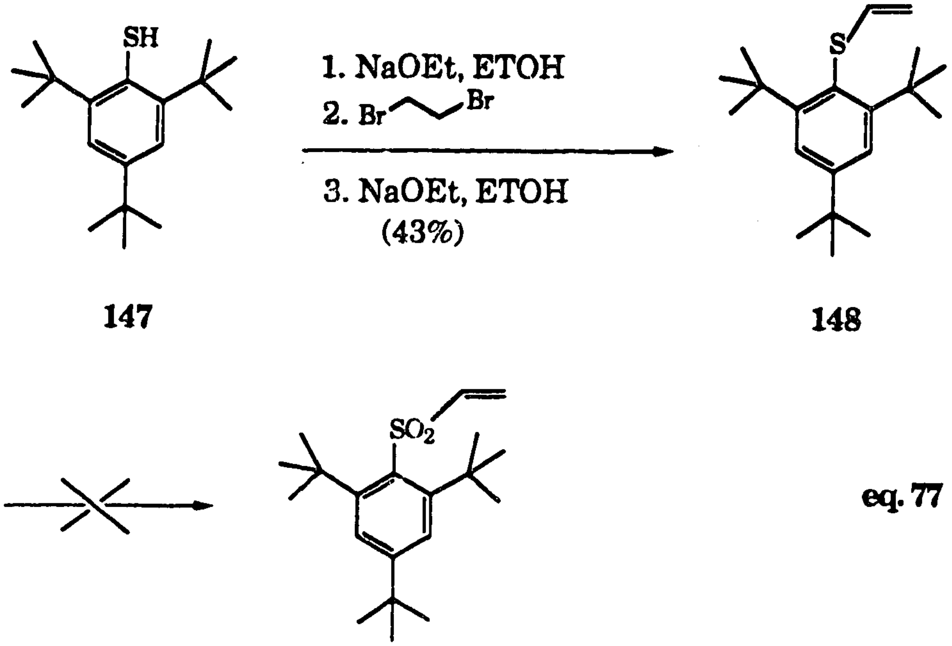
146b (46%)
(49% based on

146b' (28%)
(30% based on
conversion)

eq. 76
(E = CO_2Et)

The bulk of the three methyl groups on the benzene ring clearly was not sufficient to hinder the migration process and, evidently, an electronic activating influence prevailed.

Obviously, a Michael acceptor which had a more bulky phenyl group was required and so we attempted to prepare the corresponding tri-*t*-butyl sulfone **138** (Table 9). To this end we first prepared tri-*t*-butyl benzene thiol **147** by the literature procedure, and then alkylated it to afford compound **148** (43% yield). Oxidation of this material to sulfone **149** was extremely difficult and, in fact, we were unable to isolate any of the desired product from reactions with either 1) hydrogen peroxide and glacial acetic acid,[93] 2) sodium hypochlorite,[94] 3) oxone,[95] or 4) sodium periodate/potassium permanganate.[96]

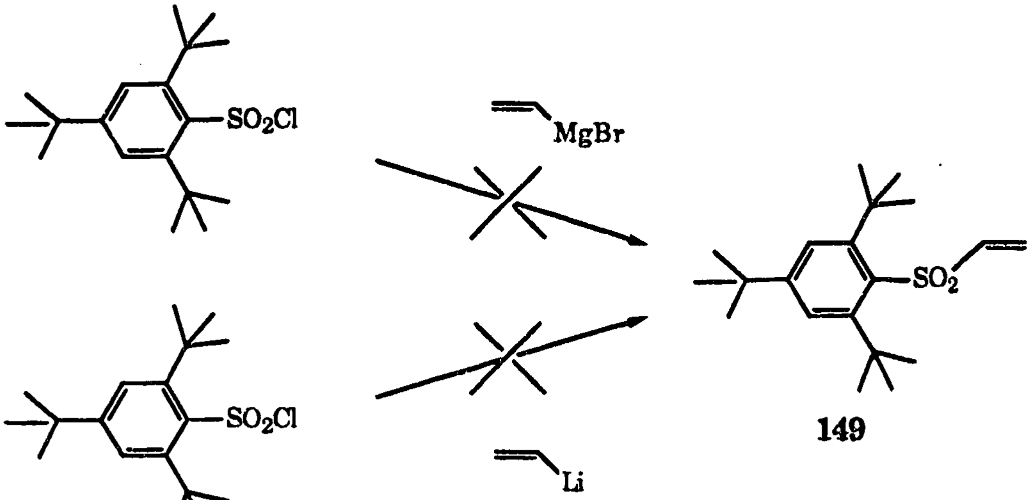


147 **148**

149

eq. 77

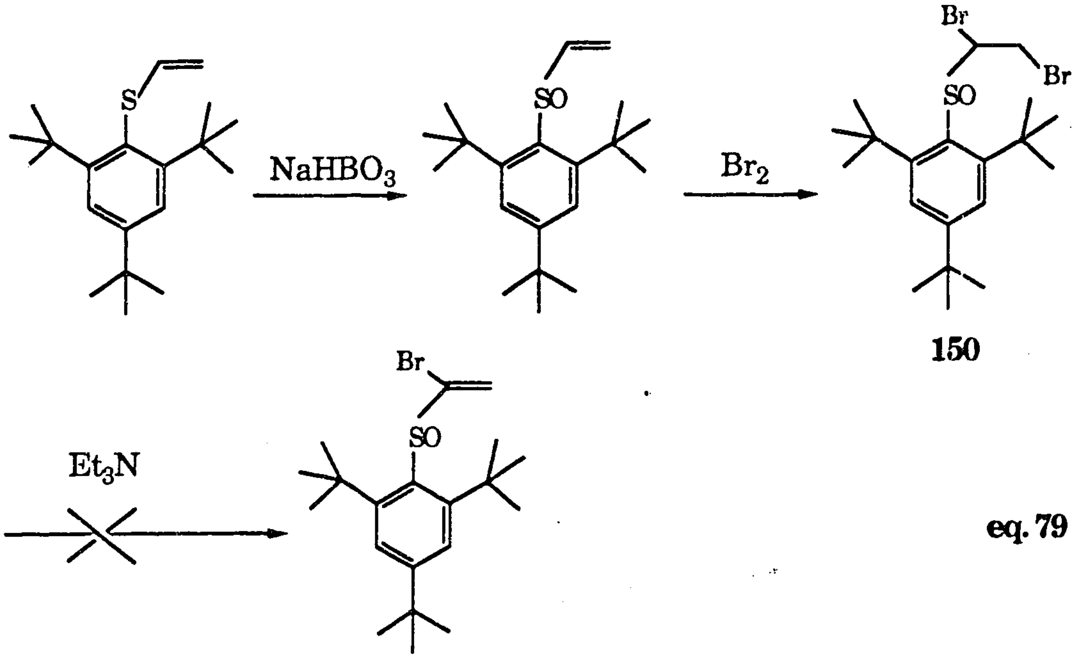
We next tried to prepare the desired sulfone **138** by a completely different route (see eq. 78) which involved reaction of tri-*t*-butyl benzenesulfonyl chloride with vinyl magnesium bromide or vinyl lithium. This attempt was also unsuccessful as the sulfonyl chloride was found to be unreactive toward the vinyl reagents.



149

eq. 78

An attempt to prepare the analogous bromosulfoxide **151** (eq. 79) instead, met with a similar fate, but at a later stage, when the intermediate dibromide **150** was found to be unreactive toward dehydrobromination.

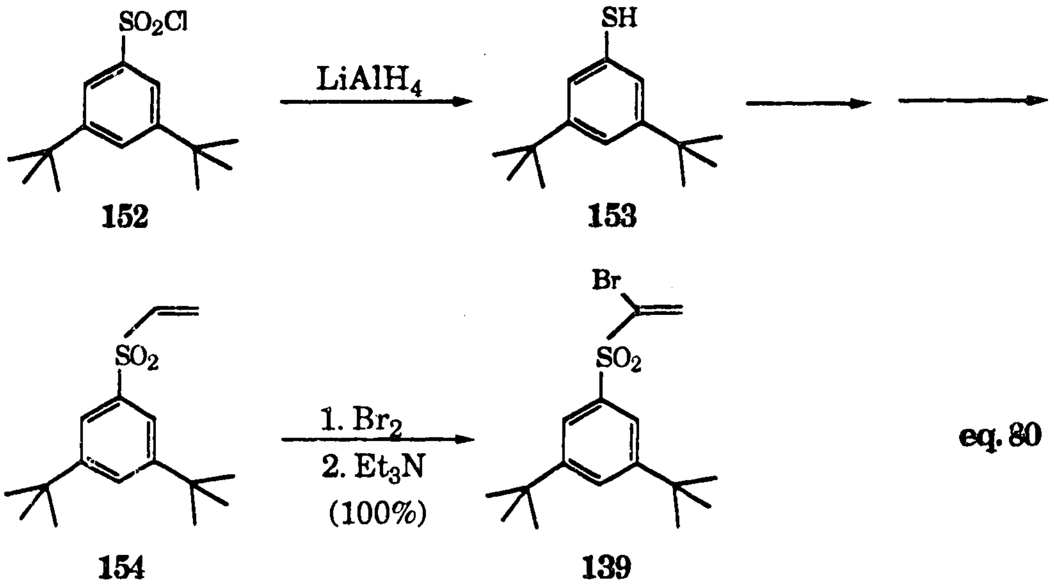


150

151

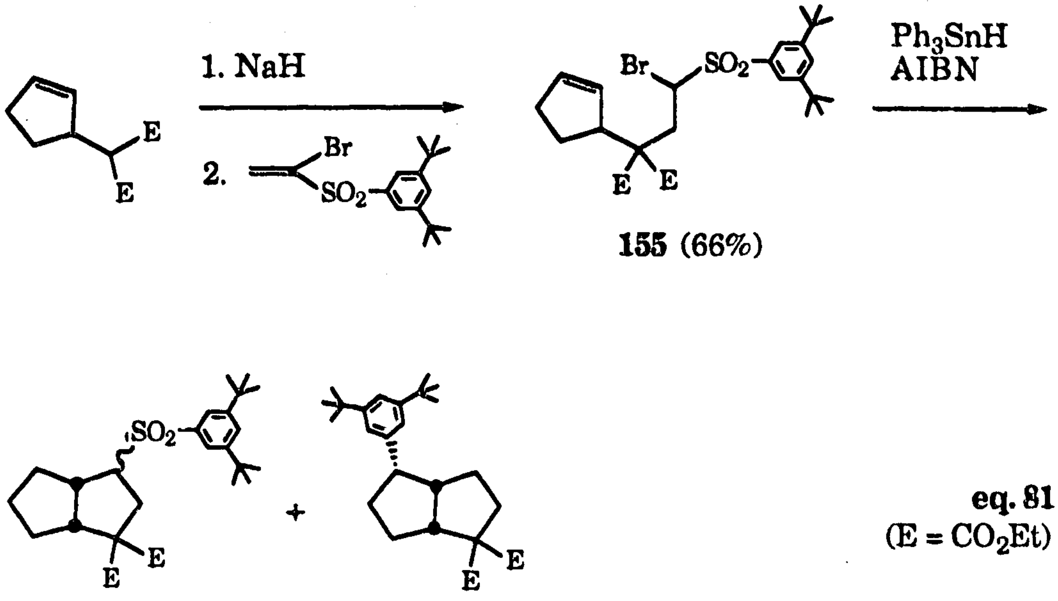
eq. 79

We did isolate, however, in the preparation of the sulfonyl chloride of eq. 78, a small amount of the corresponding di-*t*-butyl compound **152** and we decided to carry this through to the Michael acceptor stage (eq. 80).



eq. 80

The sulfonyl chloride was first reduced with lithium aluminum hydride and then the resulting thiol **153** was subjected to a literature sequence similar to that used for preparation of the mesityl sulfone (see eq. 75). We obtained the di-*t*-butyl sulfone **139**. In this compound the two *t*-butyl groups are situated meta to the sulfur function and this is not the best orientation in terms of providing maximum steric hindrance toward phenyl migration. Nevertheless, we elected to examine its usefulness in our general sequence (eq. 81). The Michael reaction went reasonably well (66%), but the radical cyclization did not. The *t*-butyl groups apparently did not impose enough of a steric constraint to impede aryl



155 (66%)

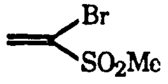
155b (54%)
(63% based on conversion)

155b' (30%)
(35% based on conversion)

eq. 81
(E = CO_2Et)

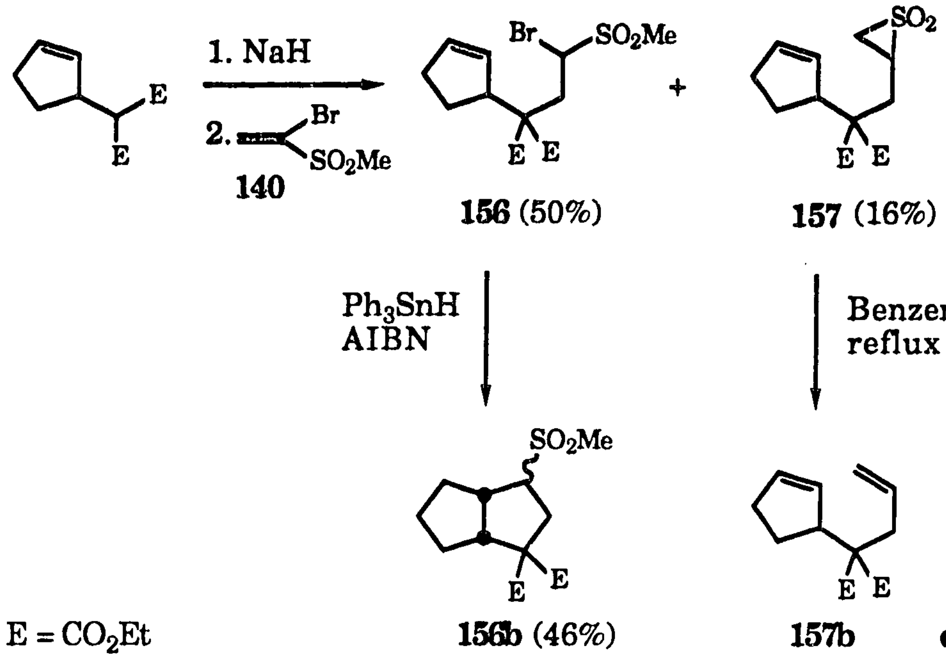
migration. We observed only a 54% (63% based on conversion) yield of the desired material **155b** [together with a 30% yield (35% based on conversion) of rearranged product **155b'**].

In a completely different approach we decided to move away from the phenyl sulfone series and examine an aliphatic sulfone instead. Bromomethyl vinyl sulfone **140** was the first choice since it is readily prepared by simple bromination followed by dehydrobromination of methyl vinyl sulfone.



140

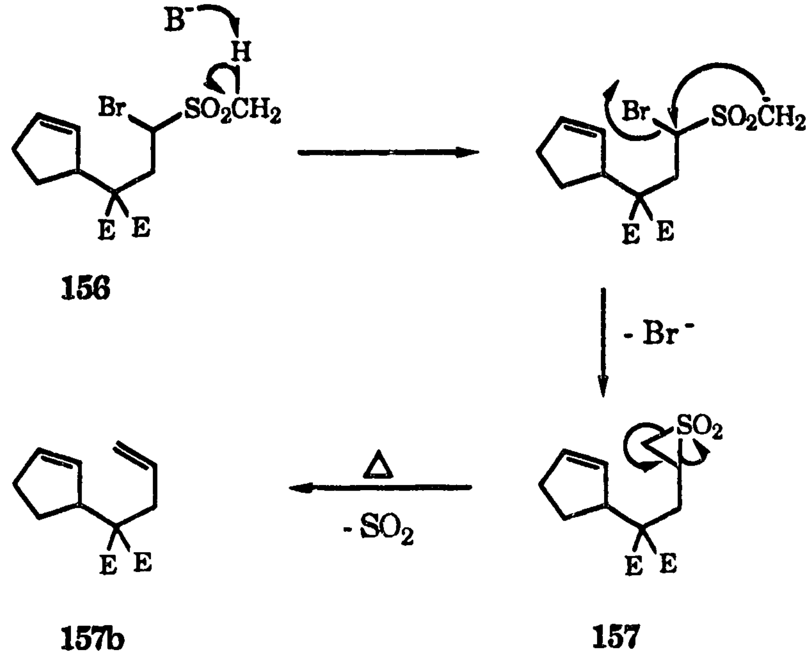
Use of this compound in our sequence is shown in eq. 82.



E = CO_2Et

eq. 82

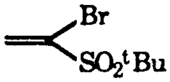
Michael addition, under our standard conditions, led to the isolation of two products, the desired adduct **156** (50% yield) and the episulfone **157** (16%). The episulfone evidently arose by a Ramberg - Bäcklund process as shown in eq. 83. This material went on to the expected diene **157b** when heated in refluxing benzene. The Michael adduct **156** gave only a low yield (46%) of cyclized product **156b** but it did serve to show that an aliphatic sulfone could work in our sequence without radical rearrangement; however, the possibility of Ramberg-Bäcklund reaction would have to be eliminated.



156 157 157b

eq. 83
$E = CO_2Et$

Encouraged by this observation we prepared the *t*-butyl vinyl sulfone **141** for evaluation and it performed very well in both the Michael addition and radical cyclization.

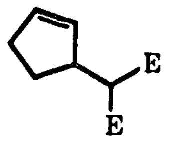
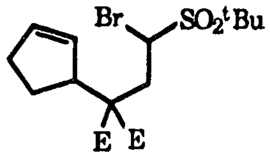
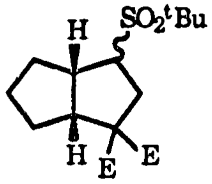
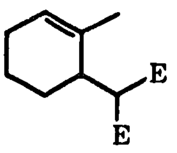
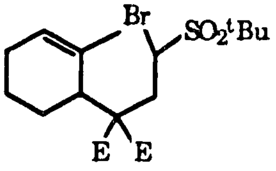
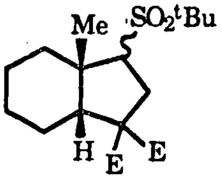
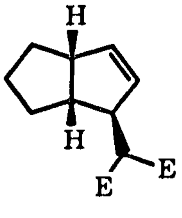
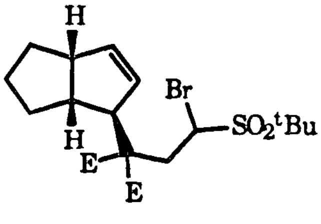
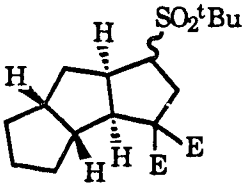


141

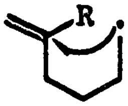
The results are shown in Table 10. In the five-membered case, cyclization was very clean with only one product being formed in 74% yield as a mixture of two isomers.

TABLE 10

tert-Butyl Sulfone Series

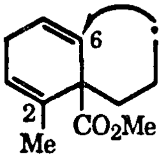
Starting Material	Michael Adduct	Cyclization Products
	 **158** (72%)	 **158b** (74%)
 **159**	 **159b** (46%) (100% based on conversion)	 **159c** (98%)
 E = CO_2Et	 **160** (74%)	 **160b** (80%)

The second entry in Table 10 should be noted since in this case the radical is closing onto the disubstituted terminus of an isolated double bond. One would not have predicted the cyclization to go in such high yield (98%) based on knowledge of the corresponding classical process for simple radical species such as **161**. For example in **161** (R = Me)



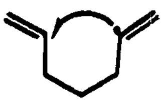
161

which involves a primary radical, the cyclization is slow compared with the simple case **161** (R = H), the latter being about 40 times as fast (at 25 °C).[7,56d] Another model with which comparison should be made, is radical **162**.[56d] Here there is an intramolecular competition between the

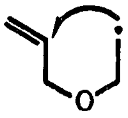


162

two differently substituted double bonds and, at 70 °C, attack at C-6 is about 30 times as fast[56d] as at C-2. However, cyclization of our compound **159b** proceeds smoothly and there are, evidently, no problems from competing hydrogen abstraction (from stannane) before closure. We have found in this work only one example of an α-sulfonyl radical where such hydrogen abstraction is serious, and this was in the open-chain material **130b** (Table 8) discussed previously. Carbocyclization onto the fully substituted terminus of a non-conjugated double bond has been observed in the case of vinyl radicals,[40, 41a, 50] and with allyl radicals as has been shown recently,[41b] and also in those situations in which a tetrahydrofuran[28, 31h] or pyrrolidine[98] is generated by a 5-*exo* pathway. Closure of vinyl radicals (as in **163**)[53] and formation of tetrahydrofurans (as in **164**)[7] have been examined kinetically: both processes have specific rate constants that are appreciably larger than



163

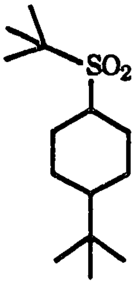


164

that which is characteristic of the classical hexenyl radical (**161**, R = H).[7] The vinyl radical is very reactive[7] and a number of other factors[7] also probably contribute to the enhanced rate of vinyl cyclizations. Formation of simple heterocycles (as in **164**) is also inherently easy, and this characteristic has been attributed to favourable C-O bond lengths and C-O-C bond angles.[7] It is evident from the behaviour of **159b** that the cyclization of α-sulfonyl radicals is another example of facile closure onto an isolated double bond that is substituted at its proximal terminus.

The third entry in Table 10 represents a useful method for preparing triquinanes which is a significant improvement on the phenyl sulfone example **131c** (Table 8) discussed previously. In this case, following our standard conditions, the Michael reaction went in 74% yield while cyclization was even more efficient (80%).

We had assumed that the standard methods for removing a phenyl sulfone unit from the cyclization products in the previous project could be used here. Unfortunately, all attempts to remove the *t*-butyl sulfone group from the model compound **165** using dissolving metal reduction (lithium, potassium, or sodium in ammonia,[99] lithium in methylamine,[99b, 100] and sodium naphthalenide in benzene[101]), or hydride reduction (to possibly produce the corresponding sulfide) using lithium aluminum hydride,[102] ultrasonically dispersed potassium in



165

toluene,[103] titanium (IV) and lithium aluminum hydride at low temperature or reflux,[104] Raney nickel,[105] and di-isobutylaluminum hydride at low temperature or reflux[106]) failed. We were unable to deprotonate the material in the α position using LDA, as judged by the results of a D_2O quench.[107] At this point an exhaustive search of the literature proved that there was no precedent for removal of a *t*-butyl sulfone from an aliphatic carbon. Typically an aromatic ring is present on the sulfone unit in desulfonylation processes. Evidently, removal of a *t*-butyl sulfonyl group would require prior modification elsewhere in the molecule so as to render the sulfone unit allylic or activated in some other way.

Since the *t*-butyl sulfone unit **141** did not satisfy our requirement that it be easily removable we continued our search for a suitable Michael acceptor. We chose to take a completely different approach and avoid using sulfones altogether. A nitro selenide unit **142** was tested first (Table 11). Under our standard conditions for Michael reaction, the five- and six-membered ring cases **166** and **167** proceeded smoothly in respective yields of 66% and 90%; however, the cyclization steps were not promising. We did not isolate any of the desired material in either case.

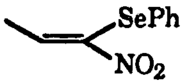
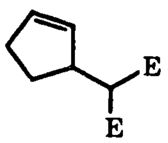
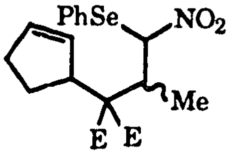
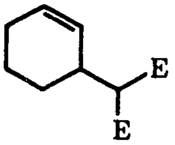
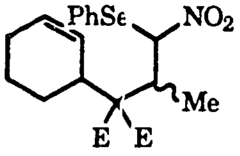
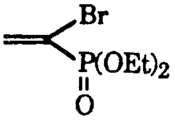

142

TABLE 11
Nitro Phenylseleno Series

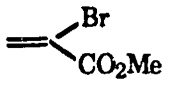
Starting Material	Michael Adduct	Cyclization Products
	 **166** (66%)	-----
	 **167** (90%)	-----

(E = CO_2Et)

The second candidate was the phosphonate **143**. It too proved unsatisfactory as we were never able to effect even a Michael reaction with it.

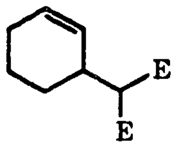
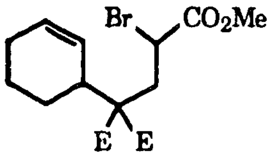
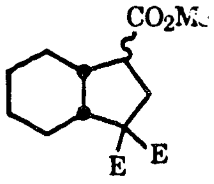
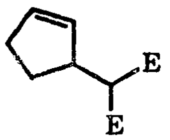
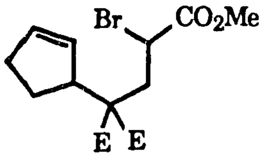
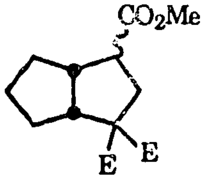

143

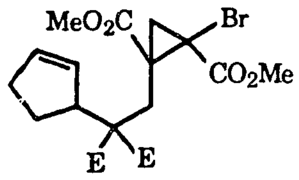
α,β-Unsaturated esters are commonly used as acceptors in Michael reactions and we decided, instead, to turn to this class of compounds since it appeared to fit our criteria. Methyl bromoacrylate **144** is readily prepared from methyl 1,2-dibromopropionate[108] and we tested it in our sequence (see Table 12).



144

TABLE 12
Bromo Methyl Acrylates in The Michael - Radical Route

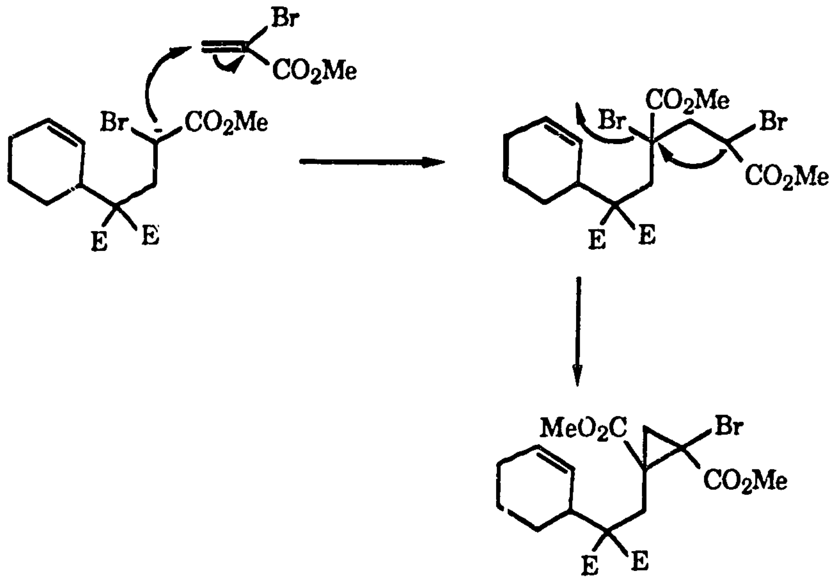
Starting Material	Michael Adduct	Cyclization Product
		
	168 (37%)	**168b** (99%) (2 isomers)
		
	169 (31%)	**169b** (89%)



170

(E = CO$_2$Et)

Under the usual conditions, in both the five- and six-membered ring examples, the Michael addition was plagued by formation of cyclopropane byproducts such as **170**. These were formed in the manner illustrated in eq. 84 in which the initially formed Michael adduct



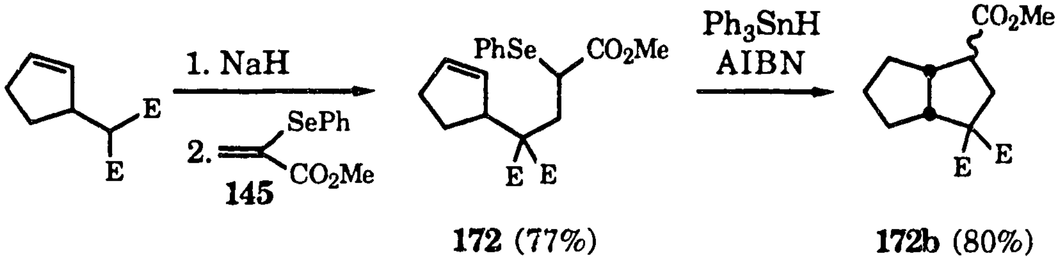
171

eq. 84
(E = CO_2Et)

attacks a second Michael acceptor which then cyclizes back on itself and expels a bromide ion. The result is formation of a three-membered ring. We tried various ways of adding the Michael acceptor to the malonate anions in an effort to reduce this side reaction, including very slow addition, fast addition, and addition at low temperature, but were never successful.

In the meantime, we did look at the cyclization step and found it to be very clean with yields of 100% in the five- and 93% in the six-membered ring examples, respectively (see Table 12). Unfortunately, we were unable to overcome the difficulties in the Michael step; these problems have been observed before by other workers but not solved.[109]

The cyclization step in the above methyl bromoacrylate examples was so successful that we decided to prepare the selenenophenyl analogue of the bromine compound and test it in the hope that it would be less reactive in the Michael step. We prepared methyl phenylselenenoacrylate **145** (eq. 85) by the literature method[67] and when it was tested in our sequence it was found to undergo the Michael addition quite well and afforded **172** in 77% yield; no products of double Michael reaction were detected. The cyclization reaction done in the usual way was also very clean and the desired *cis*-fused product **172b** was obtained in 80% yield. This Michael acceptor therefore appears to be the most useful for our Michael - radical sequence in the five-membered ring series since it satisfies all of the requirements which we originally described.



(E = CO_2Et)

eq. 85

In the above examples, the Michael products were usually isolated as mixtures of isomers in ratios that depended on the particular case (see individual experiments) but we did not observe high levels of stereoselectivity. In the cyclization reactions the products were also isolated as isomer mixtures but the ring-fusion was cleanly *cis*.

During the course of our study we were curious about the nature of the rearrangement process that took place in the aryl sulfone series. It was possible that either an *intramolecular* migration was involved, as shown in fig. 2, or an *intermolecular* process was occurring.

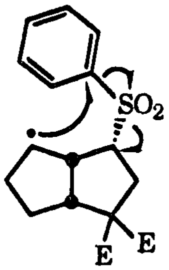
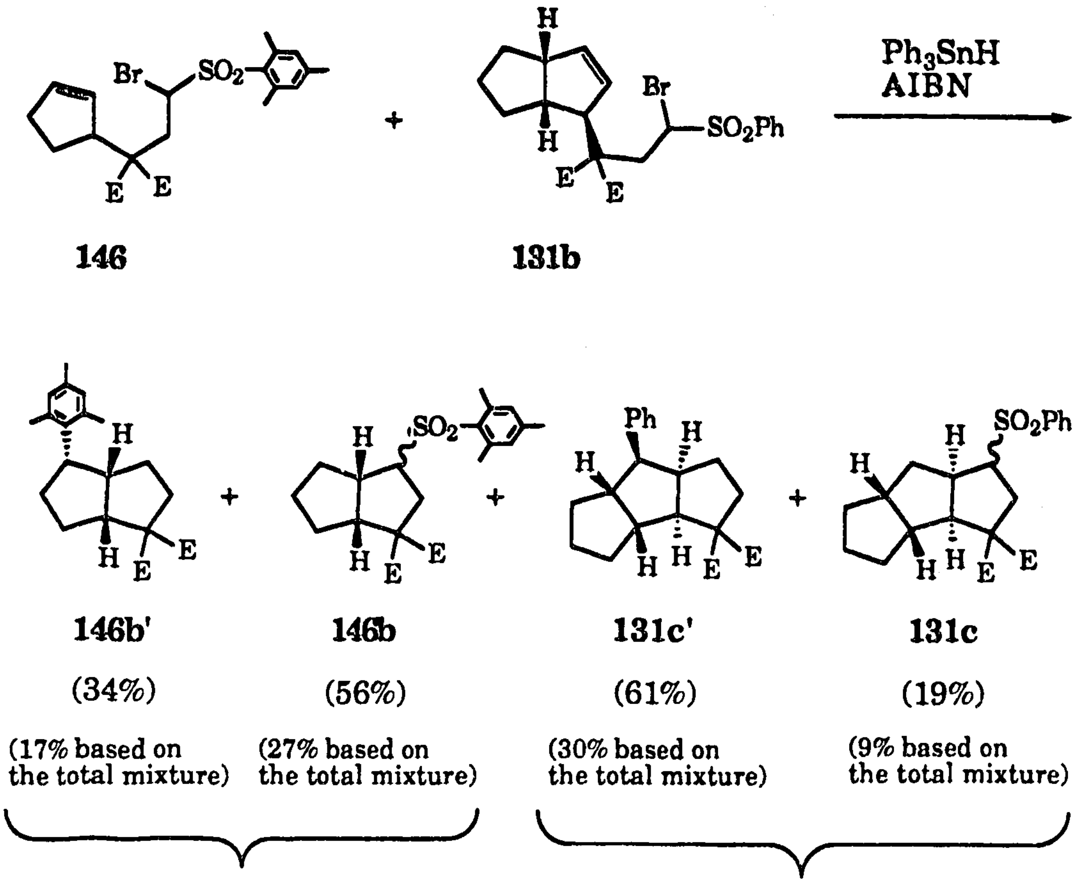


fig. 2 Aryl migration

In order to answer this question, we prepared the two Michael adducts, **131b** and **146**, (eq. 86), placed equimolar amounts in the same flask, and then subjected the mixture to our standard conditions for radical cyclization. The result was a mixture of four compounds, two (**146b** and **131c**) arising from the expected cyclizations and two others (**146b'** and **131c'**) which were identified as the rearranged materials that had been previously isolated in the individual reactions. No cross-over products such as **173** or **174** were isolated. Each of the two substrates cyclized independently of the other and the migration must, therefore, be intramolecular.



146 **131b**

Ph_3SnH AIBN

146b' (34%) (17% based on the total mixture)

146b (56%) (27% based on the total mixture)

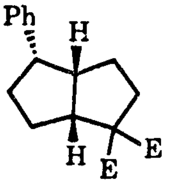
131c' (61%) (30% based on the total mixture)

131c (19%) (9% based on the total mixture)

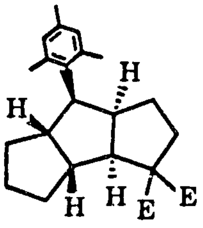
cyclized:rearranged 1.6:1

cyclized:rearranged 1:3.2

eq. 86
(E = CO_2Et)

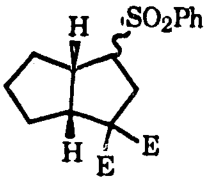


173

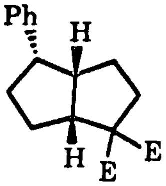


174

It should also be noted that in this experiment the ratio of cleanly cyclized products to rearranged materials for each of the two starting compounds was similar to that observed in the previous, individual experiments. In the case of **146** this was 1.6:1 (also 1.6:1 in the above experiment) and for **131b** it was 1:5.4 (1:3.2 in the above experiment). In the triquinane example **131b** the ratio of cyclized to rearranged material is reversed with respect to the example of **146** and in comparison to the more similar example of **128c** and **128c'** (see below) which was discussed previously. The ratio in that experiment was 1:3.5. More rearranged material is produced in the triquinane series and this may be rationalized in the following way.



128c



128c'

The new radical which is generated as a result of cyclization has two pathways available to it: 1) The radical can react in an intramolecular fashion with the phenyl ring to produce the migrated product or 2) it can abstract hydrogen from triphenyltin hydride. In the cyclopentane case (see fig.3) the hydrogen capture must be faster than migration since we see a greater proportion of the cleanly cyclized product.

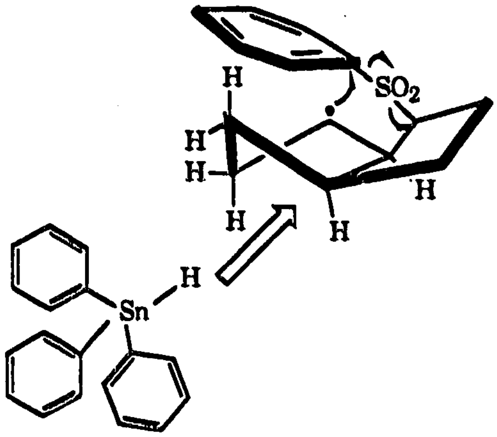


fig. 3 Approach of stannane to pentalene radical.

In the triquinane example (see fig. 4), models suggest that the additional five-membered ring may hinder approach by the stannane and therefore slow hydrogen abstraction relative to phenyl migration. The result is a higher yield of migrated compound in comparison to cleanly cyclized material.

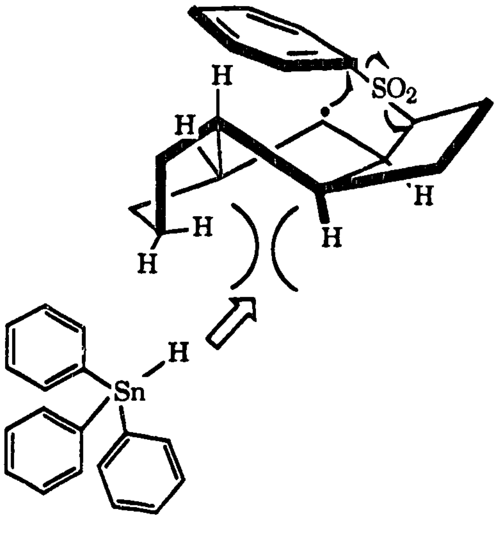


fig. 4 Hindered approach of stannane to triquinane radical.

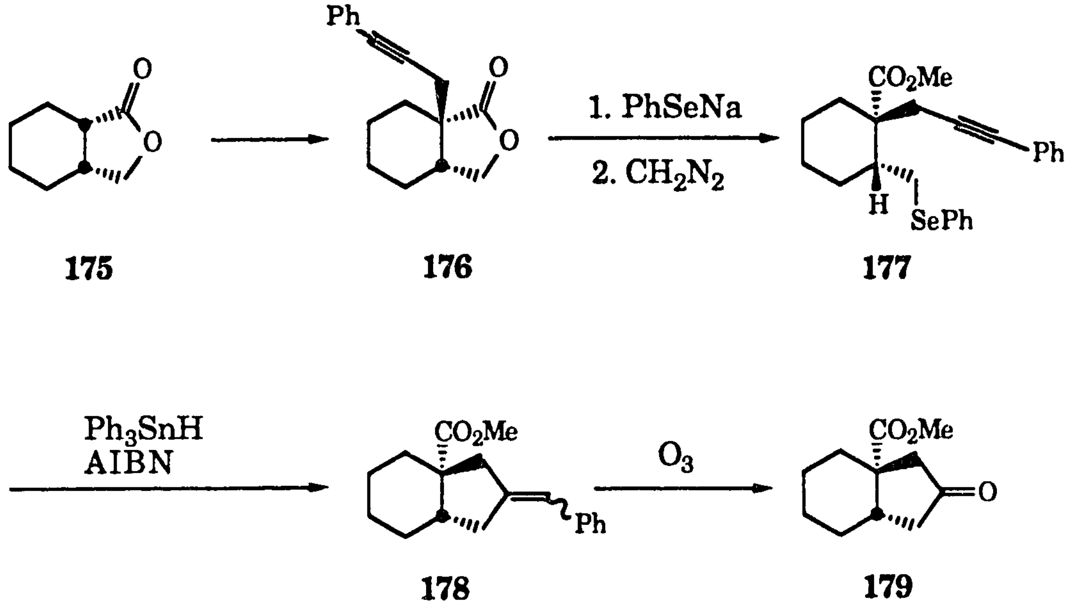
In this section the use of Michael addition - radical cyclization chemistry has been extended to include two new compound classes, aldehydes and malonate esters. The method has been shown to be convenient and flexible in terms of the choice of Michael acceptor in the six-membered ring examples. Work will continue on the development of a new method for removal or manipulation of the *tert*-butyl sulfone moiety which will make this route more useful for all of the examples studied. A total synthesis of the natural product hirsutene may also follow from this work.

(C) Preparation of *Trans* Ring-Fused Carbocycles

In the previous section we dealt with the preparation of *cis* ring-fused carbocycles by a method in which the last bond that we made was one to a ring fusion atom. In order to generate corresponding *trans* isomers, the rules for ring-fusion geometry discussed on page 81 indicated that we had to change our approach. We needed to design our starting materials so that in the cyclization process the last bond to be formed is *not* to a ring fusion atom. Consequently we required a method for placement of two pendants in a *trans* manner on an existing cyclic structure. One pendant would carry a triple bond and the other a radical precursor.

It occurred to us that such structures should be accessible from certain bicyclic lactones that are *cis*-fused. As shown in Scheme 20, it should be possible to attach a propargyl unit by alkylation at a ring junction with preservation of the original stereochemistry.* Opening of the lactone ring in the product **176** using phenylselenide anion would then give a monocyclic compound **177** with two pendants disposed in a *trans* orientation. Treatment of such compounds with a stannane should lead to C-Se bond homolysis and subsequent cyclization to a carbocycle with *trans* ring-fusion.

SCHEME 20



The purpose of using an acetylene instead of an allyl compound in the alkylation step lies in the fact that with an acetylene the resulting

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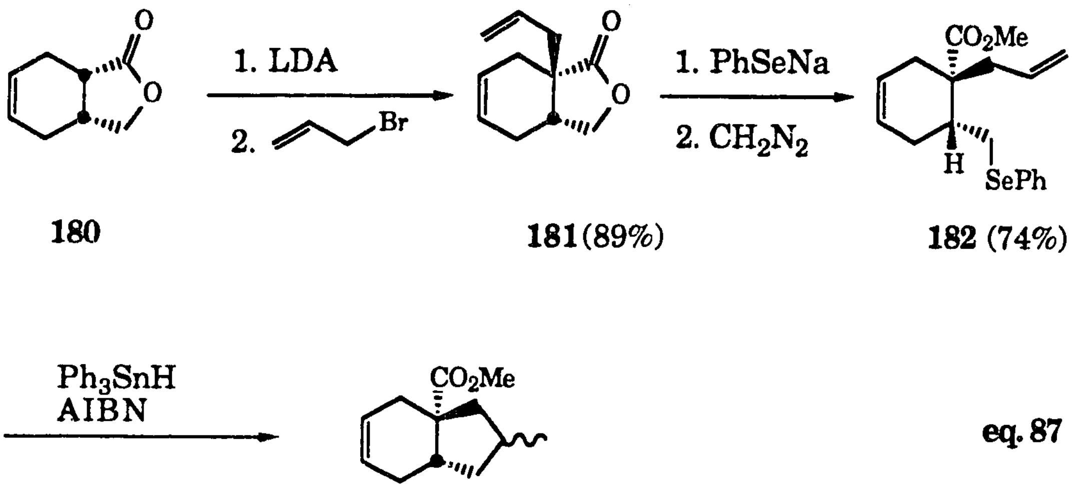
* The stereochemical assignment is by analogy to perhydroindan chemistry: House, H. O.; Blankley, C. J. *J. Org. Chem.* **1967**, *32*, 1741.

double bond can be ozonized (see above) to a ketone, which can be used for further manipulation of the molecule.

We reduced our theoretical scheme to practice and in our first example started with the lactone **180** (eq. 87) since it was readily available by Diels - Alder reaction between butadiene and maleic



180

181 (89%)

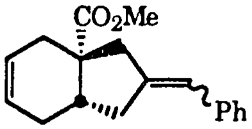
182 (74%)

183 (92%)

eq. 87

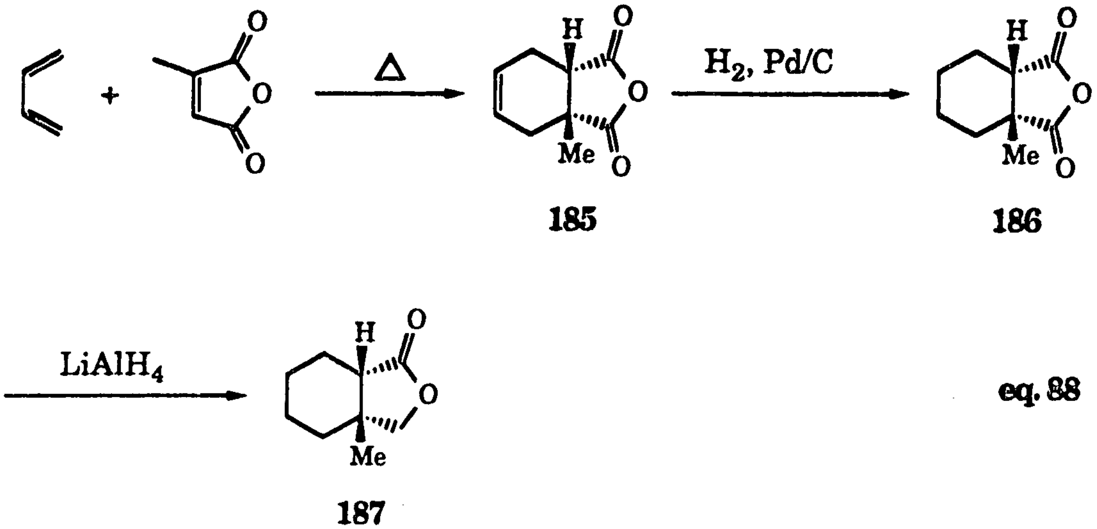
anhydride followed by lithium aluminum hydride reduction. We alkylated the lactone by deprotonation at -78 °C using LDA followed by addition of allyl bromide. We used this unit instead of an acetylene because in this first example we simply wanted to deduce the feasibility of the method and were not concerned with the resulting degree of functionality in the final, cyclized product. The reaction gave an 89% yield of **181**. Ring opening of lactones using phenyl selenide anion has been reported,[110] and we applied the standard method to our case. It is convenient to prepare the nucleophile from diphenyl diselenide and sodium hydride. Ring opening of the lactone **181** took place in refluxing THF over a period of about 12 hours and a 74% yield of the selenide **182** was obtained after methylation with diazomethane. We were now in a position to attempt the ring closure since we had material with *trans* disposed pendants. Radical cyclization using our general method gave **183** in 92% yield. There was a high degree of stereoselectivity in this process, the ratio of the two isomers being 13.5:1.

Having demonstrated the feasibility of this sequence we extended it. In the next experiment we used the identical starting lactone **180** but alkylated it with phenyl propargyl bromide. When the standard conditions of ring-opening followed by radical cyclization were applied, we obtained **184** as a mixture of *cis* and *trans* isomers in a 1:1 ratio and in 73% yield.



184

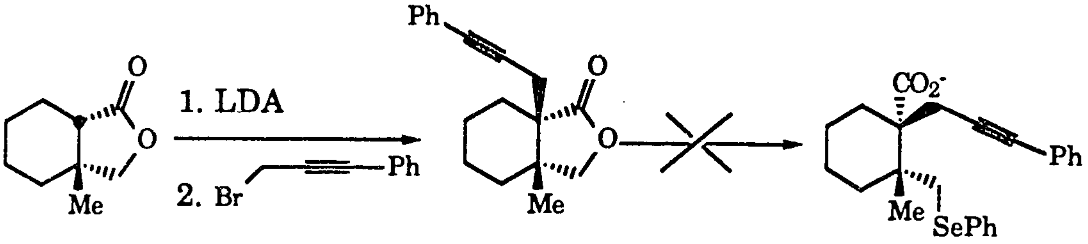
We were interested to see if we could effect a similar result using instead, the angularly methylated lactone **187**. This compound was prepared by a literature route[111] which involves Diels - Alder reaction between butadiene and citraconic anhydride followed by reduction of the resulting double bond and then conversion of the anhydride to the lactone **187** (eq. 88).



185 **186** **187**

eq. 88

When we alkylated **187** using phenyl propargyl bromide a 90% yield of the acetylene **188** (eq. 89) was obtained* but, unfortunately, our attempts at ring opening of **188** with phenylselenide anion failed and we have so far been unable to obtain any of the desired product.



187 **188** **189** **eq. 89**

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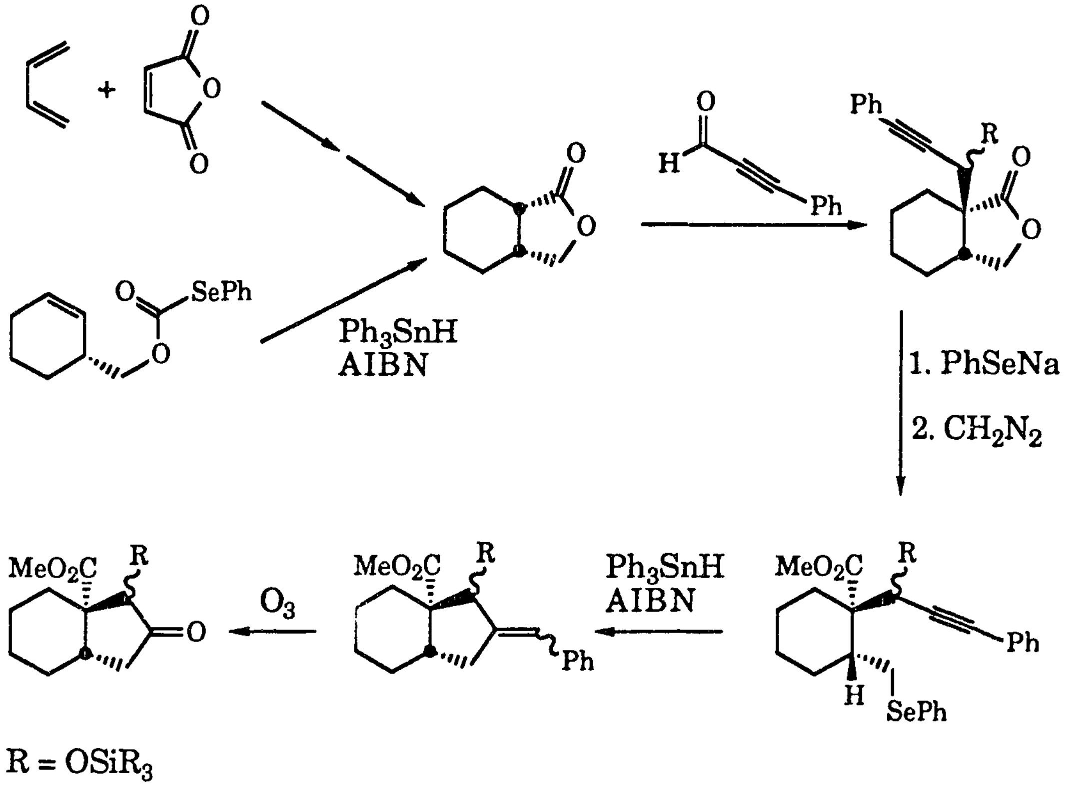
* The stereochemical assignment is very tentatively based on analogy to perhydroindan chemistry (see footnote p. 115).

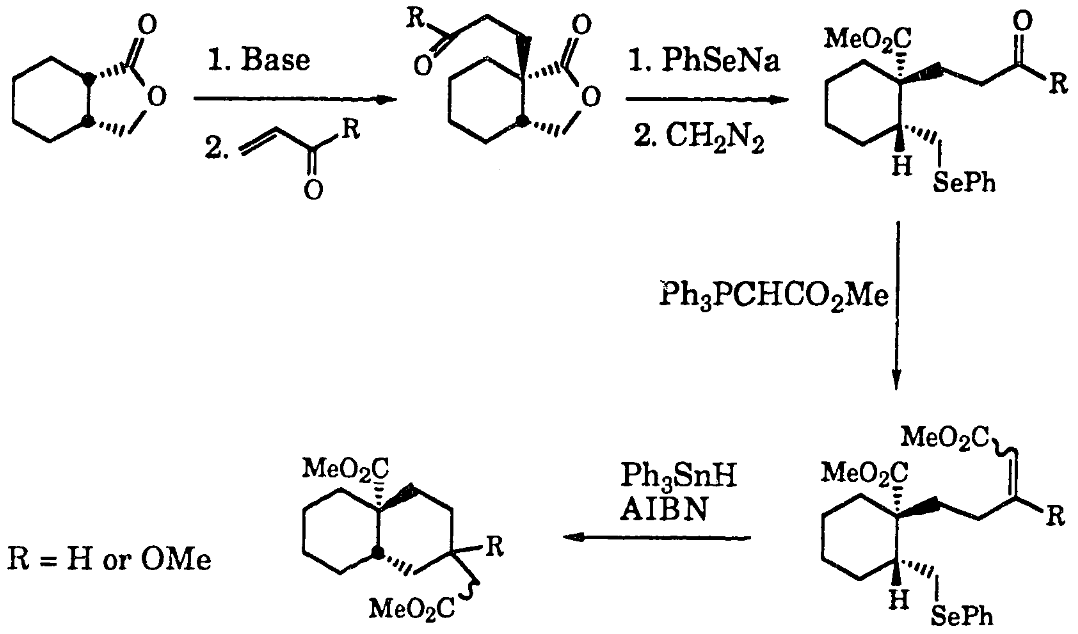
The examples discussed above represent the basics which serve to outline the essential elements of a methodology leading to *trans* ring-fused carbocycles and work is continuing in this laboratory to extend the method to other examples. In principle the pendant acetylene could be introduced by aldol reaction as shown in Scheme 21 and an advantage of this technique is that, as shown in the Scheme, cyclization and ozonolysis gives an α-substituted ketone. Regiochemically defined manipulation of that ketone should then be possible.

SCHEME 21



We may also be able to extend the technique so as to generate 6-membered rings (see Scheme 22).

SCHEME 22



III EXPERIMENTAL

Unless otherwise stated the following particulars apply. Experiments were carried out under argon that was purified by passage through a column (3.5 x 42 cm) of R-311 catalyst[112] and then through a similar column of Drierite.

Glassware was dried in an oven for at least 3 h (130 °C), cooled in a desiccator, quickly assembled, and sealed with rubber septa (when applicable). Inlet and exit needles for argon were passed through a septum on the apparatus, and argon was purged through the system. The exit needle was removed after a few minutes (provided no gas was being generated during the reaction), and the apparatus was kept under a slight static pressure of argon. Stirring was effected by using a dry, Teflon-coated magnetic stirring bar.

Materials were weighed quickly into dry flasks which were then sealed with rubber septa and purged with argon. Transfer of moisture and/or air-sensitive materials was accomplished using dry, greased syringes whenever possible. Solids were dissolved in a suitable solvent prior to transfer.

Solvents were distilled before use for chromatography or extractions. The same solvent systems that were used for thin layer chromatography were employed for flash column chromatography as well. Where required, solvents and reagents were dried with suitable drying agents and were distilled under argon. Dry ether and tetrahydrofuran (THF) were distilled from sodium-benzophenone ketyl, benzene was distilled from sodium; dichloromethane, chloroform, carbon tetrachloride, hexane, pyridine, triethylamine, diisopropylamine, and hexamethylphosphoric triamide (HMPA) were distilled from calcium hydride [the latter under reduced pressure (*ca.* 10 mm)]. U.S.P. absolute ethanol[113] was used without further drying. Commercial solutions (Aldrich) of *n*-butyllithium in hexanes were titrated before use by the diphenylacetic acid method.[114] Phenylselenenyl chloride, phenylselenenyl bromide, diphenyl diselenide (all Aldrich materials) were used as received. Phenylacetylene (Aldrich) was distilled and stored over 4Å molecular sieves prior to use. Azobis(isobutyronitrile) (AIBN) from Eastman was used without further purification and stored at 5 °C.

Products were isolated from solution by concentration under water pump vacuum at 30 °C using a rotary evaporator. Where compounds were isolated by simple evaporation of their solutions, the residues were kept under vacuum (<0.1 mm) until of constant weight. Melting points were measured with a Kofler block melting point apparatus. Boiling points quoted for products distilled in a Kugelrohr apparatus refer to the oven temperature.

Commercial silica (Merck 60F-254) thin-layer chromatography (TLC) plates were used. Silica gel for flash column chromatography was Merck type 60 (230-400 mesh). TLC plates were examined under UV radiation (254 nm), treated with iodine vapor, and charred on a hot plate after being dipped into a solution of phosphomolybdic acid,[115] or after being sprayed with an acidic solution of anisaldehyde in 95% ethanol.[116]

Elemental combustion analyses were performed by the microanalytical laboratory of the University of Alberta or by Butterworth Laboratories Ltd in England. An X-ray crystal structure was determined by Dr. R. G. Ball at the University of Alberta. Infrared spectra were recorded on a Perkin-Elmer 297 spectrophotometer or a Nicolet 7000 FT-IR model. Liquids were run as neat films on potassium chloride plates, and solids were run as solutions in the specified solvent in 0.5 mm potassium chloride cells. Proton NMR spectra were recorded on Bruker WP-80 (at 80 MHz), Bruker WH-200 (at 200 MHz), Bruker WH-300 (at 300 MHz), or Bruker WH-400 (at 400 MHz) spectrometers in deuterated chloroform with tetramethylsilane (TMS) as an internal standard. Carbon-13 NMR spectra were recorded on the latter three machines at 50.3, 75.5, and 100.6 MHz, respectively. All spectra were recorded in deuterated chloroform with TMS as an internal standard. Where indicated, the assignment of resonances to carbon type was determined using the APT[117] sequence. The following abbreviations are used in the text: s, singlet; d, doublet; t, triplet; q, quartet; q', quintet; o, octet; m, multiplet; br, broad; J, coupling constant; δ, chemical shift. Mass spectra were recorded on an A.E.I. MS50 mass spectrometer at an ionizing voltage of 70 eV.

All compounds with asymmetric centers are racemic. In those cases where two or more diastereomers were isolated as mixtures, all resonances in the ^{13}C NMR spectra were not always observed. Where possible, the missing or coincident signals have been indicated and for isomer mixtures, the ratio is given if this could be deduced from the NMR spectrum.

(A) *Cis* and *Trans* Ring-Fused Carbocycles

[[1-(Phenylseleno)ethenyl]sulfonyl]benzene (100).[68]

A solution of phenyl vinyl sulfone[93] (10.8 g, 0.064 mol) in dry carbon tetrachloride (25 mL) was added dropwise to a stirred solution (200 mL) of phenylselenenyl bromide (16.3 g, 0.064 mol) in the same solvent. The mixture was then refluxed for 18 h, cooled to room temperature, and concentrated under reduced pressure to afford [[2-bromo-1-(phenylseleno)ethyl]sulfonyl]benzene. Triethylamine (8.95 mL, 0.064 mol) in dry benzene (200 mL) was added and the mixture was stirred at room temperature for 18 h. The resulting suspension was filtered, the solvent was evaporated, and the residue was re-dissolved in dichloromethane (100 mL). The organic layer was washed with water (3 x 20 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the resulting dark red solid in three portions, each over silica gel (5 x 15 cm), using 20% ethyl acetate - hexane, followed by crystallization from ether afforded **100** (15.3 g, 74%) as a white solid: mp. 68 - 69 °C [lit.[68] mp. 68 - 69 °C]; IR (CCl_4) 3070, 1475, 1448, 1440, 1328, 1165, 1080, 692, 612 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 5.86, (d, J = 2 Hz, 1 H), 6.98 (d, J = 2 Hz, 1 H), 7.22 (m, 5 H), 7.50 (m, 3 H), 7.80 (m, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 121.32, 128.78, 129.00, 129.65, 130.65, 133.70, 134.50. Anal. Calcd for $C_{14}H_{12}O_2SSe$: C, 52.02; H, 3.74. Found: C, 52.08, H, 3.69.

A small amount of the intermediate bromide did not react with the triethylamine and was isolated: ^1H NMR ($CDCl_3$, 80 MHz) δ 3.55 (t, J = 10 Hz, 1 H), 4.25 (m, 2 H), 7.05 - 8.15 (m, 10 H).

[(1-Bromoethenyl)sulfonyl]benzene (101).[69]

A solution of bromine (5 mL, 20% w/v in carbon tetrachloride , 19.4 mmol) was added dropwise to a carbon tetrachloride solution (10 mL) of phenyl vinyl sulfone[93] (2.56 g, 15.2 mmol) at room temperature. The mixture was stirred for 8 h and then additional bromine (2.5 mL of the stock solution) was added in one portion and, after a further 15 h, the solvent was evaporated. The residue was crystallized twice from dichloromethane - ether to give the corresponding dibromide (3.65 g, 73%) as a white solid: mp 74 - 75 °C [lit.[69] mp. 73 -75 °C]; IR (CCl_4) 1450, 1347, 1343, 1195, 633 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 3.60, (dd, J = 11.5, 10.0 Hz, 1 H), 4.28 (dd, J = 11.5, 3.0 Hz, 1 H), 4.96 (dd, J= 10.0, 3.0 Hz, 1 H), 7.63 (m, 2 H), 7.76 (m, 1 H), 7.99 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 29.33, 65.11, 129.29, 129.38, 130.09, 135.06; MS (chemical ionization, NH_3), *m/z* 344, 346 (M + 18).

Triethylamine (0.54 mL, 3.87 mmol) was added dropwise over 5 min to a stirred solution of the dibromide (1.06 g, 3.23 mmol) in dry dichloromethane (20 mL) and stirring was continued at room temperature for 18 h. The solution was then washed with water (3 x 5 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the dark brown residue over silica gel (4 x 15 cm) using 15% ethyl acetate - hexane afforded **101** (706.2 mg, 88%) as a white solid: mp 36 - 37 °C [lit.[69] mp. 42 - 44 °C]; IR (CCl_4) 1448, 1353, 1337, 1165, 1076, 936, 680, 610, 560 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 6.30 (d, J= 3 Hz, 1 H), 7.14 (d, J = 3 Hz, 1 H), 7.60 (m, 2 H), 7.72 (m,1 H), 7.98 (m , 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 129.08, 129.16, 129.68, 134.30, 136.36, (one signal missing or coincident); exact mass, *m/z* calcd for $C_8H_7{}^{81}BrO_2S$ 247.9329, found 247.9329. Satisfactory combustion analytical values could not be obtained.

2-[2-(Phenylseleno)-2-(phenylsulfonyl)ethyl]cyclopentanone (106a).

{[1-(Phenylseleno)ethenyl]sulfonyl}benzene **100** (1.00 g, 3.09 mmol) in dry THF (15 mL) was injected dropwise at room temperature into a stirred solution of freshly distilled 1-(1-cyclopenten-1-yl)pyrrolidine[70] (346 mg, 2.54 mmol) in THF (60 mL). The mixture was stirred at room temperature for 3 h, water (10 mL) was added, and stirring was continued for an additional 30 min. The mixture was extracted with ether (3 x 25 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the crude product over silica gel (4 x 15 cm) using 25% ethyl acetate - hexane afforded two fractions. The material of higher R_f (222 mg, 21%) was a single isomer (^{1}H NMR) of **106a**: FT-IR ($CHCl_3$ cast) 1722, 1306, 1146, 1080, 743, 685 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.42 - 2.05 (m, 4 H), 2.08 - 2.40 (m, 4 H), 2.55 - 2.75 (m, 1 H), 5.00 (dd, J = 3.2, 11.4 Hz, 1 H), 7.24 (m, 3 H), 7.51 (m, 5 H), 7.90 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 20.63, 29.10, 30.35, 38.10, 45.29, 64.98, 127.38, 128.53, 128.80, 129.11, 129.29, 133.63, 134.84, 137.33, 220.27; MS (chemical ionization, NH_3), *m/z* 426 (M + 18). Anal. Calcd for $C_{19}H_{20}O_3SSe$: C, 56.02; H, 4.95; S, 7.87; Se, 19.38. Found: C, 56.31; H, 5.04; S, 7.91; Se, 19.6.

The fraction of lower R_f (520 mg, 50%) contained (^{1}H NMR) two components: the above faster running compound and a second isomer of **106a**: FT-IR ($CHCl_3$ cast) 1736, 1309, 1146, 1080, 740, 685 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.20 - 2.46 (m, 8 H), 2.66 (m, 1 H), 4.17 (dd, J = 4.0, 11.4 Hz, 0.7 H), 5.00 (dd, J = 3.1, 11.4 Hz, 0.3 H, higher R_f isomer), 7.28 (m, 3 H), 7.56 (m, 5 H), 7.93 (m, 2 H); MS (chemical ionization, NH_3), *m/z* 426 (M + 18). Before separation the ratio of the isomers in the total reaction product was 1:1 (^{1}H NMR).

2-[2-(Phenylseleno)-2-(phenylsulfonyl)ethyl]cyclohexanone (107a).

The procedure employed for **106a** was followed using **100** (789 mg, 2.43 mmol) in dry THF (5 mL + 2 mL rinse) and freshly distilled 1-(1-cyclohexen-1-yl)pyrrolidine[70] (352 mg, 2.33 mmol) in THF (20 mL). The reaction mixture was stirred at room temperature for 3 h and then worked up. Flash chromatography of the crude product over silica gel (3 x 15 cm) with 20% ethyl acetate - hexane gave **107a** (715.1 mg, 73%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 1:1 ratio (^{1}H NMR). An analytical sample was prepared by crystallization from dichloromethane - ether: mp 72 - 73 °C. The material from the flash chromatography had: IR (CCl_4) 1715, 1480, 1450, 1440, 1330, 1310, 1155, 1135, 1090, 695 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.10 - 2.50 (m, 10 H), 2.93 (m, 1 H), 4.30 (dd, J = 6.0, 8.5 Hz, 0.5 H), 4.58 (dd, J = 3.0, 12.0 Hz, 0.5 H), 7.27 (m, 2 H), 7.56 (m, 5 H), 7.94 (m, 3 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 24.89, 25.15, 27.69, 27.78, 29.58, 30.44, 33.55, 34.85, 42.00, 48.00, 48.51, 65.05, 66.07, 128.66, 128.78, 128.84, 129.17, 129.42, 133.64, 134.88, 135.11, 211.48, 211.95, (two signals missing or coincident); exact mass, *m/z* calcd for $C_{20}H_{22}O_3SSe$ 422.0455, found 422.0452. Anal. Calcd for $C_{20}H_{22}O_3SSe$: C, 57.00; H, 5.26; O, 11.39; S, 7.61. Found: C, 57.29; H, 5.24; O, 10.61; S, 7.73.

4-(1,1-Dimethylethyl)-2-[2-(phenylseleno)-2-(phenylsulfonyl)ethyl]-cyclohexanone (111a).

The procedure employed for **106a** was followed using **100** (584.8 mg, 1.80 mmol) in THF (5 mL + 2 mL rinse) and freshly distilled 1-[4-(1,1-dimethylethyl)-1-cyclohexen-1-yl]pyrrolidine[70] (372.0 mg, 1.80 mmol) in THF (25 mL). The reaction mixture was stirred at room temperature for 3 h and then worked up. Flash chromatography of the crude product over silica gel (4 x 15 cm) using 25% ethyl acetate - hexane gave **111a** (845.2 mg, 98%) as a colorless oil which was a chromatographically (TLC) inseparable mixture of four isomers in a 6.3:4.9:2.1:1 ratio (^{1}H NMR): IR (neat) 1712, 1478, 1448, 1322, 1312, 1155 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 0.85 (m, 9 H), 0.94 - 2.68 (m, 9 H), 2.92 (m, 1 H), 4.15 (dd, J = 4.5, 10.0 Hz, 0.07 H), 4.22 (dd, J = 2.5, 12.0 Hz, 0.15 H), 4.32 (dd, J = 6.0, 9.0 Hz, 0.34 H), 4.61 (dd, J = 3.0, 12.5 Hz, 0.44 H), 7.24 (m, 3 H), 7.49 - 7.68 (m, 5 H), 7.91 (m, 2 H); ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ (carbonyl signals only) 206.87, 211.96, 212.43, 214.53; exact mass, *m/z* calcd for $C_{24}H_{30}O_3SSe$ 478.1081, found 478.1075. Satisfactory combustion analytical values could not be obtained.

2-[2-Bromo-2-(phenylsulfonyl)ethyl]cyclohexanone (112a).

The procedure employed for **106a** was followed using **101** (564. mg, 2.29 mmol) in THF (5 mL + 1 mL rinse) and freshly distilled 1-(1-cyclohexen-1-yl)pyrrolidine[70] (293.4 mg, 1.94 mmol) in THF (20 mL). The reaction mixture was stirred at room temperature for 3 h and then worked up. Flash chromatography of the crude product over silica gel (3 x 15 cm) using 25% ethyl acetate - hexane gave **106a** (537.3 mg, 80%) as a colorless oil which was a chromatographically (TLC) inseparable mixture of two isomers in a 1:1 ratio (^{1}H NMR). White, crystalline material, enriched in one isomer, was obtained from ether - dichloromethane: mp 73 - 104 °C. The material obtained directly from the flash chromatography had: IR (CCl$_4$) 1715, 1455, 1335, 1325, 1160, 1140, 1095, 920, 700 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.30 - 2.82 (m, 11 H), 4.92 (dd, J = 5.5, 9.5 Hz, 0.5 H), 5.26 (dd, J = 2.5, 11.5 Hz, 0.5 H), 7.60

(m, 2 H), 7.72 (m, 1 H), 7.98 (m, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 24.89, 25.15, 27.61, 27.81, 32.00, 32.58, 33.13, 34.92, 41.96, 42.07, 47.72, 48.19, 62.74, 64.74, 129.73, 129.97, 134.47, 134.45, 135.33, 135.56, 210.74, 211.57; exact mass *m/z* calcd for $C_{14}H_{17}{}^{81}BrO_3S$ 346.0061, found 346.0057. Anal. Calcd for $C_{14}H_{17}BrO_3S$: C, 48.70; H, 4.96; Br, 23.14; S, 9.29. Found: C, 48.50; H, 5.04; Br, 23.08; S, 9.28.

1-(Phenylethynyl)-2-[2-(phenylseleno)-2-(phenylsulfonyl)ethyl]-cyclopentanol (106b).

n-Butyllithium (1.6 M in hexanes, 0.40 mL, 0.81 mmol) was injected dropwise into a stirred solution of phenylacetylene (0.09 mL, 0.81 mmol) in dry THF (30 mL) at -78 °C. The mixture was stirred for 15 min, and ketones **106a** (1:1 isomer mixture, 131.0 mg, 0.32 mmol) in THF (4 mL + 1 mL rinse) were added dropwise over 5 min. Stirring was continued for 2 h at -78 °C, saturated aqueous ammonium chloride (10 mL) was added, and the mixture was extracted with ether (3 x 25 mL). The combined organic extracts were washed with brine (1 x 20 mL), dried ($MgSO_4$), and evaporated.. Flash chromatography of the crude product over silica gel (1 x 15 cm) using 25% ethyl acetate - hexane gave unreacted starting material (27.0 mg, 21%) and **106b** (130.3 mg, 79%; quantitative yield based on conversion). Alcohols **106b** were obtained as a thick syrup which was a chromatographically (TLC) inseparable mixture of four isomers in a 4.3:3.7:2:1 ratio (^{1}H NMR): FT-IR ($CHCl_3$ cast) 3465, 1445, 1305, 1144, 743, 689 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.12 - 2.39 (m, 9 H), 2.59 (m, 1 H), 4.23 (dd, J = 7.0, 8.5 Hz, 0.42 H), 4.88 (dd, J = 2.5, 11.5 Hz, 0.35 H), 5.01 (dd, J= 3.5, 11.5 Hz, 0.18 H), 5.07 (dd, J = 2.5, 9.5 Hz, 0.05 H), 7.12 - 7.60 (m, 13 H), 7.84 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz), δ 20.58, 28.77, 30.36, 30.83, 31.88, 41.96, 43.05, 45.32, 47.57, 48.72, 66.08, 66.23, 78.12, 78.60, 128.21, 128.27, 128.40, 128.61, 128.77, 128.82, 129.01, 129.16, 129.35, 129.49, 131.72, 131.93, 133.37, 133.67, 134.87, 135 20, 135.36; exact mass, *m/z* calcd for $C_{27}H_{26}O_3SSe$ 510.0767, found 510.0774. Satisfactory combustion analytical values could not be obtained.

1-(Phenylethynyl)-2-[2-(phenylseleno)-2-(phenylsulfonyl)ethyl]-cyclohexanol (107b; 109b) and **(1α, 2β)-1-(Phenylethynyl)-2-[2-(phenylseleno)-2-(phenylsulfonyl)ethyl]cyclohexanol (108b).**

The procedure employed for **106b** was followed using *n*-butyllithium (1.6 M in hexanes, 0.41 mL, 0.64 mmol), phenylacetylene (0.09 mL, 0.819 mmol) in dry THF (20 mL) at -78 °C and ketones **107a** (135 mg, 0.321 mmol) in THF (4 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane gave **107b** (127.7 mg, 76%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of four isomers in a 2.6:2.8:2.6:1 ratio (^{1}H NMR): FT-IR ($CHCl_3$ cast) 3485, 1488, 1476, 1445, 1305, 1145, 1080, 755, 742, 690 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.80 - 2.86 (m, 12 H), 4.16 (m, 0.11 H), 4.34 (dd, J = 4.0, 11.0 Hz, 0.29 H), 4.94 (dd, J = 3.6, 10.6 Hz, 0.31 H), 5.06 (dd, J = 3.0, 11.5 Hz, 0.29 H), 7.10 - 8.00 (m, 15 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ (non-aromatic signals only) 20.87, 21.11, 23.82, 23.88, 24.38, 24.66, 25.08, 25.43, 25.59, 28.84, 28.91, 31.35, 31.41, 31.52, 33.03, 39.67, 40.07, 41.54, 42.13,43.49, 45.20, 45.73, 65.89, 66.97, 68.90, 72.80, 74.64, 84.60, 87.01, 87.15, 89.36, 89.52, 93.69; MS, *m/z* 524 (M^+). Anal. Calcd for $C_{28}H_{28}O_3SSe$: C, 64.24; H, 5.39; O, 9.17; S, 6.12 . Found: C, 64.03; H, 5.28; O, 8.95; S, 6.17.

The syrupy mixture of isomers afforded **108b** as a single crystalline compound (32.6% of the mixture) from dichloromethane - hexane. Compound **108b** was later assigned the indicated structure on the basis of an X-ray crystallographic analysis of its radical cyclization to product **108c**. Compound **108b** had: FT-IR (CH_2Cl_2 cast) 3560, 1445, 1302, 1288, 1146, 1140, 1080 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.20 - 2.44 (m, 11 H), 2.76 (o, J = 3.6 Hz, 1 H), 4.94 (dd, J = 3.6, 10.6 Hz, 1 H), 7.26 (m, 10 H), 7.31 (m, 3 H), 7.77 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 20.88, 28.88, 31.35, 40.07, 43.49, 66.97, 128.34, 128.45, 128.61, 128.66, 129.11, 129.51, 131.60, 133.42, 135.32; MS (chemical ionization, NH_3), *m/z* 542 (M + 18). Anal. Calcd for $C_{28}H_{28}O_3SSe$: C, 64.24; H, 5.39. Found C, 63.98; H, 5.42.

The mother liquors from the crystallization which afforded **108b** were concentrated. The residue amounted to 67% of the original mixture and contained three isomers in a 3.8:1.8:1 ratio (^{1}H NMR) and a just detectable trace of the crystalline trans isomer **108b**. The material had: IR (CCl_4) 3610, 3500, 1446, 1320, 1310, 1155 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.80 - 2.66 (m, 12 H), 4.16 (dd, J = 2.5, 12.5 Hz, 0.15 H), 4.34 (dd, J = 4.0, 11.0 Hz, 0.60 H), 5.06 (dd, J = 3.0, 11.5 Hz, 0.25 H), 7.12 - 7.66 (m, 13 H), 7.90 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ (non-aromatic signals only) 20.90, 23.73, 23.81, 25.00, 25.36, 28.73, 31.05, 31.47, 32.84, 41.42, 42.06, 43.34, 44.85, 45.52, 65.78, 66.80, 66.86, 69.80, 72.64, 74.63, 86.86, 86.97, 89.11, 89.27; MS, *m/z* 524 (M$^+$).

2-[2-(Phenylseleno)-2-(phenylsulfonyl)ethyl]-1-(1-propynyl)-cyclohexanol (110b).

Propyne (ca. 1 mL) was condensed in a test tube sealed with a septum and transferred rapidly via cannula to a stirred and cooled (-78 °C) solution of *n*-butyllithium (1.55 M in hexanes, 0.75 mL, 1.16 mmol), in THF (20 mL). The mixture was stirred for 20 min. and ketones **107a** (287 mg, 0.681 mmol) in THF (4 mL + 1 mL rinse) were added dropwise over 10 min. Stirring was continued for 4 h at -78 °C. The cooling bath was removed and after 30 min. the mixture was quenched with saturated aqueous ammonium chloride (15 mL), and extracted with ether (3 x 20 mL). The combined extracts were washed with brine (10 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane afforded **110b** (280 mg, 89%) as a white solid which was a chromatographically (TLC) inseparable mixture of three isomers, the two major ones being in a 1.4:1 ratio (^{1}H NMR): mp. 87 - 112 °C; FT-IR ($CHCl_3$ cast) 3480, 2932, 1446, 1439, 1305, 1146, 1082, 744, 690 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.90 - 2.70 (m, 15 H), 4.28 (dd, J = 4.0, 11.0 Hz, 0.6 H), 4.98 (m, 0.4 H), 7.26 (m, 3 H), 7.55 (m, 5 H), 7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 20.91, 23.80, 25.06, 28.60, 28.87, 30.61, 41.62, 45.40, 65.97, 66.85, 72.34, 128.71, 128.92, 129.08, 129.25, 129.45, 133.56, 135.21, 137.50; exact mass, m/z calcd for $C_{23}H_{26}O_3SSe$ 462.0768, found 462.0773. Satisfactory combustion analytical values could not be obtained.

4-(1,1-Dimethylethyl)-1-(phenylethynyl)-2-[2-(phenylseleno)-2-(phenylsulfonyl)ethyl]cyclohexanol (111b).

The procedure employed for **106b** was followed using *n*-butyllithium (1.6 M in hexanes, 0.33 mL, 0.52 mmol), phenylacetylene (82 mg, 0.80 mmol) in dry THF (30 mL) and ketones **111a** (124 mg, 0.260 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 25% ethyl acetate - hexane gave **111b** (119 mg, 79%) as a colorless oil which was a chromatographically (TLC) inseparable mixture of four isomers in a 2.7:1.3:2:1 ratio (^{1}H NMR): IR (CCl_4) 3620, 3465, 1480, 1450, 1325, 1315, 1155 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.69 - 2.80 (m, 20 H), 4.20 (dd, J = 1.5, 15.0 Hz, 0.14 H), 4.38 (dd, J = 3.5, 12.0 Hz, 0.29 H), 4.76 (dd, J = 4.95, 10.5 Hz, 0.19 H), 5.05 (m, 0.38 H), 7.12 - 8.12 (m, 15 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ (non-aromatic signals only) 21.23, 24.81, 27.44, 27.50, 27.55, 28.71, 29.86, 29.94, 30.93, 31.42, 31.66, 32.43, 32.67, 35.67, 40.95, 41.35, 41.69, 42.21, 43.80, 44.69, 45.60, 46.96, 47.22, 47.49, 66.24, 66.60, 67.75, 72.10, 72.92, 74.97, 87.18, 206.92, 207.50; exact mass, *m/z* calcd for $C_{32}H_{36}O_3SSe$ 580.1550, found 580.1554. Satisfactory combustion analytical values could not be obtained.

2-[2-Bromo-2-(phenylsulfonyl)ethyl]-1-(phenylethynyl)cyclohexanol (112b).

The procedure employed for **106b** was followed using *n*-butyllithium (1.6 M in hexanes, 2.0 mL, 3.20 mmol), phenylacetylene (0.44 mL, 4.0 mmol) in dry THF (30 mL) and ketones **112a** (484 mg, 1.40 mmol) in THF (9 mL + 2 mL rinse). Flash chromatography of the crude product over silica gel (3 x 15 cm) using 25% ethyl acetate - hexane gave

112b (608 mg, 97%) as a colorless oil which was a chromatographically (TLC) inseparable mixture of four isomers in a 3:2:2.3:1 ratio (^{1}H NMR). On standing, the material solidified (mp 44 - 45 °C) but attempts to recrystallize it were unsuccessful: FT-IR ($CHCl_3$ cast) 3580, 1488, 1446, 1320, 1308, 1300, 1082, 755, 678 cm^{-1}; ^{1}H NMR ($CDCl_3$, 100.6 MHz) δ 1.36 - 2.32 (m, 10 H), 2.34 - 2.70 (m, 1H), 2.84 - -3.16 (m, 1 H), 4.88 (dd, J = 4.0, 10.5 Hz, 0.12 H), 5.00 (dd, J = 4.0, 10.5 Hz, 0.28), 5.54 (dd, J = 3.5, 10.5 Hz, 0.24 H), 5.65 (dd, J = 2.5, 11.5 Hz, 0.36 H), 7.16 - 7.76 (m, 8 H), 7.94 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ (non-aromatic signals only) 20.77, 23.73, 23.82, 24.50 24.73, 24.96, 25.18, 25.28, 28.42, 28.83, 31.46, 32.85, 33.41, 34.02, 36.22, 39.72, 39.90, 41.4,0 41.49, 42.08, 43.48, 43.75, 44.76, 45.55, 64.01, 64.90, 65.84, 66.43, 68.70, 72.52, 74.42, 84.54, 87.21, 87.44, 88.90, 89.26, 93.13; exact mass, *m/z* calcd for $C_{22}H_{23}{}^{81}BrO_3S$ 448.0532, found 448.0534. Anal. Calcd for $C_{22}H_{23}BrO_3S$: C, 59.06; H, 5.18; O, 10.73; S, 7.17. Found: C, 58.74; H, 5.07; O, 11.07; S, 6.92.

2-[2-Bromo-2-(phenylsulfonyl)ethyl]-1-(ethoxyethynyl)cyclohexanol (113b).

The procedure employed for **106b** was followed using *n*-butyllithium (1.6 M in hexanes, 1.90 mL, 3.04 mmol), ethoxyacetylene[118] (291 mg, 4.16 mmol) in dry THF (40 mL) and ketones **112a** (469 mg, 1.36 mmol) in THF (4 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane gave **113b** (546 mg, 96%) as a light yellow oil which was a chromatographically (TLC) inseparable mixture of four isomers in a 4.8:3.9:4.7:1 ratio (^{1}H NMR): IR (CCl_4) 3605, 3500, 2246, 1444, 1322, 1150 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.10 - 2.02 (m, 13.5 H), 2.25 - 2.52 (m, 0.7 H), 2.81 - 3.00 (m, 0.8 H), 4.10 (dq, J = 7.0 Hz, 2 H), 4.80 (dd, J = 3.5, 12.0 Hz, 0.07 H), 4.94 (dd, J = 4.0, 10.5 Hz, 0.33 H), 5.42 (dd, J = 3.5, 10.0 Hz, 0.27 H), 5.48 (dd, J = 2.5, 11.5 Hz, 0.33 H), 7.59 (m, 2 H), 7.70 (m, 1 H), 7.99 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ (non-aromatic signals only) 14.42, 14.50, 21.18, 23.86, 23.97, 24.49, 25.12, 25.45, 28.47, 28.98, 31.63, 33.15, 34.45, 35.99, 38.09, 40.86, 42.27, 42.92, 44.02, 44.62, 45.58, 64.14, 66.08, 66.48, 72.21, 74.28, 74.74, 74.95, 95.95; exact mass, *m/z* calcd for $C_{18}H_{23}{}^{81}BrO_4S$ 416.0481, found 416.0478.

2-[2-Bromo-2-(phenylsulfonyl)ethyl]-1-[(trimethylsilyl)oxy]cyclohexanecarbonitrile (114b).

Trimethylsilyl cyanide (0.12 mL, 0.92 mmol) was injected in one portion into a stirred solution of ketones **112a** (286 mg, 0.830 mmol) and zinc iodide (1 mg, 0.003 mmol) in dichloromethane (10 mL). Stirring was continued for 2 h and the reaction mixture was quenched with saturated aqueous ammonium chloride (10 mL) and extracted with ether (3 x 10 mL). The combined extracts were washed with brine (5 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (2 x 15 cm) using 20% ethyl acetate - hexane afforded **114b** (350 mg, 95%) as a colorless oil which was a chromatographically (TLC) inseparable mixture of four isomers in a 4.3:2.5:1 ratio (^{1}H NMR): FT-IR ($CHCl_3$ cast) 1423, 1327, 1311, 1255, 1153, 1138, 1118, 847 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.21 (m, 9 H), 1.15 - 2.46 (m, 10.5 H), 2.81 (m, 0.5 H), 4.72 (dd, J = 2.5, 12.0 Hz, 0.13 H), 4.81 (dd, J = 3.5, 11.5 Hz, 0.32 H), 5.16 (dd, J = 3.5, 10.5 Hz, J = 3.5, 11.0 Hz, 0.55 H), 7.61 (m, 2 H), 7.72 (m, 1 H), 7.99 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 1.06, 1.09 1.33, 1.46, 20.05, 23.20, 24.31, 24.38, 24.68, 27.51, 28.34, 30.74, 32.98, 33.22, 35.75, 38.02, 39.63, 43.32, 43.41, 45.85, 46.06, 63.64, 64.86, 65.78, 74.71, 76.58, 119.47, 129.07, 129.11, 129.16, 139.95, 130.00, 130.23, 134.52, 134.59, 134.67, 134.87; exact mass, *m/z* calcd for $C_{18}H_{26}{}^{81}BrNO_3SSi$ 445.0566, found 445.0571.

2-[2-Bromo-2-(phenylsulfonyl)ethyl]-1-(1-propynyl)cyclohexanol (115b).

The procedure employed for **110b** was followed using propyne (ca. 2 mL), *n*-butyllithium (1.6 M in hexanes, 0.72 mL, 1.15 mmol) in THF (25 mL) and ketones **112a** (198 mg, 0.574 mmol) in THF (4 mL + 1 mL rinse). The mixture was stirred for 4 h at -78 °C and then worked up. Flash chromatography of the residue over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane afforded **115b** (209 mg, 94%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of three isomers in a 2:1.3:1 ratio (^1H NMR): ^1H NMR ($CDCl_3$, 300 MHz) δ 0.80 - 2.55 (m, 13.6 H), 2.79 (o, J = 3.5, 6.5 Hz, 0.7 H), 2.93 (o, J = 3.5, 6.5 Hz, 0.7), 4.90 (dd, J = 4.0, 11.5 Hz, 0.3 H), 5.40 (dd, J = 3.5, 10.5 Hz, 0.2 H), 5.55 (dd, J = 2.5, 11.5 Hz, 0.5 H), 7.58 (m, 2 H), 7.70 (m, 1 H), 8.00 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.21, 20.98, 21.04, 23.74, 23.86, 24.40, 25.09, 25.39, 28.27, 28.93, 31.26, 31.47, 32.84, 34.31 36.05, 49.96, 41.78, 42.36, 43.45, 44.61, 45.48, 64.20, 66.17, 66.62, 68.53, 72.23, 74.28, 79.06, 79.43, 80.75, 83.07, 83.29, 83.61, 128.96, 120.99, 129.95, 130.05, 130.08, 134.12, 134.34, 134.40, 135.53, 135.62, 135.84, (one aromatic signal missing or coincident).

Analytical material enriched in one isomer was obtained by crystallization from ethyl acetate - hexane: mp 72 - 118 °C; FT-IR ($CHCl_3$ cast) 3490, 1447, 1320, 1310, 1149, 1083, 749, 571 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.10 - 2.05 (m, 15 H), 2.79 (o, J = 3.5, 6.5 Hz, 1 H), 5.55 (dd, J = 2.5, 11.5 Hz, 1 H), 7.58 (m, 2 H), 7.70 (m, 1 H), 8.00 (m, 2 H); exact mass, *m/z* calcd for $C_{17}H_{21}{}^{81}BrO_3S$ 386.0374, found 386.0365. Anal. Calcd for $C_{17}H_{21}BrO_3S$: C, 52.99; H, 5.49; Br, 20.74; S, 8.32. Found: C, 53.09; H, 5.68; Br, 20.62; S, 8.53.

General Procedure for Radical Cyclization

Dry benzene and oven-dried apparatus were used. AIBN (Eastman) was used without further purification. The substrate (0.5 - 2.0 mmol) was placed in a 100 mL round-bottomed flask equipped with a Teflon-coated stirring bar and a reflux condenser sealed with a rubber septum. The system was flushed with argon for 5 - 10 min. and benzene (25 - 70 mL) was injected. The flask was lowered into an oil bath, preheated to 80 °C, and benzene solutions of triphenyltin hydride (1.5 equivalents, 0.01 - 0.1 M) and AIBN (0.3 equivalents, 0.006 M) were injected simultaneously over 10 h using a double syringe pump. The mixture was arbitrarily refluxed for a period of 2 h after the end of the addition, cooled, and evaporated. In the experiments using bromides, the residue was taken up in ether (*ca.* 20 mL) and stirred with an aqueous solution (10 mL) containing an excess of potassium fluoride. The precipitated tributyltin fluoride was removed by filtration, and the ether layer was separated, dried ($MgSO_4$), and evaporated. The residue was then processed as described for the individual examples.

Hexahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a(1*H*)- pentalenol (106c).

The general procedure was not followed in this experiment. Triphenyltin hydride (289 mg, 0.823 mmol) in benzene (5 mL), and AIBN (10 mg, 0.06 mmol) in benzene (5 mL) were added in one portion to a refluxing solution of selenides **106b** (272 mg, 0.533 mmol) in benzene (50 mL). The mixture was stirred under reflux for 15 h, cooled, and evaporated. Flash chromatography of the crude product over silica gel (2 x 15 cm) gave **106c** (46.6 mg, 25%; 30% based on conversion) as a thick syrup which was mostly one isomer with a trace of a second (^{1}H NMR), together with unreacted starting material (50.3 mg, 19%). Compound **106c** had: FT-IR (CCl_4 cast) 3500, 1440, 1302, 1280, 1139, 1080, 730 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.19 - 2.09 (m, 7 H), 2.71 (m, 1 H), 2.91 (m, 1 H), 3.88 (s, 1 H), 4.01 (d, 1 H), 6.03 (s, 0.94 H), 6.39 (d, J = 0.5 Hz, 0.06 H), 7.11 - 7.41 (m, 4 H), 7.58 - 7.70 (m, 4 H), 7.90 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 23.38, 24.89, 26.06, 27.17, 30.98, 31.38, 31.84, 37.76, 54.99, 74.52, 76.49, 89.03, 127.85, 128.00, 128.10, 128.40 128.60, 128.78, 129.06, 129.25, 130.29, 131.92, 133.90, 134.26, 135.19, 136.37, 140.20; exact mass, *m/z* calcd for $C_{20}H_{22}SO_3$ 354.1256, found 354.1295.

(2α, 3*E*, 3aα, 7aβ)-Octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (107c) and **(3aα, 7aα)-Octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (107c').**

The general procedure for radical cyclization was followed using selenides **107b** (346 mg, 0.661 mmol) in benzene (20 mL), triphenyltin hydride (284 mg, 0.808 mmol) in benzene (10 mL), and AIBN (5 mg, 0.03 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 x 15 cm) using ethyl acetate - hexane afforded two solids which were each recrystallized from dichloromethane - hexane. The compound of lower R_f (75.5 mg, 31% yield) was identified as the cis ring-fused compound **107c'** and had: mp 147 - 160 °C; FT-IR ($CHCl_3$ cast) 3490, 1447, 1301, 1142, 1083, 751 cm^{-1}; ^{1}H

NMR ($CDCl_3$, 400 MHz) δ 0.78 - 2.04 (m, 10 H), 2.48 (m, 1 H), 3.26 (s, 1 H), 4.25 (t, J = 8.5 Hz, 1 H), 6.81 (d, J = 1.5 Hz, 1 H), 7.32 (m, 5 H), 7.59 (m, 3 H), 7.93 (m, 2 H); exact mass, *m/z* [(M - $SO_2C_6H_5$)$^+$] calcd for $C_{16}H_{19}O$ 227.1436, found 227.1435. Anal. Calcd for $C_{22}H_{24}O_3S$: C, 71.71; H, 6.57; S, 8.70. Found: C, 71.82; H, 6.80; S, 9.04.

The compound of higher R_f (91.6 mg, 38% yield) was identified as the trans ring-fused material **107c** and had: mp 157 - 162 °C; FT-IR ($CHCl_3$ cast) 3492, 1448, 1494, 1276, 1140, 1082, 742 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.68 - 2.02 (m, 11 H), 3.10 (d, J = 1.5 Hz, 1 H), 4.17 (dt, J = 1.5, 8.5 Hz, 1 H), 6.59 (d, J = 1.5 Hz, 1 H), 7.28 (m, 5 H), 7.60 (m, 3 H), 7.94 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 21.30, 25.09, 25.43, 28.88, 34.50, 48.87, 68.72, 76.55, 127.69, 127.72, 129.17, 129.20, 129.40, 133.36, 133.89, 135.93, 137.46, 138.98; exact mass, *m/z* calcd for $C_{22}H_{24}O_3S$, 368.1446, found 368.1419.

(2α, 3*E*, 3aα, 7aβ)-Octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (108c).

The special procedure employed for **106c** was followed using selenide **108b** (72 mg, 0.138 mmol) in benzene (20 mL), triphenyltin hydride (67 mg, 0.192 mmol) in benzene (5 mL), and AIBN (5 mg, 0.03 mmol) in benzene (5 mL). The mixture was stirred under reflux for 15 h, cooled, and evaporated. Flash chromatography of the residue over silica gel (1 x 15 cm) afforded unreacted starting material (28.0 mg, 39%) and **108c** (28.1 mg, 55%; 90% based on conversion) as a white solid: mp 165 - 166 °C; FT-IR ($CHCl_3$ cast) 3485, 1442, 1303, 1142, 1078, 742 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.68 - 2.04 (m, 11 H), 3.10 (d, J = 1.5 Hz, 1 H), 4.17 (dt, J = 1.5, 8.5 Hz, 1 H), 6 59 (d, J = 1.5 Hz, 1 H), 7.29 (m, 5 H), 7.60

(m, 3 H), 7.93 (m, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 21.31, 25.10, 25.46, 28.89, 34.53, 48.88, 68.73, 76.55, 127.72, 129.20, 129.42, 133.37, 133.89, 135.98, 139.03, (three signals missing or coincident); exact mass, *m/z* [$(M - SO_2C_6H_5)^+$] calcd for $C_{16}H_{19}S$ 227.1435, found 227.1433.

In a subsequent experiment **108c** was recrystallized from ethyl acetate - hexane (mp 164 - 165 °C) and the structure of the compound was determined by single crystal X-ray analysis.

Crystal data for (108c)

empirical formula $C_{22}H_{24}O_3S$; molecular weight 368.50; $a = 9.771$ (2), $b = 6.804$ (2), $c = 28.593$ (7) Å; $\beta = 94.23$ (2)°; V = 1896 A^3; monoclinic space group $P2_1/n$; Z = 4; $D_{calcd} = 1.291$ g cm^{-3}; μ (Mo Kα) = 1.80 cm^{-1}. Data were collected with an Enraf-Nonius CAD4 automated diffractometer, ω-2ϑ scan, type $\omega = 2\vartheta$, using Mo Kα radiation (λ = 0.71073 Å) up to a maximum of 2ϑ of 50.00°, graphite crystal, incident beam monochromator. Of 3637 reflections, 1639 having $I>\sigma(I)$ were used in the structure solution and refinement. Data were corrected for Lorentz and polarization effects, but not for absorption, with the Enraf-Nonius Structure Determination Package Plus.[119] The structure was solved by the direct-methods program MULTAN.[120] Refinement of automatic parameters, with non-hydrogen atoms assigned anisotropic thermal parameters, was carried out by using full-matrix least-squares techniques on F_0 minimizing $\Sigma\omega(|F_0|-|F_c|)^2$ where $|F_0|$ and $|F_c|$ are the observed and calculated structure factor amplitudes, respectively, and the weighting factor ω is given by $\omega = 4F_0^2/\sigma^2(F_0)^2$.

During the latter stages of refinement the contributions from all H atoms were included in the calculations. The H atoms attached to C were included at their calculated positions (C-H 0.95 Å, appropriate sp^2 and sp^3 geometry) with thermal parameters 1.2 times those of the attached C atom and constrained to "ride" on these same C atoms. The H atom on O3 was located in a difference Fourier and also constrained to ride on this atom.

The final agreement factors were $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o| = 0.070$, $R_2 = (\Sigma\omega(|F_o| - |F_c|)^2/\Sigma\omega F_o^2) = 0.065$.

In the final cycle the largest shift in any parameter was 0.04 times its estimated standard deviation and the error in an observation of unit weight was 1.59 e. An analysis of R_2 in terms of F_o, l^{-1} sin ϑ, and various combinations of Miller indices showed no unusual trends. The highest peak in the final difference Fourier was 0.28 (7) e Å^{-3}; it is not located near any other atom and is without chemical significance.

(2α, 3*E*, 3aα, 7aβ)-Octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (109c) and (3aα, 7aα)-Octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (109c').

After crystallization of **108b** (see above) the mother liquor was concentrated to afford solid material. A portion (645 mg, 1.23 mmol), was cyclized by the general procedure using benzene (60 mL), triphenyltin hydride (686 mg, 1.96 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue using 25% ethyl acetate - hexane gave a solid (286 mg, 63%) containing mainly (>90%) one compound (^{1}H NMR) which was identified as the cis ring-fused material **109c'**. The solid had: mp 147 - 148 °C; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.74 - 2.17 (m, 10 H), 2.48, (m, 1 H), 3.30 (s, 1 H), 4.26 (m, 1 H), 6.81 (d, J = 1.5 Hz, 1 H), 7.32 (m, 5 H), 7.58 (m, 3 H), 7.94 (m, 2 H).

The trans ring-fused compound **109c** (44.3 mg, 12%) was also isolated from the flash chromatography and had: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.67 - 2.06 (m, 11 H), 3.10 (d, J = 1.5 Hz, 1 H), 4.17 (dt, J = 1.5, 8.5 Hz, 1 H), 6.60 (dd, J = 1.5 Hz, 1 H), 7.26 (m, 5 H), 7.58 (m, 3 H), 7.94 (m, 2 H).

3-Ethylideneoctahydro-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (110c).

The procedure employed for **106c** was followed using triphenyltin hydride (337 mg, 0.96 mmol), AIBN (5 mg, 0.03 mmol), and selenides 19b (274 mg, 0.59 mmol) in dry benzene (30 mL). Flash chromatography of the residue over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane gave two fractions as thick syrups which were each a chromatographically (TLC) inseparable mixture of two different isomers (^{1}H NMR) of **110c** together with unreacted starting material (126.0 mg, 46%). The fraction of higher R_f (24.3 mg, 13% yield; 25% based on conversion) was composed of two isomers of **110c** in a 1:1 ratio (^{1}H NMR) and had: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.02 - 2.01 (m, 13 H), 2.08 (br d, J = 11.5 Hz, 0.48 H), 2.46 (br d, J = 11.5 Hz, 0.52 H), 2.96 (d, J = 1.5 Hz, 0.54 H), 3.37 (d, J = 1.5 Hz, 0.46 H), 3.99 (br t, J = 9.0 Hz, 0.45 H), 4.33 (br t, J = 8.0 Hz, 0.55 H), 5.62 (dq, J = 1.5, 7.5 Hz, 0.51 H), 5.92 (dq, J = 1.5, 7.0 Hz, 0.49 H), 7.48 - 7.75 (m, 3 H), 7.92 (m, 2 H).

The fraction of lower R_f (41.2 mg, 23% yield; 42% based on conversion) was composed of two isomers of **110c**, different from those in the upper fraction, in a 1.6:1 ratio (^{1}H NMR) and had: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.59 - 2.56 (m, 14.5 H), 3.86 (s, 0.38 H), 3.99 (m, 0.60 H), 4.10 (m, 0.23 H), 4.40 (br t, J = 9.0 Hz, 0.32 H), 5.81 (dq, J = 1.5, 7.5 Hz, 0.62 H), 5.99 (dq, J = 1.5, 7.0 Hz, 0.38 H), 7.42 -7.75 (m, 3 H), 7.94 (m, 2 H).

6-(1,1-dimethylethyl)octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (111c).

The procedure employed for **106c** was followed using selenides **111b** (48 mg, 0.083 mmol) in benzene (40 mL), triphenyltin hydride (45 mg, 0.127 mmol) in benzene (5 mL), and AIBN (2 mg, 0.01 mmol) in benzene (5 mL). The mixture was stirred under reflux for 15 h and then worked up. Flash chromatography of the crude product over silica gel (1 x 15 cm) using 25% ethyl acetate - hexane gave **111c** (22.9 mg, 65%) as an oily mixture of three isomers in a 5:4:1 ratio (^{1}H NMR) which was resolvable into two spots by TLC (silica, 25% ethyl acetate - hexane). The total material had: FT-IR ($CHCl_3$ cast) 3480, 1440, 1295, 1285, 1141, 1078, 749 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.42 - 2.06 (m, 18.5 H), 2.54 (m, 0.5 H), 3.12 (d, J = 1.5 Hz, 0.33 H), 3.19 (d, J = 1.5 Hz, 0.17 H), 3.60 (s, 0.50 H), 4.12 (m, 0.10 H), 4.19 (dt, J = 1.5, 8.5 Hz, 0.50 H), 4.30 (dt, J = 1.5, 8.5 Hz, 0.40 H), 6.56 (d, J = 1.5 Hz, 0.17 H), 6.59 (d, J = 1.5 Hz, 0.33 H), 6.82 (d, J = 1.5 Hz, 0.50 H), 7.29 (m, 5 H), 7.60 (m, 3 H), 7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ (non-aromatic signals only) 14.20, 21.44, 22.33, 23.44, 23.50, 25.68, 25.79, 27.28, 27.36, 27.47, 27.65, 28.86, 29.61, 39.97, 31.07, 32.04, 32.12, 32.37, 32.76, 34.27, 34.34, 40.95, 43.73, 46.31, 47.69, 49.42, 49.54, 68.98, 69.53, 69.84, 76.20, 77.96, 80.50; exact mass, *m/z* [(M - $SO_2C_6H_5$)$^+$] calcd for $C_{20}H_{27}O$ 283.2062, found 283.2063.

(2α, 3*E*, 3aα, 7aβ)-Octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (112c) and (3aα, 7aα)-Octahydro-3-(phenylmethylene)-2-(phenylsulfonyl)-3a*H*-inden-3a-ol (112c') from bromide (112b).

The procedure employed for **106c** was followed using bromides **112b** (639 mg, 1.43 mmol) in benzene (60 mL), triphenyltin hydride (745 mg, 2.12 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (3 x 15 cm) using 25% ethyl acetate - hexane gave an oily mixture of two compounds **112c** and **112c'** (489 mg, 92%) in a 2.3:1 ratio: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.70 - 1.68 (m, 4 H), 1.80 - 2.04 (m, 6 H), 2.48 (m, 1 H), 3.10 (d, J = 1.5 Hz, 0.3 H), 3.30 (s, 0.7 H), 4.17 (dt, J = 1.5, 8.5 Hz, 0.3 H), 4.25 (t, J = 8.5 Hz, 0.7 H), 6.59 (d, J = 1.5 Hz, 0.3 H), 6.80 (d, J = 1.5 Hz, 0.7 H), 7.30 (m, 5 H), 7.59 (m, 3 H), 7.94 (m, 2 H).

In another experiment, the two compounds obtained as above were separated. The minor compound, which was of higher R_f was identified as trans ring-fused material **112c** and had: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.72 - 2.06 (m, 11 H), 3.10 (d, J = 1.5 Hz, 1 H), 4.16 (dt, J = 1.5, 9.0 Hz, 1 H), 6.62 (d, J = 1.5 Hz, 1 H), 7.32 (m, 5 H), 7.68 (m, 3 H), 7.96 (m, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 21.36, 25.17, 25.51, 28.97, 34.61, 48.95, 68.83, 76.61, 127.78, 129.08, 129.21, 129.77, 129.49, 133.40, 133.93, 136.07, 136.27, 139.15.

The major component, which was of lower R_f and was identified as cis ring-fused material **112c'**, was contaminated by some of the above isomer and had: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.70 - 2.08 (m, 10 H), 2.48 (m, 1 H), 3.10 (d, J = 1.5 Hz, 0.1 H), 3.30 (s, 0.9 H), 4.16 (m, 0.1 H), 4.25 (t, J = 8.5 Hz, 0.9 H), 6.62 (d, J = 1.5 Hz, 0.1 H), 6.79 (d, J= 1.5 Hz, 0.9 H), 7.31 (m, 5 H), 7.58 (m, 3 H), 7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ (signals due to major component only) 22.49, 23.85, 29.32, 29.49, 31.39, 48.27, 69.66, 80.15, 127.75, 127.82, 129.14, 129.21, 129.38, 133.86, 135.20, 135.70, 136.30, 137.47.

3-Ethylideneoctahydro-2-(phenylsulfonyl)-3a*H*-inden-3a-ol(115c) from bromides **(115b).**

The special procedure employed for **106c** was followed using triphenyltin hydride (268 mg, 0.76 mmol), AIBN (10 mg, 0.06 mmol), and bromides **115b** (193 mg, 0.50 mmol) in dry benzene (65 mL). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane gave **115c** (138.0 mg, 90%) as a thick syrup which was a mixture of four isomers in a 4.2:2.2:1.6:1 ratio (^{1}H NMR). The material was identical (^{1}H NMR) to that generated from **110b**: FT-IR ($CHCl_3$ cast) 3480, 1438, 1292, 1136 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.59 - 2.56 (m, 14.5 H), 2.96 (d, J = 1.5 Hz, 0.18 H), 3.37 (d, J = 1.5 Hz, 0.11 H), 3.86 (s, 0.24 H), 3.99 (m, 0.47 H), 4.10 (m, 0.18 H), 4.33 (br t, J = 8.0 Hz, 0.09 H), 4.40 (br t, J = 9.0 Hz, 0.20 H), 5.61 (dq, J = 1.5, 7.5 Hz, 0.19 H), 5.81 (dq, J = 1.5, 7.5 Hz, 0.36 H), 5.91 (dq, J = 1.5, 7.0 Hz, 0.19 H), 5.99 (dq, J = 1.5, 7.0 Hz, 0.25 H), 7.42 - 7.76 (m, 3 H), 7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.65, 13.99, 15.71, 21.18, 21.50, 22.21, 22.32, 23.38, 24.79, 24.97, 25.13, 25.44, 25.82, 26.53, 28.90, 29.21, 30.10, 30.50, 30.63, 32.17, 33.20, 34.39, 36.12, 46.35, 46.84, 47.31, 48.30, 58.83, 64.64, 65.00, 67.71, 67.84, 79.58, 126.85, 128.94, 129.00, 129.10, 129.32, 130.42, 133.69, 133.83, 137.04; exact mass, *m/z* calcd for $C_{17}H_{22}O_3S$ 306.1290, found 306.1283.

(3aβ, 7aα)-Octahydro-7a-hydroxy-2-(phenylsulfonyl)-*1H*-inden-1-one (108d).

A gentle stream of ozone was passed through a cold (-78 °C) solution of alkene **108c** (57 mg, 0.153 mmol) in 4:1 dichloromethane - methanol (5 mL) until a blue color developed (*ca.* 3 min.). The excess of ozone was removed by a stream of argon and dimethyl sulfide (0.5 mL) was added dropwise. The mixture was allowed to warm to room temperature over *ca.* 15 min. and stirred for 15 h. Evaporation of the solvent and flash chromatography of the residue over silica gel (1 x 15 cm) using 25% ethyl acetate - hexane gave **108d** (32.0 mg, 71%) as a white solid which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.1:1 ratio (^{1}H NMR). The material was recrystallized from ether - dichloromethane and had: mp 141 - 142 °C; FT-IR (nujol) 3509, 3487, 1744, 1447, 1377, 1318, 1302, 1292, 1180, 1146, 1084, 1073, 738, 727, 585, 565 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.10 - 1.96 (m, 9.5 H), 2.30 (m, 2.0 H), 2.62 (qd, J = 1.5, 6.5, 13.5 Hz, 0.5 H), 3.84 (dd, J = 8.5, 9.5 Hz, 0.51 H), 4.12 (dd, J = 1.5, 9.7 Hz, 0.46 H), 7.59 (m, 2 H), 7.69 (m, 1 H), 7.90 (m, 2 H); ^{13}C NMR (CDCl$_3$, 50.3 MHz) δ 20.30, 24.23, 24.29, 25.25, 25.36, 26.79, 27.02, 30.26, 42.59, 43.57, 66.91, 68.82, 75.65, 76.48, 129.00, 129.14, 129.20, 133.99, 134.10, 134.20, 137.79, 138.56, 202.27, 203.54,(two signals missing or coincident); exact mass, *m/z* [(M - CO)$^+$] calcd for $C_{14}H_{18}O_3S$ 266.0977, found 266.0975. Anal. Calcd for $C_{15}H_{18}O_4S$: C, 61.20; H, 6.16. Found: C, 61.08; H, 6.15.

(3aβ, 7aα)-Octahydro-7a-hydroxy-2-(phenylsulfonyl)-1*H*-inden-1-one (107d) and (3aα, 7aα)-Octahydro-7aα-hydroxy-2-(phenylsulfonyl)-1*H*-1-inden-1-one (107d').

The procedure for **108d** was followed using alkenes **107c** and **107c'** (237 mg, 643.2 mmol) in 5:1 dichloromethane - methane (25 mL). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane afforded two solids which were each a chromatographically (TLC) inseparable mixture of two isomers (^{1}H NMR), together with cis ring-fused unreacted starting material (49.9 mg, 21%). The material of higher R$_f$ (51.1 mg, 27% yield; 34% based on conversion) was recrystallized from ether - dichloromethane and identified as the trans ring-fused ketones **107d** in a 1.1:1 ratio that had not been altered (^{1}H NMR) by crystallization: mp. 140 - 145 °C; FT-IR (MeOH) 1752, 1307, 1147, 1084 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.09 - 1.95 (m, 9.5 H), 2.30 (m, 2 H), 2.62 (qd, J = 1.5, 6.5, 13.5 Hz, 0.5 H), 3.82 (dd, J = 8.5, 9.5 Hz, 0.55 H), 4.12 (dd, J = 1.5, 9.7 Hz, 0.45 H), 7.59 (m, 2 H), 7.69 (m, 1 H) , 7.90 (m, 2 H); ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ 20.35, 20.38, 24.31, 24.37, 25.31, 25.44, 26.82, 27.09, 30.33, 30.39, 42.66, 43.64, 66.99, 68.91, 75.75, 129.06, 129.09, 129.13, 129.21, 134.06, 134.29, (one aliphatic signal, two aromatic, and two carbonyl signals missing or coincident); exact mass, *m/z* [(M - CO)$^+$] calcd for $C_{14}H_{18}O_3S$ 266.0976, found 266.0975.

The compound of lower R$_f$ (75.6 mg, 40% yield; 50% based on conversion) was identified as the cis ring-fused materials **107d'** and had: mp. 120 - 150 °C; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 1.16 -2.46 (m, 11.65 H), 2.74

(m, 0.35 H), 3.99 (m, 1 H), 7.60 (m, 2 H), 7.70 (m, 1 H), 7.90 (m, 2 H); exact mass, *m/z* [(M - CO)$^+$] calcd for $C_{14}H_{18}O_3S$ 266.0976 found 266.0975.

Octahydro-7a-hydroxy-1-oxo-1*H*-inden-1-one (107e).

The general literature procedure[82] was followed. Three strips of aluminum foil (1 x 5 cm) were dipped into a 2% w/v aqueous solution of mercurous chloride for 15 sec, then into 95% ethanol, and finally into ether. The strips were immediately cut into 0.5 cm square pieces and dropped into a stirred solution of sulfones **107d** and **107d'** (31 mg, 0.105 mmol) in 10% aqueous THF (10 mL). Stirring was continued for 6 h and the mixture was then refluxed for 3 h, cooled, filtered, and evaporated. The resulting oil was dissolved in dichloromethane and the solution was dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (1 x 15 cm) using 25% ethyl acetate - hexane afforded unreacted starting material (8.0 mg, 25%) and **107e** (12.0 mg, 74%; 98% based on conversion) which was a chromatographically inseparable mixture of two isomers (^{13}C NMR). Compound **107e** had: FT-IR (CCl_4 cast) 3420, 1742, 1710, 1442 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.78 - 2.58 (series of multiplets); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 20.69, 24.21, 24.66, 24.91, 25.12, 25.75, 28.08, 30.53, 31.36, 34.23, 35.08, 42.21, 45.88, 49.71, 75.07, 216.63, (one aliphatic and one carbonyl signal missing); exact mass, *m/z* calcd for $C_9H_4O_2$ 154.0994, found 154.1000.

(B) *Cis* Ring-Fused Carbocycles

Michael Acceptors:

[(1-Bromoethenyl)sulfonyl]benzene (**101**) was prepared as reported on p.124. α-Bromo methyl acrylate (**144**)[15] was made by the literature procedure.

1-[(1-Bromoethenyl)sulfonyl]-2, 4, 6-trimethylbenzene (137).

(a) **1-(Ehenylthio)-2,4,6-trimethylbenzene.** The literature procedure for the preparation of phenyl vinyl sulfide[93] was followed using 2-mercaptomesitylene[122] (19.3 mg, 0.127 mmol), sodium ethoxide (0.127 mmol), and 1,2-dibromoethane (34.4 g, 0.184 mmol) in absolute ethanol (150 mL). Distillation (89 - 92 °C, 0.28 mm) of the crude products afforded the vinyl sulfide (10.3 g, 46%), as a colorless syrup: IR (neat) 1630, 1480, 1400, 1135, 880 cm^{-1}; ^{1}H NMR (CDCl$_3$, 200 MHz) δ 2.30, (s, 3 H), 2.44 (s, 6 H), 4.59 (d, J = 15.2 Hz, 1 H), 5.05 (d, J = 10.0 Hz, 1 H), 6.30 (dd, J = 10.0, 15.2 Hz, 1 H), 7.00 (s, 2 H); exact mass, *m/z* calcd for $C_{11}H_{14}S$, 178.0816, found 178.0813.

(b) **1-(Ethenylsulfonyl)-2, 4, 6-trimethylbenzene.** The above sulfide (2.05 g, 11.5 mmol), was dissolved in glacial acetic aced (5.6 mL) and hydrogen peroxide (4.5 mL, 30% solution, 39.7 mmol) was added. The mixture was refluxed for 20 min, cooled, extracted with dichloromethane (3 x 15 mL), dried (MgSO$_4$), and evaporated. Flash chromatography of the crude product over silica gel (2 x 15 cm) using

20% ethyl acetate - hexane gave the sulfone (1.75 g, 72%) as a white solid: mp 68 - 87 °C; FT-IR (CCl_4 cast) 1603, 1450, 1383, 1315, 1147, 745, 710, 676 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.30 (s, 3 H), 2.52 (s, 6 H), 5.98 (d, J = 9.8 Hz, 1 H), 6.32 (d, J = 16.0 Hz, 1 H), 6.70 (dd, J = 9.8, 16.0 Hz, 1 H), 6.96 (s, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 21.03 (q), 22.84 (q), 125.54 (t), 132.18 (d), 138.99 (d), 139.94 (s), 140.28 (s), 143.58 (s); exact mass, m/z calcd for $C_{11}H_{14}O_2S$ 210.0715, found 210.0712.

(c) **1-[(1-Bromoethenyl)sulfonyl]-2, 4, 6-trimethylbenzene (137).** A solution of bromine (0.70 mL, 13.6 mmol) in dry carbon tetrachloride (9.3 mL) was added dropwise over 6 h to a carbon tetrachloride solution (30 mL) of the above sulfone. The mixture was stirred for 8 h and the solvent was evaporated to yield the crude dibromide: ^1H NMR ($CDCl_3$, 300 MHz) δ 2.32 (2, 3 H), 2.68 (s, 6 H), 3.80 (dd, J = 10.0, 12.0 Hz, 1 H), 4.28 (dd, J = 3.5, 12.0 Hz, 1 H), 5.01 (dd, J = 3.5, 10.0 Hz, 1 H), 7.01 (s, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 21.18 (q), 23.12 (q), 29.03 (t), 65.41 (d), 130.09 (s), 132.64 (d), 141.31 (s), 144.90 (s), (one singlet missing or coincident). The crude material was used directly in the following step.

The above dibromide (13.6 mmol) was dissolved in dry dichloromethane (30 mL). Triethylamine (1.5 mL, 10.8 mmol) in dichloromethane (3 mL) was added dropwise, the mixture was stirred at room temperature for 8 h and then evaporated. The residue was dissolved in the minimum amount of ethyl acetate at room temperature, and the solution was filtered then evaporated. The crude material was

recrystallized from ethyl acetate - hexane to afford 137 (1.90 g, 73%) as a pinkish white solid: mp 85 - 86 °C; FT-IR (CCl_4 cast) 1602, 1312, 1162, 1094, 845, 657, 594 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.34 (s, 3 H), 2.65 (s, 6 H), 6.26 (d, J = 3.0 Hz, 1 H), 6.98 (d, J = 3.0 Hz, 1 H), 7.01 (s, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 21.15 (q), 22.76 (q), 126.68 (t), 129.49 (s), 131.21 (s), 132.36 (d), 141.50 (s), 144.40 (s); exact mass, *m/z* calcd for $C_{11}H_{13}{}^{81}BrO_2S$ 289.9799, found 289.9792. Anal. Calcd for $C_{11}H_{13}BrO_2S$: C, 45.69; H, 4.53; O, 11.06; S, 11.09. Found: C, 45.79; H, 4.48; O, 10.68; S, 11.04.

1-[(Bromoethenyl)sulfonyl]-3,5-di(1,1-dimethylethyl)benzene (139).

(a) **3,5-Di[1,1-dimethylethyl]-1-(1-ethenylthio)benzene.** A stock solution of sodium ethoxide (2.5 M) was prepared. An aliquot (3.8 mL) was diluted with absolute ethanol (10 mL) and 2,5-di-*t*-butylthiophenol[123] (2.09 g, 9.43 mmol) in absolute ethanol (10 mL) was added dropwise over 10 min. The mixture was stirred for 30 min and then transferred over 2 h, by syringe pump, to a solution of 1,2-dibromoethane (1.2 mL, 13.9 mmol) in absolute ethanol (35 mL). The resulting mixture was heated to 30 °C for 1.5 h and then additional sodium ethoxide (8.2 mL of the stock solution) was added dropwise over 10 min. The mixture was refluxed for a further 13 h, cooled, and partitioned between water (25 mL) and benzene (25 mL). The organic layer was removed, washed with brine (1 x 10 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (2 x 15 cm) using hexane afforded the vinyl sulfide

(1.35 g, 57%) as a colorless oil. FT-IR (CCl_4 cast) 1584, 1574, 1477, 1363, 1247, 706 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.33 (s, 18 H), 5.31 (d, J = 9.5 Hz, 1 H), 5.33 (d, J = 16.5 Hz, 1 H), 6.57 (dd, J = 9.5, 16.5 Hz, 1 H), 7.24 (d, J = 1.5 Hz, 2 H), 7.32 (t, J = 1.5 Hz, 1 H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 31.41 (q), 35.04 (s), 114.53 (t), 121.62 (d), 125.08 (d), 132.76 (d), 132.97 (s), 151.83 (s); exact mass, *m/z* calcd for $C_{16}H_{24}S$ 248.1633, found 248.1601.

(b) **3-Di[1,1-dimethylethyl]-1-(1-ethenylsulfonyl)benzene.** The method employed for **137** was followed using the above sulfide (633 mg, 2.55 mmol), hydrogen peroxide (1.2 mL, 30% solution, 10.6 mmol), and glacial acetic acid (2 mL). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 5% ethyl acetate - hexane gave the sulfone (544.1 mg, 76%) as a white solid: mp 86 - 87 °C; FT-IR (CCl_4 cast) 1306, 1155, 727 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.36 (s, 18 H), 6.04 (d, J = 9.5 Hz, 1 H), 6.48 (d, J = 16.5 Hz, 1 H), 6.72 (dd, J = 9.5, 16.5 Hz, 1 H), 7.70 (t, J = 1.5 Hz, 1 H), 7.73 (d, J = 1.5 Hz, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 31.29 (q), 35.30 (s), 121.95 (d), 127.08 (t), 128.00 (d), 138.67 (d), 138.94 (s), 152.62 (s); exact mass, *m/z* calcd for $C_{16}H_{24}O_2S$ 280.1497, found 280.1497. Anal. Calcd for $C_{16}H_{24}O_2S$: C, 68.53; H, 8.63; S, 11.43. Found: C, 68.32; H, 8.49; S, 11.27.

(c) **1-[(Bromoethenyl)sulfonyl]-3,5-di(1,1-dimethylethyl)benzene (139).** The procedure employed for **137** was followed using the above sulfone (250 mg, 0.893 mmol) in dry carbon tetrachloride (10 mL) and bromine

(0.07 mL, 1.36 mmol) in carbon tetrachloride (2 mL). The bromine solution was added over 2 h, stirring was continued for 8 h, the solvent was evaporated, and the residue was dissolved in dry dichloromethane (20 mL). Triethylamine (0.115 mL, 1.08 mmol) was added dropwise and the mixture was stirred for 8 h. Flash chromatography of the crude product over silica gel (1 x 15 cm) using 10% ethyl acetate - hexane gave **139** (320 mg, 100%) as a white solid: mp. 82 °C; FT-IR (CCl_4 cast) 2964, 1329, 1183, 626 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.35 (s, 18 H), 6.26 (d, J = 3.0 Hz, 1 H), 7.08 (d, J = 3.0 Hz, 1 H), 7.72 (t, J = 1.5 Hz, 1 H), 7.78 (d, J = 1.5 Hz, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 31.26 (q), 35.29 (s), 123.45 (d), 128.53 (t), 128.57 (d), 130.47 (s), 135.81 (s), 152.45 (s); exact mass, *m*/*z* calcd for $C_{16}H_{23}{}^{81}BrO_2S$ 360.0582, found 360.0599.

1-Bromo-1-(methylsulfonyl)ethene (140)

The procedure employed for **137** was followed using methyl vinyl sulfone[118b] (2.70 g, 25.4 mmol) in dry carbon tetrachloride and bromine (1.70 mL, 33.0 mmol) in carbon tetrachloride (8.3 mL). The mixture was stirred for 8 h and then evaporated. The residue was dissolved in dry dichloromethane, and triethylamine (4.20 mL, 30.1 mmol) in dichloromethane (6mL) was added to it, dropwise, over 10 min. Stirring was continued for 1 h. Solid triethylammonium bromide was then filtered from the solution, the filtrate was washed with water (2 x 15 mL), brine (1 x 10 mL), dried ($MgSO_4$) and evaporated. Kugelrohr distillation [83 - 85 °C, 0.4 mm, (lit ref[121] 63 - 64 °C, 0.4 mm)] of the crude residue afforded **140** (4.4 g, 94%) as a colorless syrup: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 3.07, (s, 3.H), 6.31 (d, J = 4 .0 Hz, 1 H), 6.99 (d, J = 4.0 Hz, 1 H)

1-Bromo-[(1,1-dimethylethyl)sulfonyl]ethene (141).

(a) **2-[(1,1-Dimethyl)ethylthio]ethanol.** 2-Methyl-2-propanethiol (22.5 mL, 0.20 mol) was added slowly from a dropping funnel to a magnetically stirred solution of sodium (4.6 g, 0.20 mol) in absolute ethanol (300 ml). Stirring was continued and, after an additional 15 min, 2-chloroethanol (13.4mL, 0.20mol).was added slowly. The mixture was then refluxed for 1 h and at that point, the solvent was removed slowly by distillation at atmospheric pressure. The pot residue was cooled and solid NaBr was collected. The filtrate, after evaporation, afforded the desired alcohol as a light yellow oil (26.3 g, 98%). The crude material was suitable for the next step and had: IR (neat) 3390, 1465, 1370, 1170, 1055 cm^{-1}; ^{1}H NMR (80 MHz, $CDCl_3$) δ 1.40 (s, 9 H), 2.55 (t, J = 6.6 Hz, 2 H), 2.80 (s, 1H), 3.80 (t, J = 6.6 Hz, 2 H).

(b) **(1,1-Dimethylethylthio)ethene.** The literature procedure for a similar compound was essentially followed[126] but with some alterations. A 100 ml round-bottomed flask containing a magnetic stirring bar, and solid potassium hydroxide (4.00 g, 71.3 mmol) was equipped with an 8 inch Vigreaux column that had been wrapped with several layers of cotton and aluminum foil. The column carried a thermometer and a condenser set for distillation. The flask was lowered into a 250 °C oil bath and the above sulfide (26.3 g, 195 mmol) was added quickly by pipette through the thermometer inlet. After a few moments distillation started and was allowed to continue until the pot was dry. The water which co-distilled was removed and the vinyl sulfide was further dried over anhydrous potassium carbonate. The essentially pure, colorless, extremely lacrimatory oil (20.4 g, 89%) was used directly in the next step: ^{1}H NMR (CDCl$_3$, 400 MHz) δ 1.34 (s, 9 H), 5.28 (d, J = 9.0 Hz, 1H), 5.36 (d, J = 16.0 Hz, 1H), 6.52 (dd, J = 9.0, 16.0 Hz, 1H).

(c) **[(1,1-Dimethylethyl)sulfonyl]ethene.** The literature procedure for oxidation of phenyl vinyl sulfide was essentially followed.[93] Hydrogen peroxide (68 mL, 30% solution) was added dropwise to a magnetically stirred solution of the above sulfide (20.4 g, 0.176 mol) in glacial acetic acid (80 mL). The mixture was refluxed for 20, min, cooled, extracted with dichloromethane (3 x 75 mL), dried (MgSO$_4$), and evaporated. Residual acetic acid was removed by azeotropic distillation with toluene (30 mL). This process was repeated three times to afford a yellow solid. Re-crystallization from hexane - dichloromethane gave the sulfone (14.3 g, 55%) as long, white needles which were used directly in the next step: IR (CCl$_4$ solution) 1315, 1135 cm^{-1}; ^{1}H NMR (CDCl$_3$, 400 MHz) δ 1.40 (s, 9 H), 6.28 (d, J = 10.0 Hz, 1 H), 6.48 (d, J = 17.0 Hz, 1 H), 6.68 (dd, J = 10.0, 17.0 Hz, 1 H).

(d) **1-Bromo-[(1,1-dimethylethyl)sulfonyl]ethene (141).** Bromine (3.30 mL, 64.1 mmol) in dry carbon tetrachloride (6.7 mL) was added dropwise to a solution of the above sulfone (1.90 g, 12,8 mmol) in carbon tetrachloride (35 mL). The mixture was stirred for 8 h, and then additional bromine (3.30 mL, 64.1 mmol) in carbon tetrachloride (6.7 mL) was added dropwise. After a further 24 h the solvent was evaporated. Flash chromatography of the resulting dark red material over silica gel (4 x 15 cm) using 15% ethyl acetate - hexane afforded 1,2-dibromoethyl (1,1-dimethyl)ethyl sulfone (2.85 g, 72%) as a white solid which was used immediately in the next step.

Triethylamine (1.5 mL, 10.8 mmol) in dry dichloromethane (2 mL) was added dropwise over 5 min to a stirred solution of the dibromide (2.85 g, 9.26 mmol) in dichloromethane (30 mL), and stirring was continued at room temperature for 18 h. The mixture was then cooled to 0 °C, ether was added (20 mL), the precipitate collected, and the filtrate concentrated to afford the crude, solid, substituted vinyl bromide **141**. Recrystallization from hexane - dichloromethane three times gave **141** (2.05 g, 94%) as white needles. An analytical sample was prepared by sublimation (120 °C, 0.20 mm): mp 64 °C; FT-IR (CCl_4 cast) 1300, 1131, 1070, 765, 640, 580 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.48 (s, 9 H), 6.51 (d, J = 2.5 Hz, 1 H), 6.92 (d, J = 2.5 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 24.33 (q), 61.72 (s), 125.03 (t), 134.44 (s); MS, *m/z* 227 (M^+). Anal. Calcd for $C_6H_{11}BrO_2S$: C, 31.73; H, 4.88; Br, 35.18; S, 14.12. Found: C, 31.82; H, 4.87; Br, 35.29; S, 14.09.

(Z)-1-Nitro-1-(phenylseleno)-1-propene (142).

(a) **1-Nitro-1-(phenylseleno)-2-propanol.** The literature procedure for a similar compound was followed[124] but with some alterations. Acetaldehyde (10 mL, 179 mmol) was added to a mixture of nitro-

(phenylseleno)methane[124] (1.50g, 6.95 mmol) and potassium fluoride (30 mg, 0.52 mmol) at 0 °C. The mixture was stirred for 4 h at 0 °C, allowed to warm to room temperature, and then freed of excess acetaldehyde under water pump vacuum. The residue was taken up in ether (30 mL), washed with water (1 x 15 mL) and brine (1 x 5 mL), dried ($MgSO_4$) and evaporated. Flash chromatography of the crude product over silica gel (4 x 15 cm) using 20% ethyl acetate - hexane gave the alcohol (1.72 g, 95%) as a bright yellow oil which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.5:1 ratio (^1H NMR): FT-IR (CCl_4 cast) 3440, 1548, 1477, 1438, 1356, 1123, 1068, 1021, 741, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.42 (d, J = 6.0 Hz, 1.2 H), 1.47 (d, J = 6.0 Hz, 1.8 H), 2.61 (br d, J = 6.0 Hz, 0.6 H), 3.19 (br s, 0.4 H). 4.35 (m, 1 H), 5.40 (d, J = 6.0 Hz, 0.6 H), 5.44 (d, J = 2.5 Hz, 0.4 H), 7.38 (m, 3 H), 7.64 (m, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 19.37, 19.67, 67.45, 68.16, 90.22, 92.91, 129.67, 129.85, 135.56, 135.70; exact mass, *m/z* $[(M - NO_2)^+]$ calcd for $C_9H_{11}OSe$ 214.9975, found 214.9978.

(b) **(Z)-1-Nitro-1-(phenylseleno)-1-propene (142).** The literature procedure for a similar compound was followed[124] but with some alterations. A catalytic amount of boron trifluoride etherate (2 drops) was added to a magnetically stirred solution of the above alcohol (220 mg, 0.846 mmol) in acetic anhydride (0.50 mL, 5.30 mmol). The mixture was stirred for 15 min, then poured into ice water (20 mL), extracted with chloroform (3 x 10 mL), washed with 30% aqueous sodium carbonate (1 x 10 mL), and water (1 x 10 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the crude product gave two fractions. The yellow, oily fraction of higher R_f (73.1 mg, 35%, 46% total) was identified as a single isomer (^{13}C NMR) of **142**: FT-IR ($CHCl_3$ cast) 1615, 1517, 1520, 1477, 1438, 1318, 1021, 998, 917, 772, 736, 716, 689 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.16 (d, J = 6.5 Hz, 3 H), 7.27 (m, 3 H), 7.54 (m, 5 H), 7.74 (q, J = 6.5 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 17.69 (q), 128.17 (d), 128.54 (s), 129.64 (d), 132.09 (d), 144.42 (d), 146.13 (s); exact mass, *m/z* [$(M - NO_2)^+$] calcd for C_9H_9Se 196.9869, found 196.9872.

The fraction of lower R_f (128.6 mg) was a mixture of two compounds, the intermediate acetate (104 mg,[125] 41%) together with more **142** (23.7 mg,[125] 11%). The mixture had: ^1H NMR ($CDCl_3$, 200 MHz) δ (signals assigned to the acetate) 1.50 (d, J = 6.0 Hz, 3 H), 1.98 (s, 3 H), 5.35 (dq, J = 6.0, 14.0 Hz, 1 H), 5.50 (d, J = 14.0, Hz, 1 H), 7.20 - 7.61 (m, 3 H), 7.61 (m, 2 H), (signals assigned to **142**) δ 2.16 (d, J = 6.5 Hz, 3 H), 7.20 - 7.61 (m, 5 H), 7.74 (q, J = 6.5 Hz, 1 H).

Methyl 2-(phenylseleno)propenoate (145).

The literature procedure[67] was followed, (with some alterations), using methyl acrylate (1.80 mL, 20.0 mL) and phenylselenenyl chloride (3.83 g, 20.0 mmol) in dichloromethane (20 mL), and triethylamine (2.46 g, 24.3 mmol) in benzene (50 mL). After the addition of triethylamine, the mixture was stirred for 3 h and then evaporated. Flash chromatography[127] of the crude residue over silica gel (5 x 15 cm) using 5% ethyl acetate - hexane gave **145** (3.05 g, 63%) as a light yellow oil which decomposed slowly at -5 °C: ^{1}H NMR (80.0 MHz, $CDCl_3$) δ 3.72 (s, 3 H), 5.48 (s, 1 H), 6.70 (s, 1 H), 7.15 - 7.75 (m, 5 H).

1-[(1,2-Dibromoethyl)sulfinyl]-2,4,6-tri[1,1-dimethylethyl]benzene (150). (a) **2,4,6-Tri[1,1-dimethylethyl]-1-(1-ethenylthio)benzene.** The literature procedure for preparation of a similar compound was followed[93] but with some alterations. A solution of sodium ethoxide (2 mL of a 2 M stock solution) was injected into a 25 mL round-bottomed flask which contained a stirred solution of tri-*tert*-butylbenzene thiol[122] (1.11 g, 4.00 mmol) in absolute ethanol (15 mL). The mixture was stirred for 10 min and then transferred by cannula over 15 min, to a stirred solution of 1,2-dibromoethane (0.52 mL, 6.03 mmol) in absolute ethanol (5 mL). Stirring was continued for 1.5 h and then additional sodium ethoxide solution (4 mL of the stock solution) was added. The resulting mixture was refluxed for 12 h, cooled, and partitioned between benzene (10 mL) and water (10 mL). The organic layer was separated, washed with water (2 x 5 mL) and brine (1 x 5 mL), and concentrated. Flash chromatography of the residue over silica gel (2 x 15 cm) using hexane gave the vinyl sulfide (554 mg, 46%) as a yellow oil: FT-IR (CCl_4 cast) 2806, 1591, 1583, 1360, 880 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.36 (s, 9 H), 1.55 (s, 18 H), 4.18 (d, J = 16.0 Hz, 1 H), 4.94 (d, J = 10.0 Hz, 1 H), 6.18 (dd, J = 10.0, 16.0 Hz, 1 H), 7.47 (s, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 31.40 (q), 32.47 (q), 35.19 (s), 38.38 (s), 122.99 (d), 139.64 (d), 149.99 (s), 150.85 (s), 155.60 (s); exact mass, *m/z* calcd for $C_{20}H_{32}S$ 304.225, found 304.2234.

(b) **2,4,6-Tri[1,1-dimethylethyl]-1-(1-ethenylsulfinyl)benzene.** A solution of the above sulfide (300 mg, 0.988 mmol) and sodium perborate (212 mg, 1.38 mmol) in glacial acetic acid (35 mL) was stirred at 55 °C for 12 h. Water was added (10 mL) and the product was extracted with dichloromethane (3 x 10 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (2 x 15 cm) using 5% ethyl acetate - hexane gave the sulfoxide (86 mg, 38%) as a light yellow solid: FT-IR (CH_2Cl_2 cast) 2960, 1580, 1470, 1360, 1065, 870, 660 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.31 (s, 9 H), 1.52 (s, 9 H), 1.54 (s, 9 H), 5.51 (d, J = 16.0 Hz, 1 H), 5.62 (d, J = 8.0 Hz, 1 H), 6.43 (dd, J = 8.0, 16.0 Hz, 1 H), 7.46 (s, 2 H); exact mass, *m/z* calcd for $C_{20}H_{32}OS$ 320.2174, found 320.2181.

(c) **1-[(1,2-Dibromoethyl)sulfinyl]-2,4,6-tri[1,1-dimethylethyl]benzene (150).** Bromine (0.30 mL, 0.582 mmol) was added all at once to a solution of the above sulfoxide (95.5 mg, 0.298 mmol) in dry carbon tetrachloride (5 mL). The mixture was stirred at room temperature for 1.5 h, the solvent and excess of bromine were then removed under water pump vacuum, and the residue was used immediately in the next step.

The above crude material (132 mg, 0.275 mmol) was dissolved in dry carbon tetrachloride (2 mL), and triethylamine (0.05 mL, 0.359 mmol) was injected. The mixture was refluxed for 12 h, cooled and evaporated. Flash chromatography of the residue using first hexane and then, an increasingly more polar solvent mixture (up to 10% ethyl acetate - hexane), afforded only the dibromide **150** (102 mg, 92%) as an oil. No substituted vinyl bromide was isolated. The dibromide had: FT-IR (CCl_4 cast) 2980, 1580, 1395, 1360, 1210, 1065, 1060, 880, 750, 720, 595 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.20 - 1.67 (m, 27 H), 1.98 (m, 0.6 H), 3.00 (m, 0.4 H), 4.00 - 4.28 (m, 1 H), 5.21 - 5.43 (m, 1 H), 7.35 - 7.58 (m, 2 H); exact mass, m/z calcd for $C_{20}H_{32}{}^{79}Br_2OS$ 480.0520, found 480.0506.

Michael Adducts:

4-Bromo-2-(2-cyclopenten-1-yl)-4-(phenylsulfonyl)butanal (121b).

A solution of 2-cyclopentene-1-acetaldehyde[30] (209 mg, 1.90 mmol), pyrrolidine (0.16 mL, 1.91 mmol), and p-toluenesulfonic acid (1 mg, 0.003 mmol) in benzene (70 mL) was refluxed in a Soxhlet apparatus containing a thimble packed with crushed calcium hydride for 5.5 h. The benzene solution was then cooled and evaporated, and the crude enamine was quickly dissolved in dry THF (30 mL) and then used immediately in the next step.

[(1-Bromoethenyl)sulfonyl)]benzene **101** (409 mg, 1.65 mmol) in THF (2 mL + 1 mL rinse) was injected dropwise into the enamine solution. The mixture was stirred for 1.5 h at room temperature, then quenched with saturated aqueous ammonium chloride (10 mL), and extracted with ether (3 x 25 mL). The combined extracts were washed with brine (10 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the crude product over silica gel (3 x 15 cm) using

20% ethyl acetate - hexane gave **121b** (446 mg, 75%) as a colorless syrup which was a chromatographically (TLC) inseparable mixture of three isomers in a 5.9:4.1:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 1720, 1442, 1323, 1310, 1151, 1080, 745, 685, cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.46 - 1.67 (m, 1 H), 1.85 - 2.20 (m, 1.75 H), 2.25 - 2.48 (m, 2.55 H), 2.63 - 2.76 (m, 0.70 H), 2.87 (m, 0.70 H), 2.96 - 3.08 (m, 0.30 H), 3.08 - 3.39 (m, 1 H), 4.85 - 5.03 (m, 1 H), 5.64 (m, 1 H), 5.89 (m, 1 H), 7.60 (m, 2 H), 7.72 (m, 1 H), 7.96 (m, 2 H), 9.68 (s, 0.71 H), 9.70 (d, J = 1.0 Hz, 0.12 H), 9.75 (d, J = 0.5 Hz, 0.17 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 25.50, 26.11, 26.19, 26.72, 27.04, 28.06, 28.83, 29.91, 32.17, 32.24, 45.28, 45.35, 45.64, 52.71, 52.89, 53.14, 53.28, 62.56, 63.07, 64.15, 64.19, 129.09, 129.82, 129.90, 129.94, 130.09, 130.20, 130.26, 133.86, 133.97, 134.53, 134.61, 135.41, 202.16, 202.63, 203.00, 203.20; exact mass, *m/z* calcd for $C_{15}H_{17}{}^{81}BrO_3S$, 358.0063, found 358.0066. Anal. Calcd for $C_{15}H_{17}BrO_3S$: C, 50.43; H, 4.79; S, 8.97. Found: C, 50.28; H, 4.72; S, 8.88.

4-Bromo-2-(methyl-2-cyclohexen-1-yl)-4-(phenylsulfonyl)butanal (122b).

The procedure employed for **121b** was followed using 2-(2-methylcyclohex-2-en-1-yl)ethanol^{131} (326 mg, 2.36 mmol) together with pyrrolidine (0.20 mL, 2.42 mmol) in benzene (70 mL) and **101** (540 mg, 2.19 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (3 x 15 cm) using 15% ethyl acetate - hexane afforded two fractions. The material of higher R_f (243 mg, 29%) was a thick syrupy mixture of three chromatographically (TLC) inseparable isomers of **122b** in a 2.9:1.6:1 ratio (^{1}H NMR): FT-IR (CH_2Cl_2 cast) 2932, 2850, 2830, 1721, 1447, 1324, 1311, 1152, 1083, 749, 738, 688 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.21 - 1.46 (m, 1 H), 1.46 - 1.66 (m, 2.42 H), 1.66 - 1.86 (m, 4.40 H), 1.86 - 2.00 (m 1.80 H), 2.35 - 2.58 (m, 1.70 H), 2.72 - 2.90 (m, 0.68 H), 3.06 (m, 0.60 H), 3.17 (m, 0.24 H), 3.43 (m, 0.16 H), 4.82 (dd, J = 5.5, 9.0 Hz, 0.32 H), 5.00 (t, J = 7.0 Hz, 0.17 H), 5.10 (dd, J = 2.5, 11.5 Hz, 0.52 H), 5.65 (m, 1 H), 7.60 (m, 2 H), 7.72 (m, 1 H), 7.97 (m, 2 H), 9.66 (d, J =1.5 Hz, 0.53 H), 9.69 (d, J = 1.5 Hz, 0.29 H), 9.72 (s, 0.18 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 15.31, 21.17, 21.25, 21.89, 22.13, 22.31, 24.81, 25.05, 25.15, 25.46, 26.83, 28.56, 28.61, 38.41, 38.54, 40.86, 49.75, 50.22, 51.42, 62.44, 63.08, 65.21, 65.87, 127.14, 127.68, 129.18, 129.84, 129.91, 130.16, 131.92, 132.10, 134.58, 134.72, 135.07, 135.56, 203.28, 203.36, 203.99; exact mass, *m*/*z* calcd for $C_{17}H_{21}{}^{81}BrO_3S$, 386.0374, found 386.0371.

The thick syrupy fraction of lower R_f (600 mg, 71%) was identified as a single isomer (^{1}H NMR) of **122b** which was different from those obtained in the higher R_f fraction: FT-IR (CH_2Cl_2 cast) 2929, 2850, 2830, 1721, 1447, 1322, 1311, 1152, 1084, 743, 688, cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.17 - 1.33 (m, 1 H), 1.48 - 1.80 (m, 7 H), 1.95 (m, 2 H), 2.62 - 2.75 (m, 1 H), 2.85 (m, 1 H), 3.07 (m, 1 H), 5.10 (dd, J = 2.3, 12.0 Hz, 1 H), 5.67 (m, 1 H), 7.60 (m, 2 H), 7.71 (m, 1 H), 8.00 (m, 2 H), 9.65 (d, J = 1.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 21.49, 21.57, 25.07, 25.16, 25.36, 38.18, 50.91, 65.06, 128.04, 129.16, 129.84, 131.2[illegible], 134.56, 135.68, 203.48; exact mass, *m*/*z* calcd for $C_{17}H_{21}{}^{81}BrO_3S$ 386.0375, found 386.0372.

The two fractions were combined for analysis. Anal. Calcd for $C_{17}H_{21}BrO_3S$: C, 52.99; H, 5.49; S, 8.32. Found: C, 52.92; H, 5.63; S, 8.21.

4-Bromo-2-(1-methyl-2-cyclohexen-1-yl)-4-(phenylsulfonyl)butanal (123b).

The procedure employed for **121b** was followed using diethyl 2-(1-methyl-2-cyclohexen-1-yl)ethanal **123a**[129] (330 mg, 2.49 mmol) and pyrrolidine (0.20 mL, 2.42 mmol) in benzene (70 mL) and **101** (407 mg, 1.65 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (3 x 15 cm) using 20% ethyl acetate - hexane gave **123b** (505 mg, 79%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of three isomers in a 4.8:1.8:1 ratio (^{1}H NMR): FT-IR (CH_2Cl_2 cast) 2935, 2860, 2830, 2035, 1718, 1447, 1325, 1310, 1151, 1083, 753, 729, 688, cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.12 (s, 0.75 H), 1.14 (s, 1.82 H), 1.16 (s, 0.43 H), 1.34 - 1.52 (m, 1 H), 1.55 - 1.72 (m, 3 H), 1.90 - 2.10 (m, 3 H), 2.52 - 2.95 (m, 2 H), 4.75 (dd, J = 2.5, 12.0 Hz, 0.5 H), 4.86 (dd, J = 2.0, 16.5 Hz, 0.1 H), 4.88 (dd, J = 2.5, 11.5 Hz, 0.4 H), 5.45 (m, 0.7 H), 5.60 (m, 0.3 H), 5.78 (m, 1 H), 7.60 (m, 2 H), 7.72 (m, 1 H), 7.96 (m, 2 H), 9.70 (m, 0.24 H), 9.86 (m, 0.63 H), 9.92 (d, J = 2.0 Hz, 0.13 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 15.30, 18.59, 24.63, 24.78, 25.51, 25.82, 26.13, 28.82, 31.76, 32.37, 32.49, 37.34, 37.83, 57.78, 58.79, 63.24, 64.70, 64.87, 65.86, 128.51, 128.70, 129.15, 129.85, 133.06, 133.21, 134.59, 135.59, 204.01, 204.24, 204.54; exact mass *m/z* calcd for $C_{17}H_{21}{}^{81}BrO_3S$ 386.0375, found 386.0376. Satisfactory combustion analytical values could not be obtained.

4-Bromo-2-(methyl-2-cyclohexen-1-yl)-4-(phenylsulfonyl)butan-1-ol (123d).

Sodium borohydride (16.4 mg, 0.434 mmol) was added slowly to a stirred solution of **123b** (334 mg, 0.868 mmol) in absolute ethanol (20 mL) at 0 °C. The mixture was stirred for 30 min, quenched with water (5 mL), and evaporated. The residue was taken up in ether (25 mL), washed with water (2 x 5 mL) and brine (5 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the crude material over silica gel (2 x 15 cm) using 30% ethyl acetate - hexane afforded **123d** (336 mg, 100%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of isomers: FT-IR (CCl_4 cast) 3520, 2931, 1447, 1321, 1308, 1149, 1084, 753, 730, 687, cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.12 (m, 3 H), 1.30 - 2.22 (m, 9 H), 2.38 - 2.56 (m, 1 H), 3.54 - 3.70 (m, 1 H), 3.94 (m, 1 H), 5.18 - 5.45 (m, 2 H), 5.67 (m, 1 H), 7.60 (m, 2 H), 7.70 (m, 1 H), 7.90 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 15.26, 18.82, 24.84, 25.53, 25.72, 25.97, 31.17, 31.81, 32.57, 36.78, 46.49, 63.70, 65,84, 66.59, 126.90, 127.31, 128.95, 129.90, 134.30, 134.86, 135.79; exact mass, *m/z* [$(M- H_2O)^+$] calcd for $C_{17}H_{23}{}^{81}BrO_3S$ 370.0426, found 370.0423. Satisfactory combustion analytical values could not be obtained.

[1-Bromo-4,4-dimethoxy-3-(1-methyl-2-cyclohexen-1-yl)butanesulfonyl]benzene (123f).

Trimethyl orthoformate (1.05 mL, 9.60 mmol) and *p*-toluenesulfonic acid (2.00 mg, 0.006 mmol) were added to a solution of

123b (451 mg, 1.17 mmol) in dry methanol (20 mL). The mixture was stirred at room temperature for 30 min, heated to 50 °C for 2 h, cooled, and then poured into saturated aqueous sodium bicarbonate solution (10 mL). The methanol was evaporated and the residue was taken up in ether (25 mL), washed with water (2 x 5 mL) and brine (5 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over neutral aluminum oxide (Brockmann Grade 1) using 15% ethyl acetate - hexane afforded **123f** (492 mg, 97%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of isomers: FT-IR (CCl_4 cast) 2929, 1422, 1323, 1305, 1154, 1084, 1072, 735, 685, cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.95 - 1.07 (m, 3 H), 1.22 - 1.38 (m, 1 H), 1.43 - 2.02 (m, 6.7 H), 2.06 -2.51 (m, 0.7 H), 2.56 - 2.68 (m, 0.7 H), 3.19 - 3.34 (m, 0.87 H), 3.42 (m, 0.13 H), 4.27 (m, 0.9 H), 4.35 (d, J = 1.5 Hz, 0.1 H), 5.05 - 5.35 (m, 1 H), 5.35 - 5.52 (m, 1.2 H), 5.57 - 5.71 (m, 0.8 H), 7.58 (m, 2 H), 7.69 (m, 1 H), 7.95 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 18.82, 18.94, 22.33, 24.80, 24.94, 25.74, 25.97, 26.87, 27.76, 31.47, 32.07, 36.28, 41.95, 46.83, 47.40, 55.17, 55.60, 56.41, 64.54, 66.89, 67.29, 67.43, 106.83, 107.07, 107.62, 107.72, 124.15, 126.76, 128.87, 128.94, 129.88, 134.04, 134.19, 135.25, 135.66, 135.99; exact mass, *m/z* calcd for $C_{19}H_{27}{}^{81}BrSO_4$ 432.0793, found 432.0788.

Diethyl 2-(2-cyclopenten-1-yl)-2-[2-bromo-2-(phenylsulfonyl)ethyl]propane-1,3-dioate (128b).

Diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate[87] (835 mg, 3.69 mmol) in dry THF (4 mL + 1 mL rinse) was injected dropwise into a stirred suspension of sodium hydride (182 mg, 50% dispersion in oil, 3.78

mmol) in THF (35 mL) at 50 °C. When evolution of hydrogen had ceased (*ca.* 30 min) the mixture was cooled to 0 °C and **101** (736 mg, 2.98 mmol) in THF (3 mL + 1 mL rinse) was injected over 20 min. The mixture was stirred for 3 h at 0 °C, then quenched with saturated aqueous ammonium chloride (5 mL), and extracted with ether (3 x 15 mL). The combined extracts were washed with brine (10 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the crude product over silica gel (3 x 15 cm) using 20% ethyl acetate - hexane afforded **128b** (1.02 g, 72%) as a white solid which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.4:1 ratio (^{13}C NMR): mp. 63 - 66 °C; FT-IR ($CHCl_3$ cast) 1726, 1445, 1329, 1246, 1207, 1158, 1085 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.25 (m, 6 H), 1.53 - 1.72 (m, 1 H), 1.92 - 2.15 (m, 1 H), 2.39 (m, 2 H), 2.46 (dd, J = 10.0, 16.0 Hz, 0.57 H), 2.47 (dd, J = 9.3, 16.0 Hz, 0.43 H), 3.18 (dd, J = 1.8, 3.2 Hz, 0.55 H), 3.24 (dd, J = 1.8, 3.2 Hz, 0.45 H), 3.46 (m, 1 H), 4.04 - 4.28 (m, 4 H), 5.11 (dd, J = 1.8, 10.0 Hz, 0.57 H), 5.14 (dd, J = 1.8, 9.3 Hz, 0.43 H), 5.66 (m, 0.4 H), 5.80 (m, 1.6 H), 7.60 (m, 2 H), 7.72 (m, 1 H), 7.98 (m, 2 H). Irradiation of the signal at δ 5.14 resulted in collapse of the signal at δ 3.24 and δ 3.18 to a pair of doublets and simplification of the signals at δ 2.46 and δ 2.47. ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.92, 25.10, 25.30, 31.79, 31.90, 34.78, 34.85, 49.88, 50.04, 58.93, 59.02, 60.66, 60.89, 61.56, 61.77, 61.88, 129.10, 130.11, 130.14, 130.26, 130.45, 133.36, 133.47, 134.56, 135.15, 169.78, 169.86, 170.08; exact mass, *m/z* calcd for $C_{20}H_{25}{}^{81}BrO_6S$ 474.0535, found 474.0539. Anal. Calcd for $C_{20}H_{25}BrO_6S$: C, 50.75; H, 5.32; O, 20.28; S, 6.77. Found: C, 50.77; H, 5.22; O, 20.13; S, 6.71.

Diethyl 2-(2-cyclohexen-1-yl)-2-[bromo-2-(phenylsulfonyl)ethyl]propane-1,3-dioate (129b).

The procedure employed for **128b** was followed using diethyl 2-(cyclohexen-1-yl)propane-1,3-dioate[128] (222 mg, 0.925 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (60 mg, 50% dispersion in oil, 1.25 mmol) in THF (10 mL) and **101** (186 mg, 0.752 mmol) in THF (1 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 20% ethyl acetate - hexane gave **129b** (246 mg, 67%) as a white solid which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.3:1 ratio (^{1}H NMR): mp. 77 - 82 ^{o}C, FT-IR ($CHCl_3$ cast) 1730, 1445, 1325, 1310, 1242, 1215, 1195, 1155, 1080 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.30 (m, 6 H), 1.40 - 2.05 (m, 6 H), 2.46 (dd, J = 9.5, 16.0 Hz, 0.52 H), 2.54 (dd, J = 9.5, 16.0 Hz, 0.48 H), 2.91 (m, 0.56 H), 3.00 (m, 0.44 H), 3.28 (dd, J = 1.5, 16.0 Hz, 0.54 H), 3.33 (dd, J = 1.5, 16.0 Hz, 0.46 H), 4.40 - 4.35 (m, 4 H), 5.12 (dd, J = 1.5, 9.5 Hz, 0.56 H), 5.28 (dd, J = 1.5, 9.5 Hz, 0.44 H), 5.76 (m, 2 H), 7.60 (m, 2 H), 7.72 (m, 1 H), 7.98 (m, 2 H). Irradiation at δ 5.28 resulted in collapse of the signal at δ 2.54 to a doublet and simplification of the signals at δ 3.28 and δ 3.33. Irradiation δ 5.12 resulted in collapse of the signal at δ 2.46 and simplification of the signals at δ 3.28 and δ 3.33. Irradiation at δ 3.33 resulted in collapse of the two signals at δ 5.28 and δ 5.12 to two doublets and simplification of the signals at δ 2.46 and δ 2.54; ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.90, 22.20, 22.32, 24.24, 24.48, 24.91, 34.09, 34.19, 39.97, 40.23, 58.75, 59.29, 60.86, 61.13, 61.51, 61.59, 61.74, 61.93, 65.83, 126.83, 127.47, 129.09, 129.34, 129.97, 130.07, 130.13, 134.51, 135.29, 169.41, 169.71; exact mass, *m/z* calcd for $C_{21}H_{27}{}^{81}BrO_6S$, 488.0691, found 488.0688. Anal. Calcd for

$C_{21}H_{27}BrO_6S$: C, 51.75; H, 5.58; O, 19.70; S, 6.58. Found: C, 51.79; H, 5.43; O, 19.66; S, 6.39.

Diethyl 2-(2-propen-1-yl)-2-[2-bromo-2-(phenylsulphonyl)ethyl]propane-1,3-dioate (130b).

The procedure employed for **128b** was followed using diethyl 2-(2-propen-1-yl)-2-propane-1,1-dioate[130] (411 mg, 2.05 mmol), in dry THF (2 mL + 1 mL rinse), sodium hydride (110 mg, 50% dispersion in oil, 2.29 mmol) in THF (25 mL), and **101** (457 mg, 1.85 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (3 x 15 cm) using 15% ethyl acetate - hexane gave **130b** (625 mg, 75%) as a single crystalline isomer (^{1}H NMR): mp. 76 -77 °C; FT-IR (CCl_4 cast) 1732, 1445, 1330, 1310, 1290, 1230, 1210, 1155, 1080 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.26 (dt, J = 1.5, 7.5 Hz, 6 H), 2.51 (dd, J = 10.0, 16.0 Hz, 1 H), 2.65 (dd, J = 7.5, 14.5 Hz, 1 H), 2.76 (dd, J = 7.5, 14.5 Hz, 1 H), 3.20 (dd, J = 2.0, 16.0 Hz, 1 H), 4.06 - 4.28 (m, 4 H), 4.95 (dd, J = 2.0, 10.0 Hz, 1 H), 5.12 (m, 2 H), 5.47 - 5.63 (m, 1 H), 7.61 (m, 2 H), 7.72 (m, 1 H), 7.98 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.90, 13.95, 34.67, 37.28, 55.72, 60.25, 61.85, 62.08, 120.43, 129.15, 130.20, 131.01, 134.63, 134.94, 169.70, 169.78; exact mass, *m/z* calcd for $C_{18}H_{23}{}^{81}BrO_6S$ 448.0380, found 448.0387. Anal. Calcd for $C_{18}H_{23}BrO_6S$: C, 48.33; H, 5.18; O, 21.46; S, 7.17. Found: C, 48.27; H, 5.15; O, 21.49; S, 7.39.

Diethyl 2-[(1α, 3aα, 4, 5, 6, 6aα)-hexahydropentalen-1-yl]-2-[2-bromo-2-(phenylsulfonyl)ethyl]propane-1,3-dioate (131b).

The procedure employed for **128b** was followed using diethyl 2-(3β, 3aα, 4, 5, 6, 6aα-hexahydropentalen-2-yl)propane-1,3-dioate[90] **131a** (560 mg, 2.10 mmol) in dry THF (2 mL + 1 mL rinse), sodium hydride (84 mg, 60% dispersion in oil, 2.10 mmol) in THF (20 mL), and **101** (496 mg, 2.01 mmol) in THF (5 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 15% ethyl acetate - hexane gave **131b** (376.3 mg, 35%, 54% based on conversion of starting materials) as a white solid which was a chromatographically inseparable mixture of two isomers in a 1.3:1 ratio (^{13}C NMR). Unreacted diester was also recovered (198.8 mg, 36%). An analytical sample of **131b** was recrystallized from hexane: mp 76 - 77 °C; FT-IR (CCl_4 cast) 1727, 1425, 1240, 1200, 1155, 1080, 740 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.20 - 1.88 (m, 12 H), 2.42 (m, 2 H), 3.00 - 3.26 (m, 3 H), 4.17 (m, 4 H), 5.26 (m, 1 H), 5.48 - 5.70 (m, 2 H), 7.50 - 7.76 (m, 3 H), 7.97 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 13.67, 13.94, 13.99, 25.04, 25.09, 31.55, 31.60, 34.79, 35.60, 35.93, 43.72, 44.06, 50.46, 50.53, 58.93, 59.28, 59.52, 59.60, 61.01, 61.33, 61.54, 61.66, 61.62, 128.66, 128.79, 129.05, 130.13, 130.16, 134.47, 135.29, 135.41, 138.58, 169.88, 170.10; exact mass, *m/z* calcd for $C_{23}H_{29}{}^{81}BrO_6S$ 514.0847, found 514.0851. Anal. Calcd for $C_{23}H_{29}BrO_6S$: C, 53.80; H, 5.69; O, 18.70; S, 6.24. Found: C, 53.93; H, 5.71; O, 18.73; S, 6.05.

Diethyl 2-(2-cyclopenten-1-yl)-2-[2-bromo-2-(2, 4, 6-trimethylbenzenesulfonyl)ethyl]propane-1,3-dioate (146).

The procedure employed for **128b** was followed using diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate[87] (4.77 mg, 2.11 mmol) in dry THF (2 mL + 1 mL rinse), sodium hydride (84 mg, 60 % dispersion in oil, 2.11 mmol) in THF (25 mL), and **137** (578 mg, 2.00 mmol) in THF (4 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 10% ethyl acetate - hexane gave **146** (962.2 mg, 93%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.5:1 ratio (^{1}H NMR) : FT-IR (CCl_4 cast) 1727, 1600, 1440, 1325, 1240, 1153, 1030, 600 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.26 (m, 6 H), 1.60 (m, 1 H), 1.96 (m, 0.6 H), 2.27 (m, 0.4 H), 2.27 - 2.36 (m, 5 H), 2.54 - 2.72 [m, 7 H(includes two singlets at δ 2.68 and δ 2.70)], 3.15 (dd, J = 1.5, 16.0 Hz, 0.6 H), 3.20 (dd, J = 1.5, 16.0 Hz, 0.4 H), 3.43 - 3.54 (m, 1 H), 4.06 - 4.27 (m, 4 H), 5.26 (dd, J = 1.5, 10.0 Hz, 1 H), 5.66 (m, 0.5 H), 5.80 (m, 0.5 H), 5.84 (s, 1 H), 7.02 (s, 2 H). In $CDCl_3$ containing 20% C_6D_6 the singlet at δ 5.84 collapsed to a multiplet and the vinyl hydrogen signals then appeared as: δ 5.80 (m, 0.4 H), 5.88 (m, 0.4 H), 5.92 (m 0.6 H), 5.96 (m, 0.6 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.87, 13.92, 21.07, 23.02, 25.12, 25.21, 31.78, 33.49, 33.63, 50.14, 50.25, 58.74, 58.82, 61.00, 61.15, 61.48, 61.69, 61.81, 129.75, 129.83, 130.39, 130.48, 132.34, 133.18, 133.50, 141.38, 144.13, 169.95, 170.21; exact mass, *m/z* calcd for $C_{23}H_{31}{}^{81}BrO_6S$ 516.1004, found 516.1016. Anal. Calcd for $C_{23}H_{31}BrO_6S$: C, 53.59; H, 6.06; Br, 15.50; S, 6.22. Found: C, 53.59; H, 5.99; Br, 15.30; S, 6.26.

Diethyl 2-(2-cyclopenten-1-yl)-2-[2-bromo-2-[3,5-di(1,1-dimethylethyl)benzenesulfonyl]ethyl]propane-1,3-dioate (155).

The procedure employed for **128b** was followed using diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate[87] (158 mg, 0.700 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (28 mg, 60% dispersion in oil, 0.70 mmol) in THF (10 mL), and **139** (221 mg, 0.616 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 10% ethyl acetate - hexane gave **155** (238.8 mg, 66%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 2:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 2982, 1728, 1600, 1475, 1360, 1330, 1310, 1248, 1158, 700 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.23 (m, 6 H), 1.37 (s, 18 H), 1.56 - 1.60 (m, 1 H), 1.70 (m, 0.6 H), 2.06 (m, 0.40 H), 2.35 (m, 2 H), 2.42 (m, 1 H), 3.07 (dd, J = 1.5, 16.0 Hz, 0.67 H), 3.03 (dd, J = 1.5, 16.0 Hz, 0.33 H), 3.40 (m, 1 H), 4.15 (m, 4 H), 5.09 (dd, J = 1.5, 11.0 Hz, 0.67 H), 5.12 (dd, J = 1.5, 11.0 Hz, 0.33 H), 5.53 (m, 0.40 H), 5.77 (m, 1.60 H), 7.76 (m, 3 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.90, 24.86, 25.27, 31.22, 31.68, 31.85, 35.15, 35.24, 35.35, 49.76, 50.00, 58.75, 58.86, 61.23, 61.24, 61.47, 61.68, 61.80, 124.39, 128.68, 130.21, 130.68, 133.06, 133.38, 134.05, 134.11, 152.34, 152.36, 169.71, 169.77, 169.80, 169.99; exact mass, *m/z* calcd for $C_{28}H_{41}{}^{79}BrO_6S$ 584.1087, found 584.1813. Satisfactory combustion analytical values could not be obtained.

Diethyl 2-(2-cyclopenten-1-yl)-2-[bromo-2-(methylsulfonyl)ethyl]propane-1,3-dioate (156), [(Epithioethyl)methyl]propane-1,3-dioate (157) and Diethyl 2-(2-cyclopenten-1-yl)-2-(propen-1-yl)propane-1,3-dioate (157b)

The procedure employed for **128b** was followed using diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate[87] (683 mg, 3.02 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (121 mg, 60% dispersion in oil, 3.02 mmol) in THF (30 mL), and **140** (556 mg, 3.01 mmol) in THF (1 mL + 1 mL rinse). In this case, however, **140** was added in one portion to the reaction mixture at 0 °C. Flash chromatography of the crude product over silica gel (2 x 15 cm) using 20% ethyl acetate - hexane afforded **156** (629.8 mg,[125] 50%) together with episulfone **157** (126.9 mg,[125] 16%) as a thick syrup. These compounds were not easily (TLC) separable,[125] however, a small amount of episulfone **157** was separated from the mixture by careful flash chromatography: Compound **157** had: FT-IR (CCl_4 cast) 1725, 1314, 1250, 1200, 1166, 990 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.31 (m, 6 H), 1.57 - 1.86 (m, 1 H), 1.92 - 2.73 (m, 6 H), 3.20 (dd, J = 1.0, 8.0 Hz, 0.35 H), 3.25 (dd, J = 1.0, 8.0 Hz, 0.65 H), 3.45 - 3.80 (m, 2 H), 4.12 - 4.49 (m, 4 H), 5.65 (m, 0.5 H), 5.86 (m, 1.5 H); exact mass, *m/z* calcd for $C_{15}H_{22}O_6S$ 330.1137, found 330.1136.

A mixture of the above two compounds (109 mg) in benzene (25 mL) was refluxed for 12 h. The solvent was evaporated and flash chromatography of the residue over silica gel (1 x 15 cm) using 5% ethyl acetate - hexane afforded two fractions. That of lower R_f was identified as **156** which was a thick syrupy mixture of two isomers (^{1}H NMR): FT-IR (CCl_4 cast) 1726, 1365, 1320, 1250, 1200, 1145 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.27 (two superimposed triplets, J = 7.0 Hz each, 6 H), 1.67 (m, 1 H), 1.96 - 2.22 (m, 1 H), 2.30 (m, 2 H), 2.35 (dd, J = 9.0, 15.5 Hz) and 2.37 (dd, J = 9.0, 15.5 Hz) [both signals together have an area that corresponds to 1 H], 3.12 [m, 4 H (includes singlets at δ 3.12 and at δ 3.13)], 3.58 (m, 1 H), 4.20 (m, 4 H), 5.03 (br d, J = 8.0 Hz, 1 H), 5.65 (m, 0.4 H), 5.82 (m, 1.6 H); exact mass, *m/z* calcd for $C_{15}H_{23}{}^{81}BrO_6S$ 412.0378, found 412.0388.

The fraction of higher R_f was identified as diene **157b** which was a colorless oil. An analytical sample was prepared by Kugelrohr distillation (72 -74 °C, 0.4 mm): FT-IR (CCl_4 cast) 1727, 1222, 1196 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ, 1.44 (two superimposed triplets, J = 7.0 Hz, 6 H), 1.72 (m, 1 H), 2.04 (m, 1 H), 2.29 (m, 2 H), 2.66 (d, J = 7.5 Hz, 2 H), 3.40 (m, 1 H), 4.16 (q, J = 7.0 Hz, 4 H), 5.07 (m, 2 H), 5.75 (m, 3 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.12, 14.15, 25.17, 31.75, 37.71, 49.17, 60.88, 60.92, 60.96, 118.48, 131.52, 132.00, 133.25, 170.72, 170.93; exact mass, *m/z* calcd for $C_{15}H_{22}O_4$ 266.1518, found 266.1511. Anal. Calcd for $C_{15}H_{22}O_4$: C, 67.65; H, 8.33. Found: C, 68.11; H, 8.40.

Diethyl 2-(2-cyclopenten-1-yl)-2-[2-bromo-2-[(1,1-dimethylethyl)sulfonyl]ethyl]propane-1,3-dioate (158).

The procedure employed for **128b** was followed using diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate[87] (254 mg, 1.12 mmol) in THF (1 mL + 1 mL rinse), sodium hydride (44 mg, 60% dispersion in oil, 1.10 mmol) in dry THF (10 mL), and **141** (228 mg, 1.00 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 15% ethyl acetate - hexane gave **158** (330 mg, 73%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.4:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 2972, 1728, 1311, 1246, 1119 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.24 (m, 6 H), 1.54 (s) and 1.56 (s) [both signals together correspond to 9 H], 1.60 - 1.80 (m, 1 H), 1.93 - 2.18 (m, 1 H), 2.30 (m, 2 H), 2.41 - 2.60 (m, 1 H), 3.27 (dd, J = 1.5, 3.0 Hz, 0.58 H), 3.34 (dd, J = 2.0 3.0 Hz, 0.42 H), 3.46 (m, 1 H), 4.04 - 4.30 (m, 4 H), 5.32 (dd, J = 1.5, 8.5 Hz) and 5.34 (dd, J = 2.0, 8.5 Hz) [both signals together correspond 1 H]; ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.89, 25.09, 25.32, 25.34, 31.81, 31.90, 35.30, 50.43, 50.46, 54.33, 54.73, 59.16, 59.27, 61.51, 61.70, 61.77, 63.33, 63.37, 130.19, 130.40, 133.27, 133.69, 170.01, 170.20, 170.42; exact mass, *m/z* calcd for $C_{18}H_{29}{}^{81}BrOS$ 454.0848, found 454.0845. Anal. calcd for $C_{18}H_{29}BrO_6S$: C, 47.68; H, 6.45; Br, 17.62; S, 7.07. Found: C, 47.73; H, 6.26; Br, 17.84; S, 7.05.

Diethyl 2-(2-methyl-2-cyclohexen-1-yl)propane-1,3-dioate (159).

Diethyl malonate (0.52 mL, 3.43 mmol) was injected into a magnetically stirred solution of sodium (79 mg, 3.43 mmol) in absolute ethanol (30 mL). Stirring was continued for 15 min and then 3-bromo-2-methylcyclohexene[131] (661 mg, 3.78 mmol) in ethanol (2 mL + 1 mL rinse) was injected slowly. The mixture was stirred at room temperature for 30 min and then at reflux for 6 h. The mixture was then cooled and evaporated, taken up in ether (30 mL), filtered, and evaporated. Flash chromatography of the residue over silica gel (2 x 15 cm) using 10% ethyl acetate - hexane gave **159** (590 mg, 68%, 85% based on conversion) as a colorless oil together with unreacted diethyl malonate (110 mg, 20%). An analytical sample was prepared by Kugelrohr distillation (72 - 74 °C, 0.16 mm): FT-IR (CCl_4 cast) 1754, 1732, 1252, 1222, 1175, 1149, 1138, 1029 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.27 (two superimposed triplets, J = 9.0 Hz, 6 H), 1.39 - 1.83 [m, 7 H (includes a singlet at δ 1.66)], 1.97 (m, 2 H), 2.83 (br d, J = 5.5 Hz, 1 H), 3.63 (d, J = 5.5 Hz, 1 H), 4.18 (m, 4 H), 5.51 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.09 (includes two q), 20.68 (t), 22.29 (q), 25.29 (t), 26.16 (t), 39.24 (d), 54.28 (d), 61.03 (t), 61.30 (t), 125.71 (d), 133.18 (s), 168.67 (s), 169.42 (s); exact mass, *m/z* calcd for $C_{14}H_{22}O_4$ 254.1518, found: 254.1524. Anal. Calcd for $C_{14}H_{22}O_4$: C, 66.12; H, 8.72. Found C, 65.92; H, 8.84.

Diethyl 2-(2-methyl-2-cyclohexen-1-yl)-2-[2-bromo-2-[(1,1-dimethylethyl)sulfonyl]ethyl]propane-1,3-dioate (159b).

The procedure employed for **128b** was followed using **159** (170 mg, 0.670 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (27 mg, 60% dispersion in oil, 0.670 mmol) in THF (15 mL), and **141** (140 mg, 0.617 mmol) in THF (2 mL + 1 mL rinse). In this case the crude product was Kugelrohr distilled (155 °C, 0.2 mm) after work up to afford **159b** (138 mg, 46%, 100 % based on conversion) as a thick syrup which was a chromatographically inseparable (TLC) mixture of two isomers in a 2.1:1 ratio (^1H NMR). Unreacted diester (112 mg, 65%) was also recovered during the distillation (110 °C, 0.2 mm). Compound **159b** had: FT-IR (CCl_4 cast) 2968, 2920, 1735, 1309, 1240, 1119 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.33 - 1.49 (m, 6 H), 1.49 - 2.17 (m, 18 H), 2.56 (dd, J = 8.5, 15.5

Hz, 0.69 H), 2.71 (dd, J = 9.0, 16.0 Hz, 0.31 H), 3.19 (m, 1 H), 3.59 (dd, J = 1.8, 16.0 Hz, 0.33 H), 3.64 (dd, J = 1.8, 16.0 Hz, 0.67 H), 4.19 - 4.43 (m, 4 H), 5.51 (dd, J = 1.8, 9.0 Hz, 0.3 H), 5.61 (dd, J = 1.8, 8.5 Hz, 1.2 H), 5.65 - 5.76 (m, 0.5 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.20, 14.32, 14.37, 21.81, 22.41, 23.33, 24.98, 25.41, 25.69, 25.84, 26.50, 26.60, 29.30, 36.20, 36.46, 36.67, 43.19, 43.96, 44.57, 55.45, 55,82, 56.02, 59.83, 59.96, 62.01, 62.20, 62.43, 63.95, 128.00, 129.44, 133.26, 134.52, 170.15, 170.46, 171.13, 171.22; exact mass, *m/z* calcd for $C_{22}H_{33}{}^{81}BrO_6S$ 482.1161, found 482.1162. Anal. Calcd for $C_{22}H_{33}BrO_6S$: C, 49.89; H, 6.91; Br, 16.59; S, 6.66. Found: C, 50.08; H, 6.98; Br, 16.88; S, 6.58.

Diethyl 2-[(1α, 3aα, 4, 5, 6, 6aα)-hexahydropentalen-1-yl]-2-[2-bromo-2-[(1,1-dimethylethyl)sulfonyl]ethyl]propane-1,3-dioate (160).

The procedure employed for **128b** was followed using **131a**[90] (30 mg, 1.15 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (46 mg, 60% dispersion in oil, 1.15 mmol) in THF (10 mL), and **141** (228 mg, 1.01 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 20% ethyl acetate - hexane gave **160** (367 mg, 74%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 1:1 ratio (^{1}H NMR): FT - IR (CCl_4 cast) 2940, 1729, 1310, 1242, 1202, 1119 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.18 - 1.33 (m, 6 H), 1.33 - 1.52 (m, 4 H), 1.54 (s, 4.5 H), 1.56 (s, 4.5 H), 1.58 - 1.90 (m, 2 H), 2.43 (dd, J = 9.5, 15.5 Hz, 1 H), 2.52 (dd, J = 8.0, 15.5 Hz, 1 H), 3.09 (m, 2 H), 3.27 (dd, J = 2.0, 15.5 Hz, 0.58 H), 3.29 (dd, J = 2.5, 16.0 Hz, 0.42 H), 4.15 (m, 4 H), 5.39 (dd, J = 2.5, 8.5 Hz, 0.5 H), 5.48 (dd, J = 2.0, 9.0 Hz, 0.5 H), 5.56 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.94, 14.03, 25.02, 25.13, 25.21, 31.55, 31.64, 35.26, 35.55, 35.85, 35.98, 43.78, 44.29, 50.57, 54.73, 55.30, 59.30, 59.66, 59.86, 60.01, 61.58, 61.68, 61.82, 63.35, 128.73, 128.90, 138.51, 138.83, 170.14, 170.35, 170.57, (four aliphatic and one carbonyl signal missing or coincident); exact mass *m/z* calcd for $C_{21}H_{33}{}^{81}BrO_6S$ 494.1161, found 494.1169. Anal. Calcd for $C_{21}H_{33}BrO_6S$: C, 51.12; H, 6.74; Br, 16.19; S, 6.49; Found: C, 51.25, H, 6.65; Br, 16.02; S, 6.48.

Diethyl 2-(2-cyclopenten-1-yl)-2-[1-methyl-2-nitro-2-(phenylseleno)ethyl]propane-1,3-dioate (166).

The procedure employed for **128b** was followed using diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate[87] (231 mg, 1.02 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (40.8 mg, 60% dispersion in oil, 1.02 mmol) in THF (15 mL), and (Z)-1-nitro-1-phenylseleno-2-methylethylene **142** (246 mg, 1.02 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 5% ethyl acetate - hexane gave **166** (316.4 mg, 66%) as a light yellow oil which was a chromatographically (TLC) inseparable mixture of at least three isomers (^{1}H NMR): FT-IR (CCl_4 cast) 1720, 1550, 1440, 1350, 1238, 1022, 740, 710 cm^{-1}; ^{1}H NMR ($CDCl_3$ 400 MHz) δ 1.23- 1.68 [m, 9 H (includes three doublets at δ 1.36 J = 6.0 Hz, δ 1.45, J=7.0 Hz, and δ 1.51, J = 6.0 Hz)], 1.73 - 1.90 (m, 0.6 H), 1.90 - 2.18 (m, 1.4 H), 2.30 (m, 2 H), 3.15 - 3.41 (m, 0.5 H), 3.46 (q, J = 10.5 Hz, 0.7 H), 3.61 (m, 0.8 H), 3.92 - 4.44 (m, 4 H), 5.50 - 6.02 (m, 3 H), 7.38 (m, 3 H), 7.65 (m, 2 H); 13C NMR ($CDCl_3$, 75.5 MHz) δ 12.38, 12.71, 12.96, 13.15, 13.84, 13.95, 14.03, 14.11, 24.21, 24.56, 25.13, 25.30, 27.81, 31.48, 31.54, 31.78, 31.90, 38.93, 39.29, 41.32, 41.50, 45.37, 48.78, 48.85, 49.40, 49.74, 57.10, 61.21, 61.37, 61.56, 61.65, 61.74, 61.82, 63.69, 63.77, 63.99, 88.26, 88.40, 89.96, 90.50, 127.22, 127.99, 128.24, 129.28, 129.38, 129.51, 129.56, 129.62, 129.72, 130.06, 131.00, 131.55, 131.72, 131.78, 132.87, 133.13, 133.77, 134.87, 135.26, 135.50, 135.53, 168.88, 169.24, 169.48, 169.74; exact mass, *m/z* calcd for $C_{21}H_{27}NO_6Se$ 469.1003, found 469.1006. Satisfactory combustion analytical values could not be obtained.

Diethyl 2-(2-cyclohexen-1-y)-2-[1-methyl-2-nitro-2-(phenylseleno)ethyl]propane-1,3-dioate (167).

The procedure employed for **128b** was followed using diethyl 2-(cyclohexen-1-yl)propane-1,3-dioate[128] (58 mg, 0.242 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (9.6 mg, 60% dispersion in oil, 0.240 mmol) in THF (5 mL), and (Z)-1-nitro-1-phenylseleno-2-methylethylene **142** (58 mg, 0.240 mmol) in THF (1 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 10% ethyl acetate gave **167** (104.9 mg, 90%) as a light yellow oil which was a chromatographically (TLC) inseparable mixture of several isomers (^{13}C NMR): FT-IR ($CHCl_3$ cast) 2980, 2940, 1719, 1566, 1238, 1218, 1199, 1020, 740, 690 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.24 (m, 6 H), 1.31 - 1.59 [m, 3.7 H (includes four doublets at δ 1.33, 1.39, 1.45, 1.48, J = 7.0 Hz each)], 1.59 - 1.83 (m, 3.3 H), 1.94 (m, 2 H), 3.08 (m, 1 H), 3.20 - 3.53 (m, 1 H), 3.90 - 4.42 (m, 4 H), 5.52 (m, 1 H), 5.73 (m, 1.8 H), 5.89 (m, 0.2 H), 7.35 (m, 3 H), 7.63 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 11.74, 12.74, 12.97, 13.90, 13.95, 14.06, 15.28, 22.28, 22.40, 23.47, 24.19, 24.78, 24.89, 25.02, 37.77, 38.29, 39.02, 39.95, 40.08, 61.29, 61.37, 61.44, 61.59, 61.71, 61.90, 63.50, 63.91, 65.84, 88.31, 88.36, 89.86, 90.04, 125.49, 126.48, 127.17, 127.61, 127.98, 128.32, 129.54, 129.62, 129.73, 130.52, 134.92, 135.27, 135.47, 135.56, 168.46, 168.95, 169.23, 169.36; exact mass, *m/z* calcd for $C_{22}H_{29}NO_6Se$ 483.1161, found 483.1161. Satisfactory combustion analytical values could not be obtained.

Diethyl 2-(2-cyclohexen-1-yl)-2-[2-bromo-2-(methoxycarbonyl)ethyl]propane-1,3-dioate (168).

The procedure employed for **128b** was followed using 2-(cyclohexen-1-yl)propane-1,3-dioate[128] (193 mg, 0.804 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (46 mg, 50% dispersion in oil, 0.958 mmol) in THF (10 mL), and **144** (195 mg, 1.18 mmol) in THF (1 mL + 1 mL rinse). A second equivalent of **144** (195 mg, 1.18 mmol) was added to the reaction mixture after 3 h and stirring was continued at 0 °C for 1 h. The mixture was then worked up in the usual way. Flash chromatography of the crude product over silica gel (2 x 15 cm) using 15% ethyl acetate - hexane afforded **168** (121 mg, 37%, 40% based on conversion of starting materials) as a chromatographically (TLC) inseparable mixture of two isomers in a 1.2:1 ratio (^1H NMR) together with unreacted starting material (14.9 mg, 7%). A complex mixture of other products was also observed. Compound **168** had: FT-IR (CCl_4 cast) 2890, 2870, 1745, 1733, 1440, 1370, 1280, 1249, 1230, 1195, 1050, 1095, 1045 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.16 - 1.34 (m, 6 H), 1.34 - 1.70 (m, 2 H), 1.72 - 2.06 (m, 4 H), 2.78 - 3.10 (m, 2 H), 3.74 (s, 1.38 H), 3.76 (s, 1.62 H), 3.88 - 4.34 (m, 4 H), 4.62 (m, 1 H), 5.52 - 5.90 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.66, 13.75, 13.91, 22.17, 24.26, 24.31, 24.71, 35.65, 36.94, 40.22, 40.56, 41.29, 52.65, 52.72, 60.31, 60.41, 61.30, 61.37, 61.52, 61.58, 126.77, 127.20, 129.50, 129.70, 169.69, 169.73, 169.77, 169.93, 170.40, 170.46, (four aliphatic signals missing or coincident); exact mass, *m/z* calcd for $C_{17}H_{25}{}^{81}BrO_6$, 406.0814, found 406.0827. Anal. Calcd for $C_{17}H_{25}BrO_6$: C, 50.38; H, 6.22; O, 23.69. Found: C, 50.56; H, 6.16; O, 23.71.

Diethyl 2-(2-cyclopenten-1-yl)-2-[2-bromo-2-(methoxycarbonyl)ethyl]propane-1,3-dioate (169) and **Dimethyl 1-bromo-2-[[2-(2-cyclopenten-1-yl)-2,2-diethoxycarbonyl]ethyl]-1,2-cyclopropanedicarboxylate (170)**

The procedure employed for **128b** was followed using diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate^{87} (352 mg, 1.56 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (75 mg, 50% dispersion in oil, 1.56 mmol) in THF (15 mL), and **144** (358 mg, 2.17 mmol) in THF (2 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel using 5% ethyl acetate - hexane gave two fractions. The fraction of higher R_f was identified as the desired product **169** (192.6 mg, 31%) which was a thick syrup that was a chromatographically (TLC) inseparable mixture of two isomers in a 1.2:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 1745, 1728, 1240, 1190, 1145 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ

1.23 (m, 6 H), 1.67 (m, 1 H), 2.02 (m, 1 H), 2.32 (m, 2 H), 2.44 (t, J = 3.5 Hz, 0.44 H), 2.41 (t, J = 3.5 Hz, 0.56 H), 2.79 (dd, J = 5.0, 15.0 Hz) and 2.83 (dd, J = 4.0, 15.0 Hz) [both signals together correspond to 1 H], 3.44 (m, 1 H), 3.73 (s, 1.6 H), 3.75 (s, 1.4 H), 3.90 - 4.29 (m, 4 H), 4.58 (t, J = 3.5 Hz) and 4.63 (dd, J = 3.5, 4.5 Hz) [both signals together correspond to 1 H], 5.62 (m, 0.45 H), 5.73 (m, 0.55 H), 5.82 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.83, 14.02, 24.15, 25.42, 31.91, 32.02, 36.95, 37.12, 40.96, 41.09, 50.49, 50.61, 52.82, 52.86, 60.28, 60.44, 61.44, 61.63, 130.23, 130.52, 133.46, 170.16, 170.26, 170.46, 170.56; exact mass, *m/z* calcd for $C_{16}H_{23}{}^{81}Br$ 392.0658, found 392.0672. Anal. Calcd for $C_{16}H_{23}BrO_6$: C, 49.12; H, 5.93; O, 24.54. Found: C, 49.00; H, 5.99; O, 24.34.

The fraction of lower R_f (405.5 mg, 54 %) was identified as **170** which was a thick syrup that was a chromatographically (TLC) inseparable mixture of four isomers: FT-IR (CCl_4 cast) 1739, 1737, 1435, 1249, 1100 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.24 (two superimposed triplets, J = 2.0 Hz, 6 H), 1.54 - 2.42 (m, 7 H), 2.92 (m, 1 H), 3.43 (m, 1 H), 3.71 (s) and 3.73 (s) [both signals together correspond to 3 H], 3.95 - 4.32 (m, 4 H), 5.61 (m, 0.4 H), 5.77 (m, 1.6 H); exact mass, *m/z* calcd for $C_{20}H_{27}{}^{81}BrO_8$ 476.0869, found 476.0883.

Diethyl 2-(2-cyclopenten-1-yl)-2-[2-methoxycarbonyl-2-(phenylseleno)ethyl]propane-1,3-dioate (172).

The procedure employed for **128b** was essentially followed using diethyl 2-(cyclopenten-1-yl)propane-1,3-dioate[87] (226 mg, 1.00 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (40 mg, 60% dispersion in oil, 1.00 mmol) in THF (20 mL), and **145** (527 mg, 2.19 mmol) in THF (4 mL + 1 mL rinse). In this case however, the Michael acceptor was injected into the cold solution over a period of 4 h. The reaction was then quenched and worked up in the usual way. Flash chromatography of the crude product over silica gel (2 x 15 cm) using 5% ethyl acetate - hexane gave **172** (360 mg, 77%) as a thick syrup which was a chromatographically inseparable mixture (TLC) of two isomers in a 1:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 1731, 1415, 1230, 1190, 740 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.21 (m, 6 H), 1.65 (m, 1 H), 1.96 (m, 1 H), 2.14 - 2.41 (m, 3 H), 2.55 (m, 1 H), 3.48 (m, 1 H), 3.53 (s, 1.5 H), 3.55 (s, 1.5 H), 3.85 - 4.23 (m, 5 H), 5.57 - 5.80 (m, 2 H), 7.31 (m, 3 H), 7.60 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.85, 13.99, 25.17, 25.39, 31.85, 31.94, 34.61, 34.73, 36.85, 50.30, 50.51, 51.66, 60.55, 60.67, 61.12, 61.29, 127.71, 128.79, 128.95, 130.60, 130.85, 132.81, 132.93, 136.15, 136.19, 137.94, 170.32, 170.41, 170.55, 173.05, 173.22; exact mass, *m/z* calcd for $C_{22}H_{28}O_6Se$ 468.1051, found 468.1065. Anal. Calcd for $C_{22}H_{28}O_6Se$: C, 56.53; H, 6.04; O, 20.54. Found: C, 56.33; H, 5.86; O, 20.14.

Radical Cyclizations:

The general procedure for radical cyclization is described on p.136.

(3aα, 6aα)-Octahydro-3-(phenylsulfonyl)pentalen-1-carbaldehyde (121c) and **(3aα, 4β, 6aα)-Octahydro-4-phenylpentalene-1-carbaldehyde (121c')**.

The general procedure for radical cyclization was not followed in this experiment. Triphenyltin hydride (444 mg, 1.27 mmol) in benzene

(5 mL), and AIBN (10 mg, 0.06 mmol) in benzene (5 mL) were added in one portion to a refluxing solution of bromides **121b** (302 mg, 0.845 mmol) in benzene (70 mL). The mixture was stirred under reflux for 15 h, cooled, and evaporated. Flash chromatography of the residue over silica gel (2 x 15 cm) using first 5% ethyl acetate - hexane and then an increasingly more polar solvent mixture (up to 90% ethyl acetate) gave three fractions together with a complex mixture of uncharacterised materials. The fraction of highest R_f (28.5 mg, 15%) was identified as two isomers of the rearranged product **121c'** in a 1.5:1 ratio (^{1}H NMR) which was a thick syrup: FT-IR (CCl_4 cast) 2940, 2880, 2700, 1719, 1425, 1075, 725, 698 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.86 - 1.04 (m, 0.40 H), 1.15 - 1.33 (m, 0.60 H), 1.38 - 2.00 (m, 7 H), 2.25 - 2.47 (m, 0.45 H), 2.52 - 3.10 (m, 2.55 H), 3.13 - 3.45 (m, 1H), 7.10 - 7.70 (m, 5 H), 9.62 (d, J = 3.0 Hz, 0.40 H), 9.82 (d, J = 1.0 Hz, 0.60 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 26.40 (t), 26.48 (t), 26.90 (t), 27.01 (t), 28.64 (t), 29.16 (t), 29.43 (t), 31.39 (t), 43.67 (d), 44.65 (d), 48.07 (d), 48.09 (d), 48.39 (d), 48.94 (d), 57.32 (d), 61.33 (d), 127.84 (d), 127.95 (d), 128.32 (d), 128.54 (d), 136.52 (d), 137.25 (d), 142.27 (s), 142.50 (s), 203.76 (d), 204.35 (d); exact mass, *m/z* calcd for $C_{15}H_{18}O$ 214.1357, found 214.1357. Satisfactory combustion analytical values could not be obtained.

The middle fraction (14.7 mg, 6%) was identified as **121c** which was a thick syrupy mixture of two isomers in a 2.7:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 2952, 2880, 2720, 1719, 1442, 1300, 1144, 1082, 724, 688, 580, 560 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.04 - 1.22 (m, 1.5 H), 1.26 - 1.95 (m, 4.5 H), 1.98 - 2.40 (m, 2.5 H), 2.60 - 2.88 (m, 0.4 H), 2.95 - 3.25 (m, 2.5 H), 3.33 - 3.50 (m, 0.6 H), 7.50 - 7.72 (m, 3 H), 7.90 (m, 2 H), 9.62 (d, J = 2.0 Hz, 0.27 H), 9.75 (d, J = 0.5 Hz, 0.73 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ (signals assigned to major isomer) 26.38, 27.36, 28.56, 33.39, 44.90, 44.98, 54.09, 70.13, 128.53, 129.36, 133.75, 138.24, 201.65; (signals assigned to minor isomer, three signals missing or coincident) δ 25.16, 30.30, 31.94, 32.70, 44.28, 45.13, 57.62, 70.34, 127.93, 133.85; exact mass, *m/z* calcd for $C_{15}H_{18}O_3S$ 278.0977, found 278.0969.

The fraction of lowest R_f (80.6 mg, 34%) was a thick syrup which was a mixture of three isomers of **121c** (one of which was also present in the former fraction) in a 5.4:3.6:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 2940, 2880, 2720, 1719, 1445, 1301, 1290, 1146, 1086, 720, 690 590 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.04 - 2.45 (m, 8.6 H), 2.60 - 3.25 (m, 2.7 H), 3.39 (m, 0.7 H), 7.50 - 7.72 (m, 3 H), 7.90 (m, 2 H), 9.60 (d, J = 0.5 Hz, 0.54 H), 9.62 (d, J = 1.0 Hz, 0.36 H), 9.73 (d, J = 0.5 Hz, 0.10 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ (signals assigned to major isomer) 25.55 (t), 27.63 (t), 27.68 (t), 33.97 (t), 43.78 (d), 45.19 (d), 56.86 (d), 65.64 (d), 129.28 (d), 129.35 (d), 133.63 (d), 140.30 (s), 201.28 (s); (signals assigned to less abundant isomer) δ 25.16 (t), 30.30 (t), 31.94 (t), 32.69 (t), 44.28 (d), 45.13 (d), 57.60 (d), 70.33 (d), 127.92 (d), 128.57 (d), 133.86 (d), 138.59 (d), 201.17 (d); (signals assigned to minor isomer, five signals missing or coincident) δ 25.86 (t), 28.10 (t), 29.98 (t), 43.70 (d), 44.44 (d), 53.55 (d), 65.81 (d), 128.07 (d); exact mass, *m/z* calcd for $C_{15}H_{18}O_3S$ 278.0977, found 278.0972. Anal. Calcd for $C_{15}H_{18}O_3S$: C, 64.72; H, 6.52; S, 11.52. Found: C, 64.61; H, 6.41; S, 11.25.

(3aα, 7aα)-Octahydro-3a-methyl-3-(phenylsulfonyl)indene-1-carbaldehyde (122c).

The general procedure for radical cyclization was followed using bromides **122b** (187 mg, 0.485 mmol) in benzene (65 mL), triphenyltin hydride (232 mg, 0.661 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 35% ethyl acetate - hexane gave **122c** (49.7 mg, 33%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of four isomers in a 2:1.8:1.5:1 ratio (^{1}H NMR). A complex mixture of byproducts and starting bromides **122b** were also isolated. Compound **122c** had: FT-IR (CCl_4 cast) 2920, 2850, 2720, 1720, 1440, 1300, 1145, 1080, 785, 765, 715, 685, cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.82 - 2.26 (m, 12.2 H), 2.26 - 2.64 (m, 1.8 H), 2.85 (m, 0.45 H), 2.98 - 3.15 (m, 0.90 H), 3.32 (m, 0.65 H), 7.61 (m, 3 H), 7.90 (m, 2 H), 9.54 (d, J = 1.0 Hz, 0.32 H), 9.62 (s, 0.24 H), 9.66 (d, J = 0.5 Hz, 0.28 H), 9.88 (d, J = 0.5 Hz, 0.16 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 19.82, 19.92, 20.12, 20.81, 20.99, 21.11, 21.39, 21.50, 21.77, 21.82, 22.26, 22.49, 23.28, 23.80, 24.61, 25.14, 25.66, 25.70, 25.87, 28.09, 34.99, 40.32, 45.93, 46.06, 46.79, 47.31, 48.91, 49.14, 50.86, 52.25, 52.58, 54.47, 63.25, 69.53, 70.68, 73.05, 125.51, 126.77, 127.14, 127.82, 127.97, 128.10, 128.19, 129.25, 129.28, 129.36, 132.27, 133.46, 133.57, 133.80, 140.40, 140.98, 201.71, 202.31, 203.29, 204.18; exact mass, *m/z* calcd for $C_{17}H_{22}O_3S$ 306.1290, found 306.1286. Satisfactory analytical values could not be obtained.

(3aα, 7aα)-Octahydro-7a-methyl-3-(phenylsulfonyl)-7a*H*-indene-1-carbaldehyde (123c).

The general procedure for radical cyclization was not followed in this experiment. Triphenyltin hydride (283.5 mg, 0.809 mmol) in benzene (5 mL) and AIBN (10 mg, 0.06 mmol) in benzene (5 mL) were added in one portion to a reluxing solution of bromides **123b** (186 mg, 0.482 mmol) in benzene (70 mL). The mixture was stirred under reflux for 15 h, cooled, and evaporated. Flash chromatography of the crude product over silica gel (2 x 15 cm) using 24% ethyl acetate - hexane afforded two fractions. The thick syrupy material of slightly higher R_f (51.3 mg, 34%) was a mixture of four isomers of **123c** in a 2.4:3.3:1:1 ratio (^{1}H NMR): FT-IR (CH_2Cl_2 cast) 2931, 2860, 2720, 1718, 1447, 1303, 1288, 1147, 1086, 725, 690, 600 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.82 - 2.26 (m, 12 H), 2.30 - 2.46 (m, 1.5 H), 2.66 (m, 0.5 H), 2.86 - 3.32 (m, 1 H), 3.5 - 3.76 (m, 1 H), 7.52 - 7.71 (m, 3 H), 7.92 (m, 2 H), 9.65 (m, 0.31 H), 9,73 (d, J = 1.0 Hz, 0.43 H), 9.76 (d, J = 2.0 Hz, 0.13 H), 9.85 (d, J = 2.0 Hz, 0.13 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.25, 16.91, 17.56, 20.41, 20.82, 21.03, 2115, 21.48, 21.56, 22.58, 23.44, 23.95, 24.25, 24.47, 24.67, 24.85, 25.45, 25.64, 29.53, 34.96, 45.21, 45.60, 46.42, 50.64, 52.03, 59.51, 61.86, 62.86, 65.38, 127.94, 128.00, 128.09, 128.56, 128.65, 129.39, 133.61, 133.79, 138.79, 202.32, 203.18, 204.75 (four signals missing or coincident); exact mass, *m/z* calcd for $C_{17}H_{22}O_3S$ 306.1290, found 306.1287. Satisfactory combustion analytical values could not be obtained for this compound.

The fraction of lower R_f (27.8 mg, 19%) was a thick syrup which was also a mixture of the same four isomers of **123c** but in a ratio of 1.9:1.9:1.0:7.8 (^{1}H NMR): FT-IR (CCl_4 cast) 2925, 2850, 2720, 1715, 1442, 1300, 1280, 1140, 1082, 750, 685, 580 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.73 - 2.24 (m, 13 H), 2.30 - 2.45 (m, 1.0 H), 2.84 - 3.00 (m, 1 H), 3.60 - 3.79 (m, 1 H), 7.50 -7.72 (m, 3 H), 7.92 (m, 2 H), 9.65 (m, 0.15 H), 9.73 (t, J = 1.5, 8.0 Hz, 0.15 H), 9.76 (d, J = 2.0 Hz, 0.08 H), 9.85 (d, J = 2.0 Hz, 0.62 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 20.72, 20.93, 21.38, 22.69, 23.31, 23.71, 24.14, 24.37, 24.57, 25.33, 32.28, 32.57, 33.13, 34.85, 45.56, 46.67, 48.59, 50.52, 51.91, 59.40, 61.76, 65.27, 65.59, 124.33, 127.83, 127.98, 128.45, 128.54, 129.22, 133.48, 133.76, 140.62, 202.73, 202.85, 202.12; exact mass, *m/z* calcd for $C_{17}H_{22}O_3S$, 306.1290, found 306.1275. Satisfactory combustion analytical values could not be obtained for this compound.

(3aα, 7aα)-1-[Octahydro-7a-methyl-3-(phenylsulfonyl)indene]methanol (123e) and (3aα, 4β, 7aα)-1-[7a-methyl-4-phenylindene)methanol (123e').

The general procedure for radical cyclization was followed using bromides **123d** (277 mg, 0.717 mmol) in benzene (70 mL), triphenyltin hydride (379 mg, 1.080 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane gave three fractions. The fraction of highest R_f (26.8 mg, 15%, 17% based on conversion of starting materials) was a thick syrup which was identified as a single isomer (^{13}C NMR) of the rearranged product **123e'**: FT-IR (CCl_4 cast) 3320, 2949, 2927, 2865, 1600, 1490, 1440, 1030, 780, 698 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.98 - 1.92 (m, 16 H), 2.96 (two superimposed triplets, J = 4.5 Hz each, 1 H), 3.51 (m, 1 H), 3.78 (m, 1 H), 7.16 (m, 3 H), 7.27 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 22.07, 22.25, 23.97, 24.76, 25.04, 26.93, 40.37, 42.51, 53.16, 54.14, 64.27, 125.64, 127.29, 128.10, 146.06; exact mass, *m/z* calcd for $C_{17}H_{24}O$ 244.1827, found 244.1830.

The middle fraction (32.4 mg, 11%) was identified as unreacted starting bromides **123d**. The fraction of lowest R_f (79.8 mg, 36%, 41% based on conversion) was a chromatographically (TLC) inseparable thick syrupy mixture of isomers of **123e**: FT-IR (CCl_4 cast) 3480, 2928, 2860, 1445, 1285, 1143, 1085, 690, 580 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.58 - 2.66 [m, 16 H (contains singlets at δ 1.06 and δ 1.10)], 3.24 - 3.87 (m, 3 H), 7.57 (m, 3 H), 7.88 (m, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 19.74, 20.53, 20.72, 20.92, 21.06, 21.68, 22.08, 22.30, 23.05, 23.32, 24.14, 24.85, 27.94, 28.23, 28.54, 228.87, 29.56, 30.68, 30.88, 34.80, 41.27, 42.61, 44.39, 46.30, 48.67, 49.96, 51.74, 52.33, 62.30, 63.09, 64.20, 65.20, 127.84, 128.33, 128.40, 129.10, 133.14, 133.40; exact mass, *m/z* calcd for $C_{17}H_{24}O_3S$ 308.1446, found 308.1430.

(3aα, 7aα)-Octahydro-7a-methyl-3-(phenylsulfonyl)indene-1-carbaldehyde dimethyl acetal (123g).

The general procedure for radical cyclization was followed using bromides **123f** (203 mg, 0.472 mmol) in benzene (50 mL), triphenyltin hydride (247 mg, 0.706 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 20% ethyl acetate - hexane gave **123g** (65.2 mg, 39%, 46% based on conversion) as a chromatographically (TLC) inseparable thick, syrupy mixture of isomers. Unreacted bromides **123f** (32.4 mg, 16%) were also isolated together with a complex mixture of unidentified byproducts. Compound **123g** had: FT-IR (CCl_4 cast) 2928, 1440, 1300, 1145, 1080, 1050, 690 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.82 - 2.23 (m, 15 H), 3.28 (m, 6 H), 3.41 - 3.73 (m, 1 H), 4.05 - 4.45 [m, 1 H (contains doublets at δ 4.21, J = 8.0 Hz, and at δ 4.44, J = 8.0 Hz)], 7.57 (m, 3 H), 7.90 (m, 2 H); exact mass, *m/z* calcd for $C_{19}H_{28}O_4S$ 352.1708, found 352.1715. Anal. Calcd for $C_{19}H_{28}O_4S$: C, 64.74; H, 8.01; S, 9.09. Found: C, 64.94; H, 7.84; S, 8.95.

Diethyl (3aα, 6aα)-octahydro-3-(phenylsulfonyl)pentalene-1,1-dicarboxylate (128c) and Diethyl (3aα, 4β, 6aα)-octahydro-4-phenylpentalene-1,1-dicarboxylate (128c')

The general procedure for radical cyclization was followed using bromides **128b** (362 mg, 0.764 mmol) in benzene (60 mL), triphenyltin hydride (410 mg, 1.17 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (2 x 15 cm) using first 10% ethyl acetate - hexane and then gradually a more polar mixture (up to 90% ethyl acetate) afforded two compounds. That of higher R_f (57 mg, 18%) was a solid which was recrystallized from hexane and identified as the rearranged product **128c'**: mp 48 - 49 °C; FT-IR ($CHCl_3$ cast) 3040, 1729, 1240, 1170, 1090, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.18 - 1.50 (m, 9 H), 1.70 - 2.00 (m, 4 H), 2.16 (m, 1 H), 3.10 (m, 1 H), 3.30(m, 2 H), 4.08 - 4.30 (m, 4 H), 7.12 - 7.32 (m, 5 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.08, 13.19, 24.14, 26.75, 27.82, 32.74, 47.44, 47.68, 47.78, 60.04, 60.23, 65.28, 124.79, 126.93, 127.10, 141.63, 169.98, 171.39; exact mass, *m/z* calcd for $C_{20}H_{26}O_4$ 330.1843, found 330.1837. Anal. Calcd for $C_{20}H_{26}O_4$: C, 72.70; H, 7.93. Found: C, 72.55; H, 7.90.

The thick syrupy material of lower R_f (226 mg, 61%) was a chromatographically (TLC) inseparable mixture of two isomers, corresponding to the the *cis* ring-fused compounds **128c**, in a 1.9:1 ratio (^{13}C NMR): FT-IR ($CHCl_3$ cast) 3040, 1725, 1442, 1360, 1295, 1260, 1240, 1180, 1144, 1080, 1070, 720, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.92 - 1.15 (t, J = 8.5 Hz, 2.6 H), 1.17 - 1.40 (m, 5.4 H), 1.47 - 1.75 (m, 1.2 H), 1.75 -

1.90 (m, 1.4 H), 1.90 - 2.10 (m, 1.4 H), 2.18 (dd, J = 5.5, 13.0 Hz, 0.7 H), 2.50 (dd, J = 8.5, 14.5 Hz, 0.3 H), 2.62 - 2.87 (m, 1.7 H), 3.07 (m, 0.3 H), 3.22 (q, J = 8.5 Hz, 0.7 H), 3.36 (m, 1.0 H), 3.48 (q, J = 8.5 Hz, 0.3 H), 4.02 - 4.30 (m, 4 H), 7.42 - 7.72 (m, 3 H), 7.90 (m, 2 H); ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ 13.84, 14.01, 14.06, 14.10, 14.20, 26.68, 27.49, 28.40, 28.67, 30.46, 32.07, 32.39, 36.09, 43.50, 45.39, 48.13, 50.56, 61.49, 61.57, 61.80, 62.39, 62.52, 63.98, 69.78, 127.98, 128.52, 129.21, 129.27, 133.59, 133.71, 138.79, 140.28, 169.15, 170.49, 170.66, 171.51; exact mass, *m/z* calcd for $C_{20}H_{26}O_6S$ 394.1450, found 394.1446. Anal. Calcd for $C_{20}H_{26}O_6S$: C, 60.89; H, 6.64; S, 8.13. Found: C, 60.82; H, 6.60; S, 7.98.

Diethyl (3aα, 7aα)-octahydro-3-(phenylsulfonyl)-1*H*-indene-1,1-dicarboxylate (129c).

The general procedure for radical cyclization was followed using bromides **129b** (246 mg, 0.505 mmol) in benzene (60 mL), triphenyltin hydride (275 mg, 0.782 mmol) in benzene (10 mL), and AIBN (10.0 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 20% ethyl acetate - hexane gave **129c** (191 mg, 93%) as a thick syrup which was a chromatographically inseparable mixture of two isomers in a 1.5:1 ratio (^{1}H NMR): FT-IR (CCl$_4$ cast) 1728, 1445, 1305, 1265, 1245, 1147, 1085 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300 MHz) δ 0.72 - 1.83 (m, 12 H), 188 - 2.02 (m, 2 H), 2.08 (m, 0.4 H), 2.22 (m, 0.1 H), 2.43 - 2.55 (m, 0.8 H), 2.60 (d, J = 4.5 Hz, 0.2 H), 2.75 (m, 0.3 H), 2.86 - 3.00 (m, 1.2 H), 3.22 - 3.60 (m, 2 H), 3.96 - 4.33 (m, 4 H), 7.42 - 7.70 (m 3 H), 7.90 (m, 2 H); ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ 13.69, 13.98, 14.04, 20.59, 21.14, 22.66, 23.57, 24.29, 24.50, 25.09, 25.71, 32.53, 33.69, 39.26, 40.41, 42.14, 43.60, 44.95, 60.31, 61.67, 61.79, 61.86, 62.04, 62.77, 63.35, 65.63, 128.11, 128.75, 129.15, 129.28, 130.43, 133.57, 133.72, 136.23, 169.17, 170.52, 170.73, 172.04; exact mass, *m/z* calcd for $C_{21}H_{28}O_6S$ 408.1610, found 408.1604. Anal. Calcd for $C_{21}H_{28}O_6S$: C, 61.74; H, 6.91; S, 7.85. Found: C, 61.66; H, 6.65; S, 7.91.

Diethyl 4-methyl-3-(phenylsulfonyl)-1,1-cyclopentanedicarboxylate (130c) and Diethyl 2-(2-propen-1-yl)-2-[2-(phenylsulphonyl)ethyl]propane-1,3-dioate (130d)

The general procedure for radical cyclization was followed using the bromides **130b** (331 mg, 0.740 mmol) in benzene (60 mL), triphenyltin hydride (410 mg, 1.17 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash column chromatography of the crude product over silica (2 x 15 cm) using 25% ethyl acetate - hexane gave two fractions. The thick syrupy material of lower R_f was a mixture of **130c** (82.9 mg, 30%,[20] 35% based on conversion) together with **130d** (50.8 mg, 19%,[20] 21% based on conversion). The fraction of higher R_f (44.9 mg, 13%) was unreacted starting material. The mixture of products **130c** and **130d** had: FT-IR (CCl_4 cast) 1730, 1440, 1305, 1253, 1181, 1149, 1080 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ (signals assigned to reduction product **130d**) 1.21 (t, J = 7.5 Hz, 6 H), 2.20 (two superimposed dd, J = 4.0, 13.0 Hz and J = 8.0, 9.0 Hz, 2 H), 2.58 (d, J= 7.5 Hz, 2 H), 3.14 (two superimposed dd, J = 4.0, 13.0 Hz, and J = 8.0, 9.0 Hz, 2 H), 4.14 (q, J = 7.5 Hz) and 4.15 (q, J = 7.5 Hz) [both signals together correspond to 4 H], 5.05 (m, 2 H), 5.51 (m, 1 H), 7.54 - 7.72 (m, 3 H), 7.70 (m, 2 H); (signals assigned to cyclization product **130c**) δ 0.98 - 1.49 (m, 9 H), 1.80 (m, 0.30

H), 2.38 (m, 2.3 H), 2.62 - 2.80 (m, 2.4 H), 3.25 (m, 0.4 H), 3.53 (m, 0.6 H), 4.05 - 4.32 (m, 4 H), 7.41 - 8.02 (m, 5 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.5, 15.3, 19.2, 25.4, 34.0, 34.6, 35.2, 35.9, 37.3, 41.0, 41.7, 51.3, 55.4, 57.9, 58.0, 61.2, 61.4, 65.2, 69.0, 119.4, 127.7, 128.1, 128.4, 128.7, 128.8, 130.8, 133.1, 133.3, 135.7, 139.5, 169.5, 170.2, 171.4; exact mass, *m/z* [$(M - SO_2C_6H_5)^+$] calcd for $C_{12}H_{19}O_4$ 227.1283, found 227.1283.

An authentic sample of **130d** was prepared by the procedure employed for **128b** using diethyl 2-(2-propen-1-yl)propane-1,3-dioate[130] (248 mg, 1.24 mmol) in dry THF (1 mL + 1 mL rinse), sodium hydride (66.4 mg, 50% dispersion in oil, 1.38 mmol) in THF (15 mL), and phenyl vinyl sulfone[9] (176 mg, 1.05 mmol) in THF (3 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 20% ethyl acetate - hexane gave **130d** (172 mg, 44%) as a colorless oil: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.21 (t, J = 7.5 Hz, 6 H), 2.20 (two superimposed dd, J = 4.0, 13.0 Hz and J = 8.0, 9.0 Hz, 2 H), 2.58 (d, J= 7.5 Hz, 2 H), 3.14 (two superimposed dd, J = 4.0, 13.0 Hz, and J = 8.0, 9.0 Hz, 2 H), 4.14 (q, J = 7.5 Hz), and 4.15 (q, J = 7.5 Hz) [both signals together correspond to 4 H], 5.05 (m, 2 H), 5.51 (m, 1 H), 7.54 - 7.72 (m, 3 H), 7.70 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.01, 25.91, 37.80, 51.85, 55.96, 61.72, 119.88, 128.12, 129.32, 131.30, 133.80, 138.70, 169.97; exact mass, *m/z* calcd for $C_{18}H_{24}O_6S$ 368.1294, found 368.1290.

Diethyl (3aα, 4aβ, 7aβ, 7bα)-decahydro-3-(phenylsulfonyl)-1*H*-cyclopenta[b]pentalene-1,1-dicarboxylate (131c) and Diethyl (3aα, 4β, 4aβ, 7aβ, 7bα)-decahydro-4-phenyl-1*H*-cyclopenta[b]pentalen-1,1-dicarboxylate (131c').

The general procedure for radical cyclization was not followed in this experiment. Triphenyltin hydride (116 mg, 0.331 mmol) in benzene (5 mL) and AIBN (10 mg, 0.06 mmol) in benzene (5 mL) were added in one portion to a refluxing solution of bromides **131b** (13 mg, 0.22 mmol) in benzene (50 mL). The mixture was stirred under reflux for 15 h, cooled, and evaporated. Flash chromatography of the crude product over silica gel (1 x 15 cm) using first 5% ethyl acetate - hexane and then an increasingly more polar solvent mixture (up to 25% ethyl acetate) afforded three fractions. The fraction of highest R_f (42.1 mg, 51%, 59% based on conversion) was identified as a single isomer (^{13}C NMR) of the rearranged product **131c'** which was a colorless oil: FT-IR (CCl_4 cast) 1729, 1243, 700 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.18 - 1.84 [m, 14 H (includes two superimposed triplets at δ 1.28, J = 7.0 Hz)], 1.96 (q', J = 7.0 Hz, 1 H), 2.14 (m, 1 H), 2.50 (m, 1 H), 2.86 (m, 2 H), 3.08 (m, 2 H), 4.16 (m, 4 H), 7.24 (m, 5 H); ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 14.07 (q), 14.18 (q), 24.77 (t), 26.20 (t), 31.77 (t), 32.82 (t), 34.39 (t), 46.06 (d), 46.42 (d), 52.83 (d), 53.84 (d), 56.80 (d), 61.09 (t), 61.19 (t), 65.02 (s), 125.82 (d), 128.13 (d), 128.54 (d), 142.35 (s), 171.03 (s), 172.69 (s); exact mass, *m/z* calcd for $C_{23}H_{30}O_4$ 370.2144, found 370.2131.

The fraction of slightly lower R_f (14.2 mg, 12%) was identified as recovered starting bromides **131b**. The fraction of lowest R_f (11 mg, 11%, 13% based on conversion) was a thick syrup which was identified as **131c**: FT-IR (CCl_4 cast) 2979, 2870, 1446, 1302, 1259, 1176, 1149, 1088, 724, 691 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.19 - 1.82 (m, 13 H), 2.08 (m, 1 H), 2.33 - 2.77 (m, 2 H), 2.77 - 3.23 (m, 3 H), 3.24 - 3.51 (m, 1 H), 3.67 (m, 1 H), 4.18 (m, 4 H), 7.40 - 7.72 (m, 3 H), 7.88 (m, 2 H); exact mass, *m/z* [(M - $OCH_2CH_3)^+$] calcd for $C_{21}H_{25}O_5S$ 389.1423, found 389.1408.

Diethyl (3aα, 6aα)-octahydro-3-[2, 4, 6-(trimethylbenzene)sulfonyl]pentalene-1,1-dicarboxylate (146b) and **Diethyl (3aα, 4β, 6aα)-octahydro-4-(2, 4, 6-trimethylphenyl)pentalene-1-dicarboxylate (146b').**

The general procedure for radical cyclization was followed in this experiment using bromides **146** (528 mg, 1.03 mmol) in benzene (65 mL), triphenyltin hydride (552 mg, 1.57 mmol) in benzene (10 mL), and AIBN (20 mg, 0.12 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel using 15% ethyl acetate - hexane gave three fractions. The thick syrupy fraction of lowest R_f (206 mg, 46%, 49% based on conversion) was identified as **146b** which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.5:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 1729, 1301, 1289, 1242, 1181, 1146, 666 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.07 (t, J = 3.0 Hz, 2 H), 1.27 (m, 6 H), 1.49 - 1.74 (m, 1.3 H), 1.74 - 1.90 (m, 1.3 H), 1.90 - 2.06 (m, 1.2 H), 2.10 (dd, J = 5.0, 13.0 Hz, 0.6 H), 2.28 (s) and 2.30 (s) [both signals together correspond to 3 H] 2.48 (dd, J= 9.0, 13.5 Hz, 0.6 H), 2.65 (s) and 2.67 (s) [both signals together correspond to 6 H], 2.73 (dd, J = 8.5, 13.5 Hz, 0.4 H), 2.75 - 2.97 (m, 1.2 H), 3.10 (m, 0.4 H), 3.24 (q, J = 9.0 Hz, 0.6 H), 3.42 (m, 1.0 H), 3.64 (q, 8.5 Hz, 0.4 H), 4.15 (m, 4 H), 6.95 (s, 1.2 H), 6.97 (s, 0.8 H); ^{13}C NMR ($CDCl_3$, 75.5

MHz) δ 13.91, 14.14, 14.23, 21.09, 21.13, 23.08, 23.35, 26.96, 27.67, 28.54, 28.84, 30.64, 31.72, 32.52, 35.84, 43.93, 44.92, 48.08, 50.60, 61.59, 61.63, 61.87, 62.60, 62.64, 63.79, 69.30, 132.49, 133.16, 134.50, 139.82, 140.08, 143.19, 143.33, 169.36, 170.80, 170.89, 171.78; exact mass, *m/z* calcd for $C_{23}H_{32}O_6S$ 436.1920, found 436.1908. Anal. Calcd for $C_{23}H_{32}O_6S$: C, 63.28; H, 7.39; S, 7.34. Found: C, 63.81; H, 7.56; S, 7.11.

The middle fraction was identified as the starting bromides **146** (32.3 mg, 6%). The colorless, oily fraction of highest R_f (110.5 mg, 28%, 30% based on conversion) was identified as the rearranged product **146b'**, which was a single isomer (^{13}C NMR): FT-IR (CCl_4 cast) 1729, 1248, 1234, 852 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.34 (m, 7 H), 1.44 (m, 3 H), 1.60 - 2.07 (m, 3 H), 2.15 - 2.42 [m, 10 H (includes singlets at δ 2.21 and δ 2.36)], 3.06 (m, 1 H), 3.16 - 3.47 (m, 2 H), 4.16 (m, 4 H), 6.75 (s, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.03 (q), 14.17 (q), 20.52 (q), 22.63 (q), 26.17 (t), 29.14 (t), 30.52 (t), 34.78 (t), 47.16 (d), 47.31 (d), 48.00(d), 61.01 (t), 61.20 (t), 66.49 (s), 130.45 (d), 134.97 (s), 135.47 (s), 137.22 (s), 170.99 (s), 172.40 (s); exact mass, *m/z* calcd for $C_{23}H_{32}O_4$ 372.2300, found 372.2296. Anal. Calcd for $C_{23}H_{32}O_4$: C, 74.16; H, 8.66. Found: C, 74.41; H, 8.53.

Diethyl (3aα, 6aα)-octahydro-3-[[3,5-di(1,1-dimethylethyl)benzene]sulfonyl]pentalene-1,1-dicarboxylate (155b) and **Diethyl (3aα, 4β, 6aα)-octahydro-4-[3,5-di(1,1-dimethylethyl)phenyl]pentalene-1,1-dicarboxylate (155b').**

The general procedure for radical cyclization was followed using bromides **155** (120 mg, 0.205 mmol) in benzene (35 mL), triphenyltin hydride (108 mg, 0.309 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06

mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 10% ethyl acetate - hexane gave three fractions. The fraction of highest R_f (27.6 mg, 30%, 35% based on conversion) was a single isomer (^{13}C NMR) of the rearranged product **155b'**, which was a colorless oil: FT-IR (CCl_4 cast) 2880, 1731, 1600 1250 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.06 - 1.53 (m, 27 H), 1.71 - 2.04 (m, 4 H), 2.18 (m, 1 H), 3.10 (m, 1 H), 3.28 (m, 2 H), 4.18 (m, 4 H), 7.03 (d, J = 1.5 Hz, 2 H), 7.22 (t, J = 1.5 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.14 (q), 14.21 (q), 25.19 (s), 27.72 (t), 29.12 (t), 31.58 (t), 33.69 (t), 34.81 (t), 48.50 (d), 48.72 (d), 49.27 (d), 61.02 (t), 61.22 (t), 66.29 (s), 119.67 (d), 122.17 (d), 141.60 (s), 150.22 (s), 171.04 (s), 172.52 (s); exact mass, *m/z* calcd for $C_{28}H_{42}O_4$ 442.3087, found 442.3080. Anal. Calcd for $C_{28}H_{42}O_4$: C, 75.98; H, 9.56. Found: C, 75.57; H, 9.36.

The middle fraction was identified as the starting bromides **155** (17.6 mg, 14%). The thick syrupy fraction of lowest R_f (56.2 mg, 54%, 63% based on conversion) was identified as **155b** which was a chromatographically (TLC) inseparable mixture of two isomers in a 2:1 ratio (^{13}C NMR): FT-IR (CCl_4 cast) 2963, 1730, 1600, 1305, 1248, 1158, 700 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.76 - 1.45 (m, 26 H), 1.60 (m, 2 H), 1.81 (m, 1 H), 1.97 (m, 1 H), 2.29 (dd, J = 5.0, 13.0 Hz, 1 H), 2.52 (dd, J = 8.5, 14.0 Hz, 0.3 H), 2.78 (m, 1.4 H), 3.05 (m, 0.3 H), 3.23 (q, J= 8.5 Hz, 0.6 H), 3.36 (m, 1 H), 3.45 (q, J = 8.5 Hz, 0.4 Hz), 4.15 (m, 4 H), 7.70 (m, 3 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.87, 14.12, 26.72, 27.52, 28.40, 30.44, 31.29, 32.42, 35.27, 36.08, 43.54, 45.61, 48.08, 50.64, 61.46, 61.53, 61.74, 62.40, 62.52, 64.00, 69.86, 121.96, 122.61, 127.68, 138.14, 139.69, 152.41, 152.47, 169.17, 170.56, 171.00, 171.58; exact mass, *m/z* calcd for $C_{28}H_{42}O_6$ 506.2702, found 506.2708. Satisfactory combustion analytical values could not be obtained.

Diethyl (3aα, 6aα)-otahydro-3-(methylsulfonyl)pentalene-1,1-dicarboxylate (156b).

The general procedure for radical cyclization was followed using bromides **156** (316 mg,[125] 0.770 mmol which were contaminated with episulfone **157** (37 mg,[125] 0.112 mmol)) in benzene (65 mL), triphenyltin hydride (480 mg, 1.37 mmol) in benzene (10 ml), and AIBN (20 mg, 0.12 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 15% ethyl acetate - hexane gave two fractions. The fraction of higher R_f (30 mg, 100% based on episulfone) was identified as the diene **157**. The fraction of lower R_f (118.3 mg, 46% based on starting bromide) was identified as **156b** which was a thick syrupy mixture of two isomers in a 6.5:1 ratio (^{13}C NMR): FT-IR (CCl4 cast) 1725, 1294, 1268, 1245, 1182, 1136, 1092, 1069 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.95 - 1.50 [m, 8 H (includes a triplet at δ 1.27, J = 7.0 Hz)], 1.75 - 2.05 (m, 4 H), 2.42 (dd, J = 4.0, 11.5 Hz, 1 H), 2.70 - 3.04 (m, 5 H), 3.22 - 3.57 (m, 2 H), 4.22 (m, 4 H); 13.86, 13.98, 15.14, 26.67, 27.33, 27.97, 28.57, 30.29, 31.81, 32.23, 36.03, 39.68, 41.51, 43.20, 44.79, 48.03, 50.39, 61.40, 61.55, 61.70, 61.94, 62.27, 62.32, 62.54, 65.70, 68.21, 168.91, 170.37, 170.46, 171.48; exact mass, *m/z* calcd for $C_{15}H_{24}O_6S$ 332.1294, found 332.1292.

Diethyl (3aα, 6aα)-octahydro-3-[(1,1-dimethyl)ethylsulfonyl]pentalene-1,1-dicarboxylate (158b).

The general procedure for radical cyclization was followed using bromides **158** (303 mg, 0.668 mmol) in benzene (60 mL), triphenyltin hydride (355 mg, 1.01 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash column chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane gave **158b** (185 mg, 74%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 8:1 ratio (^{13}C NMR): FT-IR (CCl_4 cast) 2968, 1730, 1460, 1288, 1264, 1182, 1115 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.98 - 1.13 (m, 1 H), (1.26 (m, 7 H), 1.39 (s) and 1.42 (s) [both signals together correspond to 9 H] 1.72 - 1.82 (m, 1.5 H), 1.82 - 1.94 (m, 1.5 H), 2.04 - 2.16 (m, 1 H), 2.40 (dd, J = 5.5, 13.5 Hz, 1 H), 2.74 (t, J = 13.5 Hz, 1 H), 2.88 (q' J = 8.0 Hz, 1 H), 3.23 (q, J = 9.0 Hz, 1 H), 3.44 (ddd, J = 5.5, 8.0, 13.5 Hz, 1 H), 4.12 - 4.28 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.98, 14.09, 14.12, 23.82, 23.89, 24.03, 26.83, 27.32, 28.97, 29.36, 30.60, 32.80, 33.73, 38.61, 44.68, 45.42, 46.68, 48.91, 55.44, 60.68, 61.46, 61.54, 61.70, 61.76, 61.93, 62.17, 62.75, 169.07, 170.0, 171.03, 171.76, (one signal missing or coincident); exact mass, *m/z* [$(M - SO_2C_4H_9)^+$] calcd for $C_{14}H_{21}O_4$ 253.1439, found 253.1429. Anal. Calcd for $C_{18}H_{30}O_6S$: C, 57.73; H, 8.07; S, 8.56. Found: C, 57.51; H, 7.78; S, 8.29.

Diethyl (3aα,7aα)-octahydro-3a-methyl-3-[(1,1-dimethylethyl)sulfonyl]-3*H*-indene-1,1-dicarboxylate (159c).

The general procedure for radical cyclization was followed using bromides **159b** (251 mg, 0.522 mmol) in benzene (55 mL), triphenyltin hydride (278 mg, 0.792 mmol) in benzene (10 mL), and AIBN (10.0 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane afforded two fractions. The thick syrupy material of higher R_f (23.2 mg, 11%) was a single isomer (^{1}H NMR) of **159c**: FT-IR (CCl_4 cast) 2976, 2936, 1732, 1207, 1287, 1271, 1243, 1179, 1116 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.02 - 1.80 (m, 25 H), 2.38 (m, 1 H), 2.65 (dd, J = 5.0, 13.0 Hz, 1 H), 2.84 (dd, J = 10.5, 15.0 Hz, 1 H), 3.08 (dd, J = 8.5, 15.0 Hz, 1 H), 3.75 (dd, J = 10.5, 8.5 Hz, 1 H), 4.02 - 4.35 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.98, 14.06, 20.94, 23.47, 23.70, 24.99, 25.18, 33.84, 34.71, 47.49, 51.02, 56.19, 61.18, 61.86, 61.91, 62.28, 170.61, 171.28; exact mass, *m/z* [$(M - OCH_2CH_3)^+$] calcd for $C_{18}H_{29}O_5S$. 357.1736, found 357.1749

The fraction of lower R_f (183 mg, 87%) was a thick syrup which was a different isomer (^{1}H NMR) of **159c**: FT-IR (CCl_4 cast) 2940, 1726, 1270, 1247, 1115 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.81 - 1.79 (m, 24 H), 1.97 (m, 2 H), 2.28 (dd, J = 7.5, 14.5 Hz, 1 H), 2.63 (m, 1 H), 3.11 (dd, J = 7.5, 13.0 Hz, 1 H), 3.58 (dd, J= 13.0, 14.5 Hz, 1 H), 4.08 - 4.35 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.72, 13.78, 19.92, 20.20, 21.34, 23.47, 24.28, 26.42, 35.84, 46.18, 48.76, 59.16, 60.75, 61.68, 61.79, 63.19, 170.64, 172.65; exact mass, *m/z* calcd. for $C_{20}H_{34}O_6S$ 402.2077, found 402.2075. Anal. Calcd for $C_{20}H_{34}O_6S$: C, 59.67; H, 8.51; S, 7.97. Found: C, 59.81; H, 8.46; S, 8.23.

Diethyl (3aα, 4aβ, 7aβ, 7bα)-decahydro-3-[(1,1-dimethylethyl)sulfonyl]-1*H*-cyclopenta[b]pentalene-1,1-dicarboxylate (160b).

The general procedure for radical cyclization was followed using bromides **160** (276 mg, 0.559 mmol) in benzene (60 mL), triphenyltin hydride (296 mg,.843 mmol) in benzene (10 mL), and AIBN (10.0 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 25% ethyl acetate - hexane gave **160b** (186 mg, 80%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 4.8:1 ratio (^{13}C NMR): FT-IR (CCl_4 cast) 2952, 1729, 1289, 1265, 1250, 1160 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.20 - 1.31 (m, 6 H), 1.38 (s) and 1.40 (s) [both signals together correspond to 9 H], 1.41 - 1.81 (m 6 H), 1.86 (ddd, J = 2.5, 8.5, 10.5 Hz, 1 H), 2.05 (m, 1 H), 2.25 (m, 1 H), 2.41 (dd, J = 13.5 Hz, 1 H), 2.51 (m, 1 H), 2.89 (t, J = 13.0 Hz, 1 H), 2.99 (dd, J = 5.0, 8.0 Hz, 1 H), 3.12 (q', J = 8.0 Hz, 1 H), 3.44 (ddd, J = 5.5, 7.5, 13.0 Hz, 1 H), 4.08 - 4.31 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 14.00, 14.08, 23.44, 23.90, 24.15, 25.54, 25.93, 31.89, 33.19, 33.59, 33.71, 34.16, 34.67, 36.84, 38.43, 43.25, 45.22, 45.96, 46.01, 48.11, 48.36, 48.60, 55.44, 55.79, 57.33, 59.69, 59.73, 60.64, 61.53, 61.63, 61.73, 61.94, 63.26, 63.77, 169.44, 170.42, 170.83, 172.07; exact mass, *m/z* calcd for $C_{21}H_{34}O_6S$ 414.2076, found 414.2122. Anal. Calcd for $C_{21}H_{34}O_6S$: C, 60.84; H, 8.27; S, 7.73. Found: C, 60.90; H, 8.23; S, 7.58.

(3aα, 7aα)-Octahydro-1*H*-indene-1,1,3-tricarboxylic acid, 1,1-diethyl 3-methyl ester (168b).

The general procedure for radical cyclization was followed using bromides **168** (195 mg, 0.481 mmol) in benzene (50 mL), triphenyltin hydride (295 mg, 0.841 mmol) in benzene (10 mL), and AIBN (20 mg, 0.12 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 10% ethyl acetate-hexane gave **168b** (156.0 mg, 99%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 1.4:1 ratio: FT-IR (CCl_4 cast) 3020, 1732, 1249, 1195 1170 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.86 - 1.84 (m, 14 H), 2.22 (dd, J = 4.0, 7.0 Hz, 0.5 H), 2.36 - 2.62 (m, 1.4 H), 2.64 - 2.81 (m, 0.6 H), 2.81 - 3.26 (m, 2.0 H), 3.26 (dd, J = 5.0, 7.0 Hz, 0.5 H), 3.66 (s, 1.7), 3.70 (s, 1.3 H), 4.02 - 4.36 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 13.95, 13.99, 14.06, 20.35, 22.17, 22.57, 23.26, 23.76, 23.96, 24.91, 25.21, 33.95, 34.17, 41.54, 42.84, 43.17, 44.09, 44.94, 45.13, 51.55, 51.70, 61.24, 61.30, 61.41, 61.95, 63.91, 169.83, 170.80, 171.84, 172.44, 174.06, 175.93; exact mass, *m/z* calcd for $C_{17}H_{26}O_6$ 326.1729, found 326. 1722. Anal. Calcd for $C_{17}H_{26}O_6$: C, 62.56; H, 8.03. Found: C, 62.56; H, 7.73.

(3aα, 6aα)-Octahydropentalene-1, 1, 3-tricarboxylic acid, 1,1-diethyl 3-methyl ester ((168b) = 172b).

The general procedure for radical cyclization was followed using bromides **169** (118 mg, 0.30 mmol) in benzene (30 mL), triphenyltin hydride (161 mg, 0.460 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Distillation of the crude product (Kugelrohr 135 ^0C, 0.12 mm) gave **168b** (83.2 mg, 89%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of isomers: ^1H NMR

(CDCl$_3$, 300.0 MHz) δ 1.07 - 1.60 [(m, 8 H, includes two superimposed triplets at δ 1.24 and at δ 1.25, J = 7.5 Hz)], 1.30 - 1.60 (m, 1 H), 1.65 - 1.85 (m, 3 H), 2.17 (dd, J = 3.0, 12.5 Hz, 1 H), 2.49 - 2.71 (m, 1 H), 2.72 - 2.97 (m, 2 H), 3.20 (m, 1 H), 3.66 (s, 0.6 H), 3.68 (s, 2.4 H), 4.17 (m, 4 H). See **172b** below for complete characterization.

(3aα, 6aα)-Octahydropentalene-1, 1, 3-tricarboxylic acid, 1,1-diethyl 3-methyl ester ((172b) = 169b).

The general procedure for radical cyclization was followed using selenides **172** (100 mg, 0.214 mmol) in benzene (30 mL), triphenyltin hydride (130 mg, 0.371 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Flash chromatography of the crude product over silica gel (1 x 15 cm) using 5% ethyl acetate - hexane gave **172b** (53.4 mg, 80%) as a thick syrup which was a chromatographically (TLC) inseparable mixture of two isomers in a 4:1 ratio (^{1}H NMR): FT-IR (CCl$_4$ cast) 1731, 1260, 1250, 1230 cm^{-1}; ^{1}H NMR (CDCl$_3$, 300.0 MHz) δ 1.07 (m, 2 H), 1.24, 1.25 (two superimposed triplets, J = 7.5 Hz, 6 H), 1.30 - 1.60 (m, 1 H), 1.65 - 1.85 (m, 3 H), 2.17 (dd, J = 3.0, 12.5 Hz, 1 H), 2.49 - 2.71 (m, 1 H), 2.72 - 2.97 (m, 2 H), 3.20 (m, 1 H), 3.66 (s, 0.6 H), 3.68 (s, 2.4 H), 4.17 (m, 4 H); ^{13}C NMR (CDCl$_3$, 75.5 MHz) δ (signals due to major isomer only) 14.05, 14.15, 27.09, 30.24, 30.43, 32.76, 44.23, 44.69, 47.55, 51.46, 61.12, 61.43, 62.95, 169.91, 172.03, 173.46; exact mass, *m/z* calcd for $C_{16}H_{24}O_6$ 312.1572, found 312.1575. Anal. Calcd for $C_{16}H_{24}O_6$: C, 61.52; H, 7.74. Found: C, 61.21; H, 7.71.

Aryl Migration Cross-Over Experiment

The general procedure for radical cyclization was not followed in this experiment. Triphenyltin hydride (110 mg, 0.314 mmol) in benzene (5 mL) and AIBN (10 mg, 0.06 mmol) in benzene (5 mL) were added in one portion to a refluxing solution of bromides **146** (53.5 mg, 0.104 mmol) and bromides **131b** (53.9 mg, 0.105 mmol) in benzene (50 mL). The mixture was stirred under reflux for 15 h, cooled, and evaporated. Flash chromatography of the residue over silica gel (1 x 15 cm) using 10% ethyl acetate - hexane gave three fractions. Comparison of 400 MHz ^{1}H NMR spectra for each of the three fractions with that observed from previous, separate cyclization reactions, showed no evidence of crossover products and the ratios of rearranged products versus cyclized products remained the same for each starting compound as in the previous, separate experiments: The oily fraction of highest R_f contained both the rearranged product **146b'** (13.4 mg,[20] 34%, 17% of the total) and the rearranged product **131c'** (23.8 mg,[20] 61%, 30% of the total). The middle fraction (25.5 mg, 56%, 27% of the total) was identified as the cyclized product **146b**. The fraction of lowest R_f (9.0 mg, 19%, 9% of the total) was identified as the cyclized product **131c**.

1,1-Dimethylethyl 4-(1,1-dimethylethyl)cyclohexyl sulfone (165):

(a) **4-(1,1-Dimethylethyl)cyclohexyl methanesulfonate.** Methanesulfonyl chloride (858 mg, 7.70 mmol) was injected dropwise into a magnetically stirred mixture of (1,1-dimethylethyl)cyclohexanol (784 mg, 5.02 mmol) *cis* and *trans* isomers and pyridine (2.00 mL, 25.0 mmol) in dry dichloromethane (25 mL) at -30 °C. Stirring was continued for 1 h and the reaction mixture was then allowed to warm to room temperature over 8 h. The solvent was evaporated and the residue was taken up in ethyl acetate (25 mL), washed with water (1 x 10 mL), dilute HCl (2 x 10 mL, 1 M solution), and brine (1 x 5 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (4 x 15 cm) using 20% ethyl acetate - hexane gave the mesylate (1.098 g, 93%): ^{1}H NMR ($CDCl_3$, 80 MHz) δ 0.68 - 2.30 [m, 18 H (includes a singlet at δ 0.82)], 3.02 (s, 3 H), 4.55 (m, 1 H).

(b) **1,1-Dimethylethyl 4-(1,1-dimethylethyl)cyclohexyl sulfone (165).** 2-Methyl-2-propanethiol (0.41 mL, 3.6 mmol) was added dropwise by syringe to a magnetically stirred solution of sodium (83 mg, 3.61 mmol) in absolute ethanol (20 mL). Stirring was continued for 15 min, and then the above mesylate (845 mg, 3.60 mmol), in ethanol (5 mL), was added slowly. The mixture was refluxed for 72 h, cooled, and evaporated. The residue was taken up in ethyl acetate (50 mL), washed with water (2 x 10 mL), dried ($MgSO_4$), and evaporated. The resulting white solid sulfide (361 mg, 44%) was used directly in the next step. The sulfide had: ^{1}H NMR ($CDCl_3$, 80 MHz) δ 2.40 [m, 27 H (includes singlets at δ 1.00 and at δ 1.50)], 3.25 (m, 1 H).

Hydrogen peroxide (0.62 mL, 30% solution) was added to a stirred solution of the above sulfide (361 mg, 1.58 mmol) in glacial acetic acid (1 mL). The white sulfone precipitated almost immediately. The mixture was stirred at reflux for 2 h and then cooled. Ether was added (20 mL) and the solution was washed with water (3 x 15 mL), dried ($MgSO_4$), and evaporated. The residue was recrystallized twice from ethyl acetate to give **165** (205 mg, 50%) as a white solid: FT-IR (CCl_4 cast) 2940, 1273, 1112, 1070, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.86 (s, 9 H), 0.92 - 1.28 (m, 1 H), 1.41 (s, 9 H), 1.65 (m, 6 H), 2.40 (m, 2 H), 3.40 (m, 1 H); MS (chemical ionization, NH_3), *m/z* 278 (M + 18).

(C) *Trans* Ring-Fused Carbocycles:

The general procedure for radical cyclization is reported on p.136.

(1α, 5α)-1-Prop-2-en-1-yl-3-oxabicyclo[4.3.0]non-7-en-2-one (181).

Lithium diisopropylamide (LDA) was prepared by dropwise addition of *n*-butyllithium (4.71 mL, 1.4 M in hexanes, 6.60 mmol) to a cold (0 °C), stirred solution of diisopropylamine (1.00 mL, 7.14 mmol) in dry THF (20 mL). Stirring was continued for 20 min. The mixture was then cooled to -78 °C and lactone[133] **180** (830 mg, 6.01 mmol) in THF (5 mL + 1 mL rinse) was injected over 10 min. The mixture was stirred for 30 min and then freshly distilled allyl bromide (0.78 mL, 9.0 mmol) was added dropwise. Stirring was continued at -78 °C for 1.5 h and then the dry ice - acetone bath was replaced by an ice bath and the reaction mixture was stirred for an additional 2 h. Saturated aqueous ammonium chloride (10 mL) was added, the mixture was allowed to warm to room temperature and was then extracted with ether (3 x 15 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (2 x 15 cm) using 15% ethyl acetate - hexane gave **181** (961 mg, 89%) as a colorless liquid. An analytical sample was prepared by Kugelrohr distillation (75 - 78 °C, 0.3 mm): FT-IR (CCl_4 cast) 1770, 1175, 1010 cm^{-1};^1H NMR ($CDCl_3$, 200 MHz) δ 1.88 - 2.70 (m, 7 H), 3.87 (t, J = 8.5 Hz, 1 H), 4.26 (dd, J = 7.5, 8.5 Hz, 1 H), 5.08 (m, 2 H), 5.74 (m, 3 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 22.89 (t), 28.91 (t), 36.03 (d), 39.89 (t), 43.60 (s), 70.29 (t), 119.05 (t), 124.58 (d), 124.77 (d), 132.95 (d), 180.98 (s); exact mass, *m/z* calcd for $C_{11}H_{14}O_2$ 178.0994, found 178.0988. Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 73.91; H, 7.93.

Methyl (1α, 6α)-(phenylseleno)methyl-1-(2-propenyl)-3-cyclohexenecarboxlate (182).

The literature procedure for cleavage of lactones using phenyl selenide anion[135] was followed with some alterations: Diphenyl diselenide (468 mg, 1.50 mmol) and sodium hydride (108 mg, 60% in oil, 2.70 mmol) were placed in a 15 mL round-bottomed flask equipped with a serum stopper and argon inlet. Dry THF (5 mL) was injected and the mixture was refluxed for 60 min. The reaction mixture was allowed to cool to room temperature and then freshly distilled HMPA (0.2 mL) was added by syringe followed by lactone **181** (356 mg, 2.00 mmol) in THF (1 mL + 1 mL rinse). The reaction mixture was refluxed for 11.5 h, cooled, and then methanol (1 mL) was added. The solvents were removed by evaporation and the residue was taken up in water (10 mL), extracted with ether (3 x 10 mL). The aqueous solution was acidified with 10% hydrochloric acid and re-extracted with ether (3 x 10 mL). The extracts were combined, dried ($MgSO_4$), and cooled to 0 °C. Freshly prepared diazomethane in ether was added dropwise until no further reaction could be detected by TLC. The ether and excess of diazomethane were evaporated and flash chromatography the crude methyl ester **182** using 2% ethyl acetate - hexane, and then an increasingly more polar solvent mixture (up to 20% ethyl acetate) gave **182** (516 mg, 74%) as a colorless oil: FT-IR ($CHCl_3$ cast) 1732, 1435, 1214, 1100 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.96 - 1.45 (m, 7 H), 2.74 (m, 2 H), 3.55 (s, 3 H), 4.97 (m, 2 H), 5.56 (m, 3 H), 7.20 (m, 3 H), 7.45 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 26.41 (t), 27.39 (t), 30.48 (t), 39.53 (d), 40.65 (t), 49.61 (s), 51.96 (q), 118.76 (t), 124.32 (d), 124.86 (d), 127.30 (d), 129.43 (d), 130.97 (s), 133.16 (d), 133.79 (d), 176.39 (s); exact mass, m/z calcd for $C_{18}H_{22}O_2Se$ 350.0785, found 350.0791. Anal. Calcd for $C_{18}H_{22}O_2Se$: C, 61.89; H, 6.34; O, 9.16. Found: C, 62.11; H, 6.34; O, 9.07.

Methyl (3aα, 7aβ)-1, 2, 3, 4, 7, 7a,-hexahydro-2-methyl-3a*H*-indene-3a-carboxylate (183).

The general procedure for radical cyclization was followed using selenide **182** (350 mg, 1.00 mmol) in benzene (50 mL), triphenyltin hydride (557 mg, 1.58 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Kugelrohr distillation (55 °C, 0.2 mm) of the crude product gave **183** (179 mg, 92%) as a colorless oil which was a chromatographically (TLC) inseparable mixture of two isomers in a 10:5:1 ratio (^{13}C NMR): FT-IR (CCl_4 cast) 2950, 1730, 1194, 1174 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.95 - 1.12 (m, 1 H), 1.02 (d, J = 6.0 Hz, 3 H), 1.38 (m, 1 H), 1.80 - 2.10 (m, 3 H), 2.10 -2.36 (m, 4 H), 2.67 - 2.90 (m, 1 H), 3.61 (s) and 3.63 (s) [both signals together correspond to 3 H], 5.62 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ (signals assigned to major isomer) 22.91 (q), 28.71 (t), 30.39 (d), 36.80 (t), 37.04 (t), 43.74 (d), 46.80 (t), 51.25 (q), 52.99 (s), 125.88 (d), 128.06 (d), 176.35 (s); (signals assigned to minor isomer) δ 22.03 (q), 25.19 (d), 28.38 (t), 31.18 (d), 37.55 (t), 38.06 (t), 44.82 (t), 46.14 (q), 126.06 (d), 128.75 (d), (both singlets missing or coincident with major isomer); exact mass, m/z [(M - H)$^+$] calcd for $C_{12}H_{17}O_2$ 193.1228, found 193.1223. Anal. Calcd for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.54; H, 9.35.

Methyl (3aα, 7aβ)-1, 2, 3, 4, 7, 7a-hexahydro-2-(phenylmethylene)-3a*H*-indene-3a-carboxylate (184):

(a) **(1α, 5α)-1-(3-phenyl-2-propynyl)-3-oxabicyclo[4.3.0]non-7-en-2-one.** The procedure employed for **181** was followed using *n*-butyllithium (2.40 mL, 1.4 M in hexanes, 3.36 mmol), diisopropylamine (0.52 mL, 3.70 mmol) in THF (20 mL), lactone[133] **180** (419 mg, 3.03 mmol) in THF (4 mL + 1 mL rinse), and phenyl propargyl bromide[134] (878 mg, 4.50 mmol) in THF (4 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 10% ethyl acetate - hexane gave **184a** (728 mg, 95%) as a white solid. An analytical sample was prepared by recrystallization from dichloromethane - hexane: mp 79 °C; FT-IR (CCl_4 cast) 1763, 1490, 1160, 995 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.92 - 2.20 (m, 2 H), 2.38 (m, 2 H), 2.60 - 2.90 (m, 2 H), 2.98 (m, 1 H), 3.88 (t, J = 8.0 Hz, 1 H), 4.34 (t, J = 8.0 Hz , 1 H), 5.75 (m, 2 H), 7.22 (m, 3 H), 7.32 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 23.29 (t), 26.67 (t), 28.98 (t), 36.55 (d), 44.21 (s), 70.65 (t), 83.31 (s), 85.02 (s), 123.16 (s), 124.74 (d), 125.00 (d), 128.09 (d), 128.27 (d), 131.70 (d), 180.29 (s); exact mass, *m/z* calcd for $C_{17}H_{16}O_2$ 252.1150, found 252.1155. Anal. Calcd for $C_{17}H_{16}O_2$: C, 80.93; H, 6.39. Found: C, 80.77; H, 6.32.

(b) **Methyl (1α, 6α)-6-(phenylseleno)methyl-1-(3-phenyl-2-propynyl)-3-cyclohexenecarboxylate.** The procedure employed for **182** was followed using diphenyl-diselenide (468 mg, 1.50 mmol), sodium hydride (108 mg, 60% in oil, 2.70 mmol), HMPA (0.20 mL), and lactone **184a** (502 mg, 1.99 mmol). Flash chromatography of the crude product over silica gel (2 x 15 cm) using 5% ethyl acetate gave **184b** (699 mg, 83%) as a colorless syrup which solidified on cooling: mp 52 °C; FT-IR (CCl_4 cast) 1734, 1488, 1478, 1436, 1204, 1290 1059, 756, 736, 691 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.13 - 2.97 (m, 9 H), 3.60 (s, 3 H), 5.57 (m, 2 H), 7.19 (m, 8 H), 7.42 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 26.16 (t), 27.00 (t), 28.10 (t), 29.80 (t), 38.64 (d), 49.35 (s), 51.95 (q), 83.22 (s), 85.58 (s), 123.47 (s), 123.95 (d), 124.50 (d), 126.93 (d), 127.86 (d), 128.20 (d), 129.04 (d), 130.32 (s), 131.67 (d), 132.77 (d), 175.11 (s); exact mass, *m/z* calcd for $C_{24}H_{24}O_2Se$ 424.0941, found 424.0934. Anal. Calcd for $C_{24}H_{24}O_2Se$: C, 68.08; H, 5.71; O, 7.56. Found: C, 68.12; H, 5.70; O, 7.49.

(c) **Methyl (3aα, 7aβ)-1, 2, 3, 4, 7, 7a-hexahydro-2-(phenylmethylene)-3a*H*-indene-3a-carboxylate (184).** The general procedure for radical cyclization was followed using selenide **184b** (117 mg, 0.276 mmol) in benzene (40 mL), triphenyltin hydride (116 mg, 0.331 mmol) in benzene (10 mL), and AIBN (5 mg, 0.03 mmol) in benzene (10 mL). The residue was Kugelrohr distilled (90 °C, 0.100 mm) three times to afford **184** (54 mg, 73%) as a colorless oil which was a chromatographically (TLC) inseparable mixture of two isomers in a 1:1 ratio (^{1}H NMR): FT-IR (CCl_4 cast) 1728, 1440, 1205, 1192, 1174 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.94 - 3.15 (m, 9 H), 3.54 (s, 1.5 H), 3.60 (s, 1.5 H), 5.67 (m, 2 H), 6.30 (m, 1 H), 7.04 - 7.34 (m, 5 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 28.10 (t), 28.38 (t), 35.47 (t), 36.17 (t), 36.69 (t), 38.51 (t), 43.35 (t), 43.68 (d), 45.13 (d), 47.33 (t), 50.51 (s), 51.50 (q), 52.05 (s), 122.38 (d), 122.69 (d), 125.93 (d), 125.98 (d), 127.83 (d), 127.91 (d), 128.05 (d), 128.23 (d), 138.43 (s), 138.48 (s), 142.72 (s), 142.60 (s), 175.62 (s), 175.68 (s), [one OMe (s) signal and four aromatic methines (d) signals all missing or coincident]; exact mass, *m*/*z* calcd for $C_{18}H_{20}O_2$ 268.1463, found 268.1463.

(1α, 5α)-5-Methyl-1-(3-phenyl-2-propynyl)-3-oxabicyclo[4.3.0]nonan-2-one (188).

The procedure employed for **181** was followed using *n*-butyllithium (2.40 mL, 1.4 M in hexanes, 3.36 mmol), diisopropylamine

(0.52 mL, 3.70 mmol) in THF (15 mL), lactone[111] **187** (470 mg, 3.05 mmol) in THF (4 mL + 1 mL rinse), and phenyl propargyl bromide[134] (875 mg, 4.49 mmol) in THF (4 mL + 1 mL rinse). Flash chromatography of the crude product over silica gel (2 x 15 cm) twice, using 10% ethyl acetate - hexane afforded **188** (742 mg, 90%) as a white solid: mp 40 ^{0}C; FT-IR (CCl_4 cast) 1772, 1510, 1440, 1140, 1090, 1012 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.20 (s, 3 H), 1.22 - 1.82 (m, 7 H), 2.05 (m, 1 H), 2.57 (d, J = 1.0 Hz, 2 H), 3.88 (d, J = 8.5 Hz, 1H), 4.14 (d, J = 8.5 Hz, 1 H), 7.21 (m, 3 H), 7.32 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 18.67 (q), 21.38 (t), 22.80 (t), 25.17 (t), 29.69 (t), 35.59 (t), 41.07 (s), 48.55 (s), 75.90 (t), 83.54 (s), 85.47 (s), 123.25 (s), 128.00 (d), 128.24 (d), 131.49 (d), 179.45 (s); exact mass, *m/z* calcd for $C_{18}H_{20}O_2$ 268.1463, found 268.1453. Anal. Calcd for $C_{18}H_{20}O_2$: C, 80.56; H, 7.51. Found: C, 80.67; H, 7.68.

REFERENCES

(1) Julia, M. *Rec. Chem. Prog.* **1964**, *25*, 2. Julia, M. *Acc. Chem. Res.* **1971**, *4*, 386.

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

(3) Büchi, G.; Wüest, H. *J. Org. Chem.* **1979**, *44*, 546.

(4) Curran, D. P. *Synthesis* **1988**, 417. Curran, D. P. *Ibid.* **1988**, 489. Ramaiah, M. *Tetrahedron* **1987**, *43*, 3541. Hart, D. J. *Science* **1984**, *223*, 883.

(5) The 5-hexenyl radical was first generated in the gas phase by mercury-sensitized photolysis of cyclohexane: Arai, S.; Sato, O.; Shida, S. *J. Chem. Phys.* **1960**, *33*, 1277. It was first generated in solution in 1963 by pyrolysis of 6-heptenoyl peroxide: Lamb, R. C.; Ayers, P. W.; Toney, M. K. *J. Am. Chem. Soc.* **1963**, *85*, 3483.

(6) Beckwith, A. L. J.; Ingold, K. U. In "Rearrrangements in Ground and Excited States" DeMayo, P., Ed.; Academic Press: New York, 1980; Vol. 2, p. 161. Surzur, J.-M. In "Reactive Intermediates" Abramovich, A. A., Ed.; Plenum Press: New York, 1981; Vol. 2, Ch. 3. Beckwith, A. L. J. *Tetrahedron* **1981**, *37*, 3073. Griller, D.; Ingold, K. U. *Acc. Chem. Res.* **1980**, *13*, 317.

(7) (a) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron* **1985**, *41*, 3925.
(b) Beckwith, A. L. J. *Tetrahedron* **1981**, *37*, 3073.

(8) Baldwin, J. E. *J. Chem. Soc., Chem. Commun.* **1976**, 734.

(9) Eliel, E. L.; Allinger, N. L.; Angyal, S. J.; Morrison, G. A. "Conformational Analysis" Wiley Interscience: New York, 1965; p.191.

(10) Beckwith, A. L. J.; Lawrence, T. *J. Chem.Soc., Perkin Trans. II* **1979**, 1535.

(11) (a) Choi, J.-K.; Hart, D. J. *Tetrahedron* **1985**, *41*, 3959. (b) Burnett, D. A.; Choi, J.-K.; Hart, D. J.; Tsai, Y.-M. *J. Am. Chem. Soc.* **1984**, *106*, 8201. (c) Hart, D. J.; Tsai, Y.-M. *Ibid.* **1984**, *106*, 8209. (d) Hart, D. J.; Tsai, Y.-M. *J. Org. Chem.* **1982**, *47*, 4403. (e) Hart, D. J.; Tsai, Y.-M. *J. Am. Chem. Soc.* **1982**, *104*, 1430. (f) Choi, J.-K.; Hart, D. J.; Tsai, Y.-M. *Tetrahedron Lett.* **1982**, *23*, 4765.

(12) Corey, E. J.; Mehrotra, M. M. *Tetrahedron Lett.* **1988**, *29*, 57.

(13) Keck, G. E.; Enholm, E. J. *Tetrahedron Lett.* **1985**, *26*, 3311.

(14) (a) Kano, S.; Yuasa, Y.; Asami, K.; Shibuya, S. *Chem. Lett.* **1986**, 735. (b) Kano, S.; Yuasa, Y.; Yokomatsu, T.; Asami, K.; Shibuya, S. *J. Chem. Soc., Chem. Commun.*, **1986**, 1717.

(15) Sacripante, G.; Tan, C.; Just, G. *Tetrahedron Lett.* **1985**, *26*, 5643.

(16) (a) Padwa, A.; Nimmesgern, H.; Wong, G. S. K. *J. Org. Chem.* **1985**, *50*, 5620. (b) Clive, D. L. J.; Mohammed, A. Y. *Heterocycles*, **1988**, in press.

(17) Ueno, Y.; Chino, K.; Okawara, M. *Tetrahedron Lett.* **1982**, *23*, 2575.

(18) Jones, K.; Thompson, M.; Wright, C. *J. Chem. Soc., Chem. Commun.* **1986**, 115. Dittami, J. P.; Ramanathan, H. *Tetrahedron*

Lett. **1988**, *29*, 45. Togo, H.; Kikuchi, O. *Tetrahedron Lett.* **1988**, *29*, 4133.

(19) Boger, D. L.; Coleman, R. S. *J. Am. Chem. Soc.* **1988**, *110*, 4796.

(20) Danishefsky, S. J.; Panek, J. S. *J. Am. Chem. Soc.* **1987**, *109*, 917.

(21) Kametani, T.; Honda, T. *Heterocycles* **1982**, *19*, 1861.

(22) Beckwith, A. L. J.; Boate, D. R. *Tetrahedron Lett.* **1985**, *26*, 1761.

(23) Bachi, M. D.; Frolow, F.; Hoornaert, C. *J. Org. Chem.* **1983**, *48*, 1841.

(24) (a) Kametani, T.; Chu, S.-D.; Itoh, A.; Maeda, S.; Honda, T. *J. Org. Chem.* **1988**, *53*, 2683. Kametani, T.; Chu, S.-D.; Itoh, A.; Maeda, S.; Honda, T. *Heterocycles* **1988**, *27*, 875. (b) Knight, J.; Parsons, P. J. *J. Chem. Soc., Perkin Trans. I* **1987**, 1237. Knight, J.; Parsons, P. J.; Southgate, R. *J. Chem. Soc., Chem. Commun.* **1986**, 78. (c) Just, G.; Sacripante, G. *Can. J. Chem.* **1987**, *65*, 104.

(25) Bachi, M. D.; DeMesmaeker, A.; Stevenart-DeMesmaeker, N. *Tetrahedron Lett.* **1987**, *28*, 2637. see also Bachi, M. D.; DeMesMaeker, A.; Stevenart-DeMesMaeker, N. *Tetrahedron Lett.* **1987**, *28*, 2887. Bachi, M. D.; Hoornaert, C. *Ibid.* **1981**, *22*, 2689. Bachi, M. D.; Hoornaert, C. *Ibid.* **1981**, *22*, 2693.

(26) (a) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron Lett.* **1985**, *26*, 375. Beckwith, A. L. J.; Schiesser, C. H. *Ibid.* **1985**, *26*, 373.

(27) For example: Ueno, Y.; Chino, K.; Watanabe, M.; Moriya, O.; Okawara, M. *J. Am. Chem. Soc.* **1982**, *104*, 5564. Ueno, Y.;

Moriya, O.; Chino, K.; Watanabe, M.; Okawara, M. *J. Chem. Soc. Perkin Trans. I* **1986**, 1351.

(28) Stork, G.; Mook, R., Jr.; Biller, S. A.; Rychnovsky, S. D. *J. Am. Chem. Soc.* **1983**, *105*, 3741.

(29) Moriya, O.; Okawara, M.; Ueno, Y. *Chem. Lett.* **1984**, 1437.

(30) Clive, D. L. J.; Beaulieu, P. L. *J. Chem. Soc., Chem. Commun.* **1983**, 307.

(31) (a) Pezechk, M.; Brunetiere, A. P.; Lallemand, J. Y. *Tetrahedron Lett.* **1986**, *27*, 3715. (b) Srikrishna, A. *J. Chem. Soc., Chem. Commun.* **1987**, 587. Srikrishna, A.; Pullaiah, K. C. *Tetrahedron Lett.* **1987**, *28*, 5203. Srikrishna, A.; Sunderbabu, G. *Ibid.* **1987**, *28*, 6393. (c) Ardisson, J.; Férézou, J. P.; Julia, M.; Pancrazi, A. *Ibid.* **1987**, *28*, 2001. (d) Dulcere, J. P.; Rodriguez, J.; Santelli, M.; Zahra, J. P. *Ibid.* **1987**, *28*, 2009. Dulcere, J. P.; Mihoubi, M. N.; Rodriguez, J. *J. Chem. Soc., Chem. Commun.* **1988**, 237. (e) Stork, G.; Krafft, M. E.; Biller, S. A. *Tetrahedron Lett.* **1987**, *28*, 1035. (f) Ariamala, G.; Balasubramanian, K. K. *Ibid.* **1988**, *29*, 3335. (g) Haaima, G.; Weavers, R. T. *Ibid.* **1988**, *29*, 1085. (h) Hutchinson, J. H.; Pattenden, G.; Meyers, P. L. *Tetrahedron Lett.* **1987**, *28*, 1313. Begley, M. J.; Ladlow, M.; Pattenden, G. *J. Chem. Soc., Perkin Trans. I* **1988**, 1095. (i) McDonald, C. E.; Dugger, R. W. *Tetrahedron Lett.* **1988**, *29*, 2413. (j) Kim, M.; Gross, R. S.; Sevestre, H.; Dunlap, N. K.; Watt, D. S. *J. Org. Chem.* **1988**, *53*, 93.

(32) (a) Ladlow, M.; Pattenden, G. *Tetrahedron Lett.* **1984**, *25*, 4317. (b) Bhandal, H.; Pattenden, G.; Russell, J. J. *Ibid.* **1986**, *27*, 2299. Begley, M. J.; Bhandal, H.; Hutchinson, J. H.; Pattenden, G. *Ibid.* **1987**, *28*, 1317. Morikawa, T.; Nishiwaki, T.; Iitaka, Y.; Kobayashi, Y. *Ibid.* **1987**, *28*, 671.

(33) (a) Stork, G.; Sher, P. M. *J. Am. Chem., Soc.* **1983**, *105*, 6765. (b) Stork, G.; Kahn, M. *Ibid.* **1985**, 107, 500. (c) Stork, G.; Sher, P. M. *Ibid.* **1986**, *108*, 303. (d) Stork, G.; Sher, P. M.; Chen, H.-L. *Ibid.* **1986**, *108*, 6384.

(34) Keck, G. E..; Burnett, D. A. *J. Org. Chem.* **1987**, *52*, 2960.

(35) (a) Moriya, O.; Kakihana, M.; Urata, Y.; Sugizaki, T.; Kageyama, T.; Ueno, Y.; Endo, T. *J. Chem. Soc., Chem. Commun.* **1985**, 1401. Abeywickrema, A. N.; Beckwith, A. L. J. *J. Chem. Soc., Chem. Commun.* **1986**, 464. (b) Meijs, G. F.; Beckwith, A. L. J. *J. Am. Chem. Soc.* **1986**, *108*, 5890. Beckwith, A. L. J.; Meijs, G. F. *J. Org. Chem.* **1987**, *52*, 1922. Abeywickrema, A. N.; Beckwith, A. L. J.; Gerba, S. *Ibid.* **1987**, *52*, 4072. (c) Ahmad-Junan, S. A.; Whiting, D. A. *J. Chem. Soc., Chem. Commun.* **1988**, 1160. (d) Gopalsamy, A.; Balasubramanian, K. K. *Ibid.* **1988**, 28. (e) Parker, K. A.; Spero, D. M.; Inman, K. C. *Tetrahedron Lett.* **1986**, *27*, 2833. Parker, K. A.; Spero, D. M.; Van Epp, J. *J. Org. Chem.* **1988**, *53*, 4628. (f) Hanessian, S.; Beaulieu, P.; Dubé, D *Tetrahedron Lett.* **1986**, *27*, 5071. (g) Ihara, M.; Taniguchi, N.; Fukumoto, K.; Kametani, T. *J. Chem. Soc., Chem. Commun.* **1987**,

1438. (h) Shankaran, K.; Sloan, C. P.; Snieckus, V. *Tetrahedron Lett.* **1985,** *26,* 6001.

(36) Snieckus, V. "Lectures in Heterocyclic Chemistry", Castle, T. N., Ed.; Heterocorp: Tampa, Fl., 1984; p. 95. Beak, P.; Snieckus, V. *Acct. Chem. Res.* **1982,** *15,* 306.

(37) Miscellaneous radical cyclization routes to heterocycles: Middleton, D. S.; Simpkins, N. S. *Tetrahedron Lett.* **1988,** *29,* 1315. Ladlow, M.; Pattenden, G. *J. Chem. Soc., Perkin Trans. I* **1988,** 1107. Singh, A. K.; Baskshi, R. K.; Corey, E. J. *J. Am. Chem. Soc.* **1987,** *109,* 6187. Degueil-Castaing, M.; DeJeso, B.; Kraus, G. A.; Landgrebe, K.; Maillard, B. *Tetrahedron Lett.* **1986,** *27,* 5927. Beckwith, A. L. J.; Pigou, P. E. *J. Chem. Soc., Chem. Commun.* **1986,** 85. Kraus, G. A.; Landgrebe, K. *Tetrahedron Lett.* **1984,** *25,* 3939. Ueno, Y.; Khare, R. K.; Okawara, M. *J. Chem. Soc., Perkin Trans. I* **1983,** 2637.

(38) (a) Boger, D. L.; Mathvink, R. J. *J. Org. Chem.* **1988,** *53,* 3377. (b) Bachi, M. D.; Bosch, E. *Tetrahedron Lett.* **1986,** *27,* 641.

(39) Porter, N. A.; Chang, V. H.-T. *J. Am. Chem. Soc.* **1987,** *109,* 4976. Porter, N. A.; Magnin, D. R.; Wright, B. T. *Ibid.* **1986,** *108,* 2787. See also: Nicolaou, K. C.; McGarry, D. G.; Somers, P. K.; Veale, C. A.; Furst, G. T. *Ibid.* **1987,** *109,* 2504.

(40) Stork, G.; Mook, R., Jr. *J. Am. Chem. Soc.* **1987,** *109,* 2829.

(41) (a) Stork, G.; Mook, R., Jr. *J. Am. Chem. Soc.* **1983,** *105,* 3720. (b) Stork, G.; Reynolds, M. E. *J. Am. Chem. Soc.* **1988,** *110,* 6911.

(42) Mook, R., Jr.; Sher, P. M. *Org. Syn.* **1987**, *66*, 75.

(43) Broka, C. A.; Reichert, D. E. C. *Tetrahedron Lett.* **1987**, *28*, 1503.

(44) Nozaki, K.; Oshima, K.; Utimoto, K. *J. Am. Chem. Soc.* **1987**, 109, 2547.

(45) Hanessian, S.; Dhanoa, D. S.; Beaulieu, P. L. *Can J. Chem.* **1987**, *65*, 1859.

(46) Harris, F. L.; Weiler, L. *Tetrahedron Lett.* **1987**, *28*, 2941.

(47) Wilcox, C. S.; Thomasco, L. M. *J. Org. Chem.* **1985**, *50*, 546. Wilcox, C. S.; Gaudino, J. J. *J. Am. Chem. Soc.* **1986**, *108*, 3102.

(48) RajanBabu, T. V. *J. Am. Chem. Soc.* **1987**, *109*, 609. RajanBabu, T. V. *J. Org. Chem.* **1988**, *53*, 4522.

(49) Hashimoto, H.; Furuichi, K.; Miwa, T. *J. Chem. Soc., Chem. Commun.* **1987**, 1002.

(50) Bartlett, P. A.; McLaren, K. L.; Ting, P. C. *J. Am. Chem. Soc.* **1988**, *110*, 1633.

(51) Stork, G.; Mook, R., Jr. *Tetrahedron Lett.* **1986**, *27*. 4529. Stork, G.; Baine, N. H. *J. Am. Chem. Soc.* ***1982***, *104*, 2321.

(52) Stork, G.; Baine, N. H. *Tetrahedron Lett.* **1985**, *26*, 5927.

(53) Beckwith, A. L. J.; O'Shea, D. M. *Tetrahedron Lett.* **1986**, *27*, 4525.

(54) Marinovic, N. N.; Ramanathan, H. *Tetrahedron Lett.* **1983**, *24*, 1871.

(55) Curran, D. P.; Chen, M.-H.; Kim, D. *J. Am. Chem. Soc.* **1986**, *108*, 2489. Curran, D. P.; Chang, C.-T. *Tetrahedron Lett.* **1987**, *28*, 2477.

Curran, D. P.; Kim, D.; Liu, H. T.; Shen, W. *J. Am. Chem. Soc.* **1988**, *110*, 5900.

(56) (a) Clive, D. L. J.; Cheshire, D. R.; Set. L. *J. Chem. Soc., Chem. Commun.* **1987**, 353. (b) Chuang, C.-P.; Hart, D. J. *J. Org. Chem* **1983**, *48*, 1782. Chenera, B.; Chuang, C.-P.; Hart, D. J.; Hsu, L.-Y. *Ibid.* **1985**, *50*, 5409. Chuang, C.-P.; Gallucci, J. D.; Hart, D, J. *Ibid.* **1988**, *53*, 3210. Chuang, C.-P.; Gallucci, J. D.; Hart, D. J.; Hoffman, C. *Ibid.* **1988**, *53*, 3218. (c) Hart, D. J.; Huang, H.-C. *Tetrahedron Lett* **1985**, *26*, 3749. Hart, D. J.; Huang, H.-C. *J. Am. Chem. Soc.* **1988**, 110, 1634. (d) Beckwith, A. L. J.; Roberts, D. H. *Ibid.* **1986**, *108*, 5893. (e) Clive, D. L. J.; Beaulieu, P. L.; Set, L.; *J. Org. Chem.* **1984**, *49*, 1313. (f) Mohammed, A. Y.; Clive, D. L. J. *J. Chem. Soc., Chem. Commun.* **1986**, 588. Clive, D. L. J.; Cheshire, D. R. *Ibid.* **1987**, 1520. (g) Clive, D. L. J.; Boivin, T. L. B. Boivin; Angoh, A. G. *J. Org. Chem.* **1987**, *52*, 4943. (h) Clive D. L. J.; Boivin, T. L. B. in press, *J. Org. Chem.* **1988**.

(57) Leonard, W. R.; Livinghouse, T. *Tetrahedron Lett.* **1985**, *26*, 6431.

(58) (a) Set, L.; Cheshire, D. R.; Clive, D. L. J. *J. Chem. Soc., Chem. Commun.* **1985**, 1205. Clive, D. L. J; Bennett, S. M. *Ibid.* **1986**, 878. (b) Clive, D. L. J.; Angoh, A. G.; Bennett, S. M. *J. Org. Chem.* **1987**, *52*, 1339.

(59) Curran, D. P.; Rakiewicz, D. M. *Tetrahedron,* **1985**, *41*, 3943. Curran, D. P.; Chen, M.-H. *Tetrahedron Lett.* **1985**, *26*, 4991. Curran, D. P.; Rakiewicz, D. M. *J. Am. Chem. Soc.* **1985**, *107*, 1448.

Curran, D. P.; Kuo, S.-C. *Ibid.* **1986**, *108*, 1106. Fevig, T. L.; Elliot, T. L.; Curran, D. P. *Ibid.* **1988**, *110*, 5064.

(60) Gnosh, T.; Hart, H. *J. Org. Chem* **1988**, *53*, 2396.

(61) Parsons, P. J.; Willis, P. A.; Eyley, S. C. *J. Chem. Soc., Chem. Commun.* **1988**, 283.

(62) Tsang, R.; Fraser-Reid, B. *J. Am. Chem. Soc.* **1986**, *108,* 2116.

(63) Winkler, J. D.; Sridar, V. *J. Am. Chem.* Soc. **1986**, *108*, 1708. *cf.* Porter, N. A.; Chang, V. H.-T.; Magnin, D. R.; Wright, B. T. *Ibid.* **1988**, *110,* 3554.

(64) Some miscellaneous radical cyclization routes to carbocycles: Barton, D. H. R.; daSilva, E.; Zard, S. Z. *J. Chem. Soc., Chem. Commun.* **1988**, 285. Wehle, D.; Fitjer, L. *Angew. Chem. Int. Ed. Engl.* **1987**, *26*, 130. Suzuki, M.; Koyano, H.; Noyori, R. *J. Org. Chem.* **1987**, *52*, 5583. Ziegler, F. E.; Zheng, Z.-L. *Tetrahedron Lett.* **1987**, *28*, 5973. Dowd, P.; Choi, S.-C. *J. Am. Chem. Soc.* **1987**, *109*, 6548. Urabe, H.; Kuwajima, I. *Tetrahedron Lett.* **1986**, *27*, 1355. Cekovic, Z.; Saicic, R. *Ibid.* **1986**, *27*, 5893. Kulkarni, Y. S.; Snider, B. B. *Ibid.* **1985**, *26*, 5675.

(65) (a) Angoh, A. G.; Clive, D. L. J. *J. Chem. Soc., Chem. Commun.* **1985**, 941. (b) Angoh, A. G. University of Alberta Thesis, 1985.

(66) *Cf.* (a) Madsen, J. O.; Lawesson, S.-O. *Bull. Soc. Chim. Belg.* **1976**, *85*, 805. (b) Cook, A. G. *Enamines: Synthesis, Structure and Reactions;* Marcel Dekker: New York, 1969, p. 16.

(67) Janousek, Z.; Piettre, S.; Gorissen-Hervens, F.; Viehe, H.G. *J. Organomet. Chem.* **1983**, *250*, 197.

(68) Piettre, S.; Janousek, Z.; Merenyi, R.; Viehe, H.G. *Tetrahedron* **1985**, *41*, 2527.

(69) Carlier, P.; Gelas-Mialhe, Y.; Vessiere, R. *Can. J. Chem.* **1977**, *55*, 3190.

(70) Stork, G.; Brizzolara, A.; Landesman, H.; Szmuszkovicz, J.; Terrell, R. *J. Am. Chem. Soc.* **1963**, *85*, 207. Barieux, J.-J.; Gore, J. *Bull. Soc. Chim. Fr.* **1971**, 1649.

(71) For a discussion of the stereoselectivity of enamine reactions, see: Hickmott, P. W. *Tetrahedron* **1982**, *38*, 1975. Hickmott, P. W. *Ibid.* **1982**, *38*, 3363.

(72) R = SiR'_3 is not ideal: Büchi, G.; Wüest, H. *J. Am. Chem. Soc.* **1978**, *100*, 294.

(73) Crandall, J. K.; Michaely, W. J. *J. Org. Chem.* **1984**, *49*, 4244.

(74) Ohnuki, T.; Yoshida, M.; Simamura, O. *Chem. Lett.* ***1972***, 797.

(75) Evans, D. A.; Truesdale, L. K.; Carroll, G. L. *J. Chem. Soc., Chem. Commun.,* **1973**, 55.

(76) 5-*exo* closure of a radical onto a nitrile triple bond is slower than onto a terminal acetylene: Griller, D.; Schmid, P.; Ingold, K. U. *Can. J. Chem.* **1979**, *57*, 831.

(77) Ashby, E. C.; Laemmle, J. T. *Chem. Rev.* **1975**, *75*, 521.

(78) Trost, B. M.; Florez, J.; Jebaratnam, D. J. *J. Am. Chem. Soc.* **1987**, *109*, 613. Stork, G.; Stryker, J. M. *Tetrahedron Lett.* **1983**, *24*, 4887.

(79) Beckwith, A. L. J.; Roberts, D. H.; Schiesser, C. H.; Wallner, A. *Tetrahedron Lett.* **1985,** *26,* 3349.

(80) Clive, D. L. J.; Chittattu, G. J.; Farina, V.; Kiel, W. A.; Menchen, S. M.; Russell, C. G.; Singh, A.; Wong, C. K.; Curtis, M. J. *J. Am. Chem. Soc.* **1980,** *102,* 4438.

(81) The chemical shift of the vinylic proton in 1-phenylcyclohexene is δ 6.0 ($CDCl_3$): Yamamoto, H.; Miura, M.; Nojima, M.; Kusabayashi, S. *J. Chem. Soc., Perkin Trans. I* **1986**, 173. In benzylidenecyclopentane it is δ 6.34 ($CDCl_3$): Moore, W. M.; Salajegheh, A.; Peters, D. G. *J. Am. Chem. Soc.* **1975,** *97*, 4954.

(82) (a) Corey, E.J.; Chaykovsky, M. *J. Am. Chem. Soc.* **1965,** *87*, 1344. (b) Trost, B. M.; Arndt, H. C.; Strege, P. E. Verhoeven, T. R. *Tetrahedron Lett.* **1976,** *39*, 3477.

(83) Cis ring fusion was observed here: Beckwith, A. L. J.; O'Shea, D. M.; Roberts, D. H. *J. Chem. Soc., Chem. Commun.* ***1983***, 1445.

(84) Eg., Trost, B. M.; Rise, F. *J. Am. Chem. Soc.* **1987,** *109*, 3161. Trost, B. M.; Jebaratnam, D. J. *Tet. Lett.* **1987,** *28*, 1611.

(85) Kupchik, E. J. In "Organotin Compounds" Sawyer, A. K., Ed.; Marcel Dekker; **1971**; Vol. 1, p. 49.

(86) Spencer, T. A.; Newton, M. D.; Baldwin, S. W. **1964**, 787.

(87) Moffett, R.B. *Org. Synth.* **1963,** *Coll. Vol 4,* 291.

(83) House, H. O. *Modern Synthetic Reactions;* W. A. Benjamin, Inc.: Menlo Park, California, **1972**, pp. 595 - 623 and references therein.

(89) White, D. A.; Baizer, M. M. *Tetrahedron Lett.* **1973**, 3597.

(90) (a) Salomon, M.F.; Pardo, S.N.; Salomon, R.G. *J. Org. Chem.* **1984,** *49*, 2446. (b) Salomon, M.R.; Pardo, S.N.; Salomon, R.G. *J. Am. Chem. Soc.* **1984,** *106*, 3797. (c) Pardo, S.N.; Ghosh, S.; Salomon, R.G. *Tetrahedron Lett.* **1981,** *22*, 1885. In the deoxygenation step of Scheme 2 of this reference, Li/NH_3 should be used; in our hands the procedure reported in Table 1 of ref 90c did not work.

(91) Paquette, L. A.; Doherty, A. M. *Polyquinane Chemistry*; Springer-Verlag: Germany, **1987**.

(92) Stapp, P. R.; Kleinschmidt, R. F. *J. Org. Chem.* **1965,** *30*, 3006.

(93) Paquette, L.A.; Carr, R.V.C. *Org. Synth.* **1985,** *64*, 157.

(94) McDowell, S. T.; Stirling, C. J. M. *J. Chem. Soc, B* **1967**, 348.

(95) Trost, B.; Curran, D. P. *Tetrahedron Lett.* **1981**, 1287.

(96) Purrington, S. T.; Glenn, A. G. *Org. Prep. and Proc. Int.* **1985**, *17*, 227.

(97) Tanner, D. D.; Kharrat, A. *J. Org. Chem.* **1988,** *53*, 1646 and references therein.

(98) Padwa, A.; Nimmsgern, H.; Wong, G. S. K. *Tetrahedron Lett.* **1985,** *26*, 957.

(99) Ref. 88, p. 145. (b) Truce, W. E.; Tate, D. P.; Burdge, D. N. *J. Am. Chem. Soc.* **1960,** *82*, 2872.

(100) Truce, W. E.; Frank, F. J. *J. Org. Chem.* **1967,** *32*, 1918.

(101) Stetter, H.; Dierichs, B. *Chem. Ber.* **1952,** *85*, 1060.

(102) Bordwell, F. G.; McKellin, W. H. *J. Am. Chem. Soc.* **1951**, 2251. Weber, W. P.; Stromquist, P.; Ito, T. I. *Tetrahedron Lett.* ***1974***, 2595.

(103) Chou, T.-S.; You, M.-L. *Tetrahedron Lett.* **1985** *26*, 4495.

(104) Malinowski, M. *Synthesis* **1987**, 732.

(105) Grimm, R. A.; Bonner, W. A. *J. Org. Chem.* **1967**, *32*, 3470.

(106) Gardner, J. N.; Kaiser, S.; Krubiner, A.; Lucas, H. *Can. J. Chem.* ***1973***, *51*, 1419.

(107) In some cases there are problems with this technique, see: Seebach, D.; Boes, M.; Naef, R.; Schweizer, W., B. *J. Am. Chem. Soc.* **1983**, *105*, 5390.

(108) Marvel, C.S.; Cowan, J.C. *J. Am. Chem. Soc.* **1939,** *61,* 3156.

(109) *Cf.* Fouchet, B.; Joucla, M.; Messager, J. C.; Toupet, L. *J. Chem. Soc., Chem. Commun.* **1982**, 858

(110) Dowd, P.; Kennedy, P. *Synth. Commun.* **1981**, *11*, 935.

(111) Bloomfield, J. J.; Lee, S. L. *J. Org. Chem.* **1967**, *32*, 3919.

(112) Supplied by Chemical Dynamics Corp., South Plainfield, N.J.

(113) 100% "Punctilious" ethanol was used without further drying. Supplied by United States Industrial Chemicals Co., New York, New York 10016.

(114) Kofron, W.G.; Backlawski, L.M. *J. Org. Chem.* **1976,** *41*, 1879.

(115) Phosphomolybdic acid (15 g) and ceric ammonium sulfate (2.5 g) dissolved in a mixture of water (485 mL) and concentrated sulfuric acid (15 mL).

(116) Anisaldehyde (15 drops) in a mixture of 95% ethanol (94 mL) and concentrated sulfuric acid (6 mL).

(117) (a) Patt, S.L.; Shoolery, J.N. *J. Magn. Reson.*, **1982**, *46*, 535. (b) Brown, D.W.; Nakashima, T.T.; Rabenstein, D.L. L. *Magn. Reson.*, **1981**, *45*, 302. (c) Rabenstein, D.L.; Nakashima, T.T. *Anal. Chem.*, **1979**, *51*, 1465A.

(118) Supplied by Aldrich Chemicals.

(119) The computer programs used in this analysis include several locally written or modified programs and the Enraf-Nonius Structure Determination Package: Frenz, B.A. *Computing in Crystallography*; Delft University: Delft, Holland, 1978; pp 64 - 71.

(120) Main, P.; Fiske, S.J.; Hull, S.E.; Lessinger, L.; Germain, G.; Declercq, J.P.; Woolfson, M.M. *Multan 11/12. A System of Computer programs for the Automatic Solution of Crystal Structures from X-Ray Diffraction Data;* Universities of York and Louvain: York, England, and Louvain, Belgium, 1982.

(121) Philips, J. C.; Oku, M. *J. Am. Chem. Soc.* **1972**, *94*, 1012.

(122) Wang, C.-H.; Cohen, S.G. *J. Am. Chem. Soc.*, **1957**, *19*, 1012.

(123) Prepared from (2,5-di-*tert*-butylbenzene)sulfonyl chloride by the method of: Rundel, W. *Chem. Ber.* **1968**, *101*, 2956.

(124) Sakakibara, T.; Manandhar, M.D.; Ishido, Y. *Synthesis* **1983**, 920.

(125) This weight is calculated from the weight of the mixture and from its composition as determined by ^{1}H NMR.

(126) Price, C.C.; Gillis, R.C. *J. Am. Chem. Soc.* **1953**, *75,* 4750.

(127) The compound should not be purified by distillation as it is thermally unstable.

(128) Moffett, R.B.; Hart, C.A.; Hoehn, W.M. *J. Am. Chem. Soc.* **1947,** *69*, 1854.

(129) Vig, O.P.; Vig, A.K.; Handa, V.K.; Sharma, S.D. *Indian J. Chem.* **1974**, *12,* 1158.

(130) Linstead, R.P.; Rydon, H.N. *J. Chem.Soc.* **1933**, 580.

(131) Vig, O.P.; Salota, J.P.; Sharma, M.P.; Sharma, S.D. *Indian J. Chem.* **1968**, *16,* 188.

(132) Prepared by DIBAL reduction of 2-cyclopentene-1-acetic acid at -78 °C.

(133) Preparation of the starting anhydride: Sample, T. E., Jr.; Hatch, L. R. *J. Chem. Ed.* **1968**, *45*, 55. Conversion of the anhydride to the desired lactone: Bloomfield, J. J.; Lee, S. L. *J. Org. Chem.* **1967**, *32*, 3919.

(134) (a) Lai, T.Y. *Bull. Chim. Soc. Fr.* **1933**, 53. (b) Preparation of the starting alcohol: Denis, J.-N.; Greene, A.E.; Serra, A.A.; Luche, M.J. *J. Org. Chem.* **1986,** *51*, 46.

(135) Dowd, P.; Kennedy, P. *Synthetic Comm.*, **1981**, *11*, 935.