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THE UNIVERSITY OF ALBERTA

FREE RADICAL METHODOLOGY FOR PREPARING CARBOCYCLES

by

LU SET

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF PH.D.

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NAME OF AUTHOR LU SET

TITLE OF THESIS FREE RADICAL METHODOLOGY FOR PREPARING CARBOCYCLES

DEGREE FOR WHICH THESIS WAS PRESENTED PH.D.

YEAR THIS DEGREE GRANTED 1987

(Signed) Lu Set

PERMANENT ADDRESS:

14-WOODBRIDGE HOSPITAL QTS
JALAN WOODBRIDGE
SINGAPORE 1954

DATED November 19 1986

"...whatever you do, do all to the glory of God." 1 Corinthians 10:31b

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled FREE RADICAL METHODOLOGY FOR PREPARING CARBOCYCLES.

submitted by LU SET

in partial fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY.

D. C. J. Clive

Supervisor

Irene L. Kopka

Ronald B. Bates

Monica Balasz

W. F. Tuer

David G. Hall

External Examiner

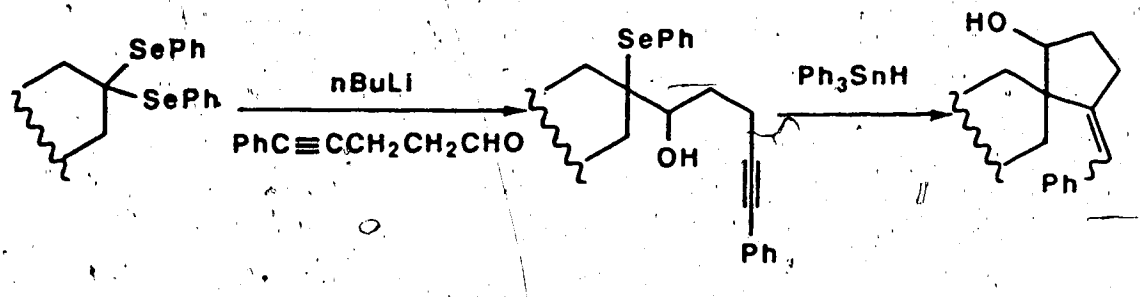
DATE November 19, 1986

To my parents

ABSTRACT

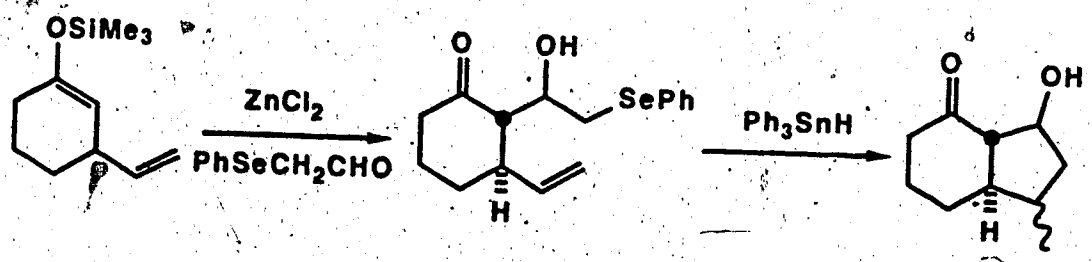
The associated problems of generating spiro-structures and quaternary carbon centres are often difficult and much work has been done in this area in an effort to develop useful synthetic routes. In this thesis a new and general procedure is described as shown in Scheme 1.

Scheme 1



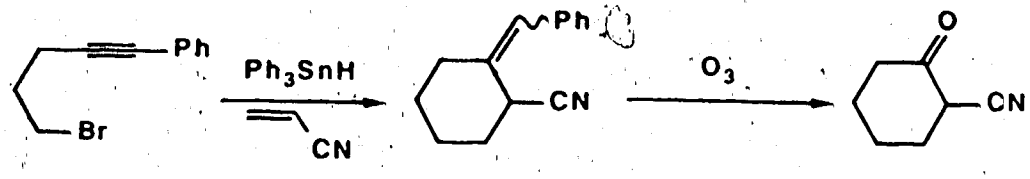
Aldol condensation with (phenylseleno)acetaldehyde and radical cyclization leads to trans-ring fused bicyclic compounds. The preparation involves the sequence of Scheme 2.

Scheme 2



A radical annulation process (Scheme 3) was developed.

Scheme 3



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I. INTRODUCTION

A very important aspect of organic chemistry is the formation of C-C bonds. Most procedures used for this purpose belong to one of four categories:

1. concerted processes
2. carbanion reactions
3. carbonium ion reactions
4. free radical reactions.

Of these areas, the free radical route to C-C bonds has been neglected by synthetic organic chemists until recently, apart, of course, from those involved in making polymers.

Free radical chemistry offers a number of useful features. It often works under mild and neutral conditions and the radical reactions are usually not much influenced by the nature of the solvent. One does not have to protect hydroxyl or carbonyl groups as is the case when carbanions are used. Furthermore, some free radical reactions are not very sensitive to steric factors and so they can be used to prepare sterically congested molecules. Although this thesis is concerned with the development of synthetic methods based on radical cyclization, the considerable literature on intermolecular

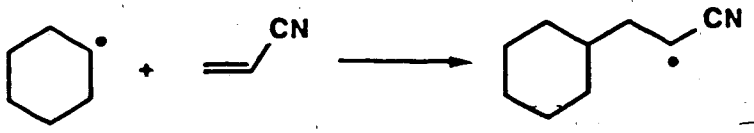
radical processes to make C-C bonds is also reviewed briefly. This subject has been reviewed in detail[1,2] and so, only the main features are summarized below.

Intermolecular Processes

Chain reactions are terminated by combination or disproportionation and, therefore the rate of reaction between non radicals and radicals as in (eq. 1) should be

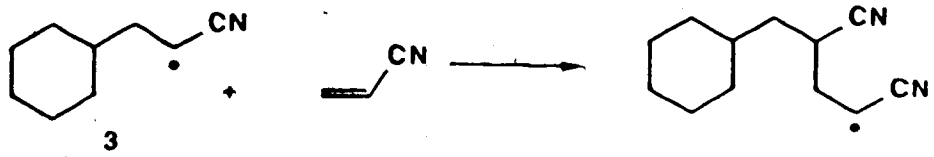
1 2 eq. 1

greater than the rate of termination.[2] For the process of (eq. 1) to represent a synthetically useful process, R• and 2 must differ appreciably in reactivity. If R• is a nucleophilic alkyl radical, then electron deficient alkenes such as acrylonitrile, are suitable because the adduct radical is much less nucleophilic. Thus, the reaction shown in (eq. 2) has a rate constant 10^6



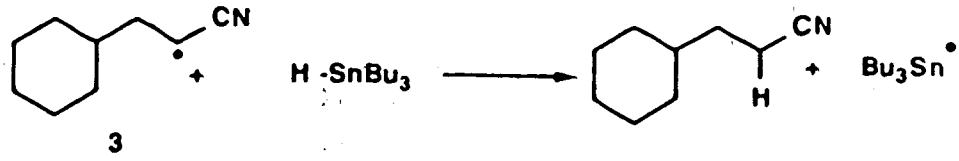
3 eq. 2

$Lmol^{-1}s^{-1}$, and that shown in (eq. 3) has $k = 10^2$ $Lmol^{-1}s^{-1}$ at 20°C.



eq. 3

The second reaction (eq. 3) is so slow that the radical 3 is trapped by tributyltin hydride (eq. 4) before it can react further with acrylonitrile, the rate constant being 10^6 $Lmol^{-1}s^{-1}$ at 20°C.



eq. 4

From the rates shown above, it is clear that the concentration of acrylonitrile must be higher than that of tributyltin hydride. However, the concentration ratio

$$\frac{[\ \text{CH}_2{=}\text{CH}{-}\text{CN}\ ]}{[\ Bu_3SnH\ ]}$$

also influences the fate of 3. If the excess of

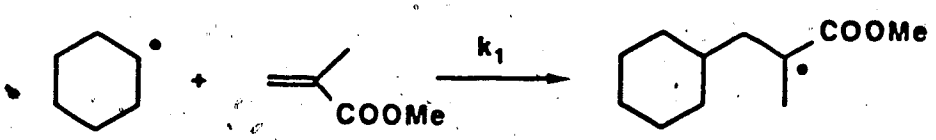
acrylonitrile is too large, then 3 will react noticeably with acrylonitrile instead of with tributyltin hydride. Therefore, it is necessary to find the optimum concentration ratio

$$\frac{[\ \text{CH}_2{=}\text{CH(CN)}\ ]}{[\ Bu_3SnH\ ]}$$

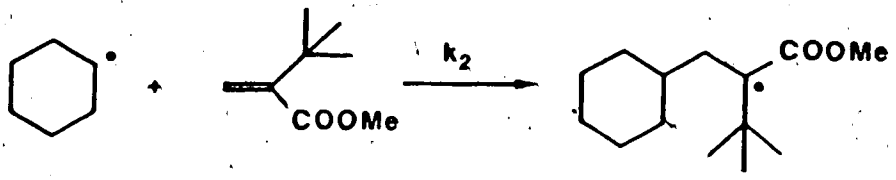
for a particular radical-electron deficient olefin pair. The nature of the substituent Y in 1 exerts a strong influence on the rate of addition of R•. Since R-Br and 1 (as well as other electron deficient olefins) react at comparable rates with $Bu_3Sn^•$, one should use R-I, which are 10-100 times more reactive towards $Bu_3Sn^•$.

Generally, cyclohexyl radicals react faster with E-alkenes than with Z-alkenes, and for terminal alkenes, the relative reactivity as the substituent is changed varies as shown in Table 1.[3]

Bulky substituents in the α position have little influence on the rate (eq. 5) and (eq. 6). For these

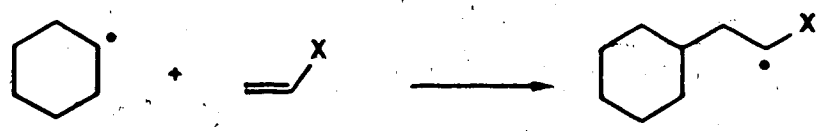


eq. 5



eq. 6

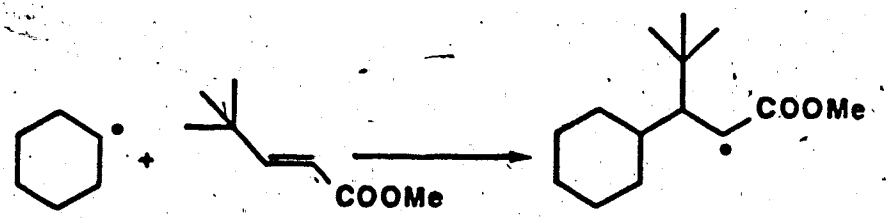
Table 1. Relative rates of reaction with Michael acceptors at 20°C.



X	CHO	CN	COMe	COOMe	$CONH_2$
rel rate	34	24	13	6.7	1.1

X	Ph	Cl	OAc	H	Bu
rel rate	1	0.12	0.16	0.15	0.004

reactions $k_1/k_2 = 2.95$. However, β-substitution has a considerable influence on the rate (eq. 7) which is 2×10^4 slower than when methyl acrylate is used.



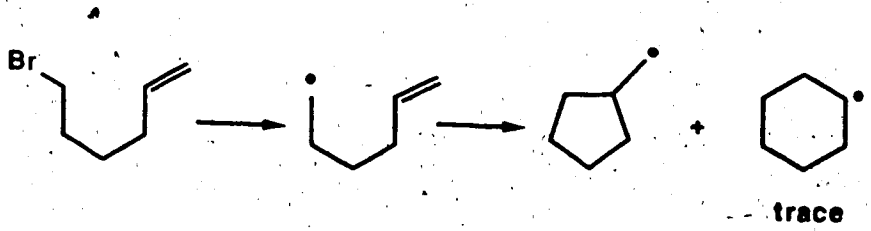
eq. 7

Electron releasing groups (e.g. Me) attached to a radical site (as in $CH_3\dot{C}H_2$ versus $\dot{C}H_3$) increase the rate of reaction, while large (isopropyl, t-butyl) alkyl substituents at a radical site (as in t-Bu-$\dot{C}H_2$) decrease the rate of addition by exerting a steric effect. Unsaturated, radical-stabilizing substituents (e.g. C≡N, Ph) decrease the rate of addition of that radical.

Radical cyclizations, involving double bonds have been examined from a physical organic chemical point of view, especially by Beckwith.[4]

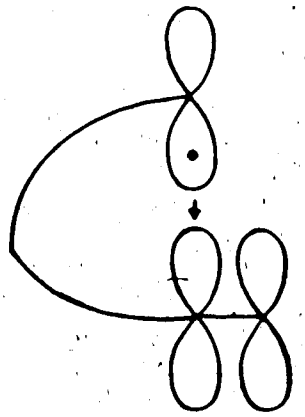
Intramolecular Processes

A longstanding problem in the intramolecular process of (eq. 8) was the reason for formation of the thermodynamically less stable cyclopentylmethyl radical.



eq. 8

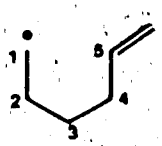
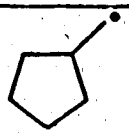
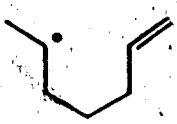
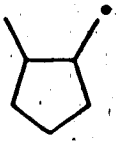
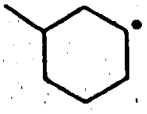
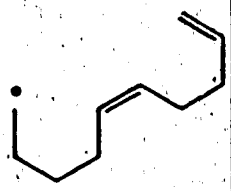
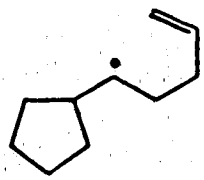
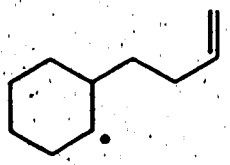
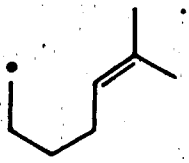
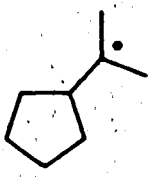
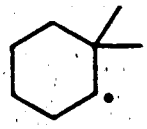
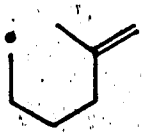
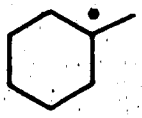
Beckwith proposes[5] that the ease of cyclization is determined by the ease of access of the transition state shown below.



and the preference for 5-exo closure (eq. 8) is interpreted in these terms, i.e. the preferred approach pathway of the radical to the double bond is more easily accommodated by a transition state leading to 5-exo closure than by one leading to 6-endo closure. The transition state is early, and so the thermodynamic stability of the product (in this irreversable reaction) is not important in controlling the regiochemical outcome.

The direction and relative rates of cyclization of different hex-5-enyl radicals have been determined.[6] Substituents on the olefinic bond at C-(5) have a profound effect on the rate of 1,5-cyclization, and substituents at C-(6) retarded the rate of 1,6-cyclization (Table 2). Entries (1 & 2) show that the substitution at C-(1) has only a small effect on $k_{1,5}$rel values. Entries (3 & 4) show that substituents at C-(6) have a small effect on $k_{1,5}$rel values. The last entry (5) shows that a

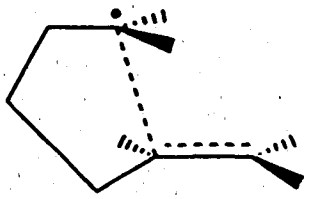
Table 2. Relative rate values for $k_{1,5}$ and $k_{1,6}$ at 20° C.

Entry		1,5 exo	1,6 endo	$k_{1,5}$	$k_{1,6}$
1				1	0.02
2				1.4	0.02
3				1.4	0.007
4				2.4	0.011
5				0.022	0.04

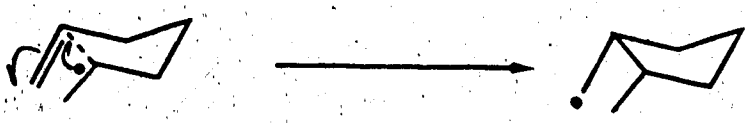
substituent at C-(5) has a large effect on the value of $k_{1,5}$el.

In summary, intramolecular addition under kinetic control in lower alkenyl and related species occurs preferentially in the exo mode.[7] The same is true for alkynyl radicals. This exo mode is kinetically favoured,

because the strain generated by accommodation of the triangular disposition of centres required for homolytic addition leading to endo closure outweighs the thermochemical and other factors disfavouring the formation of the thermodynamically less stable product.[8]



1,5 Ring closures of substituted hex-5-enyl and related radicals are stereoselective. This is due to orbital symmetry effects on cyclization of the type shown in (eq. 9).[7]

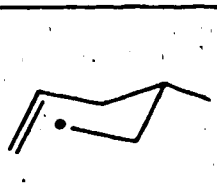
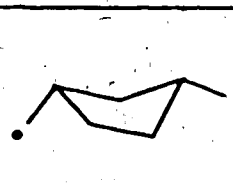
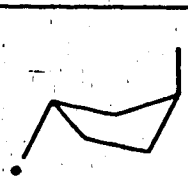
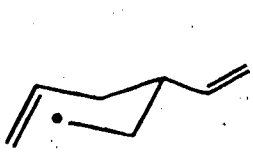
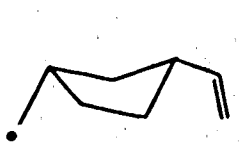
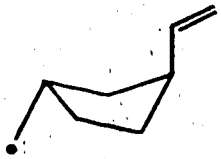
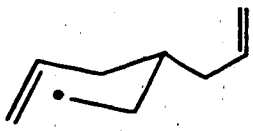
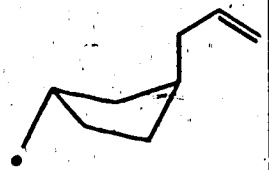
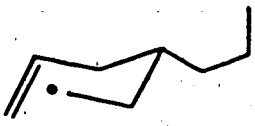
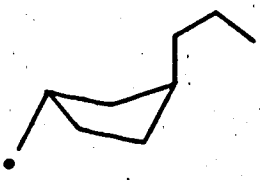


eq. 9

The stereochemical consequences are predicted by assuming a chair-like transition state with the substituents preferentially equatorial. Thus, bulky substituents should lead to pronounced stereoselectivity. The following observations - in conformity with

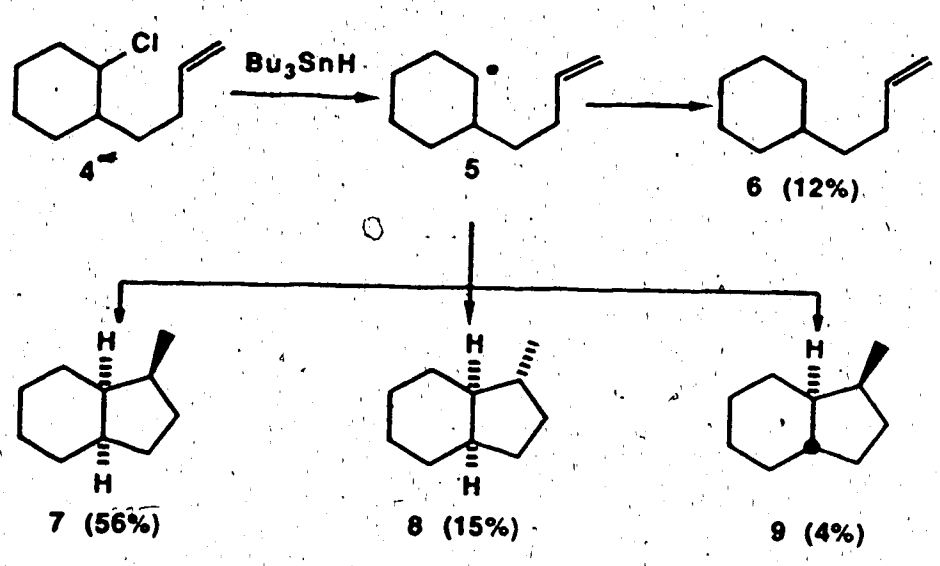
these ideas have been made (Table 3).[9] The situation with

Table 3. Relative k values for cis and trans stereochemistry.

Entry		cis	trans	k_{cis} / k_{trans}
1				2.35
2				3.3
3				4.0
4				4.5

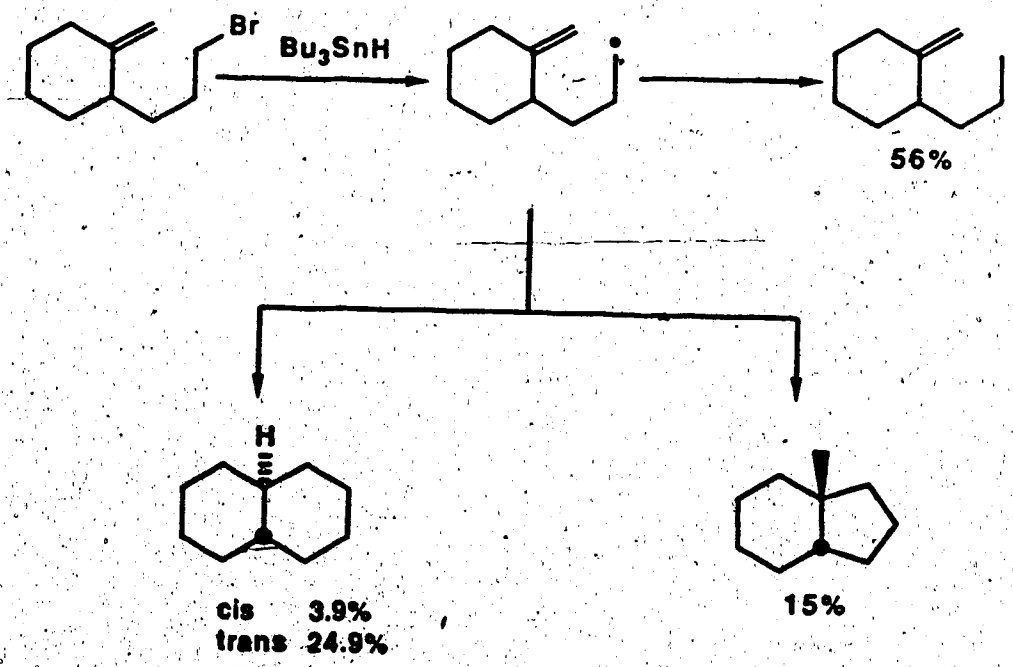
cyclic systems is more complicated. For example, compound 4 Scheme 1[10] gave 6, 7, 8, and 9 in the yields indicated. The ring imposes steric restraints on the reaction that are not present in the acyclic case. Inspection of 5 with the butenyl group equatorial, allows poor overlap of the semioccupied and π^* orbitals. Maximum overlap is achieved when ring closure occurs through the

Scheme 1



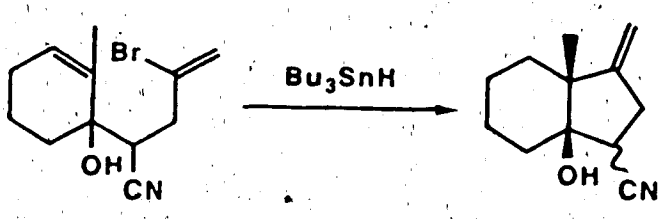
conformation in which the substituents are axial. This feature leads to cis fusion. From an inspection of models the stereochemical fate of the methyl group is not easy to understand. The case shown in Scheme 2[10] was also examined.

Scheme 2.



As expected, the C-(5) substituents (Scheme 2) disfavour 1,5-closure and the main path is the 6-endo one. However, the 5-exo product, as expected, has the methyl group and formal C-(4) substituent trans.

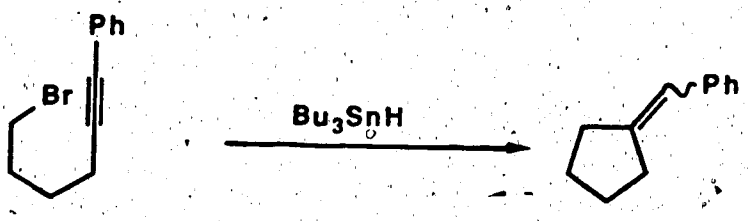
In suitable systems, however, high regioselectivity can be observed in closure onto substituted double bonds as in (eq. 10).[11]



(70%) eq. 10

In the above example, a quaternary centre is formed. The cis ring junction is the result of the required geometry of approach of the vinyl radical to the ring double bond.

Intramolecular cyclization of acetylenic radicals as in (eq. 11)[12] is likely to become a useful process in



(99%) eq. 11

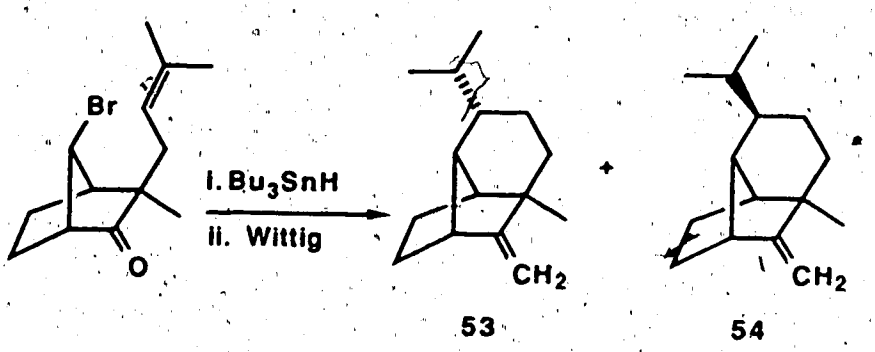
organic synthesis because the final product contains a

double bond, which can be used as the starting point for further manipulation, such as ozonolysis to a ketone. Little mechanistic work has been reported for processes of the type shown in (eq. 11).

Synthetic Applications of Radical Cyclization

The synthetic applications of radical cyclization have been receiving growing attention during the last few years.

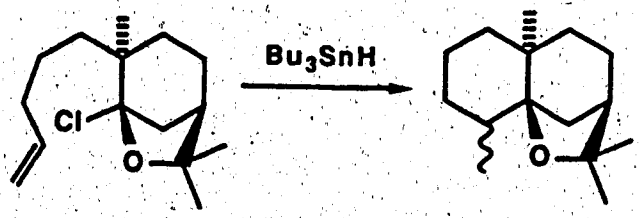
The initial isolated applications by Bakuzis (eq. 12)[13]



53 54

eq. 12

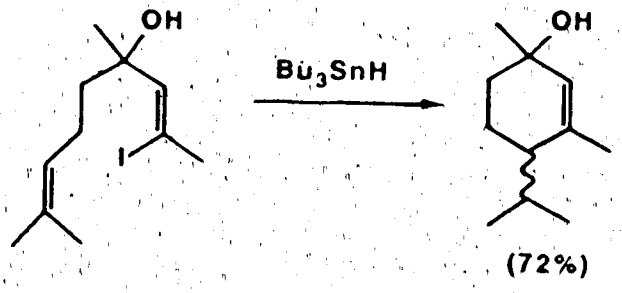
and Büchi (eq. 13)[14]



eq. 13

and the earlier pioneering studies (1964-1968) of Julia[15] were not followed up by the chemical community.

In 1981 Bachi[16] reported the use of radical cyclization in the penicillin series. Shortly afterwards Stork published his initial work on vinyl radical cyclization (eq. 14)[11] and Hart described the first of



eq. 14

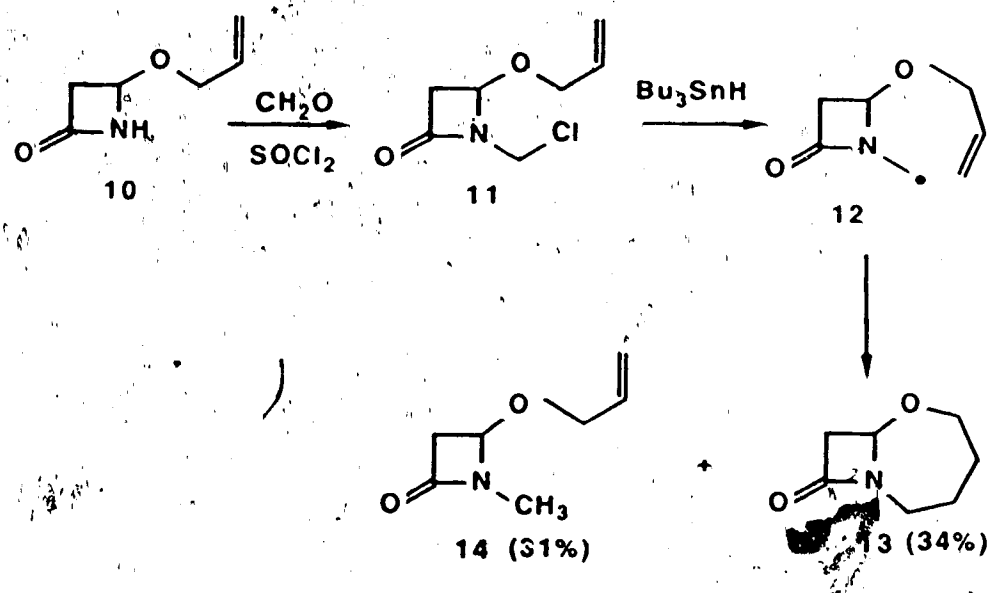
a series of researches aimed at making pyrrolidine alkaloids by radical closure.

Work in this laboratory was begun in 1982 with the aim of devising general methods for converting readily available compound types such as olefins, ketones, alcohols, etc., into materials that are correctly constituted to undergo radical cyclization. The initial aim was to make carbocycles, although the first useful results were in the area of heterocycles.[32]

In the following pages, the main synthetic applications of radical cyclization are reviewed and, in so far as possible, classified according to whether a heterocycle or a carbocycle is produced. Each section is

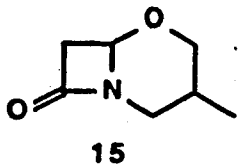
further subdivided as to whether a double or triple bond is used as the radical trap.

One of the early applications of radical cyclization was in the area of β-lactam antibiotics.[16] The readily accessible β-lactam **10** was converted into the chloromethyl derivative **11**. Treatment with tributyltin hydride formed the radical **12**, which cyclized by a 7-endo pathway **12** → **13** (eq. 15). The product **13** was isolated in 34%. A



eq. 15

substantial amount (31% isolated yield) of uncyclized material **14** was produced and no product arising from

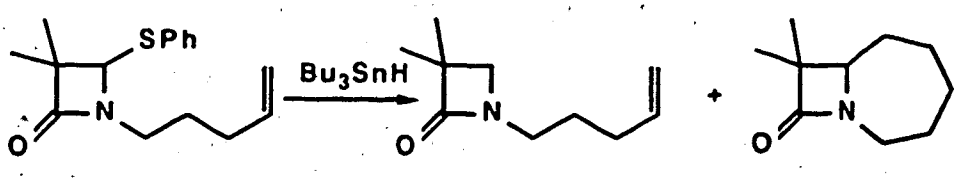


15

6-exo closure (cf. **15**) was formed. On the basis of

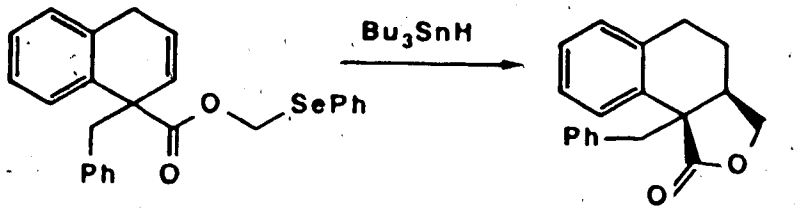
kinetic measurements, 6-exo (and 7-endo) cyclizations are slower than 5-exo and so the relatively high proportion of non cyclized material is understandable. Allylic H-abstraction may also be involved in affording the non cyclized material. It is possible that a higher proportion of cyclized material would result if the tin hydride were added slowly during the course of the reaction, but the reason for the preference of 7-endo over 6-exo closure is not clear. Possibly, the 4-membered ring imposes geometric restraints on the relative positions of the pendants and makes the route to the 7-membered ring easier.

Bicyclic β-lactams can also be approached in another way.[17] When the sulfide **16** was heated with tributyltin hydride and a trace of AIBN, it gave the direct reduction product **17** (25%) and only one cyclized product **18** (55%) resulting from endo closure. This unusual preference for the endo mode, again probably reflects the strain in the exo transition structures engendered by the azetidinone ring (eq. 16).



16 **17 (25%)** **18 (55%)** eq. 16

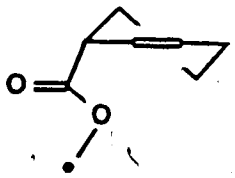
Another class of heterocycle available by radical closure is the γ-lactone group. Work in this area done in our laboratory will be described later. As shown in (eq. 17)[18] the phenylseleno ester **19** gave the lactone **20** (65%) on treatment with tributyltin hydride and AIBN.



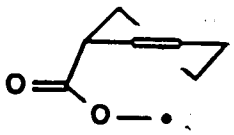
eq. 17

19 **20 (65%)**

Evidently, the conformational preference of the ester[19] (see **21**) is not large enough to prevent rotation to **22**, from which 5-exo cyclization occurs.

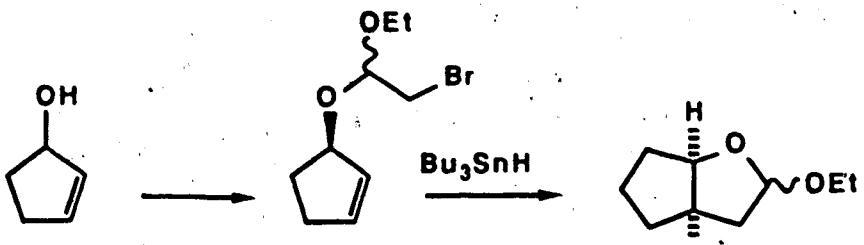


21



22

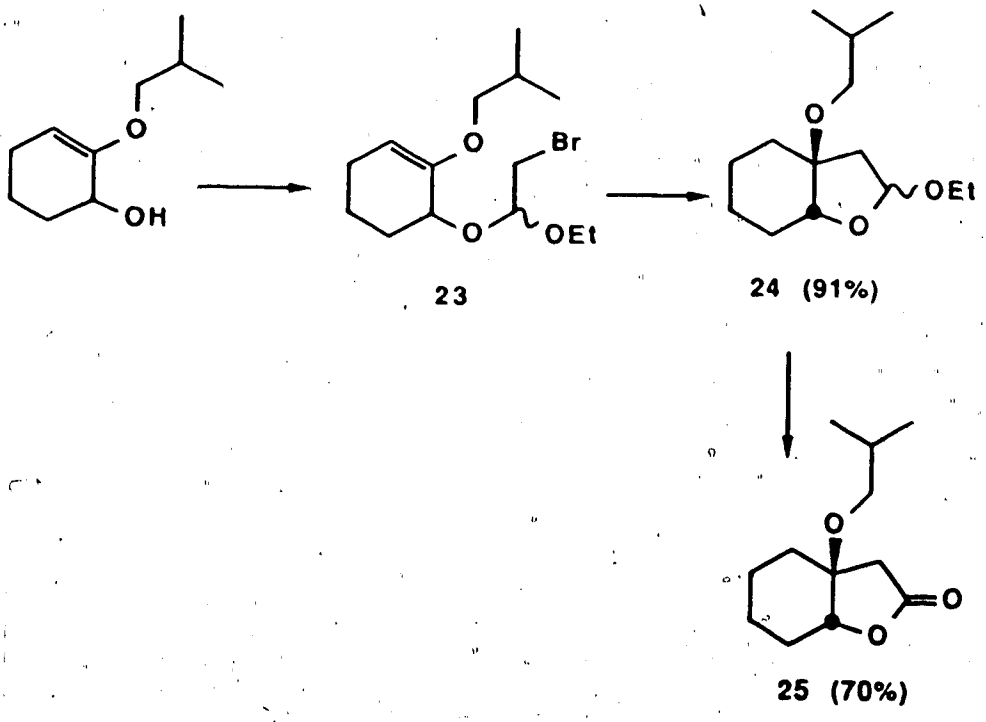
Another approach to lactones is illustrated by (eq. 18),



(55%)

eq. 18

which shows one of a number of cases[20] that have been published. In another example, bromo acetal **23** was easily produced, as a mixture of diastereoisomers, starting from 2-isobutoxy-2-cyclohexeneone following reduction to the carbinol and reaction with 1,2-dibromoethyl ethyl ether. When subjected to radical cyclization conditions, the cyclic ether **24** was formed, and oxidation using Jones' reagent gave the corresponding lactone **25** (70%)[21] (eq. 19).



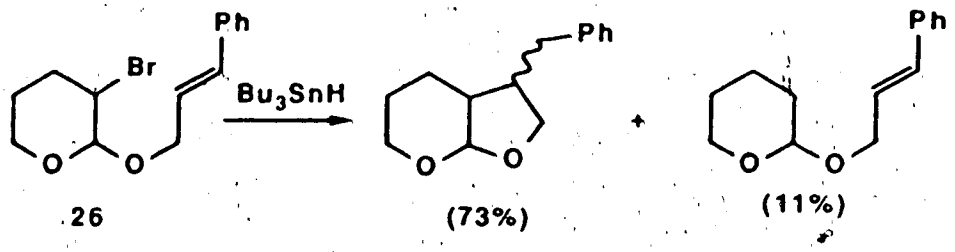
23 **24 (91%)**

25 (70%)

eq. 19

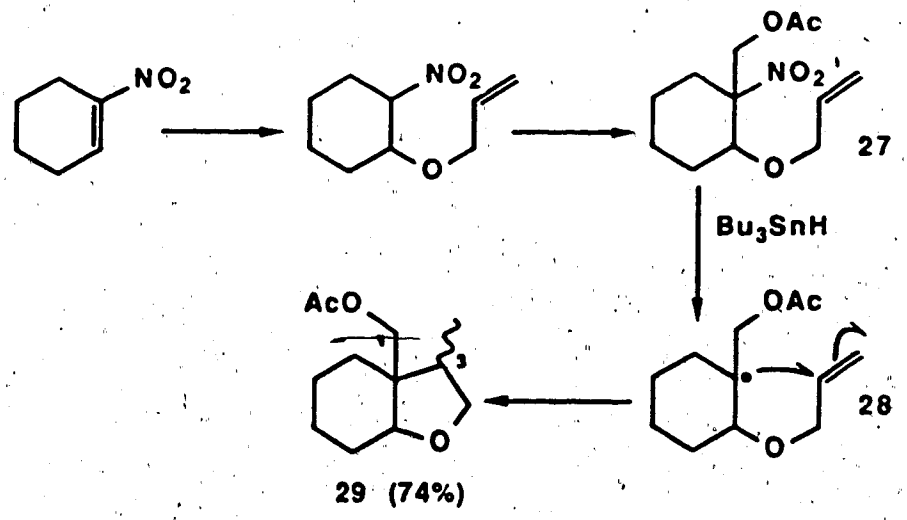
In a related study, dihydropyran was converted into **26** by treatment with NBS in the presence of cinnamyl alcohol. Radical cyclization then proceeded as shown in

(eq. 20).[22]



eq. 20

Tertiary nitro groups have also been used as a source of carbon radicals. For example, Michael addition of allyl alcohol to 1-nitrocyclohexene proceeded as shown in (eq. 21),[23]

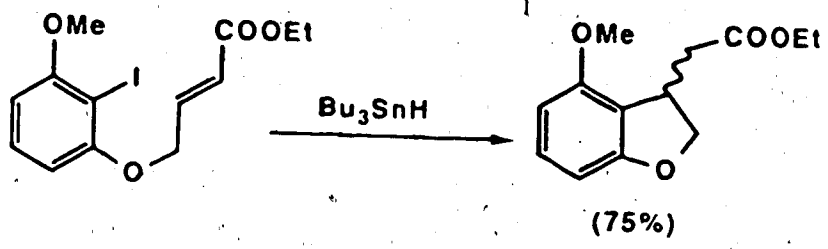


eq. 21

and Henry reaction with formaldehyde, followed by acetylation afforded the tertiary nitro compound 27. Treatment with tributyltin hydride proceeded via radical

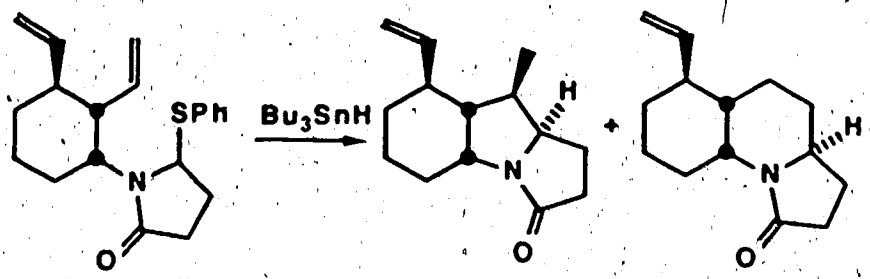
28, to a mixture of tetrahydrofurans 29, epimeric at C-3, (74% yield).

The radical undergoing cyclization is not restricted to aliphatic species; aryl radicals are also suitable. The example shown in (eq. 22)[24] provides a general route to benzofurans and also constitutes a connection between radical cyclization and the area of directed lithiation, which is the technique used to prepare the starting aryl halide.



eq. 22

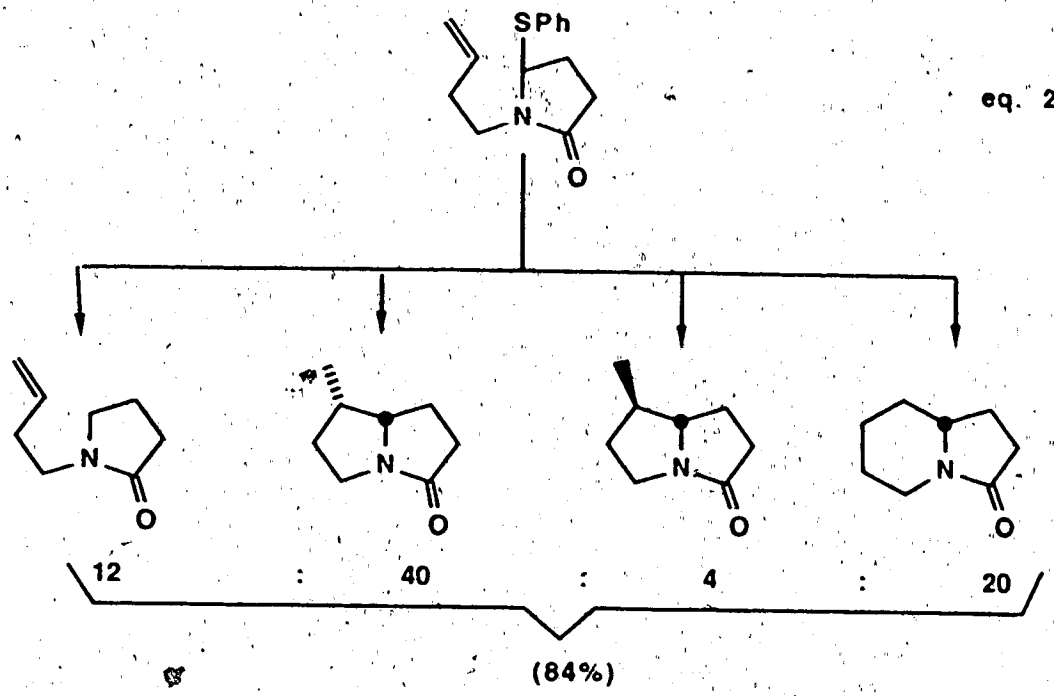
A great deal of attention has been focused upon pyrollidine rings using radical cyclization methods. Construction of C-C bonds adjacent to nitrogen plays a central role in alkaloid chemistry and the use of α-amino and α-acylamino radicals for assembling these bonds has recently been applied, in an extensive research program, to the synthesis of indolizidines and pyrolizidines, which are important sub-structures found in many alkaloids. The potential utility of this method in alkaloid synthesis is shown in (eq. 23).[25]



30 31 (51%) 32 (31%) eq. 23

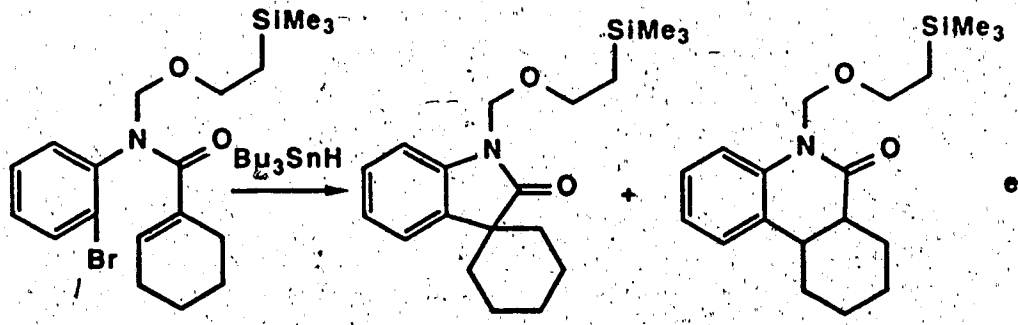
Treatment of thiophenoxylactam **30** with tributyltin hydride gave **31** (51%) and **32** (31%), which is an intermediate in the synthesis of the Dendrobatid alkaloid gephyrotoxin.[26] It is noteworthy that no reduction product was obtained and that both cyclizations proceed with high stereoselectivity at the radical centre. The considerably smaller exo:endo ratios in this case are probably due to the geometric constraints imposed by the sp^2 character at nitrogen. A more typical example from the same laboratory is given in (eq. 24).[25] It should be noted that the phenylthio-acylamino species are easily synthesized.

As with oxygen heterocycles, aryl radicals can be used to make nitrogen heterocycles. In connection with work directed towards the synthesis of the Gelsemium alkaloids, a mild method to produce the 3-spiro-2-oxindole system was required and, although several methods are available for the synthesis of 2-oxindoles, none was judged suitable. However, radical cyclization was shown



eq. 24

to be useful in this regard. When the bromide 33 was cyclized under the usual conditions, the product of 5-exo



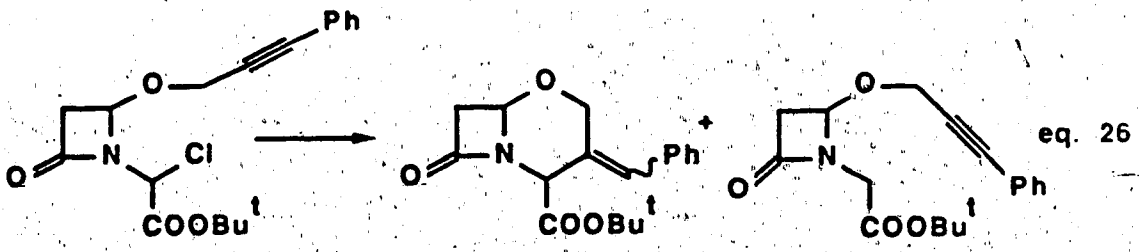
eq. 25

closure 34 was the predominant one. This high regio-selectivity is probably caused by the shorter C-N bond

lengths which, coupled with the conformational rigidity of the acylamides, favours 5-exo closure, despite steric hindrance around the cyclization terminus[27] (eq. 25).

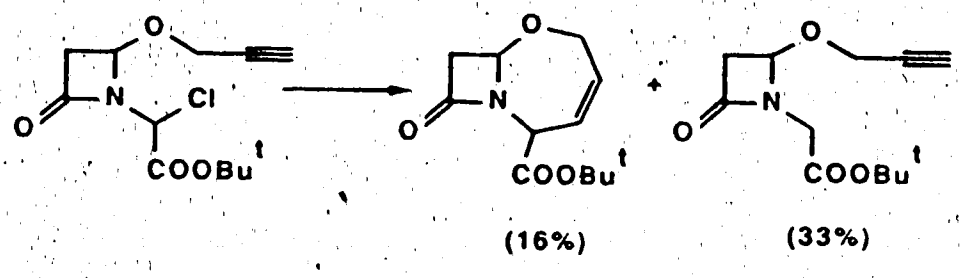
In the heterocyclic compounds mentioned above, ring closure of the radical takes place onto a double bond and so there is a loss of functionality once hydrogen abstraction has occurred. However, if the radical closes onto a triple bond, the product still contains unsaturation and so further opportunities exist for chemical modification.

In one of the early studies in this area, a side arm containing an alkyne function was used in β-lactam chemistry. Compound 35 gave the product of 6-exo closure as a 1.3:1 mixture of E and Z isomers 36. A small amount (18%) of non fused material 37 was isolated[28] (eq. 26).



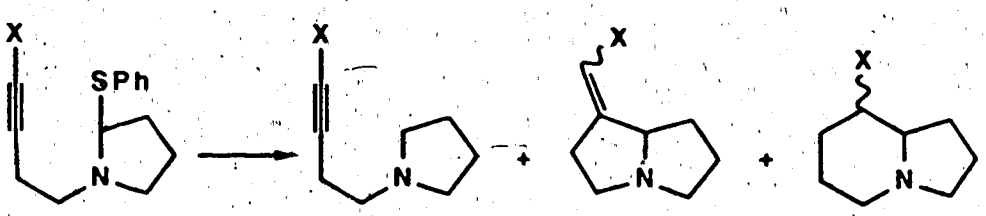
eq. 26

The phenyl ring evidently plays an important role because the unsubstituted compound cyclized by the 7-endo pathway (eq. 27). Other examples in which the course of the reaction is sensitive to the substituent on the acetylene are shown in Table 4.[29] With the trimethylsilyl alkyne



(16%) (33%) eq. 27

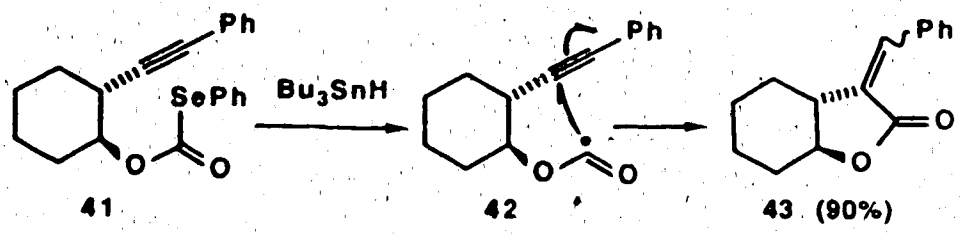
Table 4. Substitution effect on alkyne unit.



X =	$SiMe_3$	38	38a (22%)	38b (70%)	-
	Me	39	39a (61%)	-	39c (27%)
	CMe_3	40	40a (35%)	40b (49%)	-

38, the product of 5-exo closure 38b was isolated in 70% yield; with a methyl acetylene 39, the product 39c (27%) resulting from 6-endo closure was formed and, with t-butyl acetylene 40, the 5-exo product 40b was isolated in 49% yield. Like pyrrolidine ring systems, lactones can be

generated with an exocyclic double bond (eq. 28).

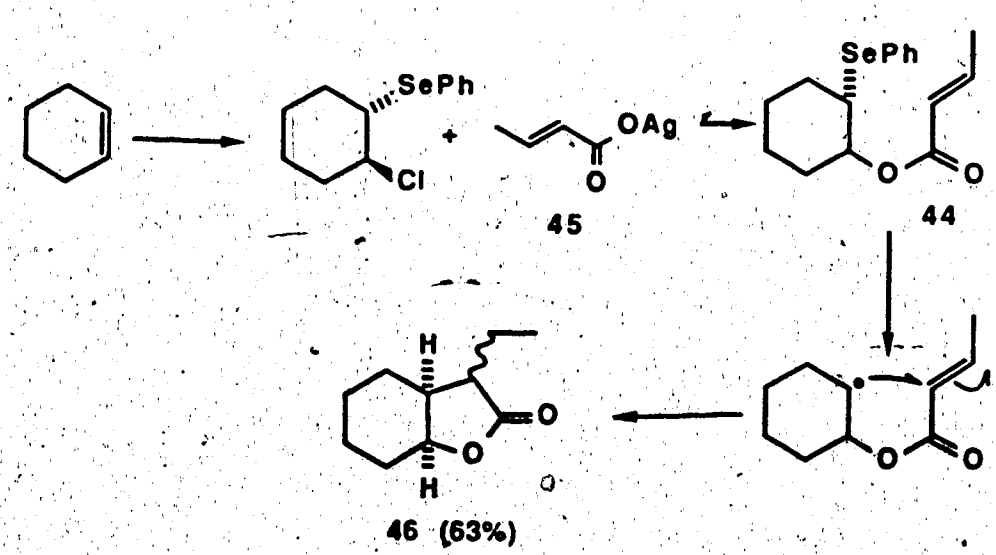


41 42 43 (90%) eq. 28

When phenylselenocarbonate **41**,[30] was treated with tributyltin hydride, the 5-exo cyclized product **43** as an E/Z mixture (5:1) was obtained in 90% yield. In this case the acyl radical **42** underwent cyclization before decarbonylation.[31]

The contribution from this laboratory for making lactone rings is summarized in Scheme 3.[32]

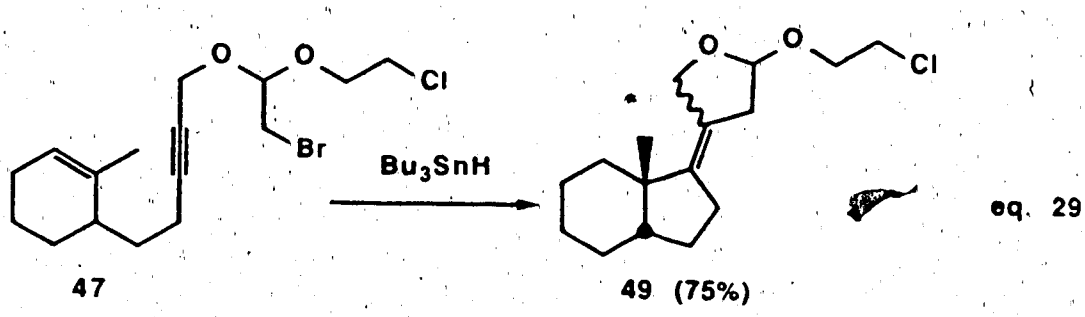
Scheme 3



45 44 46 (63%)

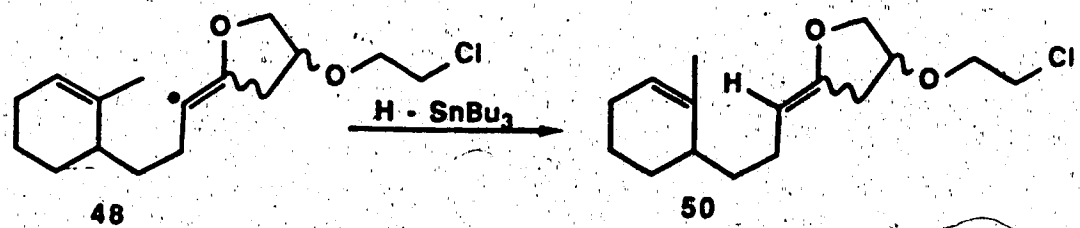
Cyclohexene was converted into **44** by treatment with phenylselenenyl chloride and silver crotonate **45**. When subjected to usual radical cyclization conditions, the adduct **44** formed the lactone **46** in 63% yield.

The combined use of a triple bond, followed by another cyclization onto a double bond is shown in the next example. When **47** was treated with tributyltin



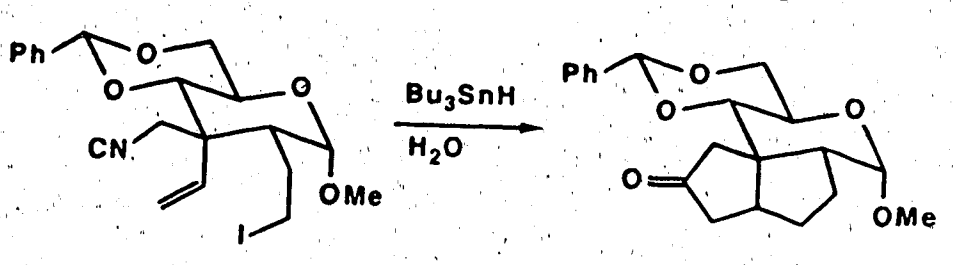
47 **49** (75%) eq. 29

hydride, the radical that was formed underwent 5-exo closure onto the triple bond to produce a vinyl radical **48**. This cyclized in a 5-exo manner onto the suitably located double bond to give **49** (75%) (eq. 29).[33] The cyclization of the intermediate vinyl radical was evidently much faster than hydrogen abstraction to give **50**.



48 **50**

A combination of the synthetic potential of free radical reactions and the utility of carbohydrates in organic synthesis has been explored recently by Fraser-Reid.[34] When substrate **51** was treated under the usual conditions for radical cyclization, the product **52** was obtained in 91% yield. In this case the initial radical generated underwent 5-exo cyclization to give a primary radical, which then closed onto a C≡N triple bond. After hydrolysis the ketone **52** was obtained (eq. 30). Recent



eq. 30

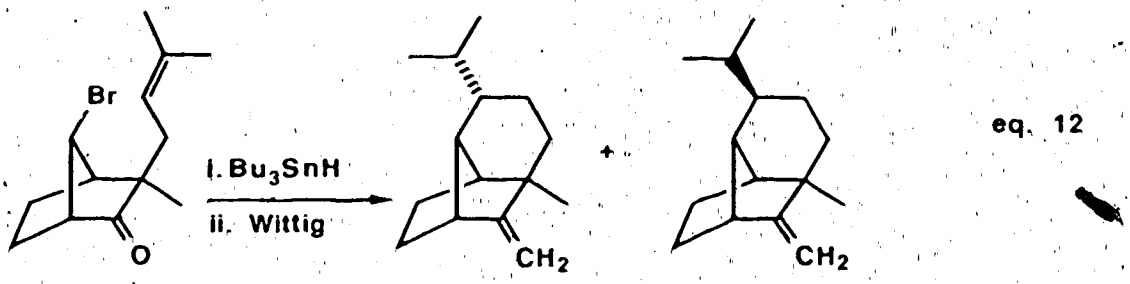
51 **52 (91%)**

publications have emphasized the merits of "annulated sugars" for stereocontrol synthesis[35] of optically active carbocycles, and the effectiveness of the pyranoside ring as an agent for controlling stereoselectivity.

It seems that formation of heterocycles by radical ring closure has been more extensively studied than the formation of carbocycles. We believe, on the basis of the experience in this laboratory in both areas, that the situation is due to the fact that the precursors to radicals that would afford heterocycles are more readily accessible than the corresponding precursors to

carbocycles.

One of the earlier uses in natural product synthesis, of radical cyclization onto a double bond so as to make a carbocycle, is the work of Bakuzis[13] (see page 13, eq. 12).

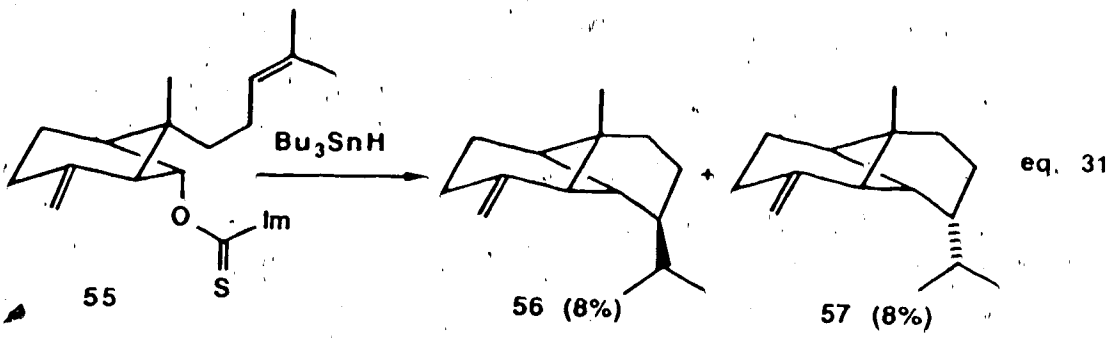


53 54

eq. 12

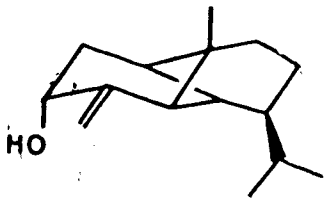
The tricyclic sesquiterpene sativene **54** and copacamphene **53**, which each possess five chiral centres, were prepared by the radical cyclization shown in (eq. 12). The yield was 62% and the resulting ketones were transformed by Wittig reaction into **54** and **53**. The cyclization was not stereoselective and both epimers **53** and **54** were obtained after olefination of the initial ketone.

In a similar, but much more recent example, **55** was treated with tributyltin hydride in toluene at reflux to give a 1:1 mixture of β-copaene **57** and β-ylangene **56** in 16% combined yield (eq. 31).[36] These compounds were readily separated by preparative GC. Although the yield



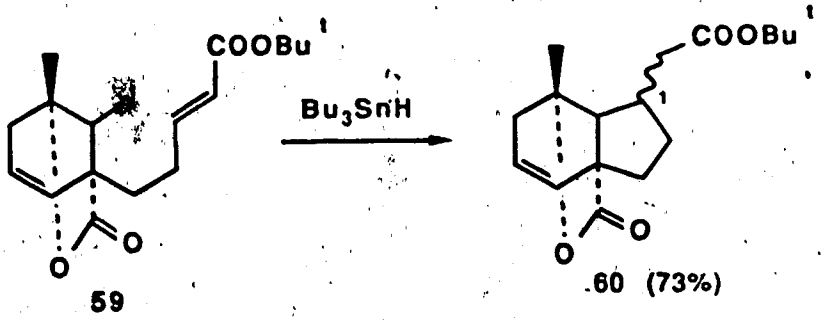
eq. 31

is poor, this method is an improvement over the procedures used in previous syntheses[37] of the compounds. Oxidation of β-ylangene **56** with selenium dioxide and tert-butyl hydroperoxide gave a 76% yield of the antitumor agent lemnalol **58**.



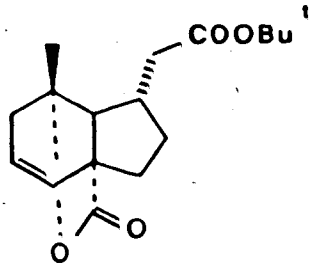
58

Another example in which a multi-ring system is formed is provided by the reaction shown in (eq. 32).[38]



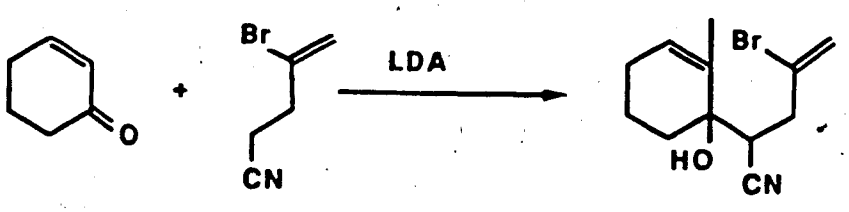
eq. 32

Reductive alkylation of 3-methyl benzoic acid followed by iodolactonization gave 59, and free radical cyclization then provided an efficient stereoselective route to the trans-perhydroidans shown, in 73% yield. The product 60 was a 7:1 mixture of diasterisomeric perhydroindans epimeric at C-1 with 61 as the major isomer.

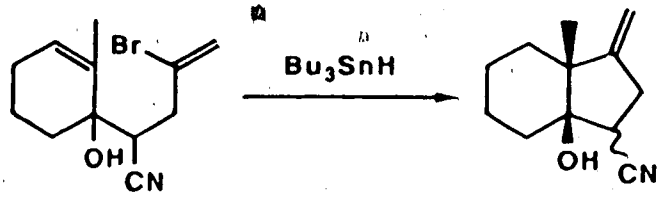


61

Vinyl radicals have also been used to make carbocycles. Such radicals are highly reactive and will close efficiently even onto a disubstituted double bond terminus. The use of vinyl radicals is attractive because it results in the formation of a ring that contains a double bond at a predictable position. This can then serve as a site of further synthetic manipulations. An example of vinyl radical cyclization is given in (eq. 33 and 10)[11] a direct application to natural product

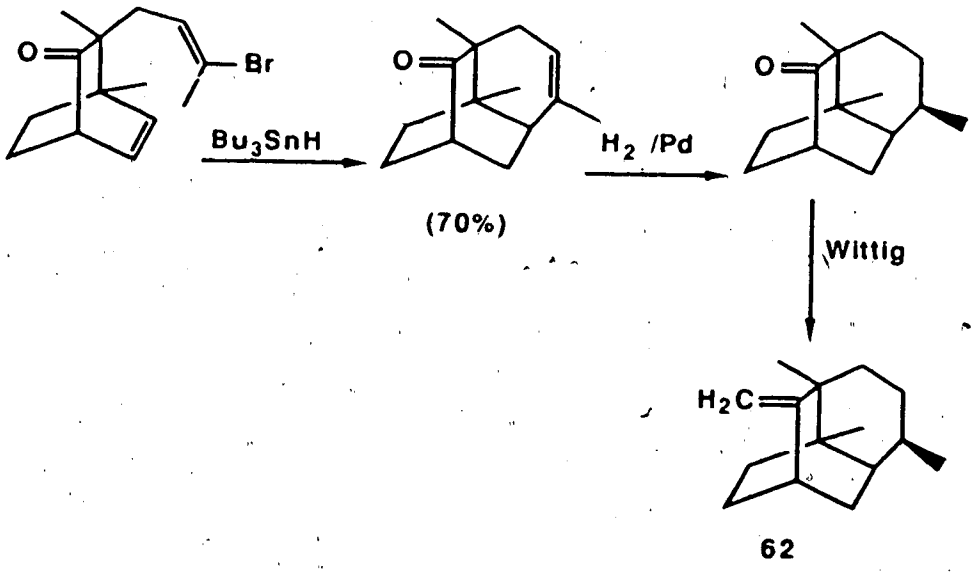


eq. 33



(70%) eq. 10

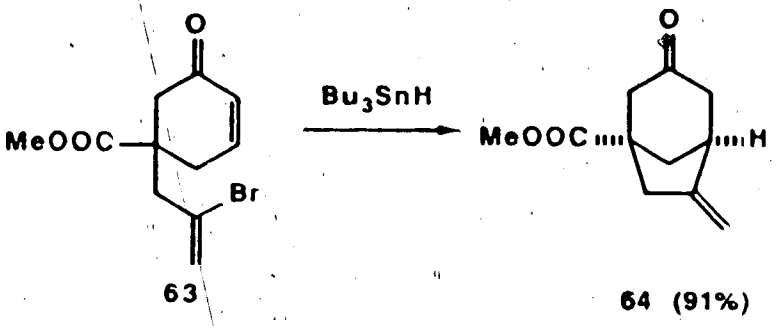
synthesis, in this case Seychellene 62, is summarized in (eq. 34).[39] It should be noted that the geometry of the vinyl bromide is not significant because the intermediate vinyl radical isomerizes rapidly.[39]



(70%) eq. 34

62

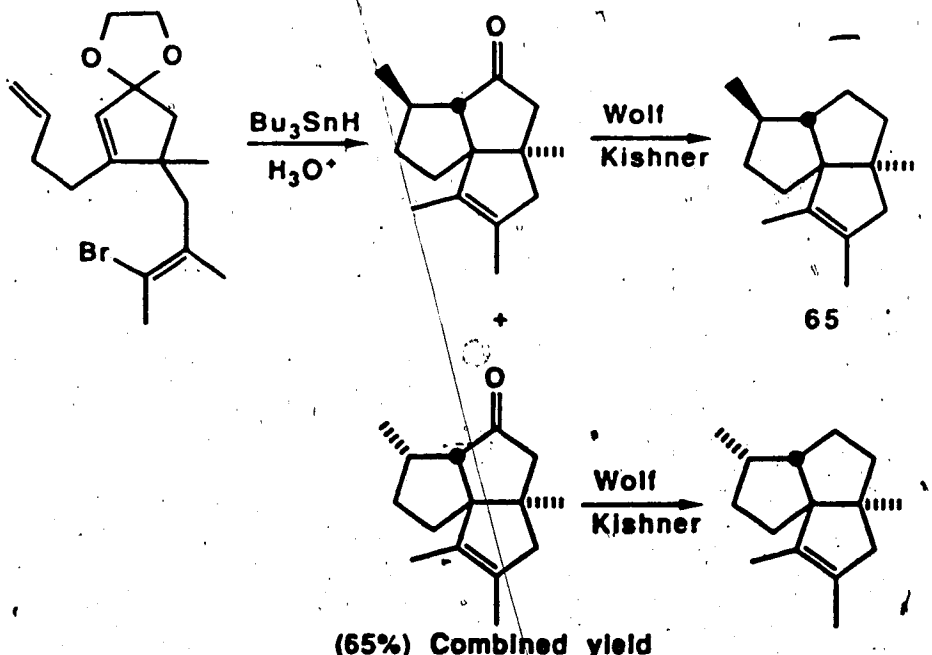
Reductive alkylation methodology has also been used in conjunction with vinyl radical cyclization. For example 63 was made from 3-methoxybenzoic acid in several steps, including reductive alkylation using 2,3-dibromo-



63 64 (91%) eq.35

propene. Treatment with tributyltin hydride then gave the bicyclic ketone **64** in 91% yield (eq. 35).[40]

Multiple cyclizations, initiated by a vinyl radical, offer a highly convergent route to angularly fused triquinanes. By way of illustration the sequence of (eq. 36)[41] should be mentioned. One of the products was converted as shown into (±)silphiperfol-6-ene **65**.

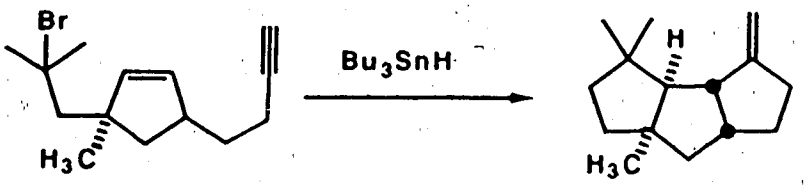


(65%) Combined yield eq. 36

In related work, (eq. 37),[42] the linearly fused

triquinanes $\Delta^{9(12)}$-capnellene **66** was prepared in a very concise manner.

Another aspect of radical cyclization methodology that is receiving attention is the control of

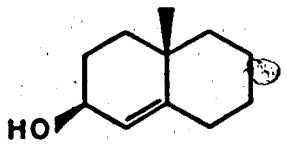


eq. 37

66 (61%)

stereochemistry. Progress in this area has been made in this laboratory[47] and elsewhere.[43]

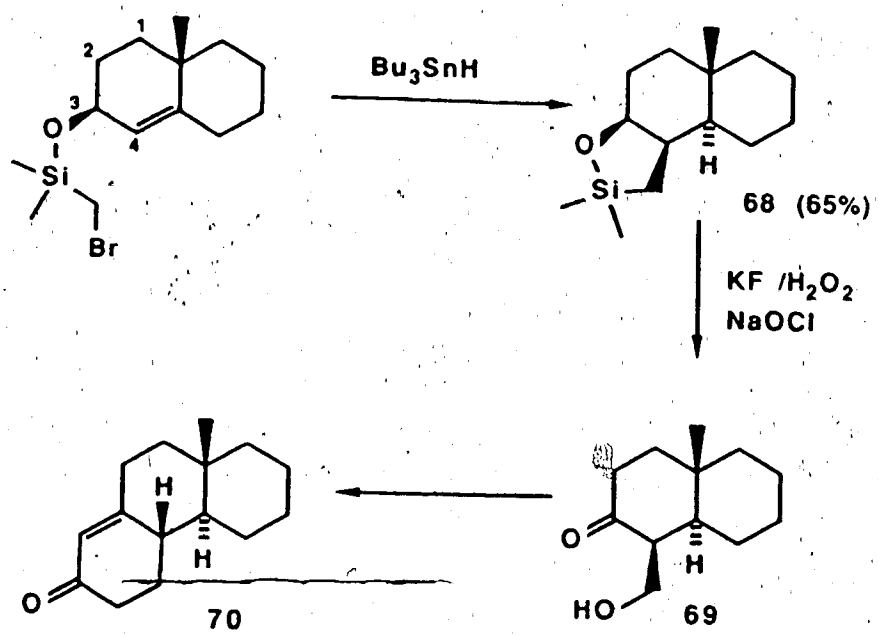
Reaction of allylic alcohol **67** with (bromomethyl)-



67

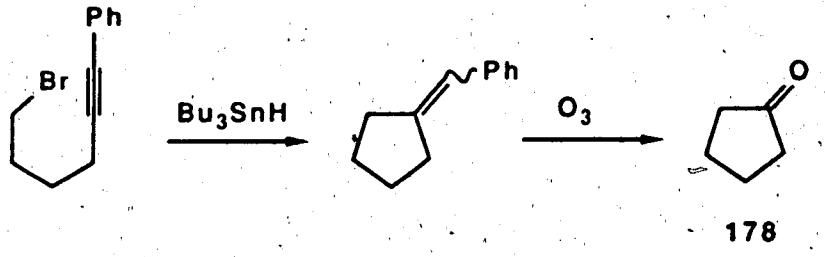
chlorodimethylsilane followed by refluxing with tributyltin hydride gave the cyclic compound **68** in 65% yield. This was essentially one isomer. The stereochemistry of the hydroxyl directs the stereochemistry at position 4 and the cup shape of the resulting tricyclic radical ensures that hydrogen abstraction occurs from the α-face to give the indicated stereochemistry at C-(5). The removal of silicon (KF, 30% H_2O_2), oxidation of the resulting diol

(NaOCl) to ketol **69**, acetylation, and annulation (ethyl acetoacetate) gave the tricyclic enone **70** (eq. 38).[43]



eq. 38

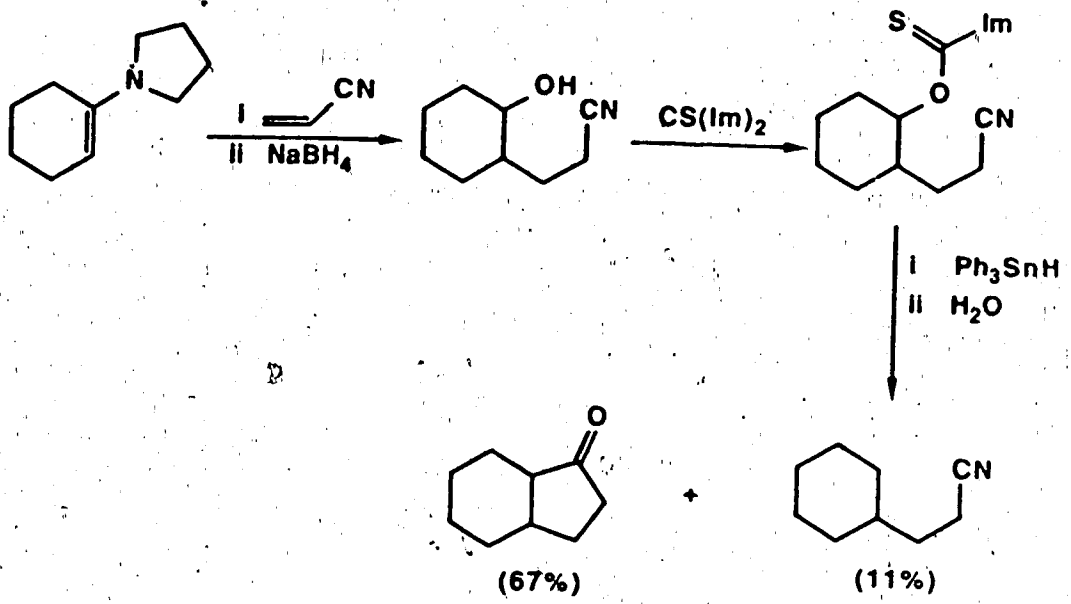
Cyclization of ω-acetylenic radicals has been studied in this laboratory. As shown in (eq. 39), ozonolysis of



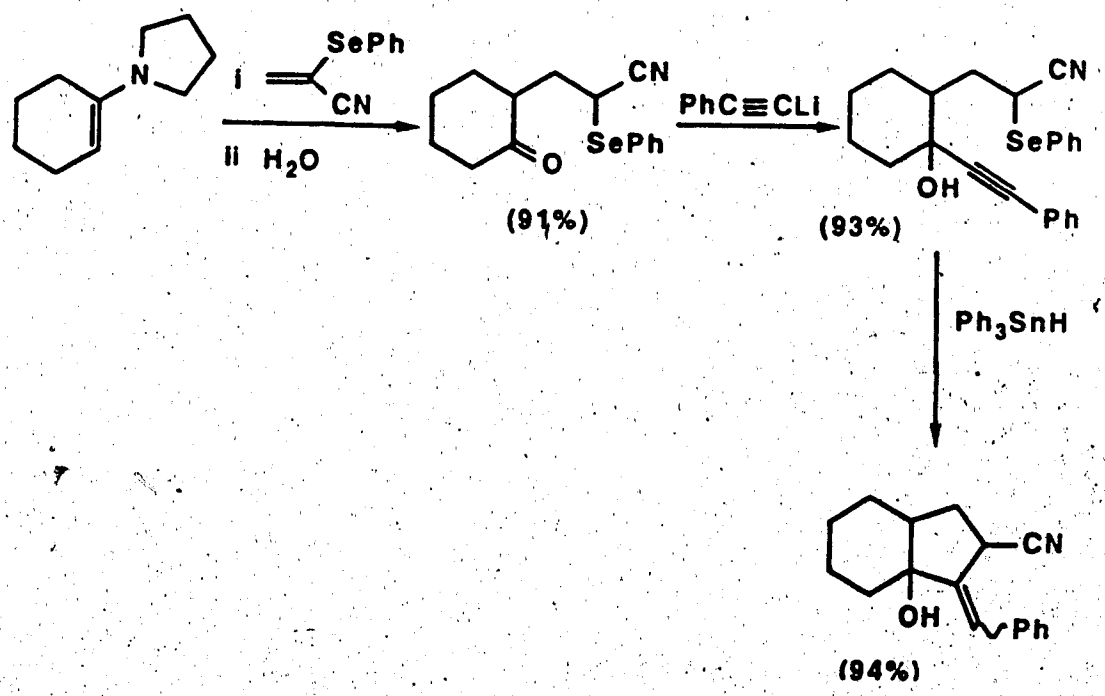
eq. 39

the product affords a ketone which is, of course, a very useful compound class. The aim of the work in this laboratory has been to make the common compound classes (olefins, ketones, allylic alcohols) amenable to the cyclization. Schemes 4-7[44,45,46] summarize what had been accomplished in this regard before my own work was begun.

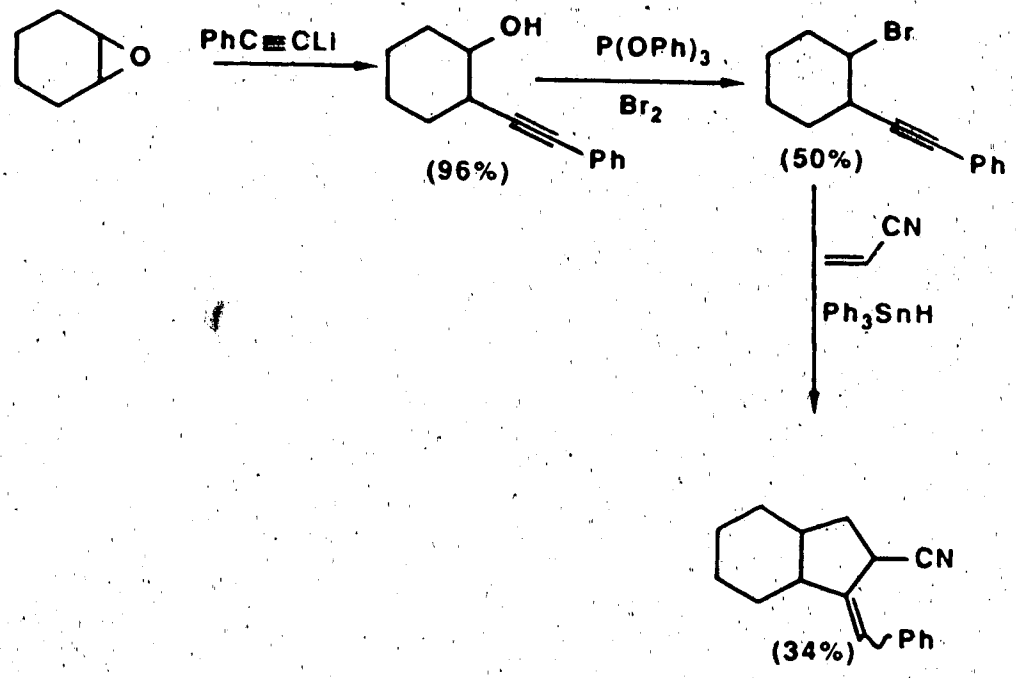
Scheme 4



Scheme 5

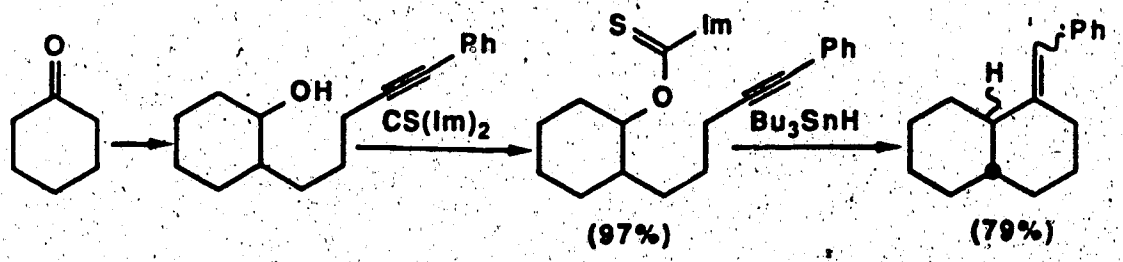


Scheme 6



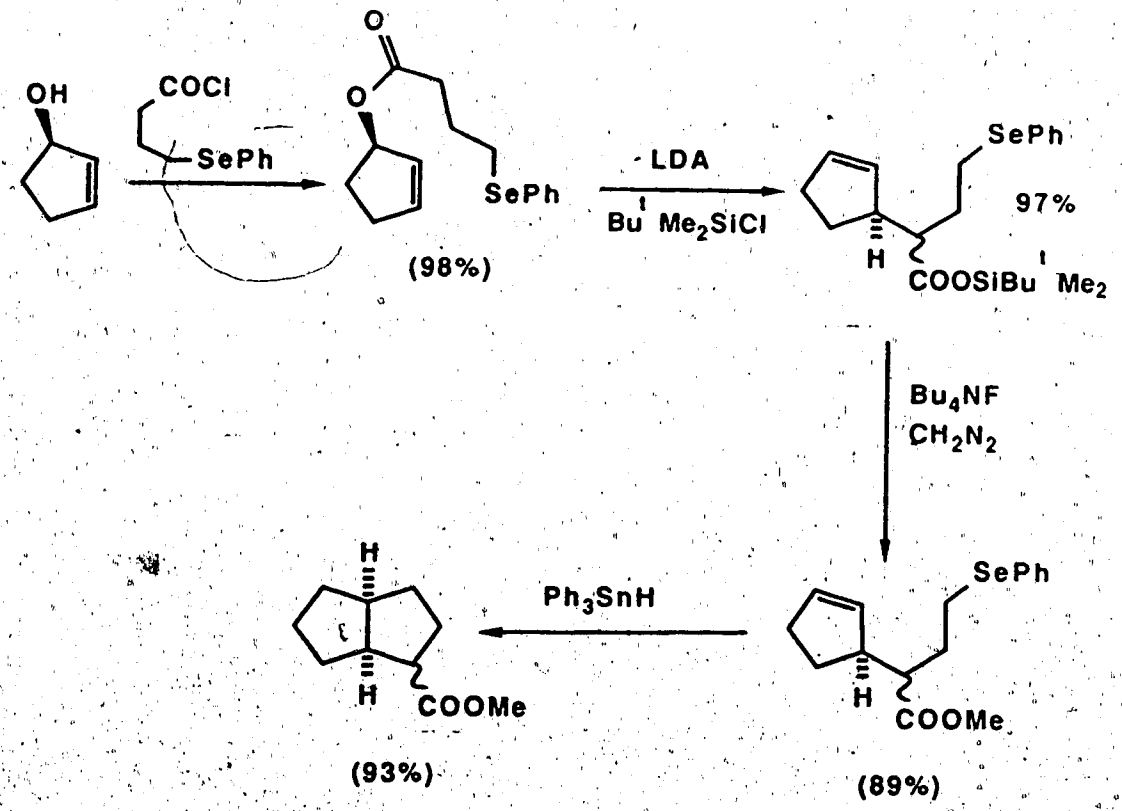
The group had been able to develop convenient methods for converting ketones or olefins into bicyclic compounds Scheme 4-7.[44,45,46]

Scheme 7



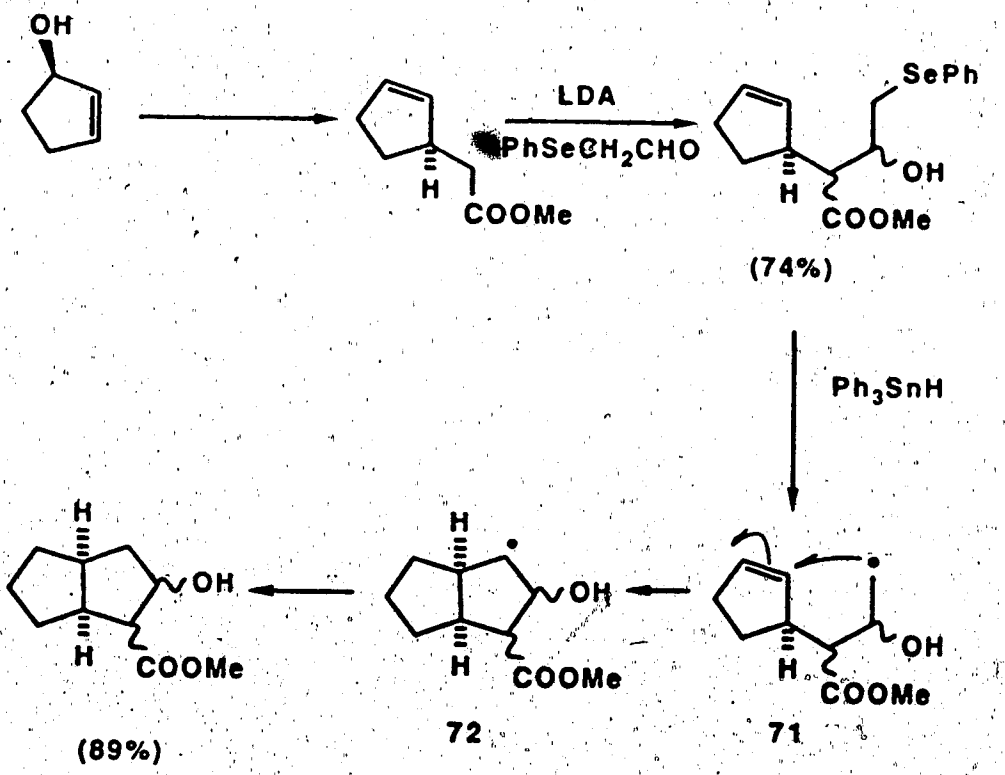
Stereochemical control remained a problem but progress in that area had also been made. Scheme 8[47] shows a procedure for converting allylic alcohols into bicyclic compounds of predictable stereochemistry at the ring fusion atoms.

Scheme 8



Another example of stereochemical control has been studied recently, and will be described in detail in the Discussion section of this work. The radical **71** formed as shown Scheme 9,[48] gave after cyclization, a new radical **72**. In certain circumstances, such as that shown, the ring fusion stereochemistry can be predicted (see Discussion section).

Scheme 9

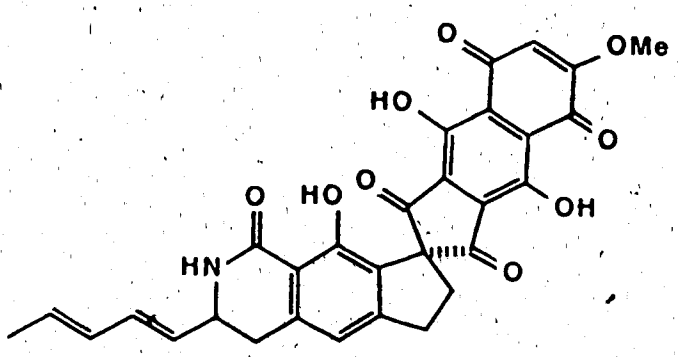


In summary, the use of free radicals to make carbocycles is a promising technique. Widespread adoption of cyclizations based on acetylenic radicals depends upon the development of simple and general methods of access to such species and progress in this area is being made rapidly.

II. RESULTS AND DISCUSSION

A. Synthesis of Spiro Compounds

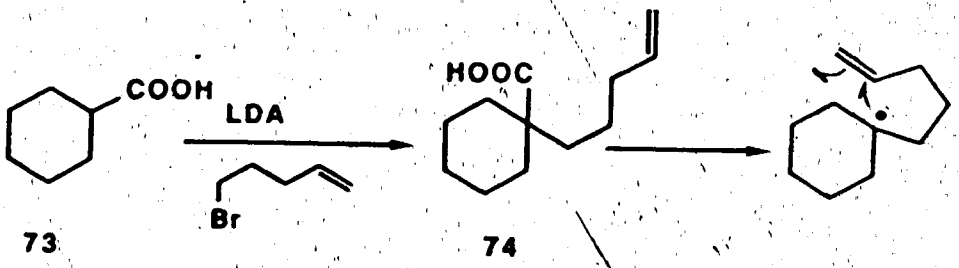
The synthesis of the antitumor antibiotic fredericamycin A,[49] which has the unique spiro structure shown, was being undertaken in this laboratory and the



Fredericamycin A

synthetic approach viewed the central problem as the construction of the spirocyclic system. It was felt that our research in radical cyclizations was suitable to tackle this problem. First of all, in some senses, the central spiro unit can be regarded as congested, certainly making that portion involved making a quaternary carbon. It is known that the transition state for radical addition onto a double bond is an early one and so appropriate radical reactions leading to the generation of a

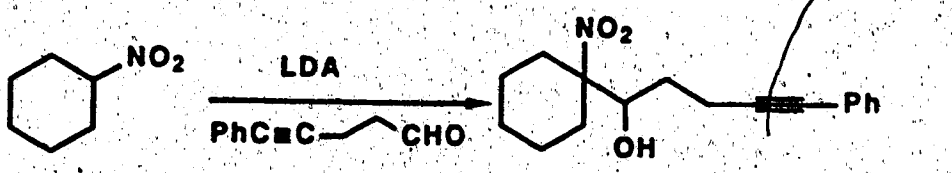
quaternary carbon may not be sensitive to steric factors. On this basis we planned to develop a route to spiro structures based on radical chemistry. The approach we used initially is summarized in (eq. 40). The



73 74 eq.40

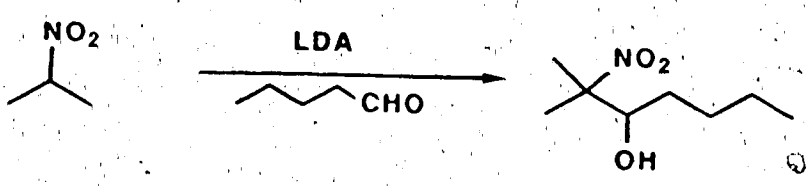
carboxylic acid 73 was doubly deprotonated[50] and reacted with the appropriate olefin. However, our attempt to convert acid 74 to the derivative formed with 2-mercapto-pyridine-N-oxide[51] was unsuccessful so we were unable, therefore, to try the intended radical cyclization.

We next looked at the possibility of using a nitro compound, since it is known through the work of Ono,[23] that tertiary nitro compounds are readily denitrated by radical chemistry. To this end, we took nitrocyclohexane, deprotonated it, and carried out an alkylation with the acetylenic aldehyde shown in (eq. 41). Unfortunately, we



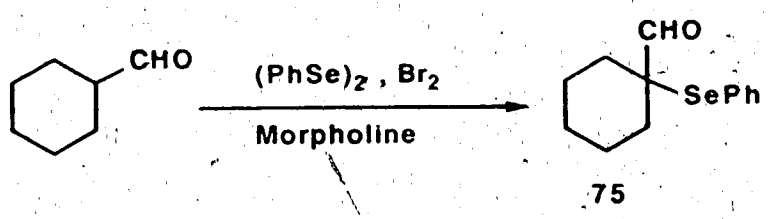
eq.41

were unable to affect this simple Henry reaction and we were equally unsuccessful in converting 2-nitropropane to the corresponding hydroxy alkylated species using a variety of conditions (eq. 42).



eq. 42

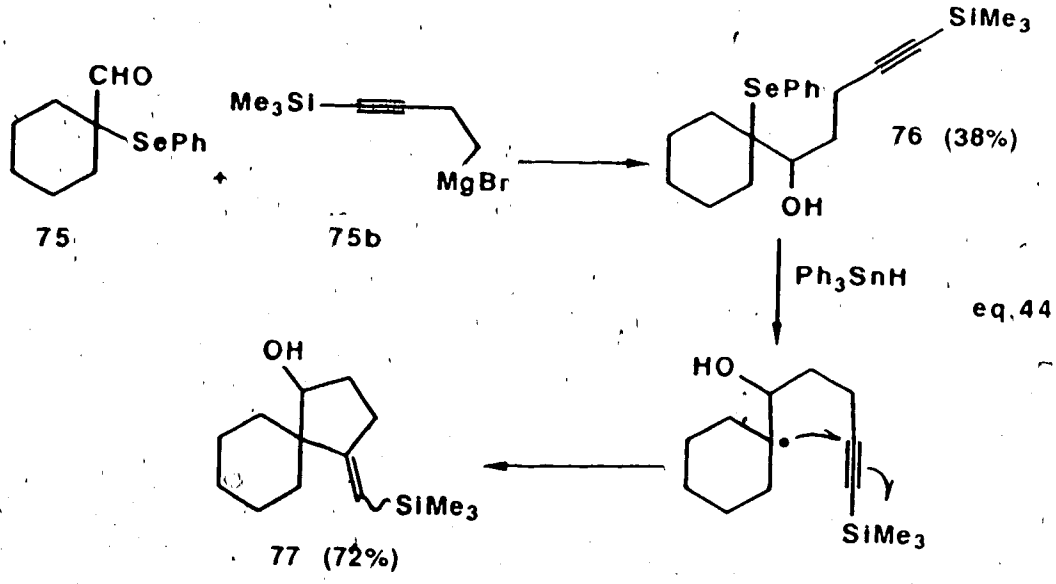
At this stage, therefore, we turn our attention to a slightly different route, summarized in (eq. 44).[52]



75

eq. 43

Cyclohexanecarboxaldehyde was converted into the α-(phenylseleno)carbonyl compound as shown in (eq. 43) using a standard procedure, and the product was treated with the Grignard reagent **75b**[53] to give, although in poor yield (38%), the desired (phenylseleno)acetylene **76**. Compound **76** was correctly set up for radical cyclization because homolysis of the aliphatic C-Se bond would give a radical that could close onto the triple bond. When compound **76** was treated with triphenyltin hydride in benzene, in the

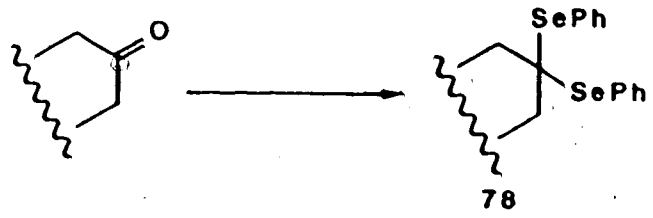


presence of AIBN at reflux, it was possible to isolate the cyclic product 77 in 72% yield. This experiment clearly demonstrated the possibility of preparing spirocyclic compounds that are at an oxidation level suitable for further manipulation.

Having demonstrated the feasibility of the process, we had to find a way of gaining access to the starting materials in a convenient fashion.

It occurred to us that bis(phenylseleno)acetal chemistry could be adapted conveniently for this purpose. It has been reported that carbonyl compounds can be converted by a variety of methods to bis(phenylseleno)-

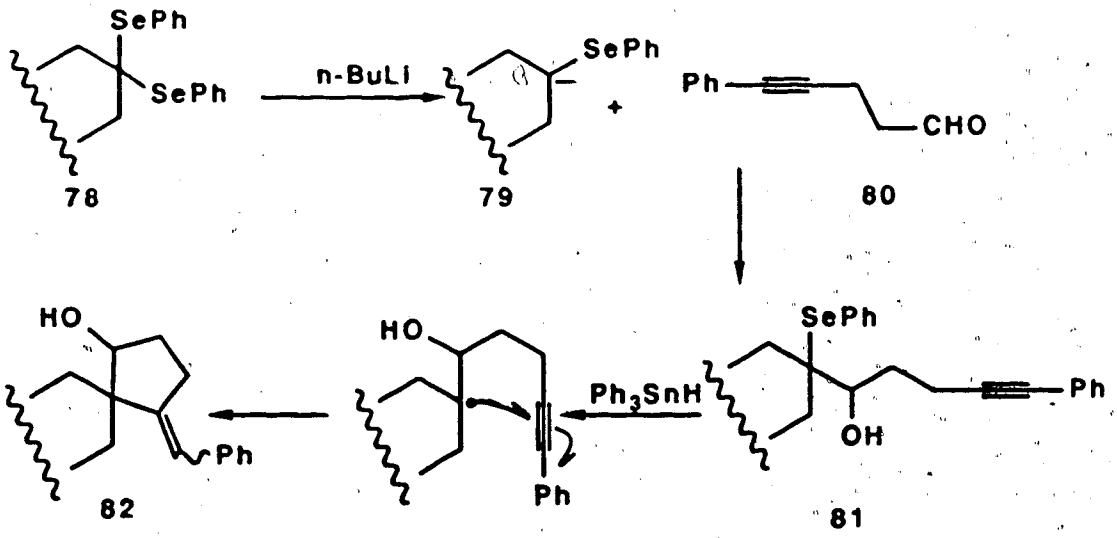
acetals as shown in (eq. 45)[54] and, in fact, several



78 eq. 45

reagents have been developed previously[55,56,57] to effect this transformation. It is known that bis(phenylseleno)-acetals **78**, on treatment with n-butyllithium, generate a selenium-stabilized carbanion **79** (see Scheme 10). We

Scheme 10

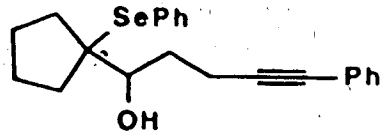
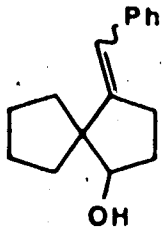
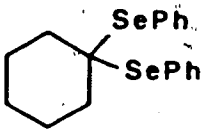
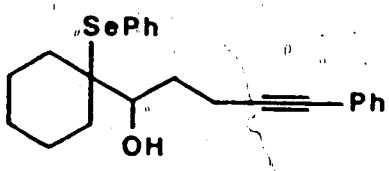
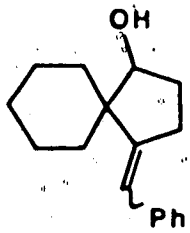
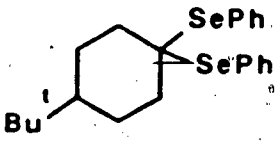
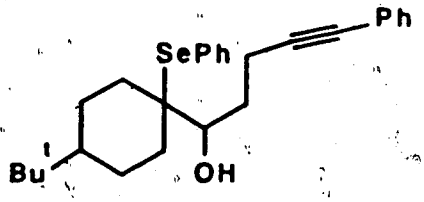
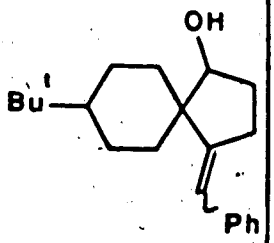
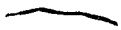
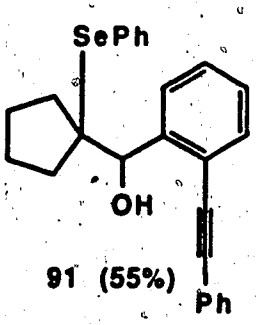
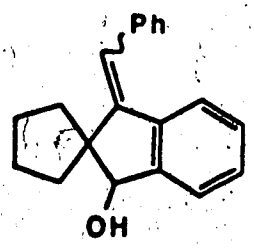


hoped that the carbanion would react with the acetylenic aldehyde 80[60] to afford the desired β-hydroxy selenide 81. On the basis of the experience with our initial experiment, this material, on treatment with triphenyltin hydride, should generate a radical that would undergo cyclization. The whole sequence is then, as follows: The carbonyl carbon is converted first into a carbanion, the carbanion is used in an alkylative or aldol type reaction to attach a pendant chain with a suitably located triple bond, and then the carbonyl carbon is converted into a radical. The radical undergoes cyclization onto the triple bond to give 82.

The early stages of the sequence, i.e. formation of bis(phenylseleno)acetals, their cleavage to selenium-stabilized carbanions, and the use of these carbanions for reactions with simple aldehydes was actually well known[59] but had not been used in the present context. The general procedure shown in Scheme 10 was easily reduced to practice and we have examined a number of examples, our results being collected in Table 5.

The required bis(phenylseleno)acetals were made from the corresponding ketones by literature methods in yields of about 50%.[54,57] No attempt was made to optimize this standard reaction, although it should be noted that when carried out carefully, it is possible to get high

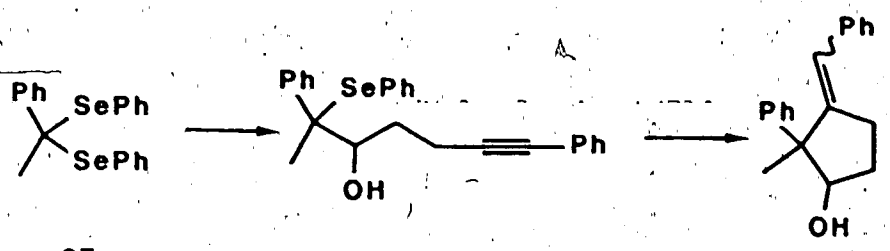
Table 5. Alkylation and cyclization.

Entry	Seleno Acetals	Alkylated product	Cyclized product
1	 84	 88 (74%)	 93 (68%)
2	 85	 89 (65%)	 94 (75%)
3	 86	 90 (86%)	 95 (86%)
4	 84	 91 (55%)	 96 (91%)

yields.[56] The carbanions (c.f. Scheme 10) were generated by the action of n-butyllithium (1 equiv.) in hexanes at -78°C (ca. 5 min), and were then quenched by rapid addition of an aldehyde: 5-phenylpent-4-ynal **80**[60] or 2-(phenylethynyl)benzaldehyde **83**.[61] The desired hydroxy selenides **81** were isolated after a brief reaction period (ca. 2 min) in yields of 50-86%.

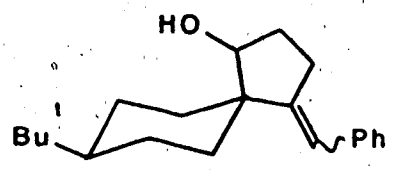
The cyclizations shown in the table were carried out by our general procedure: dilute benzene solutions of triphenyltin hydride (1.1-1.4 mmol per mmol **81**, 0.2-0.4 M) and of azobisisobutyronitrile (0.10-0.23 mmol per mmol **81**, 0.01 M) were added simultaneously over 7-8 h (syringe pump) to a refluxing solution of substrate **81** (0.02-0.04 M) in benzene. After the end of the addition, refluxing was arbitrarily continued for 2-6 h and the products were isolated in the yields shown.

Some comment about the stereochemical composition of the products is in order. Compounds **93**, **94**, and **96** were two geometrical isomers readily discernable by the presence of two vinyl signals in the ^{1}H NMR spectra. The ^{13}C spectra also showed the presence of two compounds. In the case of **97** (eq. 46) there is an additional stereochemical complication because two asymetric centres are present. Although we expect 4 isomers as racemic forms, only 2 were isolated from the reaction mixture. The

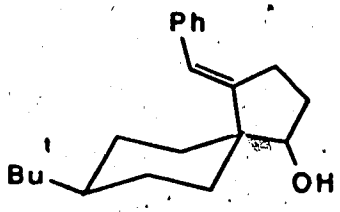


87 92 (51%) 97 (64%) eq. 46

cyclization product **95** was separated chromatographically into two components; **98** and **99** (39% and 47% isolated



99 (47%)

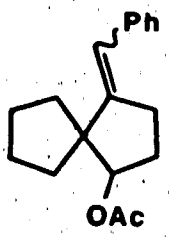
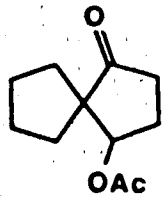
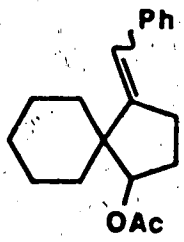
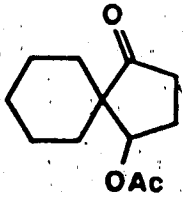
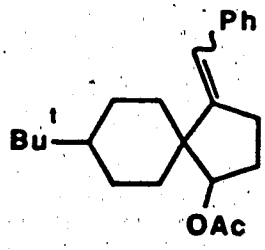
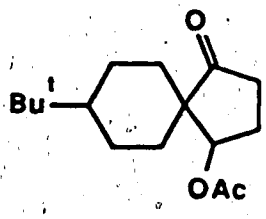
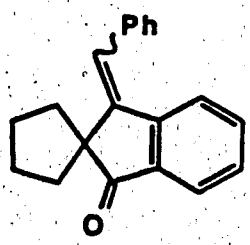


98 (39%)

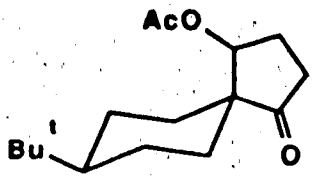
The chair conformations shown and the E-geometry for **98** are arbitrary assignments in this case. All the cyclized products were acetylated and the resulting acetates were subjected to ozonolysis, to produce the corresponding cyclopentanones (ν_{max} 1740 cm^{-1}).

In the particular case of **96**, ozonolysis was not used; instead the radical cyclization product was oxidized to cyclopentanone **108** (see Table 6). Acetylation of **98** and **99** to **102** and **103**, respectively, proceeded smoothly and ozonolysis gave the expected products to which we assign structures **106** and **107**. The yields are 89% and 80%, respectively. The acetoxy ketones are known compounds and

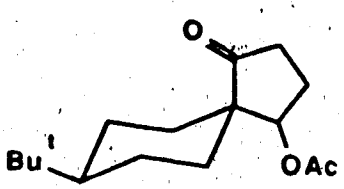
Table 6. Acylation and Ozonolysis / or Oxidation.

Entry	Alcohol	Acetate	Ozonized or Oxidized product
1	93	 100 (94%)	 104 (65%)
2	94	 101 (88%)	 105 (64%)
3	95	 102 (63%) 103 (90%)	 106 (80%) 107 (85%)
4	96	 108 (83%)	

our samples had the reported spectral characteristics.[62]

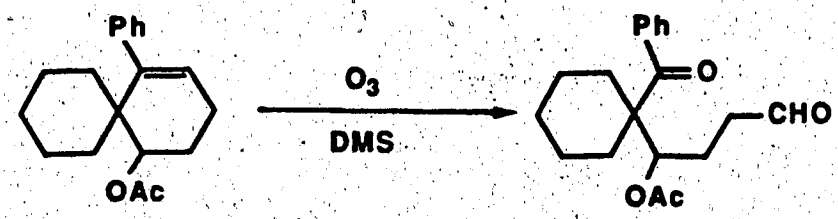


106 (80%)



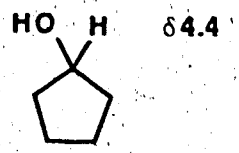
107 (85%)

During the course of this study, we were concerned about the nature (5-exo or 6-endo) of the radical cyclization. The isolation of 5-membered ketones as described above was undertaken in order to establish which of these two pathways had been followed. In the cases of **100** and **101**, a further test was carried out. The ozonolysis was conducted and the total ozonolysis mixture, before attempted isolation of the products, was examined by high field ^{1}H NMR. Only one aldehyde signal corresponding to the chemical shift of benzaldehyde was present in each case. Had there been any product resulting from 6-endo closure, we would again have obtained an aldehyde signal, but that signal would be split into a triplet because the product would have been of the structure shown in (eq. 47).

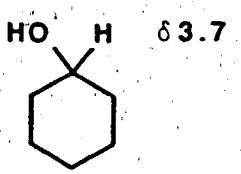


eq. 47

The ozonolysis experiments also served the synthetically important purpose of proving that the cyclization products are synthetically equivalent to ketones. We had initially hoped that we could determine the 5-exo or 6-endo nature of the cyclization by examination of the chemical shift of the $>C<^{H}_{O}$ signal. This proved not to be a reliable indicator of ring size. The methine H signal of cyclopentanol occurs ($CDCl_3$) at δ4.4 and the value for cyclohexanol is δ3.7. However, we



δ4.4



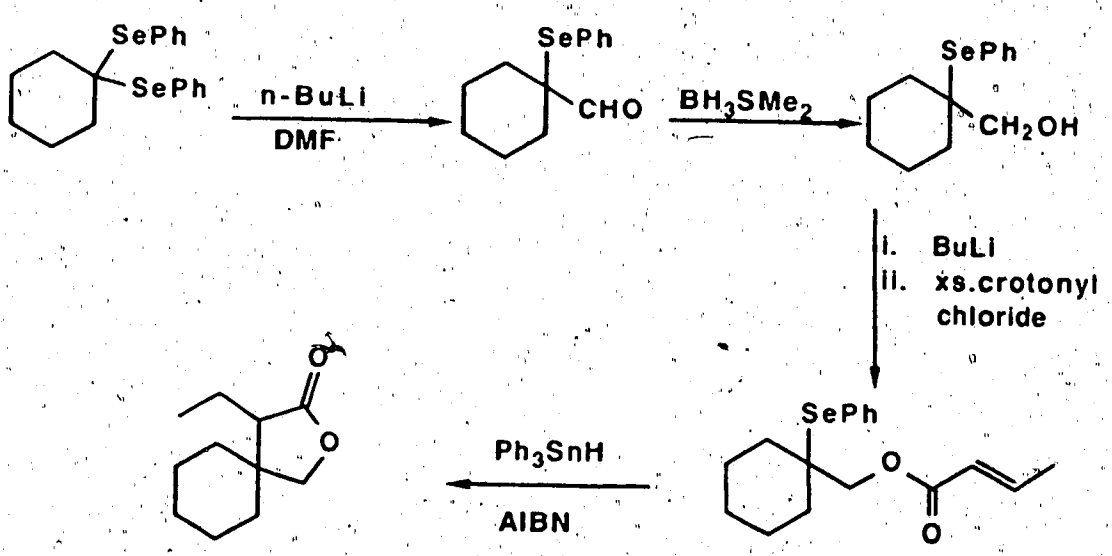
δ3.7

observed signals in the range δ3.5-4.9 for the cyclization products even though each one is a cyclopentanol derivative.

In our experiments, we have used Ph-C≡C- rather than -C≡C-H or -C≡C-CH_3 units, in order to minimize potential problems due to 6-endo closure, but it is not yet clear whether this precaution is necessary. There are some examples in the literature in which radical cyclization onto an acetylene proceeds by 6-endo closure[63] but precise reasons for that are not understood. The present methodology based on selenoacetals and radical cyclization is likely to be quite versatile, it is certainly not

limited to the production of spiro-carbocycles. For example, it can easily be adapted (Scheme 11)[65] for spiro-lactones.

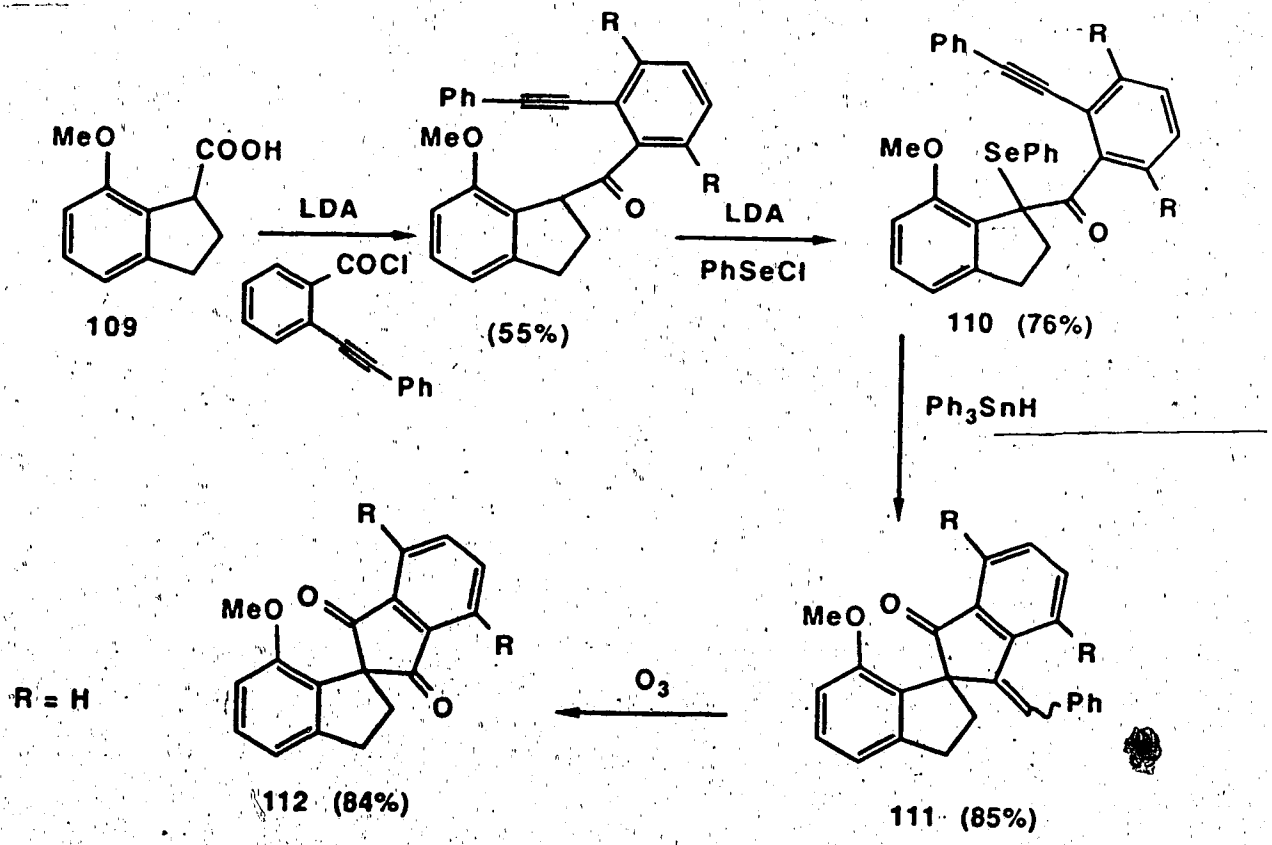
Scheme 11



Since the original intention of our work was to develop a methodology that could be applied to the synthesis of fredericamycin A, we were pleased to observe that the ring closure of **91** to **96** (see Table 5) proceeded in excellent yield. Presumably the rigidity of the system ensures that the triple bond is held close to the radical

that is generated. In point of fact, this method has been applied as shown in Scheme 12[66] to an on-going synthesis of fredericamycin A.

Scheme 12



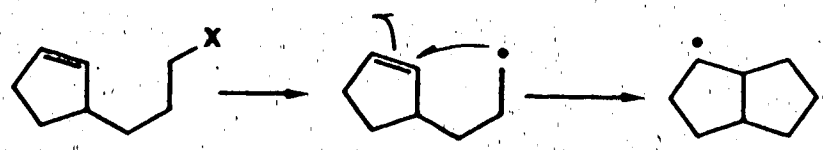
Thus, the acid **109** was transformed by the method summarized in Scheme 12, into (phenylseleno)ketone **110** and, on treatment with triphenyltin hydride, it underwent radical cyclization to give **111**. Ozonolysis then gave diketone **112**. This procedure has also been adapted to those cases in which R = OMe, thereby forming the central portion of the antitumor agent.

Finally, it should be noted that we confined our attention to acetylenes that lead, after cyclization, to 5-membered rings. We have not tested the possibility of making 6-membered rings - a process that may be complicated by abstraction of propargylic hydrogen.

B. Preparation of trans Ring-fused Bicyclic Compounds

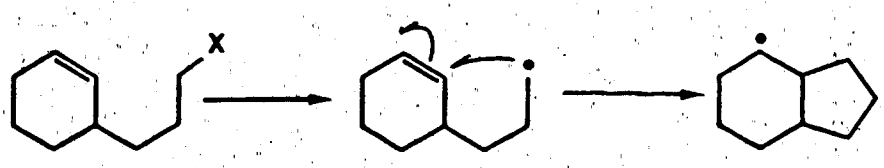
As described previously, one of the main problems in the use of radical cyclization is in the development of simple methods for assembling the precursors to the appropriate unsaturated radical species. It occurred to us that it should be possible to combine the well-established aldol reaction with the new technique of radical cyclization. An attractive feature of this combination was the possibility of controlling certain aspects of the stereochemistry of the products. When a bicyclic compound is formed by a sequence of the type

shown in (eq. 48) the stereochemistry of the ring



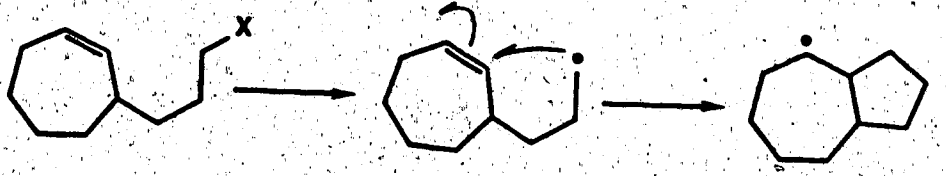
eq.48

fusion can be predicted.[67] In order to discuss this, it is useful to introduce a simple nomenclature. The ring closure shown in (eq. 48) will be described as a 5-exo-[endo-5] process. The first part of the name "5-exo" has the standard definition and indicates the formation of a 5-membered ring by an exo trigonal cyclization. The parenthetical prefix "endo" indicates the status of the double bond onto which the radical closes; in this case, the double bond is endocyclic to a five membered ring. The sequence shown in (eq. 49) is, correspondingly, a



eq. 49

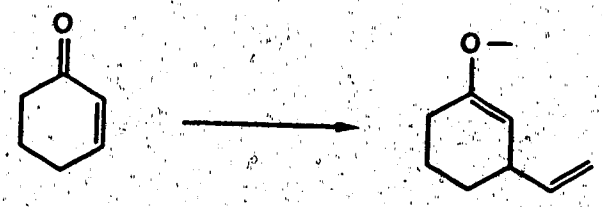
5-exo-[endo-6] closure and that shown in (eq. 50) is a 5-exo-[endo-7] example.



eq. 50

It turns out that prior experience has shown that the formation of trans ring-fusion in the case of 5-exo-[endo-5] and 5-exo-[endo-6] reactions is strongly disfavoured,

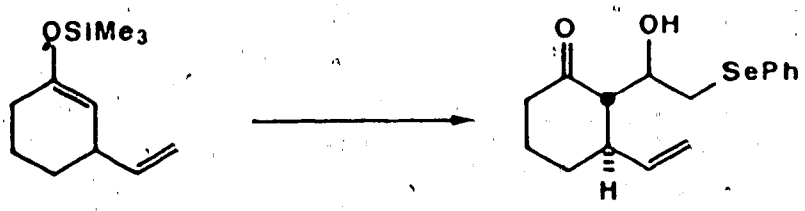
while in the last example, 5-exo-[endo-7], the trans ring-fusion is allowed. On this basis then it is important to note that radical cyclizations of the type shown in (eq. 48) are processes where a bicyclic material is formed in such a manner that the last bond to be produced is a bond to one of the ring fusion atoms. Processes like this will invariably lead, for ring sizes 5,5 and 5,6, to cis ring-fusion. It occurred to us that the aldol reaction using (phenyiseleno)acetaldehyde,[68] a reagent that had been employed in a totally different context in this laboratory,[69] would allow us to make substances by radical ring closure which had either trans or cis ring-fusion. The latter would involve processes in which the last bond to be formed was a bond to the ring fusion atom, whereas the former would involve processes in which that bond was not one to a ring-fusion atom. For example, organocuprate delivery of a vinyl unit to an α,β-unsaturated system is well known to proceed as shown in (eq. 51).



eq. 51

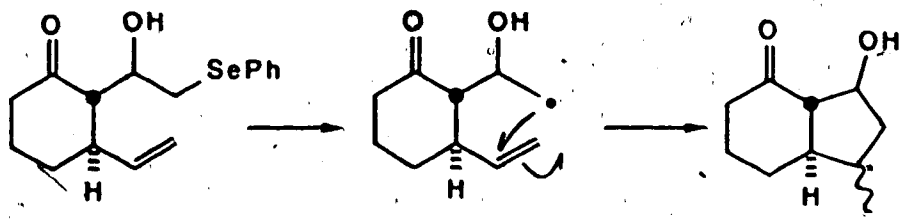
If the resulting enolate were then trapped by (phenyl-seleno)acetaldehyde, it should, according to prior

experience, proceed with the stereochemical result shown, that is to say, the two pendants would bear a trans relationship to one another (eq. 52).



eq. 52

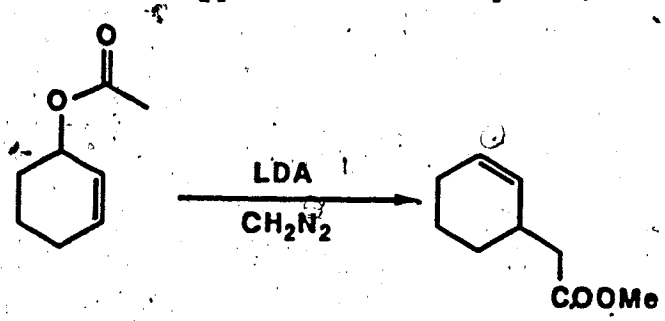
Now the selenium unit could be used to create a radical, and this radical would undergo 5-exo closure as in (eq. 53).



eq. 53

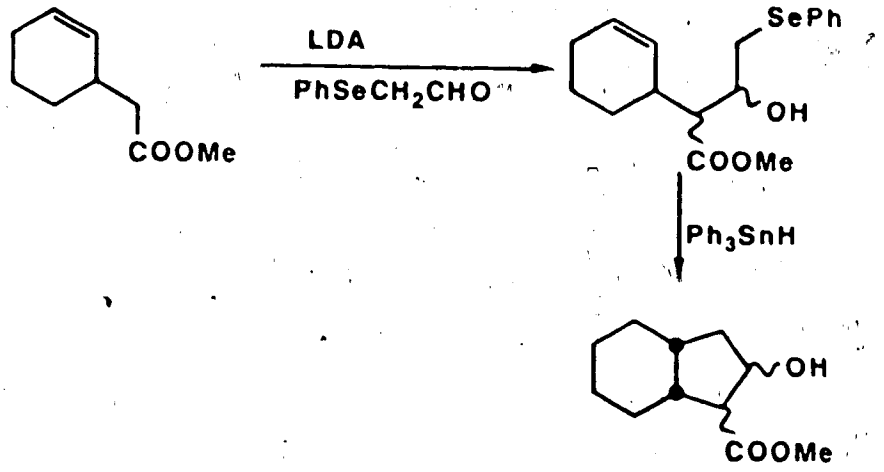
This type of process then permits the formation of a trans ring-fused 5 6 bicyclic system. There is still the problem of stereochemical control at the asymmetric centre marked with an asterisk (see eq. 53).

To make cis-fused compounds, one would begin with an ester of the type shown in (eq. 54). Deprotonation and



eq. 54

aldol reaction with (phenylseleno)acetaldehyde, as summarized in (eq. 55) would be followed by radical cyclization. Ring closure now is of the standard 5-*exo*-[*endo*-5] type and should proceed to give *cis* ring-fusion. This aspect of the work has been pursued in this laboratory by D.R. Cheshire.

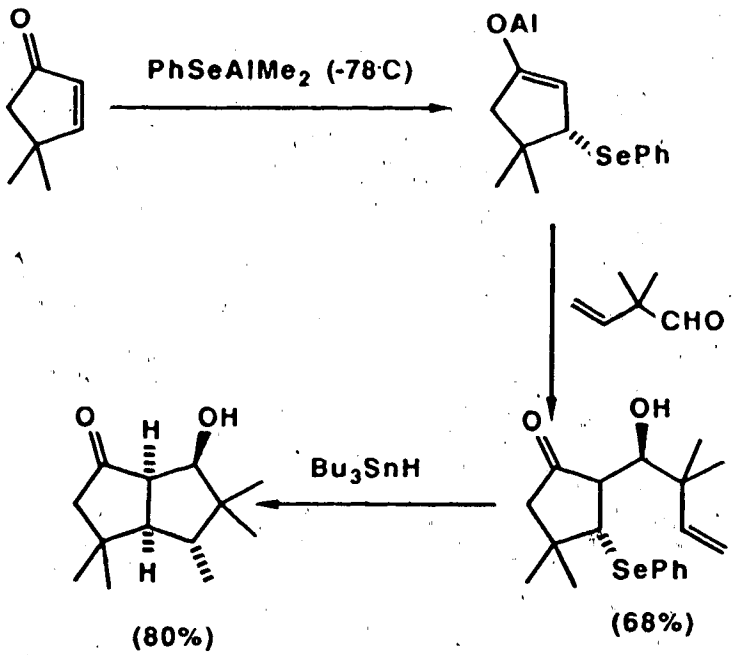


eq. 55

The aldol reaction can be used in a different manner (Scheme 13) to yield a *cis*-fused system, and this approach was reported recently.[70]

My own research involved developing the route to *trans* ring-fused compounds. As described above, this involved the formation of ketones with *trans* pendants, one being the vinylic unit and the other one being a pendant derived from (phenylseleno)acetaldehyde.

Scheme 13

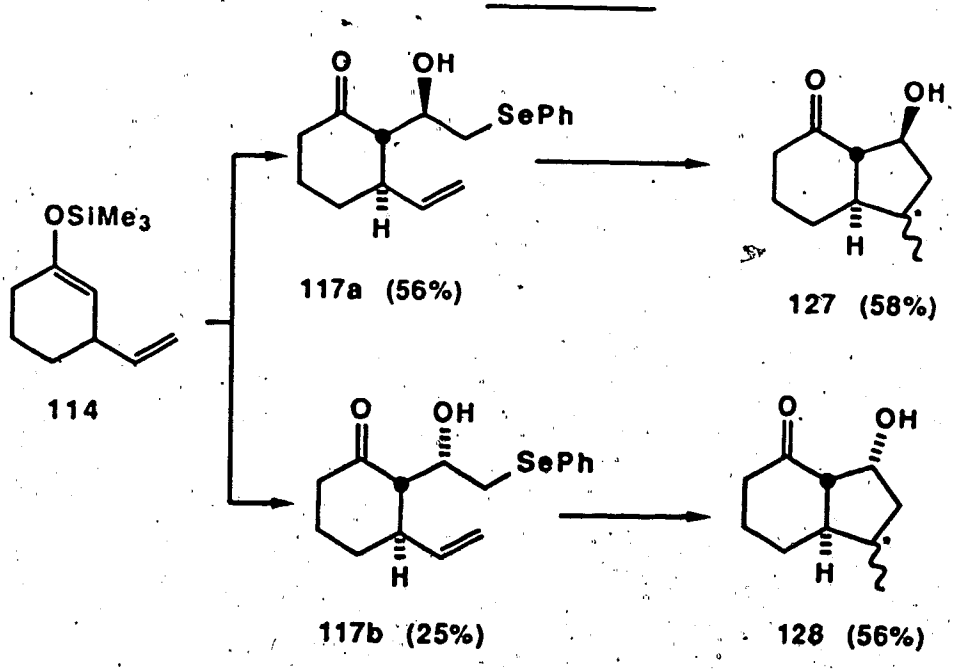


In our first example, divinyllithium cuprate was allowed to react with the 2-cyclohexenone and the resulting enolate was trapped by silylation.[71] The silyl enol ether was then subjected to standard conditions previously worked out in this laboratory for aldol condensations with (phenylseleno)acetaldehyde.[69,73] As had been found earlier, the reaction proceeded in high yield to give a mixture of two isomers 117a and 117b, in both of which the pendants to the six membered ring bear a trans relationship. The differences between the two

isomers is due to the fact that they are epimeric at the hydroxyl-bearing carbon. The isomers were separated and subjected to our standard method of radical cyclization, i.e. dilute benzene solutions of triphenyltin hydride and of AIBN were injected simultaneously into a refluxing solution of compound **117a**. The aliphatic C-Se bond was broken by homolysis and the radical underwent cyclization to give **127**.

We noticed a high degree of stereoselectivity in this process and these products vary in terms of the stereochemistry marked by an asterisk in Scheme 14, the ratio of the isomers being 4:1 for **127**.

Scheme 14

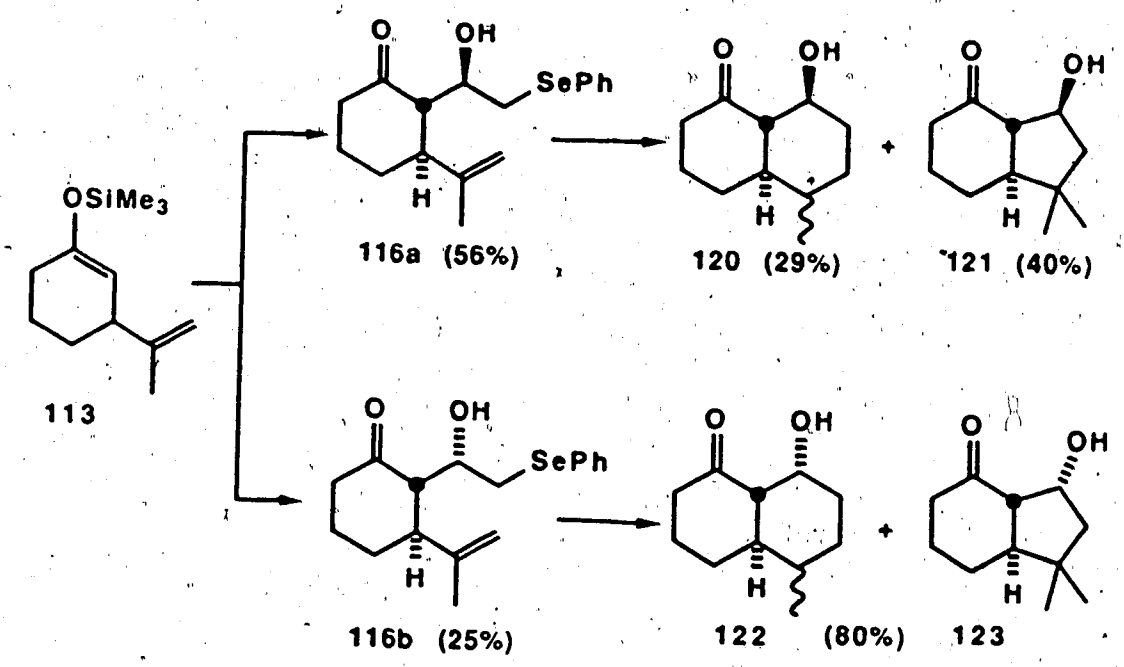


Having demonstrated the feasibility of the process, we then sought to extend it. For the next experiment we took the other isomer that had been formed from the silyl enol ether, i.e. **117b**. When subjected to the standard cyclization conditions, it gave a mixture of products **128** (56%) differing in stereochemistry at the marked centre. The isomer ratio was 9:1.

It was of interest to see what would happen if the pendant group that had been added by organo copper chemistry was substituted. For this purpose we treated 2-cyclohexenone with dipropenylmagnesium cuprate and trapped the enolate in the usual way with chlorotrimethylsilane. The silyl enol ether was converted into its enolate which was then allowed to undergo aldol condensation with (phenylseleno)acetaldehyde. We obtained once more a mixture of two isomers, epimeric at the hydroxyl-bearing carbon. They were easily separated by chromatography and were cyclized individually. The isomer of higher R_f **116a** gave two products, **120** and **121** in 29% and 40% yield, respectively. Compound **121** was a single substance but **120** was a mixture of two materials in a ratio of 2:3. Likewise **116b** gave **122** and **123** as an inseparable mixture of isomers.

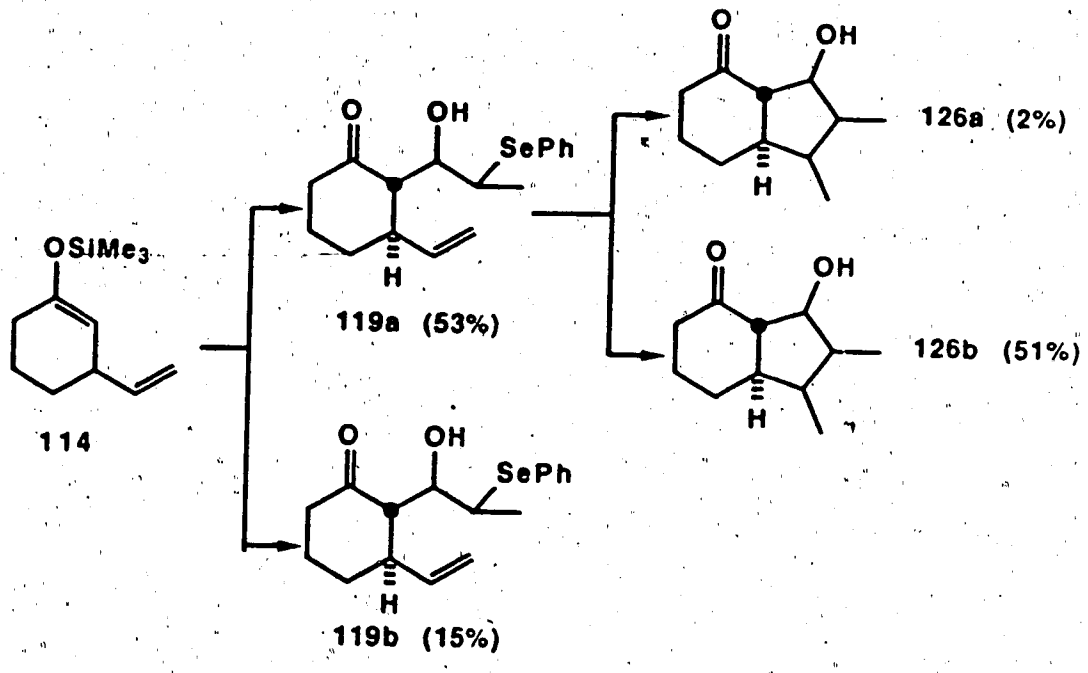
The occurance of both 5-*exo* and 6-*endo* closure is understandable. It is known, through the work of

Scheme 15



Beckwith,[6] that a substituent in the 5 position of the hexenyl radical considerably slows down the rate of 5-exo closure. Consequently, the proportion of 6-endo closure is increased and this is exactly what we observe in the present case. We also examined the possibility of extending the reaction to higher aldehydes apart from (phenylseleno)acetaldehyde. Propionaldehyde was converted in the usual manner to 2-(phenylseleno)propanal,[72] which was used in the aldol reaction with the silyl enol ether

Scheme 16

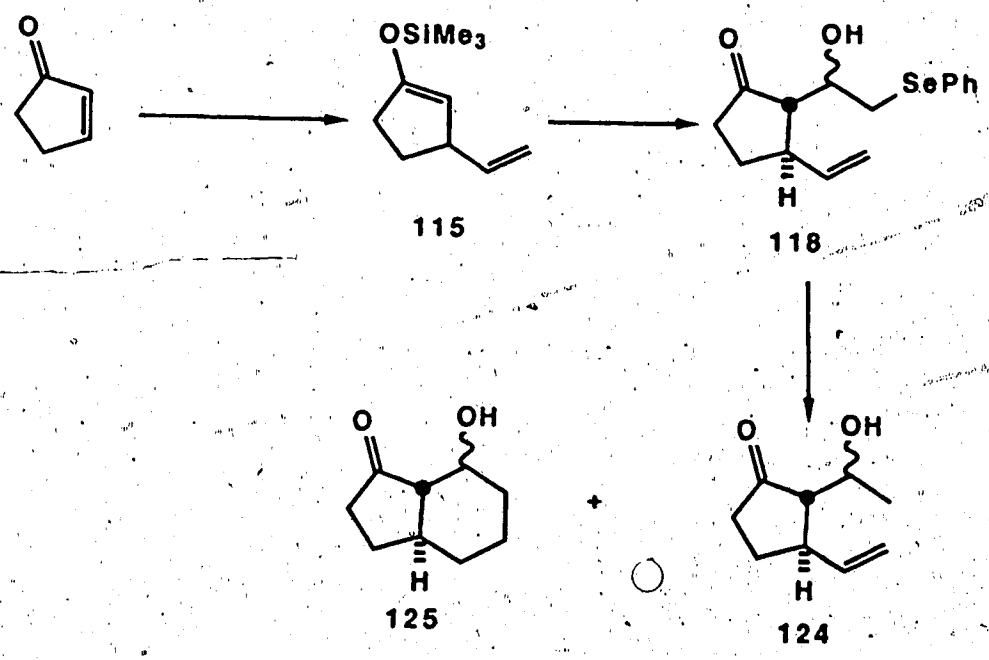


114. Compounds 119a and 119b were formed. The former was isolated in 53% yield as one isomer. We did not examine 119b which was a mixture of several isomers. The single isomer 119a underwent radical cyclization and, as expected, the process occurred by the 5-exo route to give 126a, again as a mixture of two isomers whose detailed stereochemistry was not determined. Another fraction, 126b, composed of another two isomers, was isolated in 51% yield.

Finally, we examined the use of cyclopentenone.

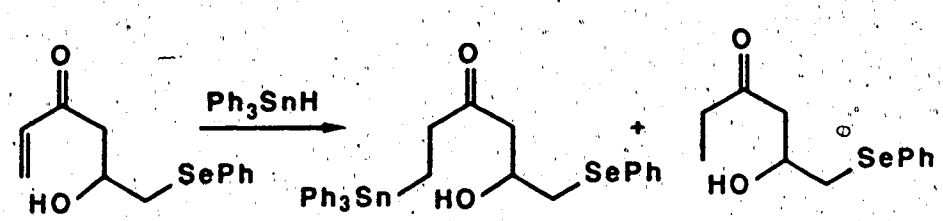
However, we realized that in the resulting aldol condensation product **118**, the trans disposition of the two groups strongly disfavours 5-exo closure, because such reaction would result in the highly strained trans 5,5 fused system. We anticipated that the closure might follow the 6-endo path.

Scheme 17



In the event, some of the 6-endo product **125** was formed but only in poor yield. The main product that we observed was the simple reduction product **124**, which was partially resolved chromatographically.

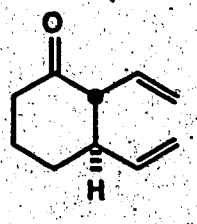
The hydroxy selenide **138** obtained from reaction of 2-(trimethylsilyloxy)-1,3-butadiene and (phenylseleno)-acetaldehyde failed to undergo cyclization and instead gave **139** and **140** in 23% and 22% yield, respectively.



138 **139 (23%)** **140 (22%)** eq. 56

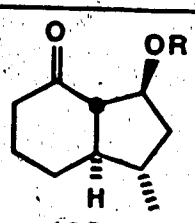
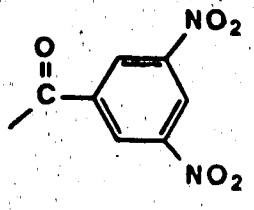
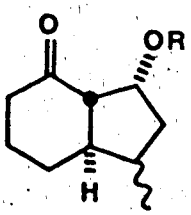
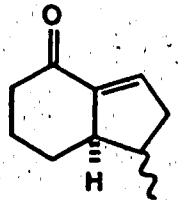
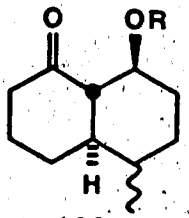
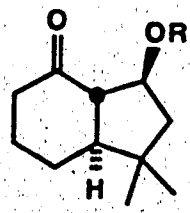
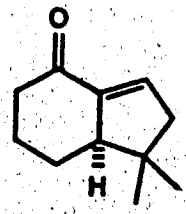
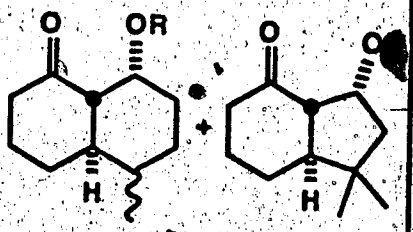
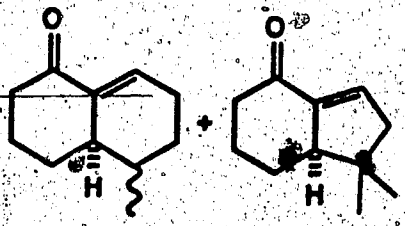
Clearly this type of aldol reaction in which the PhSe-unit is α to the aldehyde is best used with six-membered and presumably with larger rings. Some comment about the stereochemistry of the materials shown in Table 7 is in order.

Earlier work in this laboratory had involved transformation of compound **117a** into the corresponding divinyl ketone **141**[69] whose ^{1}H NMR spectrum showed clearly



141

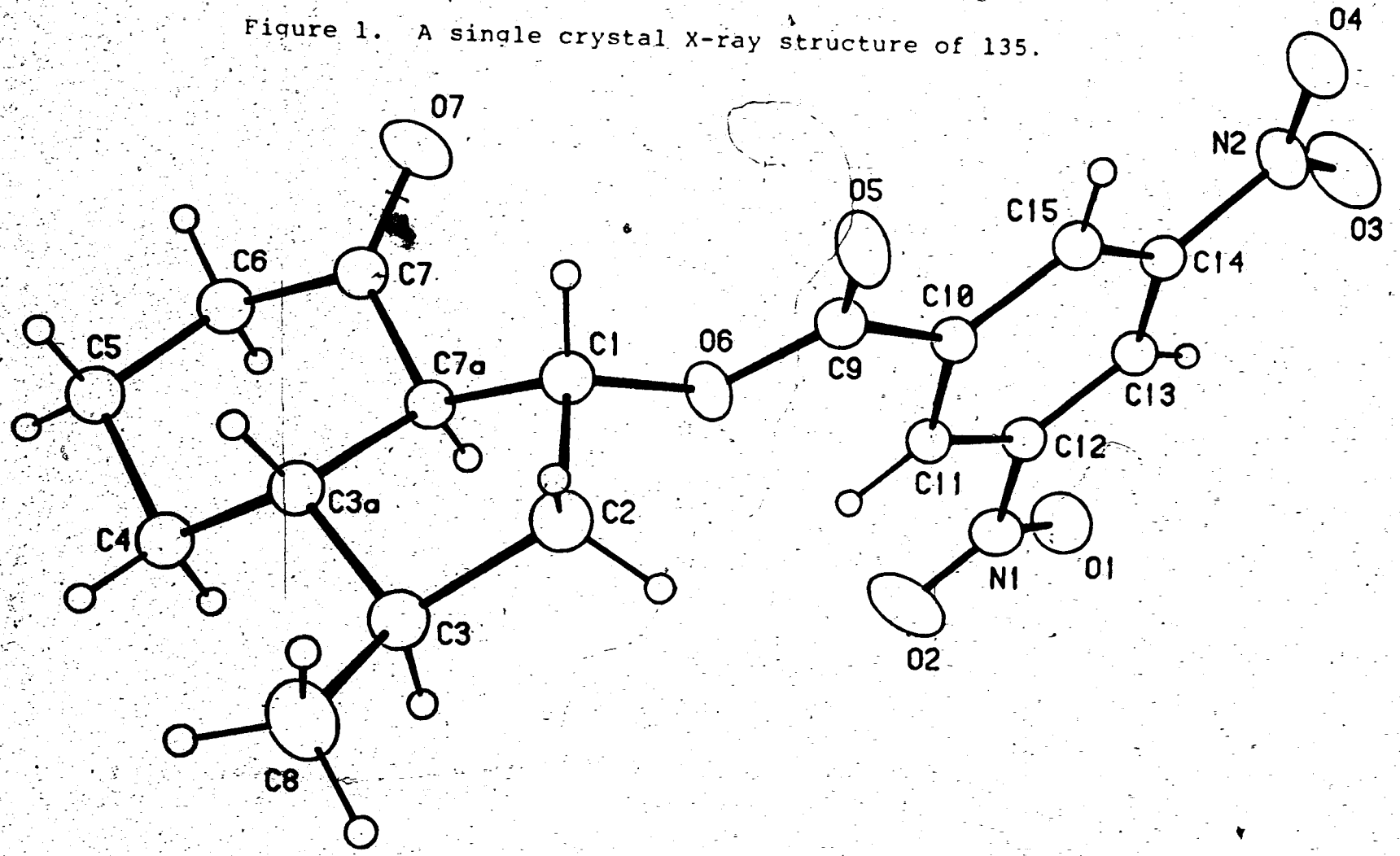
Table 7. Acylation of alcohols.

Entry	Alcohol	3,5 -Dinitrobenzoate	eliminated product
1	127	 135	R = 
2	128	 137	 136
3	120	 129	—
4	121	 131	 130
5	122+123	 133 134	 132 130

precursor **117a** has the same stereochemistry although we did not know the stereochemistry of the hydroxyl group. In the case of the radical cyclization product from the faster-running aldol **117a** we prepared a crystalline 3,5-dinitrobenzoate. The major isomer was recrystallized from ethanol and a single crystal X-ray analysis then defined the stereochemistry (Figure 1). Hence, the stereochemistry of **117a** and **117b** could be assigned. In the case of **120** (Scheme 15), the hydroxyl is in a 6-membered ring, and after conversion of **120** to **129** (see Table 7), standard ^1H NMR analysis of the appropriate coupling constants, served to define the stereochemistry shown and hence also of the starting material **116a** (Scheme 15). Consequently, the opposite stereochemistry was applicable to **116b**. Thus, we can also specify the stereochemistry of **121** (Scheme 15). Conversion of alcohols **121**, **123**, **122** (Scheme 15) and **128** (Scheme 14) to the corresponding 3,5-dinitrobenzoates produced some eliminated products **130**, **132**, and **136** (Table 7).

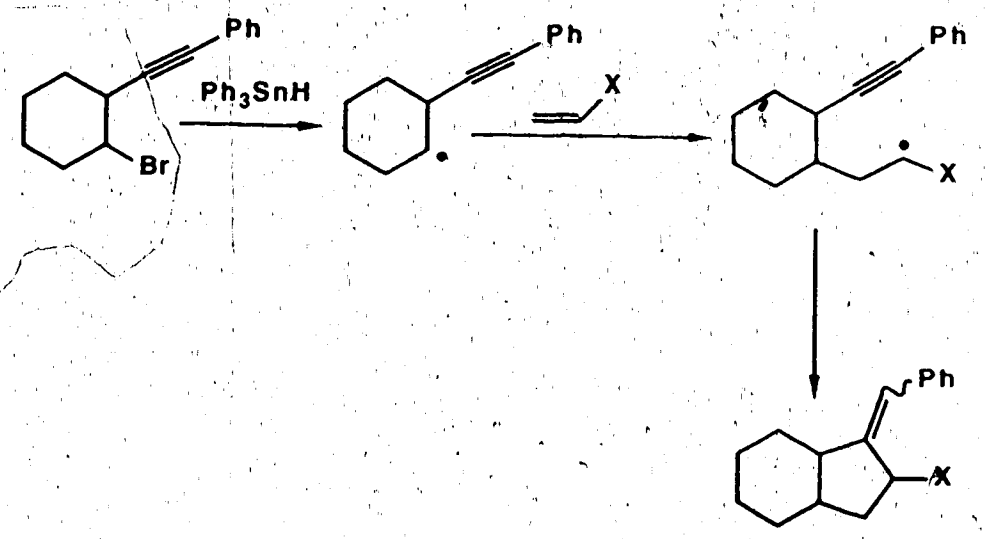
In conclusion, (phenylseleno)acetaldehyde as well as, in principle, higher α-(phenylseleno)aldehydes, can be used with conjugate vinyl addition, aldol condensation, and radical cyclization to give in favourable cases 5,6-systems of clearly defined geometry, the important point being that the ring fusion geometry is trans.

Figure 1. A single crystal X-ray structure of 135.



C. Radical Annulation Reactions

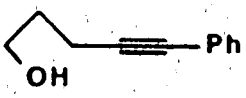
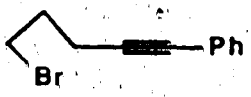
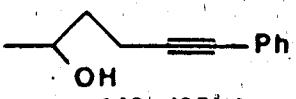
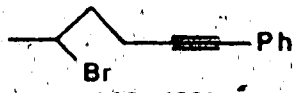
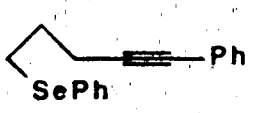
During the course of my studies, other work on radical cyclization was being pursued in the group. One process discovered, called radical annulation, was a sequence in which two bonds in a newly formed ring were made by radical processes. Equation 57 summarizes a typical example.[77] I undertook to see whether this



eq. 57

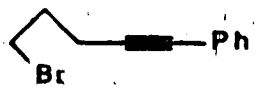
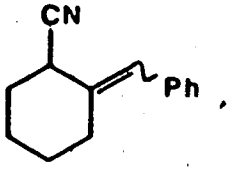
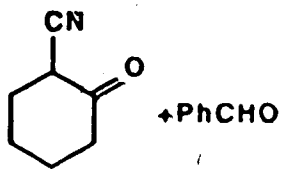
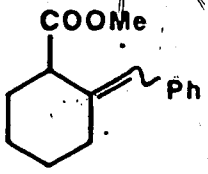
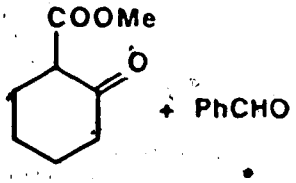
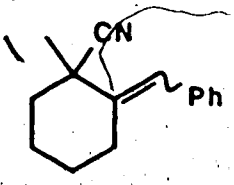
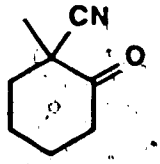
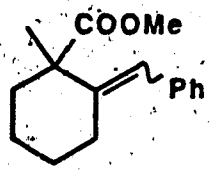
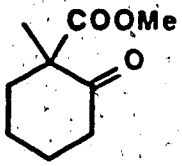
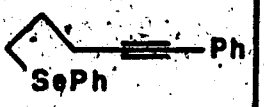
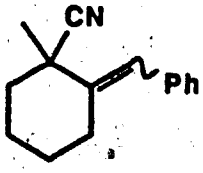
procedure could be applied to make 6-membered rings. Accordingly, a number of bromides such as **148**, **149**, and also selenide **151** were prepared (Table 8). These substances were made from the corresponding alcohols, the latter being obtained by reaction of oxetanes, lithium phenyl acetylide, and boron trifluoride etherate.[78] The hydroxyl groups in the case of **142** and **143** were treated with triphenylphosphite, bromine, and pyridine,[79] and in

Table 8. Preparation of Bromides and Selenide.

Entry	Oxetane	Alcohol	Bromide
1		 OH 142 (83%)	 Br 149 (89%)
2		 OH 143 (25%)	 Br 148 (60%)
3		142	 SePh 151 (80%)

the case of selenide 151 the standard procedure involving the reaction between an alcohol and N-(phenylseleno)-phthalimide and tributylphosphine was employed.[80] The bromide 149 was mixed with a large excess of acrylonitrile in benzene at reflux and to this mixture was added 1.2 equivalents of triphenyltin hydride and 0.1 equivalents of AIBN over 10 h. It was possible to isolate the desired product 156 in 33% yield as a mixture of geometrical isomers (Table 9, Entry 1). The isomers could be

Table 9. Annulation of 1° Bromide, Selenide and Ozonolysis.

Entry	Starting material	Cyclized product	Ozonized product
1	 149	 156 (33%)	 174
2	149	 157 (21%)	 175
3	149	 158 (70%)	 171 (63%)
4	149	 159 (33%)	 173 (53%)
5	 151	 158 (66%)	

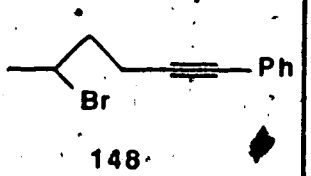
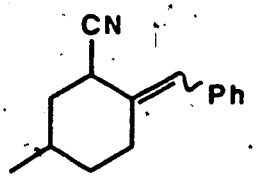
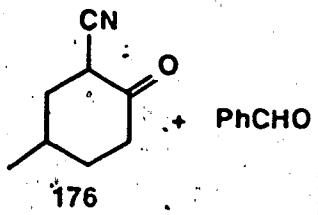
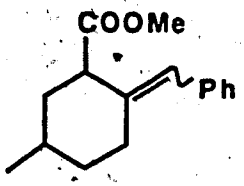
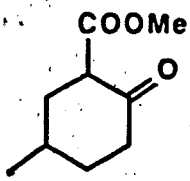
separated and each one, on ozonolysis, gave a reaction mixture which was examined by ^{1}H NMR spectroscopy. Only a single aldehyde signal corresponding to benzaldehyde was observed, confirming that the final cyclization had occurred in a 6-exo manner. The reaction was extended to the use of methyl acrylate. The product **157** was isolated in 21% yield (Table 9, Entry 2). Ozonolysis and ^{1}H NMR examination of the mixture confirmed the nature of the cyclization as 6-exo. When the Michael acceptor was changed to methacrylonitrile, then the product **158** was obtained in 70% yield as a single isomer. Ozonolysis on a preparative scale gave the corresponding ketone **171**[81] in 63% yield (Table 9, Entry 3).

Use of methyl methacrylate gave the desired product **159** but the yield was only 33%. Again, preparative ozonolysis gave the corresponding ketone **173**[82,83] in 53% yield (Table 9, Entry 4). In both cases **171** and **173**, the crude ozonolysis mixture was examined (before purification) by ^{1}H NMR spectroscopy to confirm that only benzaldehyde had been produced. It should be explained that if the cyclization pathway was 7-endo, then the aldehyde produced on ozonolysis would show a formyl proton that would be split into a triplet. There was no evidence for this. We examined also the corresponding primary selenide **151**. In this case, with excess acrylonitrile,

the desired cyclohexane carbonitrile **158** was isolated in 66% yield (Table 9, Entry 5). These experiments, show therefore, that radical annulation could be used to make 6-membered rings.

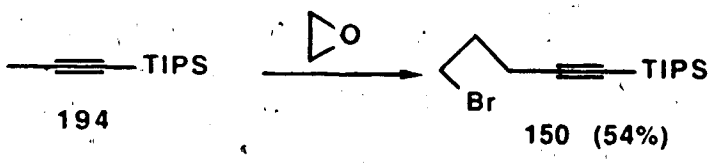
We next examined the secondary bromide **148** (Table 8), which we prepared from 1-methyl oxetane followed by conversion of alcohol **143** into bromide **148** (Table 8, Entry 2). Radical annulation with acrylonitrile gave cyclohexane carbonitriles **160**, isolated in 38% yield. This material could be separated into three fractions (Table 10, Entry 1).

Table 10. Annulation of 2 Bromide and Ozonolysis.

Entry	Starting material	Cyclized product	Ozonized product
1	 **148**	 **160 (38%)**	 **176**
2	**148**	 **161 (25%)**	 **172 (25%)**

Two of them corresponded to pure isomers and the third was a mixture of two other isomers. Each fraction was ozonized and again the total reaction mixture was examined by ^1H NMR spectroscopy. Only the benzaldehyde signal was observed in the formyl region.

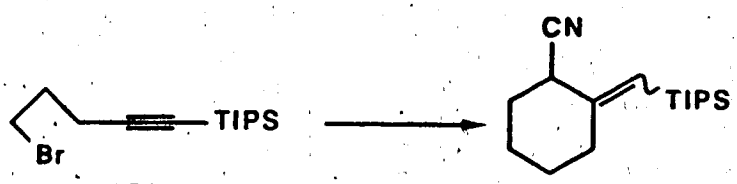
When the secondary bromide was used in conjunction with methyl acrylate, the product **161** was isolated in 25% yield (Table 10, Entry 2). Upon ozonolysis, the keto ester **172**[84] was formed in 25% yield. We also tried to establish whether or not the benzene unit attached to the triple bond is essential. To this end we prepared the triisopropylsilyl acetylene **194**[85] (eq. 58). The use of



eq. 58

the triisopropylsilyl unit was dictated by the fact that the synthetic route involved reaction between an epoxide and an anion **195**, and it is known that the specific anion shown,

reacts as such, rather than as an allene anion **196**.[85] The bromide **150** underwent, with acrylonitrile, the standard cyclization, and gave a mixture of isomers **162** in 56% yield (eq. 59). Some other cyclizations were attempted



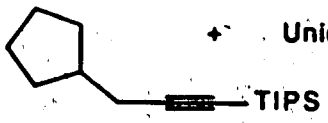
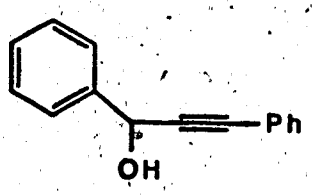
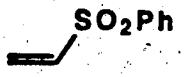
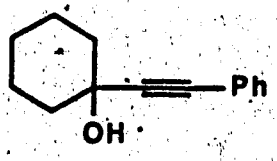
150 **162 (56%)** eq. 59

with the results collected in Table 11. Of these experiments, only Entry 3 led to some cyclization as judged by the presence of vinyl signals in the ^{1}H NMR spectrum. All required starting materials containing the triisopropylsilyl group were prepared as summarized in Tables 12 and 13.

We made a brief attempt to optimize the conditions for annulation. The primary bromide **149** (see Table 8) was mixed with 1 equivalent of acrylonitrile and the remaining 4 equivalents were added using a third syringe at the same time as the triphenyltin hydride and AIBN. By use of an internal standard and ^{1}H NMR spectroscopy, the yield of cyclized product **156** (see Table 9) was measured and found to be 55%. Uncyclized material **170** ammounted to 20% yield (Table 14, Entry 1).

When the reaction was repeated, using 2 equivalents of acrylonitrile with 3 equivalents being added during the

Table 11 Attempted cyclization reactions.

Entry	Starting material	Conclusion
1	154 (Toluene)	Starting material recovered
2	154 (Benzene)	Starting material recovered
3	147	Some cyclization observed
4	153	+ Unidentified oil  166
5	155	 167
6	169† Bu_3GeH	Starting material recovered
7	169 	 168

All experiments were carried out under usual radical annulation conditions with Ph_3SnH and acrylonitrile except where marked (°).

† see Table 15 for structure.

Table 12. Preparation of starting material alcohols and ester.

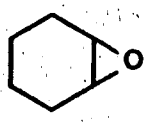
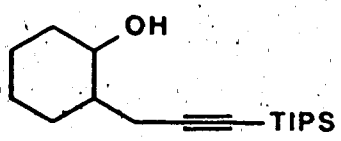
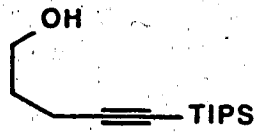
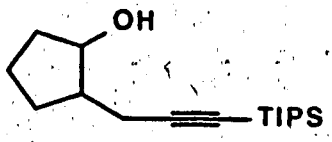
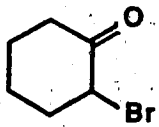
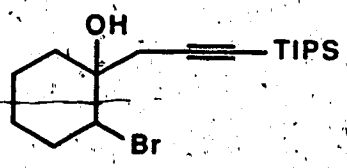
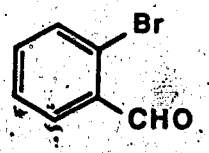
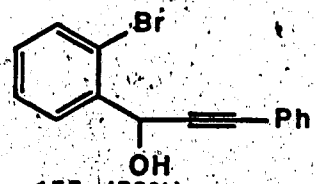
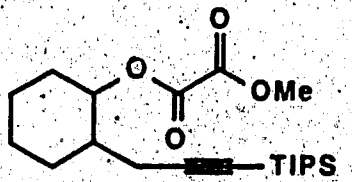
Entry	Starting material	Alcohol
1		 144 (48%)
2		 145 (54%)
3		 146 (53%)
4		 147 (61%)
5		 155 (50%)
6	144	 154 (57%)

Table 13. Preparation of starting material for annulation.

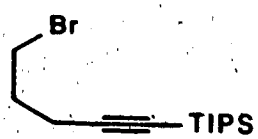
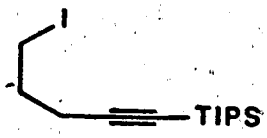
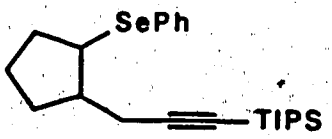
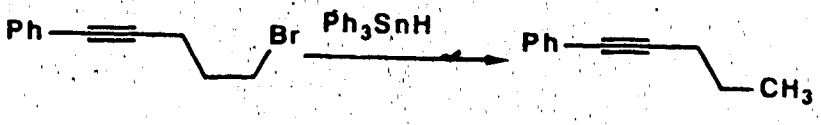
Entry	Stating Material	Product
1	145	 150 (80%)
2	150	 152 (76%)
3	146	 153 (50%)

Table 14. Varying conditions for annulation reactions.

Entry	Starting material	Equiv. of Michael Acceptor in the reaction flask	Equiv. of Michael Acceptor added over a period	Reagent	Cyclized product	Uncyclized product
1	149	1 equiv.	4 equiv.	Ph_3SnH	156 (55%)	170 (20%)
2	149	2 equiv.	3 equiv.	Ph_3SnH	156 (46%)	170 (24%)
3	150	2 equiv.	3 equiv.	Bu_3SnH	162 (24%)	–
4.	150	4.5 equiv	–	Bu_3GeH	–	–
5	152	6.6 equiv.	–	Bu_3SnH	162 (15%)	–
6	150	7 equiv.	–	Ph_3SnH	162 (54%)	–

course of the reaction, the results were rather similar: the yield of **156** was 46% and of **170**, 24% (Table 14, Entry 2). An authentic sample of **170** was generated as in eq. 60. It seems, on the basis of these experiments, that our



eq. 60

170

initial conditions, i.e. addition of 5 equivalents of acrylonitrile to the reaction vessel at the beginning of the experiment, were the best conditions that we could find.

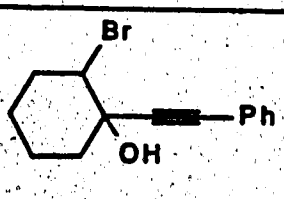
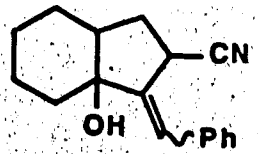
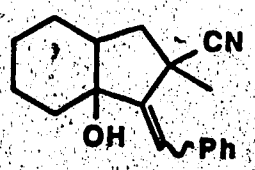
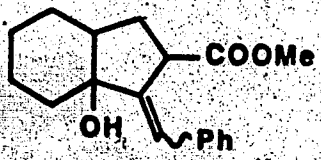
We also examined the silyl bromide **150** (eq. 59) and carried out two experiments. In the first, 2 equivalents of acrylonitrile were placed in the reaction vessel with 3 equivalents being added during the reaction. The yield of **162** was 24% (Table 14, Entry 3). When 7 equivalents were placed in the reaction vessel, and none more added during the course of the reaction the yield of cyclized material rose to 54% (Table 14, Entry 6). This result again confirmed that our initial conditions of adding all acrylonitrile (5-7 equivalents) at the start were probably best. The iodide **152** was subjected to the reaction under standard conditions. There appeared to be only 15% cyclization, judged by ^{1}H NMR measurements (Table 14,

Entry 5).

Finally tributylgermanium hydride was examined with 150 and acrylonitrile; the reaction did not work (Table 14, Entry 4). Only starting material was recovered and it is suspected that there is a problem in maintaining the chain reaction.

We then carried out another experiment in which 5-membered annulation was involved. When the bromohydrin 169[77] had first been subjected to the annulation conditions in the presence of acrylonitrile, the cyclized product 163 was isolated in 64% yield. We repeated the experiment and found the yield of cyclized product could be raised to 73% (Table 15, Entry 1). When we used

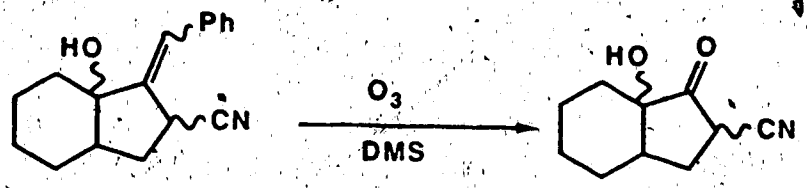
Table 15. Five - membered ring annulation.

Entry	Starting material	Annulated product
1	 169	 163 (73%)
2	169	 164(85%)
3	169	 165 (41%)

methacrylonitrile the yield was 85% (Table 15, Entry 2) but with methyl methacrylate, the yield fell to 41% (Table 15, Entry 3).

It is clear from the above experiments that radical annulation can be used to make 5-membered or 6-membered rings and in the case of bromohydrin **169**, especially with acrylonitrile or, better, methacrylonitrile, the yields are synthetically useful.

The structure of **163** was examined in detail. The substance was separated into three fractions and each was subjected to ozonolysis (eq. 61). It was possible to



eq. 61

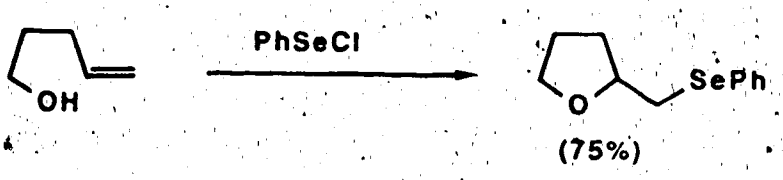
163 **177**

isolate 4 isomers of **177**, in 2 fractions, each fraction containing 2 isomers. Ozonolysis of the faster running fraction of the olefin **163** gave **177** in 59% yield (as a mixture of 2 isomers). Ozonolysis of the intermediate running fraction of the olefin **163** gave **177** in 68% (as a mixture of 2 isomers). Ozonolysis of the lower running fraction of the olefin **163** gave **177** in two fractions: The higher R_f as a mixture of 2 isomers (11%) and the lower R_f as a mixture of 2 isomers (28%). In all 4 different

ketone isomers 177 were obtained.

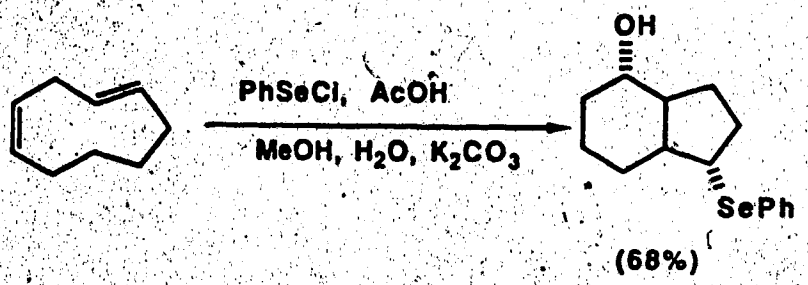
D. Appendix

Cyclofunctionalization is an efficient route to heterocycles containing[92,93] the synthetically useful (phenylseleno) group and a number of examples, such as that shown in (eq. 62),[94] had been studied.



eq. 62

At the time this work was initiated (1977), it was not known if cyclofunctionalization with selenium reagents could be used to make C-C bonds, and so the especially favourable case of transannular reactions was studied. It has been found (eq. 63)[95] that the reagent can be used to make a C-C bond.



eq. 63

Since that time several other examples of C-C bond formation (S. Ley)[96,97] have been published. We completed the experiments that had been done, in the following way. An acetic acid solution of phenylselenenyl chloride was added to (1E,5Z)-cyclodeca-1,6-diene in acetic acid containing anhydrous sodium acetate. The acetate 183 was produced in 61% yield. A similar reaction was carried out and the crude product was treated with methanol-water-potassium bicarbonate at room temperature for 16 h. The alcohol 184 was isolated as an analytically pure solid in 58% yield (Scheme 18). The same procedure was used with (1E,6E)-cyclodeca-1,6-diene to give us the acetate 182 (54%) and the alcohol 185 (54%) (Scheme 19).

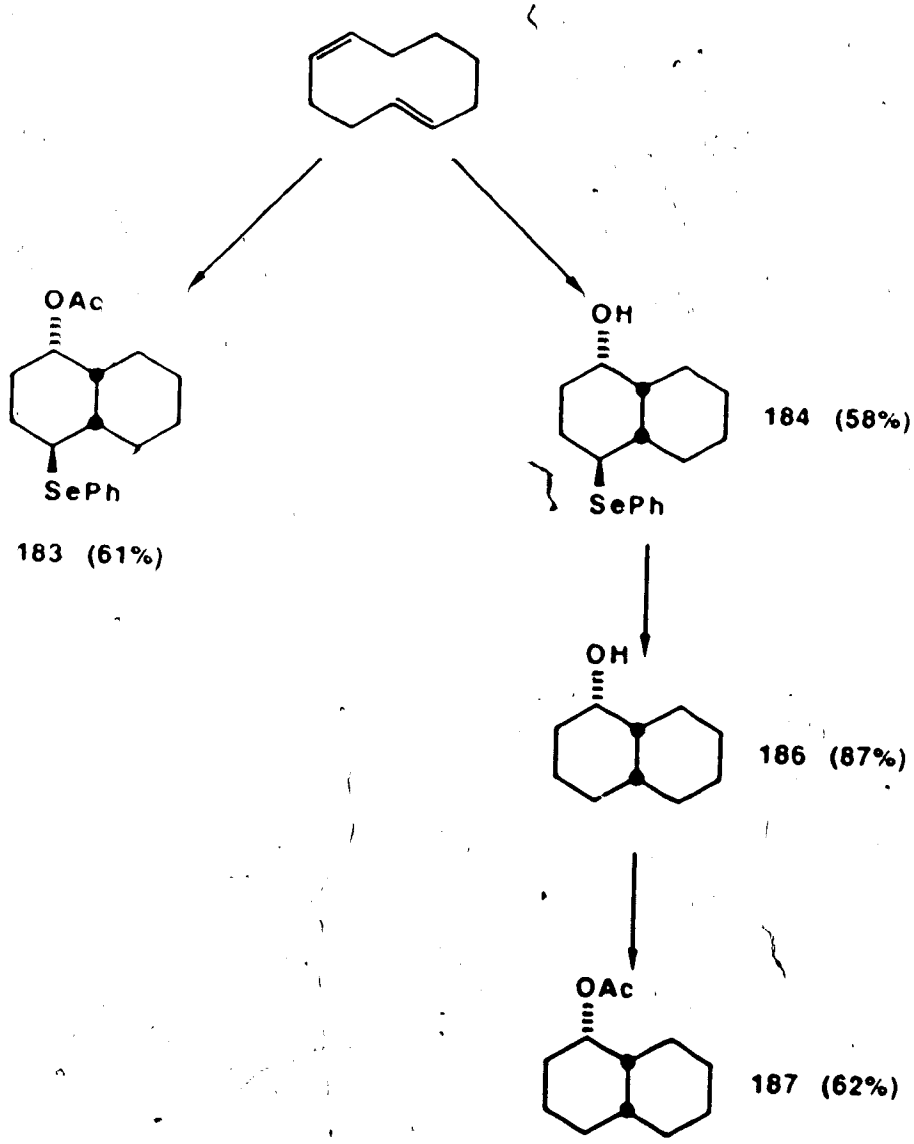
Alcohol 184 was subjected to normal C-Se bond cleavage by treatment with tributyltin hydride and AIBN in benzene to give the alcohol 186 (87%), which was then acetylated to produce 187 (62%) (Scheme 18).

Alcohol 185 was also subjected to the C-Se homoly to give alcohol 186a (87%), and, after acetylation, 187a 97% (Scheme 19).

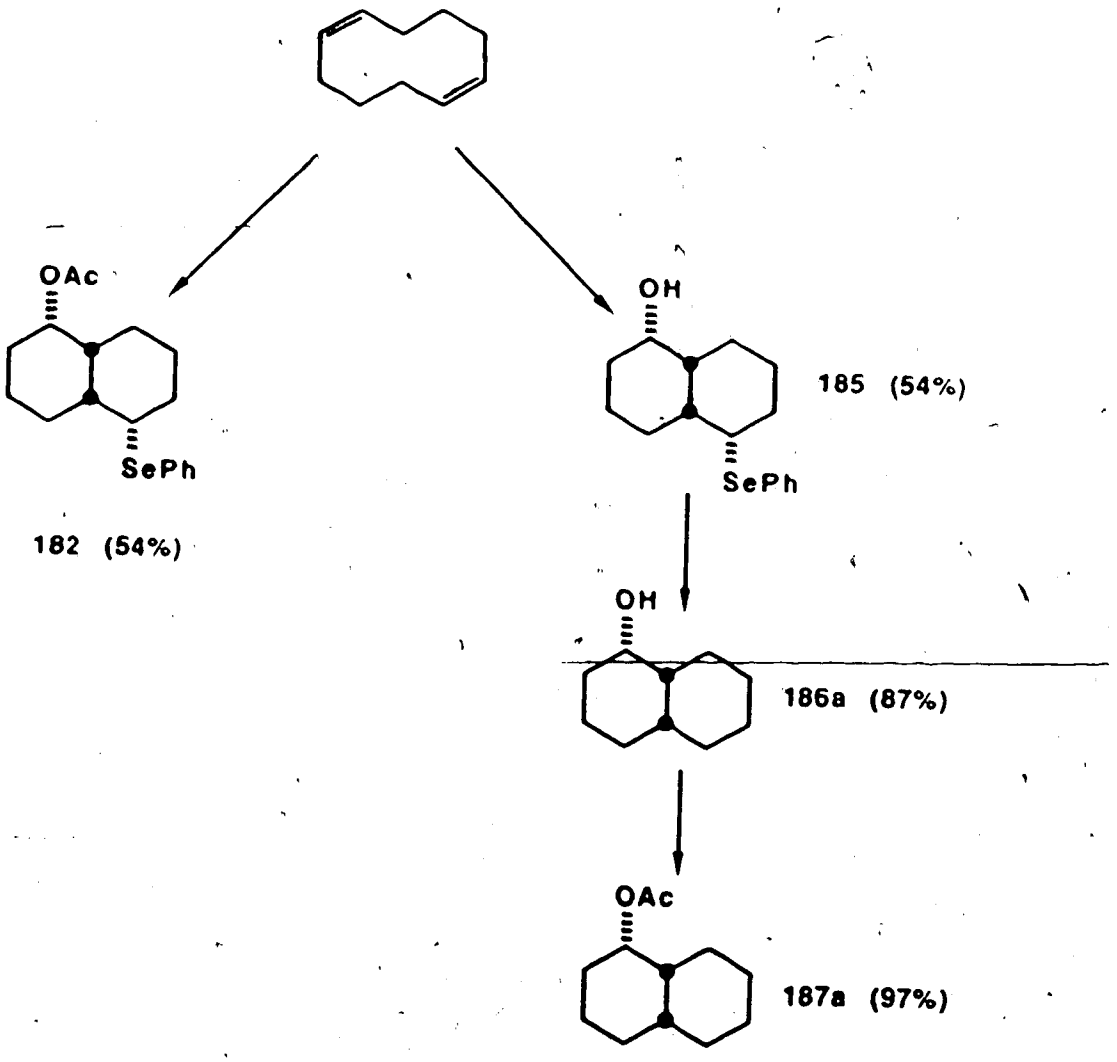
Authentic samples of alcohol 186[91] were made by the literature procedure and the corresponding acetate 187 was prepared. These compounds were used to identify the materials formed by transannular reaction.

(1E,5Z)-Cyclodeca-1,5-diene could also be converted

Scheme 18

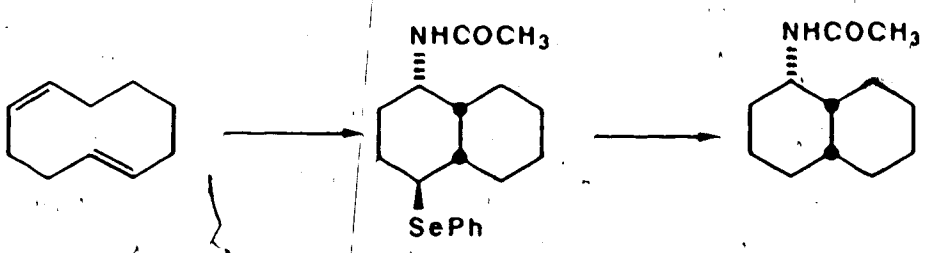


Scheme 19



into amide **179** (66%) by treatment with iodine, acetonitrile, and diphenyldiselenide. After homolysis of the C-Se bond in the usual manner **181** was formed in 86% yield (Scheme 20).

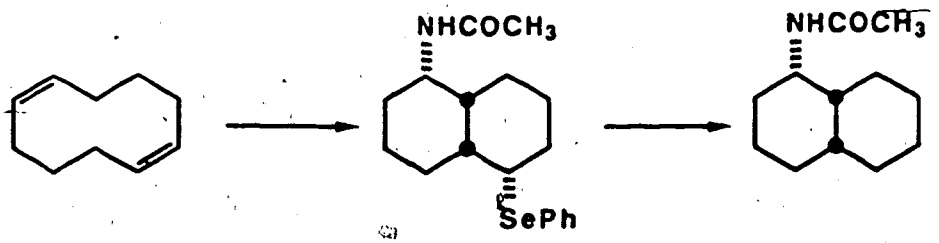
Scheme 20



179 (66%) **181** (86%)

Similarly, (1E-6E)-cyclodeca-1,6-diene was converted into **180** (63%) and, after homolysis, **181a** (89%) (Scheme 21).

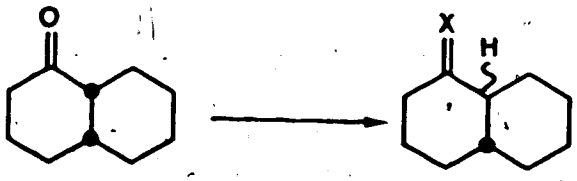
Scheme 21



180 (63%) **181a** (89%)

On the basis of the firmly established trans mode of addition of selenenyl reagents to double bonds, the transannular reactions of Scheme 20 and Scheme 21 are expected to proceed to the products indicated and these expectations were confirmed by spectral measurements.

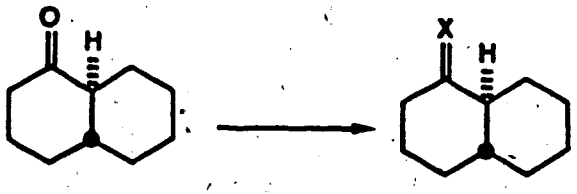
Finally, authentic samples of 190, 191,[105] 192, and 193 were made by using the cis ketone 189 and trans ketone 188, by Wittig chemistry (eq. 64 and eq. 65). Authentic samples of these compounds were needed to confirm the structure of material made by radical cyclization.[44]



189 (79%)

X = CHPh 192 and 193 (15%)
X = CH_2 190 and 191 (15%)

eq. 64



188 (82%)

X = CHPh 193 (24%)
X = CH_2 191 (15%)

eq. 65

E. Conclusions

The results discussed in this thesis illustrate the utility of free radical methodology for preparing carbocycles.

The present work, together with independent and prior contributions in the literature, suggests that the subject is likely to develop and to acquire a significant place in general organic synthesis.

III. EXPERIMENTAL

Unless otherwise stated, the following particulars apply. Experiments were carried out under argon purified by passage through a column (3.5 × 42 cm) of R 311 catalyst[98] and then through a similar column of Drierite.

Glassware was dried in an oven for at least 3 h (130°C), cooled in a dessicator, assembled quickly, and sealed with rubber septa (where applicable). Inlet and exit needles for argon were passed through septa on the apparatus and argon was purged through the system. The exit needle was removed after a few minutes and the apparatus was kept under a slight static pressure of argon (provided no gas was to be generated in the reaction). 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, well-greased syringes whenever possible, solids being dissolved in a suitable solvent prior to transfer. Solvents were distilled before use for chromatography or extractions. Where required, solvents and reagents were dried with

suitable drying agents and distilled under argon. Dry ether and tetrahydrofuran (THF) were distilled from sodium-benzophenone ketyl; benzene and toluene were distilled from sodium; dichloromethane, chloroform, carbon tetrachloride, hexane, pyridine, triethylamine, diisopropylamine, acetonitrile, and hexamethylphosphoric triamide (HMPA) were distilled from calcium hydride [the latter under reduced pressure (ca. 10 mm)]. Methanol was distilled from magnesium methoxide; U.S.P. absolute ethanol[99] was used without further drying. The commercial solutions (Aldrich) of methyllithium in ether, n-butyllithium in hexanes, vinylmagnesium bromide in tetrahydrofuran, and vinyllithium (Lachat) in tetrahydrofuran were titrated before use by the diphenylacetic acid method.[100] Phenylselenenyl chloride, pyridinium chlorochromate, diphenyldiselenide (all Aldrich materials), were used as received. Azobisisobutyronitrile (AIBN) from Eastman was stored at 0°C and used without further purification.

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 and microanalysis was carried out. Melting points were measured using 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 chromatography was Merck type 60 (230-400 mesh). TLC plates were examined under uv radiation (254 nm), treated with iodine vapour, and charred on a hot plate after being sprayed with sulphuric acid (6 N in methanol) or phosphomolybdic acid [prepared from phosphomolybdic acid (3 g, $MoO_3 \cdot 2H_3PO_4 \cdot 48H_2O$) and ceric sulphate [0.5 g, $H_4Ce(SO_4)_4$] in 100 mL of 3% aqueous H_2SO_4.

Elemental combustion analyses were performed in the microanalytical laboratories of the University of Alberta. Infrared spectra were recorded on a Perkin-Elmer 297 spectrophotometer or a Nicolet 7000 FT-IR instrument. Liquids were run as neat films on potassium chloride plates and solids were run as solutions in the specified solvent, using 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. ^{13}C NMR spectra were recorded on Bruker HFX-90 (at 22.6 MHz), Bruker WH-200 (at 50.3 MHz), Bruker WH-300 (at 75.5 MHz), or Bruker WH-400 (at 100.6

MHz) spectrometers in deuterated chloroform with TMS as an internal standard. The following abbreviations are used in the text: s, singlet; d, doublet; t, triplet; q, quartet; q', quintet; m, multiplet; s', sextet; J, coupling constant; δ, chemical shift.

Mass spectra were recorded on an A.E.I. MS'50 mass spectrometer at an ionizing voltage of 70 EV. All compounds with asymetric centres are racemic.

1,1-Bis(phenylseleno)-4-(1,1-dimethylethyl)cyclohexane 86:[56]

Concentrated sulphuric acid (1 mL, 18.76 mmol) was added dropwise to a stirred solution of 4-tert-butylcyclohexanone (1.79 g, 11.6 mmol) and benzeneselenol[64] (3 mL, 28.4 mmol) in carbon tetrachloride (9 mL). Stirring was continued for 1 h and the mixture was then quenched with saturated aqueous sodium bicarbonate (30 mL) and extracted with ether (3 x 50 mL). The solvent was evalporated and the residue was diluted with methanol (10 mL) and treated with sodium borohydride until the yellow colour had been discharged. The mixture was quenched with 5% aqueous sodium bicarbonate solution (10 mL) and extracted with pentane (50 mL). Evaporation of the solvent and recrystallization of the residue from hexane gave **86**[56] (2.72g, 52%) as a homogeneous (TLC, silica gel, hexane)

solid: mp. 81-89°C, [lit, mp. 81-89°C];[56] IR (CCl_4) 3080, 3060, 2940, 1480, 1440, 1370, 1025, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 80 MHz) δ 1.8 (s, 9H), 1.25-2.25 (m, 9H), 7.25-7.5 (m, 6H), 7.6-7.9 (m, 4H); exact mass, m/z 452.0504 (calcd for $C_{22}H_{28}Se_2$, 452.0504).

1,1-Bis(phenylseleno)cyclopentane 84:[56]

The procedure employed for **86** was followed using cyclopentanone (600 mg, 7.14 mmol), benzeneselenol[64] (1.5 mL, 14.2 mmol), and concentrated sulphuric acid (1 mL, 18.76 mmol) in carbon tetrachloride (10 mL). After work up flash chromatography of the residue over silica gel (5 × 15 cm) with 5% ethyl acetate-hexane followed by recrystallization from hexane gave **84**[56] (1.26 g, 46%) as a homogeneous (TLC, silica gel, hexane) solid: mp. 73-75°C, [lit. mp. 73-75°C];[56] IR (CCl_4) 3080, 3060, 2960, 1475, 1440, 1170, 1020, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 80 MHz) δ 1.5-2.1 (m, 8H), 7.25-7.55 (m, 6H), 7.6-7.9 (m, 4H).

1,1-Bis(phenylseleno)ethylbenzene 87:[56]

The procedure employed for **86** was followed using acetophenone (954 mg, 7.95 mmol), benzeneselenol[64] (1.5 mL, 14.2 mmol), and concentrated sulphuric acid (1 mL, 18.76 mmol) in carbon tetrachloride (6 mL). After work up flash chromatography of the residue over silica gel (4 ×

15 cm) with 2% ethyl acetate-hexane gave 87[56] (431 mg, 13%) as a homogeneous (TLC, silica gel, hexane) oil: IR (CCl_4) 3080, 3060, 1475, 1440, 1050, 1025, 910, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 80 MHz) δ 2.1 (s, 3H), 7.1-7.25 (m, 9H), 7.25-7.8 (m, 6H).

1,1-Bis(phenylseleno)cyclohexane 85:[54]

Hydrogen chloride was bubbled into a cooled (0°C) solution of cyclohexanone (2.06 g, 21.0 mmol) and benzeneselenol[64] (5.0 mL, 47.35 mmol) in benzene (20 mL) for 30 min. Stirring was continued for 1 h and the mixture was quenched by addition of saturated aqueous sodium bicarbonate (50 mL) and extracted with ether (3 × 100 mL). The combined organic extracts were washed with brine (50 mL) and dried. Evaporation of the solvent and recrystallization of the residue from hexane gave 85[54] (1.31 g, 23%) as a homogeneous (TLC, silica gel, hexane) solid: mp. 80-82°C; IR (CCl_4) 3080, 3060, 2940, 1470, 1445, 1435, 1250, 1120, 1020, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 80 MHz) δ 1.1-1.8 (m, 10H), 7.1-7.2 (m, 6H), 7.5-7.8 (m, 4H); exact mass, m/z 395.9865 (calcd for $C_{18}H_{20}Se_2$, 395.9895).

1-(Phenylseleno)cyclohexanecarboxaldehyde 75:[52]

Bromine (0.5 mL, 9.7 mmol) was added dropwise to a

stirred solution of diphenyl diselenide (3.04 g, 9.7 mmol) in dichloromethane (30 mL). Stirring was continued for 10 min, morpholine (1.7 mL, 1.9 mmol) was then added slowly and stirring was continued for 30 min. Cyclohexanecarboxaldehyde (2.3 mL, 1.89 mmol) was added and the mixture was stirred for 12 h at room temperature. The solvent was evaporated and the residue was passed through a short column (ca. 3 x 7 cm) of Florisil with 10% ethyl acetate-hexane (100 mL). The filtrate was evaporated and flash chromatography of the residue over silica gel (5 x 15 cm) with 5% ethyl acetate-hexane followed by 10% ethyl acetate-hexane gave **75**[52] (3.17 g, 62%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (Neat) 3080, 3060, 2940, 2860, 2720, 1700, 1440, 1025, 745, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 80 MHz) δ 1.1-2.0 (m, 10H), 7.1-7.5 (m, 5H), 9.1 (s, 1H).

α-(4-Phenyl-3-butynyl)-1-(phenylseleno)cyclopentanemethanol 88:

n-Butyllithium (1.79 mL, 1.55 M in hexanes, 2.77 mmol) was injected dropwise into a stirred solution of the selenoacetal **84** (1.05 g, 2.76 mmol) in THF (30 mL) at -78°C. After a further period of 15 min, a solution of aldehyde **80**[60] (224 mg, 1.42 mmol) in THF (6 mL) was added rapidly. Stirring was continued for a further 2 min and

the mixture was partitioned between 10% hydrochloric acid (50 mL) and ether (3 × 100 mL). The combined organic extracts were washed with brine (50 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (4 × 15 cm) with 10% ethyl acetate-hexane gave **88** (406 mg, 74%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3500, 3060, 2960, 1950, 1490, 1140, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.6-2.0 (m, 10H), 2.6-2.75 (m, 3H), 3.6-3.75 (m, 1H), 7.2-7.4 (m, 8H), 7.6-7.7 (m, 2H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 16.8, 24.5, 24.8, 31.9, 34.5, 36.1, 67.7, 75.5, 81.0, 89.8, 123.8, 127.5, 128.0, 128.1, 128.6, 128.8, 131.5, 137.7; exact mass, m/z 384.0994 (calcd for $C_{22}H_{24}SeO$, 384.0992). Anal. Calcd for $C_{22}H_{24}SeO$: C, 68.92; H, 6.31; O, 4.17. Found: C, 68.76; H, 6.19; O, 4.37.

α-(4-Phenyl-3-butynyl)-1-(phenylseleno)cyclohexanemethanol 89:

The procedure employed for **88** was followed using selenoacetal **85** (116 mg, 0.29 mmol) in THF (5 mL), n-butyllithium (0.19 mL, 1.55 M in hexanes, 0.29 mmol), and aldehyde **80** (51 mg, 0.32 mmol) in THF (2 mL). After work up flash chromatography of the residue over silica gel (2 × 15 cm) with 10% ethyl acetate-hexane gave **89** (76 mg,

65%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3480, 3080, 3060, 2940, 1490, 1436, 1060, 910, 692 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.4-2.3 (m, 12H), 2.65-2.95 (m, 2H), 3.15 (br, s, 1H), 3.8 (m, 1H), 7.4-7.6 (m, 8H), 7.8-7.9 (m, 2H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 17.1, 22.6, 22.8, 26.2, 30.1, 30.8, 31.9, 64.0, 74.6, 81.0, 89.8, 123.9, 126.2, 127.5, 128.1, 128.7, 128.9, 131.5, 138.1; exact mass, m/z 398.1155 (calcd for $C_{23}H_{26}SeO$, 398.1149). Anal. Calcd for $C_{23}H_{26}SeO$: C, 69.51; H, 6.59; O, 4.03. Found: C, 69.62; H, 6.61; O, 4.04.

4-(1,1-Dimethylethyl)-α-(4-phenyl-3-butynyl)-1-(phenylseleno)cyclohexanemethanol 90:

The procedure employed for **88** was followed using selenoacetal **86** (636 mg, 1.41 mmol) in THF (20 mL), n-butyllithium (0.94 mL, 1.5 M in hexanes, 1.41 mmol), and aldehyde **80** (249 mg, 1.57 mmol) in THF (5 mL). After work up flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane gave **90** (555 mg, 86%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3500, 3080, 3060, 2940, 1470, 1380, 1065, 910, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.7 (s, 9H), 0.8-1.05 (m, 1H), 1.2-1.7 (m, 5H), 1.75-2.1 (m, 4H), 2.1-2.4 (m, 2H), 2.6-2.75 (m, 2H), 4.1-4.2 (m, 1H),

7.2-7.45 (m, 8H), 7.6-7.75 (m, 2H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 17.0, 22.6, 22.7, 26.1, 30.1, 30.8, 31.8, 63.7, 74.6, 81.0, 89.8, 123.9, 126.2, 127.4, 128.0, 128.6, 128.8, 131.5, 138.0; exact mass, m/z 454.1768 (calcd for $C_{27}H_{34}SeO$, 454.1775). Anal. Calcd for $C_{27}H_{34}SeO$: C, 71.51; H, 7.56; O, 3.53. Found: C, 71.42; H, 7.30; O, 3.66.

2,7-Diphenyl-6-(phenylseleno)hept-4-yn-5ol 92:

The procedure employed for **88** was followed using selenoacetal **87** (207 mg, 0.5 mmol) in THF (5 mL), n-butyllithium (0.31 mL, 1.6 M in hexanes, 0.5 mmol), and aldehyde **80** (79 mg, 0.5 mmol) in THF (2 mL). After work up flash chromatography of the residue over silica gel (2 x 15 cm) with 10% ethyl acetate-hexane gave **92** (107 mg, 51%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3500, 3060, 2940, 1490, 1430, 1270, 1050, 900, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.45-2.0 [m, 5H (includes two singlets of equal intensity at δ 1.75 and 1.8)], 2.48-2.7 (m, 2H), 2.76 (br, s, 0.38H), 3.05 (br, s, 0.62H), 4.05 (m, 0.38H), 4.5 (m, 0.62H), 7.0-7.6 (m, 15H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 17.1, 29.4, 60.3, 73.1, 89.4, 126.6, 127.6, 127.8, 128.1, 128.6, 128.7, 131.5, 137.8, 143.0; exact mass, m/z 420.0989 (calcd for $C_{25}H_{24}SeO$, 420.0993). Anal. Calcd for

$C_{25}H_{24}SeO$: C, 71.59; H, 5.77; O, 3.81. Found: C, 71.60; H. 5.46; O, 3.96.

2-(Phenylethynyl)-α-[1-(phenylseleno)cyclopentyl]benzenemethanol 91:

The procedure employed for **88** was followed using selenoacetal **84** (307 mg, 0.8 mmol) in THF (10 mL), n-butyllithium (0.54 mL, 1.5 M in hexanes, 0.8 mmol), and aldehyde **83**[61] (165 mg, 0.8 mmol) in THF (2 mL). After work up flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane gave **91** (138 mg, 55%) as a homogeneous (TLC, silica gel, 15% ethyl acetate-hexane) oil: IR (CCl_4) 3480, 3060, 2960, 1490, 1440, 1380, 1180, 1040, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.4-2.15 (m, 8H), 3.9 (br, s, 1H), 5.4 (s, 1H), 7.0 (m, 2H), 7.2-7.5 (m, 9H), 7.7-7.85 (m, 3H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 23.4, 31.3, 34.8, 71.2, 73.2, 87.4, 123.3, 127.1, 127.3, 127.9, 128.0, 128.3, 128.5, 128.9, 131.3, 132.2, 137.6, 139.8; exact mass, m/z 432.0993 (calcd for $C_{26}H_{24}SeO$, 432.0992). Anal. Calcd for $C_{26}H_{24}SeO$: C, 72.38; H, 5.61. Found: C, 72.83; H, 5.53. A satisfactory carbon analysis could not be obtained.

α[4-(Trimethylsilyl)-3-butynyl]-1-(phenylseleno)cyclohexanemethanol 76:

A few drops of 1,2-dibromoethane were added to a mixture of magnesium (113 mg, 4.6 mmol) in THF (2 mL). When the Grignard reaction had started, a mixture of 75a[53] (494 mg, 3.1 mmol) and 1,2-dibromoethane (283 mg, 1.5 mmol) in THF (10 mL) were added over 30 min. The reaction mixture was then refluxed for 3 h, cooled to room temperature and then to -78°C. Aldehyde 75 (306 mg, 1.15 mmol) in THF (2 mL) was added dropwise and the mixture was stirred at -78°C for 2 h. After being allowed to warm to 0°C, the mixture was quenched with saturated aqueous ammonium chloride (30 mL). The aqueous layer was extracted with ether (2 x 50 mL), and the combined organic extracts were washed with water (20 mL) and brine (20 mL), and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (3 x 15 cm) with 10% ethyl acetate-hexane gave 76 (175 mg, 38%) as a homogeneous (TLC, silica gel, 15% ethyl acetate-hexane) oil: IR (CCl_4) 3480, 3060, 2940, 2180, 1450, 1250, 1050, 900, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 80 MHz) δ 0.2 (s, 9H), 1.0-1.9 (m, 12H), 2.3-2.25 (m, 2H), 2.7 (d, J = 2 Hz, 1H), 3.3-3.6 (m, 1H), 7.2-7.4 (m, 3H), 7.5-7.6 (m, 2H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 0.1, 17.6, 22.6, 22.8, 26.2, 30.3, 30.7, 31.0, 32.1, 64.0, 74.5, 107.2, 126.1, 128.8, 128.9, 138.1; exact

mass, m/z 394.1231 (calcd for $C_{20}H_{30}SeOSi$, 394.1231).

General Procedure for Radical Cyclization

The experiments were performed with anhydrous solvents and oven dried apparatus. AIBN (Eastman material) was used without purification. The substrate (0.4-1.0 mmol) was placed in a 100 mL round-bottomed flask containing a Teflon coated magnetic stirring bar and equipped with a reflux condenser closed by a rubber septum. The system was purged with argon for 5 min and benzene (15-30 mL) was injected into the flask which was then immersed in an oil bath preheated to 80°C. Benzene solutions of triphenyltin hydride (1.2 equiv., 0.05-0.07 M) and of AIBN (0.1 equiv., 0.01 M) were then injected simultaneously over 7 h by means of a double syringe pump. During this period the reaction mixture was stirred magnetically and maintained under a slight static pressure of argon. Refluxing was continued for a further arbitrary period of 2 h. The mixture was then cooled and evaporated under water pump vacuum. The residue was processed as described for the individual examples.

4-(Phenylmethylene)spiro[4.4]nonan-1-ol 93:

The general procedure for radical cyclization was followed using selenide **88** (159 mg, 0.42 mmol) in benzene

(10 mL), triphenyltin hydride (165 mg, 0.47 mmol) in benzene (5 mL), and AIBN (11 mg, 0.07 mmol) in benzene (5 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 10% ethyl acetate-hexane gave **93** (64 mg, 68%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4 cast) 3360, 2860, 1500, 1440, 1060, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.25-2.1 (m, 11H), 2.3-2.8 (m, 2H), 3.72 (m, 0.77H), 3.8 (m, 0.23H), 6.22 (t, J = 2.5 Hz, 0.21H), 6.5 (s, 0.79H), 7.1-7.4 (m, 5H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 25.4, 25.7, 25.8, 26.2, 27.8, 30.6, 30.7, 31.8, 31.9, 38.9, 39.3, 58.0, 79.4, 81.6, 118.8, 119.0, 120.6, 123.0, 125.8, 126.0, 127.7, 128.1, 128.3, 128.5, 129.1, 138.7; exact mass, m/z 228.1512 (calcd for $C_{16}H_{20}O$, 228.1514).

4-(Phenylmethylene)spiro[4.5]decan-1-ol 94:

The general procedure for radical cyclization was followed using selenide **89** (81 mg, 0.20 mmol) in benzene (5 mL), triphenyltin hydride (104 mg, 0.30 mmol) in benzene (5 mL), and AIBN (8 mg, 0.05 mmol) in benzene (5 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (1 × 15 cm) with 15% ethyl acetate-hexane gave **94** (37 mg, 75%) as an apparently homogeneous (TLC, silica gel, 15% ethyl acetate-hexane)

oil that consisted of two isomers: IR (CCl_4) 3630, 3030, 2940, 1450, 1060, 920, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.22-1.9 (m, 12H), 2.0-2.1 (m, 1H), 2.7-2.9 (m, 2H), 4.3 (br, s, 0.87H), 4.38 (br, s, 0.13H), 6.25 (br, s, 0.85H), 6.56 (s, 0.15H), 7.12-7.4 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 23.0, 23.3, 23.4, 23.5, 25.9, 26.2, 28.3, 29.4, 30.3, 30.5, 31.5, 32.0, 35.7, 37.1, 52.4, 75.7, 121.3, 123.6, 125.8, 126.0, 127.6, 128.1, 128.4, 129.3, 138.6, 138.9, 152.5; exact mass, m/z 242.1668 (calcd for $C_{17}H_{22}O$, 242.1670). Anal. Calcd for $C_{17}H_{22}O$: C, 84.25; H, 9.15. Found: C, 84.00; H, 8.94.

8-(1,1-Dimethylethyl)-4-(phenylmethylene)spiro[4.5]decan-1-ol 95:

The general procedure for radical cyclization was followed using selenide **90** (483 mg, 1.07 mmol) in benzene (30 mL), triphenyltin hydride (515 mg, 1.46 mmol) in benzene (10 mL), and AIBN (17 mg, 0.1 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 5% ethyl acetate-hexane gave **95** as two apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) alcohols of combined weight 275 mg (86%). The material of higher R_f **99** (151 mg, 47%) consisted of two isomers and had: IR (CCl_4) 3620, 3030, 2940, 1450, 1365, 1060, 910, 700 cm^{-1}; ^1H NMR

($CDCl_3$, 200 MHz) δ 0.8-2.2 [m, 21H (includes two singlets at δ 0.8 and δ 0.9)], 2.6-2.9 (m, 2H), 4.3 (d, J = 1 Hz, 1H), 6.2 (br, s, 0.71H), 6.6 (br, s, 0.29H), 7.1-7.4 (m, 5H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 24.0, 24.4, 24.5, 24.7, 27.7, 27.8, 28.8, 30.0, 30.5, 31.4, 31.9, 32.3, 32.6, 32.7, 36.4, 38.3, 47.7, 48.3, 51.9, 52.6, 75.3, 78.0, 121.2, 123.9, 126.1, 126.3, 127.8, 128.4, 128.6, 129.5, 139.0, 139.1, 150.8, 153.0; exact mass, m/z 298.2301 (calcd for $C_{21}H_{30}O$, 298.2297).

The material of lower R_f **98** (124 mg, 39%) was a single isomer and had: IR (CCl_4) 3620, 2940, 1445, 1365, 1075, 910, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.8-1.15 [m, 10H (includes a singlet at δ 0.9)], 1.32-2.0 (m, 10H), 2.0-2.2 (m, 1H), 2.5-2.8 (m, 2H), 3.6 (t, J = 4 Hz, 1H), 6.55 (br, s, 1H), 7.15-7.4 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 23.3, 27.0, 27.6, 28.7, 30.0, 32.5, 34.0, 48.0, 50.2, 81.3, 123.8, 126.0, 128.1, 128.6, 138.4, 149.3; exact mass, m/z 298.2302 (calcd for $C_{21}H_{30}O$, 298.2296).

2-Methyl-2-phenyl-3-(phenylmethylene)cyclopentanol 97:

The general procedure for radical cyclization was followed using selenide **92** (115 mg, 0.27 mmol) in benzene (10 mL), triphenyltin hydride (106 mg, 0.30 mmol) in benzene (5 mL), and AIBN (10 mg, 0.06 mmol) in benzene (5 mL). Evaporation of the solvent and flash chromatography

of the residue over silica gel (1 × 15 cm) with 10% ethyl acetate-hexane gave **97** (46 mg, 64%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4) 3620, 3060, 3020, 2950, 1600, 1490, 1440, 1075, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 Hz) δ 2.18 (s, 2.28H), 2.3 (s, 0.72H), 2.32-2.64 (m, 3H), 3.2-3.4 (m, 2H), 4.35 (t, J = 4 Hz, 1H), 6.4 (br, s, 1H), 6.6 (m, 2H), 6.75 (m, 2H), 6.8-7.1 (m, 6H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 17.9, 21.3, 28.2, 29.5, 30.6, 32.7, 81.6, 85.4, 124.9, 125.8, 125.9, 126.2, 126.7, 127.0, 127.3, 128.2, 128.3, 128.4, 128.9, 137.1, 146.9, 149.1; exact mass, m/z 264.1513 (calcd for $C_{19}H_{20}O$, 264.1513).

1',3'-Dihydro-3'-(phenylmethylene)spiro[cyclopentane-1,2'-2H-inden]-1'-ol 96:

The general procedure for radical cyclization was followed using selenide **91** (137 mg, 0.32 mmol) in benzene (10 mL), triphenyltin hydride (157 mg, 0.45 mmol) in benzene (6 mL), and AIBN (12 mg, 0.07 mmol) in benzene (6 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane gave **96** (81 mg, 91%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4) 3600, 3030,

2960, 1470, 1445, 1385, 1050, 910, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.55-1.9 (m, 7H), 2.0-2.1 (m, 2H), 4.5 (d, J = 8 Hz, 0.1H), 4.68 (d, J = 8 Hz, 0.9H), 6.5 (s, 1H), 7.0 (m, 1H), 7.1-7.42 (m, 8H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 25.2, 25.4, 26.8, 29.5, 31.5, 32.1, 38.7, 39.7, 61.3, 80.5, 82.5, 120.4, 121.0, 121.6, 124.6, 124.7, 125.5, 126.6, 126.7, 127.7, 127.8, 128.3, 128.4, 128.8, 129.1, 138.1, 138.9, 146.5, 148.1; exact mass, m/z 276.1512 (calcd for $C_{20}H_{20}O$, 276.1514). Anal. Calcd for $C_{20}H_{20}O$: C, 86.92; H, 7.29. Found: C, 86.99; H, 7.02.

4-[(Trimethylsilyl)methylene]spiro[4.5]decan-1-ol 77:

The general procedure for radical cyclization was followed by using selenide **76** (175 mg, 0.45 mmol) in benzene (16 mL), triphenyltin hydride (178 mg, 0.51 mmol) in benzene (5 mL), and AIBN (10 mg, 0.06 mmol) in benzene (5 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 5% ethyl acetate-hexane and then with 10% ethyl acetate-hexane gave **77** (76 mg, 72%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) solid: mp. 60-62°C; IR (CCl_4) 3620, 2920, 1610, 1450, 1245, 1050, 860 cm^{-1}; ^1H NMR ($CDCl_3$, 100 MHz) δ 0.2 (s, 9H), 1.0-2.0 (m, 13H), 2.4-2.7 (m, 2H), 4.3 (br, s, 1H), 5.35 (m, 1H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 0.02, 23.2, 23.6, 26.2, 29.2, 30.3, 31.1, 37.1,

52.7, 75.6, 117.4, 168.4; exact mass, m/z 238.1749 (calcd for $C_{14}H_{26}SiO$, 238.1752). Anal. Calcd for $C_{14}H_{26}SiO$: C, 70.52; H, 10.99. Found: C, 70.68; H, 11.02.

4-(Phenylmethylene)spiro[4.4]nonan-1-ol acetate 100:

Acetic anhydride (6.0 mL, 63.6 mmol) and a crystal of DMAP were added to a stirred solution of alcohols **93** (213 mg, 0.93 mmol) and pyridine (6.0 mL, 74.2 mmol). The mixture was stirred at room temperature for 1 h, quenched with ice cold 10% hydrochloric acid (30 mL), and extracted with ether (3 × 30 mL). The combined organic extracts were washed with saturated aqueous sodium bicarbonate (30 mL) and brine (20 mL), and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 10% ethyl acetate-hexane gave **100** (237 mg, 94%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4) 2960, 1740, 1370, 1240, 1030, 910, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.43-2.2 [m, 13H (includes a singlet at δ2.08)], 2.7-2.9 (m, 2H), 4.9 (m, 0.18H), 5.0 (m, 0.82H), 6.28 (m, 0.81H), 6.5 (br, s, 0.19H), 7.1-7.4 (m, 5H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 21.2, 25.2, 25.4, 25.8, 28.3, 28.5, 29.6, 31.3, 32.3, 32.8, 39.6, 58.9, 81.5, 83.5, 120.1, 122.4, 125.8, 126.0, 127.6, 128.1, 128.2, 129.1, 138.4, 151.3, 170.8; exact mass, m/z

270.1615 (calcd for $C_{18}H_{22}O_2$, 270.1620). Anal. Calcd for $C_{18}H_{22}O_2$: C, 79.96; H, 8.20. Found: C, 80.13; H, 8.01.

4-(Phenylmethylene)spiro[4.5]decan-1-ol acetate 101:

The procedure employed for **100** was followed using acetic anhydride (2.0 mL, 21.2 mmol), a crystal of DMAP, alcohols **94** (64 mg, 0.26 mmol), and pyridine (2.0 mL, 24.7 mmol). After work up flash chromatography of the residue over silica gel (1 × 15 cm) with 10% ethyl acetate-hexane gave **101** (67 mg, 88%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4) 2940, 1735, 1450, 1370, 1240, 1160, 1030, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.2-2.2 [m, 15H (includes a singlet at δ2.05)], 2.7-2.9 (m, 2H), 5.4 (m, 1H), 6.28 (m, 0.86H), 6.55 (m, 0.14H), 7.1-7.4 (m, 5H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 21.3, 23.1, 23.2, 23.3, 26.1, 28.8, 29.7, 30.0, 31.2, 35.6, 37.4, 51.3, 76.4, 78.1, 78.6, 80.1, 116.6, 120.9, 121.4, 123.9, 126.0, 126.1, 127.7, 128.3, 128.4, 129.4, 138.7, 152.5, 170.9; exact mass, m/z 284.1781 (calcd for $C_{19}H_{24}O_2$, 284.1777). Anal. Calcd for $C_{19}H_{24}O_2$: C, 80.24; H, 8.51. Found: C, 80.50; H, 8.67.

8-(1,1-Dimethylethyl)-4-(phenylmethylene)spiro[4.5]decan-1-ol acetate 102:

The procedure employed for **100** was followed using acetic anhydride (1.0 mL, 10.6 mmol), a crystal of DMAP, alcohols **99** (34 mg, 0.12 mmol), and pyridine (1.0 mL, 12.4 mmol). After work up flash chromatography of the residue over silica gel (1 x 15 cm) with 10% ethyl acetate-hexane gave **102** (25 mg, 63%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4) 2950, 1735, 1450, 1370, 1240, 1170, 1030, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.67 (s, 6H), 0.78 (s, 3H), 1.0-2.1 [m, 14H (includes two singlets at δ2.04 and δ2.05)], 2.6-2.9 (m, 2H), 5.4 (t, J = 4 Hz, 1H), 6.25 (t, J = 2.5 Hz, 0.43 H), 6.6 (s, 0.57H), 7.15-7.4 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 23.6, 23.7, 24.1, 24.2, 27.4, 27.5, 28.5, 28.9, 29.7, 30.1, 31.6, 32.3, 32.4, 36.0, 38.1, 47.2, 47.8, 50.3, 51.1, 78.2, 80.0, 120.4, 122.9, 125.9, 126.0, 127.6, 128.2, 128.3, 129.2, 138.6, 138.7, 150.5; exact mass, m/z 340.2401 (calcd for $C_{23}H_{32}O_2$, 340.2401).

8-(1,1-Dimethylethyl)-4-(phenylmethylene)spiro[4.5]decan-1-ol acetate 103:

The procedure employed for **100** was followed using alcohol **98** (25 mg, 0.09 mmol), pyridine (1.0 mL, 12.4

mmol), and acetic anhydride (1.0 mL, 10.6 mmol). After work up flash chromatography of the residue over silica gel (1 × 15 cm) with 10% ethyl acetate-hexane gave **103** (26 mg, 90%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3020, 2940, 1730, 1450, 1370, 1240, 1030, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.88 (s, 9H), 1.2-2.0 (m, 11H), 2.05 (s, 3H), 2.6-2.8 (m, 2H), 4.78 (dd, J = 5.5, 4Hz, 1H), 6.52 (t, J = 2.5 Hz, 1H), 7.15-7.4 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 21.2, 22.7, 23.3, 27.5, 27.7, 29.3, 32.4, 34.1, 47.8, 49.2, 83.3, 123.3, 126.0, 128.1, 128.6, 138.4, 148.7, 170.9; exact mass, m/z 340.2402 (calcd for $C_{23}H_{32}O_2$, 340.2403).

1',3'-Dihydro-3'-(phenylmethylene)spiro[cyclopentane-1,2'-2H-inden]-1'-one 108:

Alcohols **96** (81 mg, 0.29 mmol) in dry dichloromethane (5 mL) was added to a stirred mixture of pyridinium chlorochromate (368 mg, 1.7 mmol) in dichloromethane (5 mL). Stirring was continued for a further 1 h at room temperature and the mixture was then poured into 20% ethyl acetate-hexane and stirred vigorously. The resulting mixture was passed through a short column of Florisil with 20% ethyl acetate-hexane (50 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 10% ethyl acetate-hexane gave

108 (67 mg, 83%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4 cast) 2940, 1712, 1600, 1460, 770, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.9-2.2 (m, 8H), 6.84 (s, 1H), 7.27-7.47 (m, 8H), 7.76-7.84 (m, 1H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 26.9, 27.3, 36.2, 38.7, 59.8, 120.3, 122.7, 123.6, 123.8, 124.5, 124.7, 127.2, 127.4, 128.1, 128.3, 128.6, 128.8, 129.1, 133.9, 136.0, 137.6, 146.5, 146.9, 202.5; exact mass, m/z 274.1354 (calcd for $C_{20}H_{18}O$, 274.1357). Anal. Calcd for $C_{20}H_{18}O$: C, 87.56; H, 6.61. Found: C, 87.67; H, 6.54.

4-Acetoxy spiro[4.5]decan-1-one 105:

An ozone-oxygen stream was bubbled through a solution of olefins **101** (51 mg, 0.18 mmol) in dry methanol (5.0 mL) at -78°C until the starting material had just disappeared [5 min, TLC control (silica, 10% ethyl acetate-hexane)]. Argon was passed through the solution for 5 min to remove the excess of ozone, and dimethyl sulfide (0.1 mL, 1.36 mmol) was added. The cold bath was removed and the solution was stirred for 12 h (during which time it attained room temperature). Evaporation of the solvent, followed by flash chromatography of the residue over silica gel (1 x 15 cm) with 10% ethyl acetate-hexane gave **105** (24 mg, 64%) as a homogeneous (TLC, silica gel, 10%

ethyl acetate-hexane) oil: IR (CCl_4) 2940, 1735, 1450, 1370, 1240, 1030 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.2-1.8 (m, 10H), 2.0-2.15 [m, 4H (includes a singlet at δ2.1)], 2.2-2.48 (m, 3H), 5.44-5.5 (m, 1H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 21.0, 21.8, 22.0, 25.4, 25.8, 26.3, 31.1, 34.1, 53.1, 77.5, 170.2, 219.6; exact mass, m/z 210.1256 (calcd for $C_{12}H_{18}O_3$, 210.1256). Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63. Found: C, 68.34; H, 8.60.

4-Acetoxy spiro[4.4]nonan-1-one 104:

The procedure employed for **105** was followed using olefins **100** (86 mg, 0.32 mmol) in dry methanol (7 mL) and for work up, dimethyl sulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent followed by flash chromatography of the residue over silica gel (1 x 15 cm) with 10% ethyl acetate-hexane gave **104** (41 mg, 65%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 2960, 1740, 1370, 1240, 1020 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.5-1.9 (m, 8H), 2.0-2.3 [m, 5H (includes a singlet at δ2.05)], 2.3-2.42 (m, 2H), 5.12-5.2 (m, 1H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 20.9, 25.9, 26.1, 29.0, 33.5, 35.6, 60.2, 79.5, 170.2, 219.2; exact mass, m/z 196.1099 (calcd for $C_{11}H_{16}O_3$, 196.1099). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.60; H, 8.19.

4-Acetoxy-8-(1,1-dimethylethyl)spiro[4.5]decan-1-one 106:[62]

The procedure employed for **105** was followed using olefins **102** (90 mg, 0.27 mmol) in dry methanol (7 mL) and for work up, dimethyl sulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent followed by flash chromatography of the residue over silica gel (1 × 15 cm) with 15% ethyl acetate-hexane gave **106**[62] (57 mg, 80%) as a homogeneous (TLC, silica gel, 15% ethyl acetate-hexane) oil: IR (CCl_4) 2940, 1740, 1450, 1370, 1240, 1025 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.83-1.4 [m, 13H (includes a singlet at δ0.85)], 1.5-1.8 (m, 5H), 2.0-2.4 [m, 7H (includes a singlet at δ2.08)], 5.52 (m, 1H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 21.1, 23.0, 23.2, 26.0, 26.8, 27.4, 32.0, 32.4, 34.1, 47.2, 53.6, 76.2, 170.2, 220.5; exact mass, m/z 266.1882 (calcd for $C_{16}H_{26}O_3$, 266.1882).

4-Acetoxy-8-(1,1-dimethylethyl)spiro[4.5]decan-1-one 107:[62]

The procedure employed for **105** was followed using olefin **103** (76 mg, 0.22 mmol) in dry methanol (7 mL) and for work up, dimethyl sulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent followed by flash chromatography of the residue over silica gel (1 × 15 cm) with 10% ethyl acetate-hexane gave **107**[62] (51 mg, 85%) as a

homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 2960, 1740, 1450, 1370, 1235, 1030 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.82 (s, 9H), 1.2-1.43 (m, 4H), 1.5-2.0 (m, 6H), 2.03 (s, 3H), 2.2-2.45 (m, 3H), 5.0 (m, 1H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 21.0, 22.1, 22.3, 25.1, 27.2, 27.5, 31.8, 32.4, 34.7, 47.6, 50.9, 81.4, 170.4, 218.4; exact mass, m/z 266.1881 (calcd for $C_{16}H_{26}O_3$, 266.1881).

[3-(1-Methylethenyl)-1-(cyclohexen-1-yl)oxy]trimethyl-silane 113:[74,75]

A mixture of magnesium turnings (540 mg, 23.5 mmol) and THF (15 mL) was placed under argon in a 250 mL 3-necked round bottomed flask carrying a reflux condenser and containing a magnetic stirring bar, the side necks being closed by stoppers and the condenser by a rubber septum. A crystal of iodine was added to the flask, a few drops of 2-bromopropene were injected and the stirrer was started. When the reaction had begun (ca. 10 min), more 2-bromopropene (total used = 3.66 g, 30.3 mmol) in THF (5 mL + 1 mL rinse) was added over 10 min. The reaction mixture was then refluxed for 15 min, cooled to room temperature, and diluted with THF (15 mL). One of the side stoppers was removed and a side arm addition funnel containing copper(I) iodide (210 mg, 1.1 mmol) was quickly

fitted in place. The reaction mixture was cooled to 0°C, the copper salt was added in one portion (stirring), and a solution of 2-cyclohexen-1-one (1.00 g, 10.4 mmol) in THF (10 mL + 1 mL rinse) was injected over 10 min. Stirring at 0°C was continued for a further 1 h and chlorotrimethylsilane (3.20 mL, 25.2 mmol) followed by triethylamine (4.8 mL, 34 mmol) were injected. The ice bath was removed, and after 2 h, the mixture was partitioned between hexane (100 mL) and saturated aqueous ammonium chloride (50 mL). The aqueous layer was extracted with ether (2 x 50 mL) and the combined organic extracts were dried and evaporated. The resulting oil was distilled (Kugelrohr) and the distillate was purified by flash chromatography over silica gel (3 x 15 cm) with 20% chloroform-hexane. Appropriate fractions (TLC) were combined and Kugelrohr distillation (bp 80°C, 3 mm) gave 113[74,75] (0.926 g, 42%) as a homogeneous (TLC, silica gel, 20% chloroform-hexane) colourless liquid: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.2 (s, 9H), 1.3-1.4 (m, 1H), 1.5-2.1 [m, 9H (includes a triplet at δ1.7, J = 1 Hz)], 2.8 (m, 1H), 4.7-4.8 (m, 2H).

[(3-Ethenyl-1-cyclohexen-1-yl)oxy]trimethylsilane 114:[69]

Copper(I) iodide (2.40 g, 12.6 mmol) was added from a side arm addition tube to a cooled (-5°C) and stirred

solution of vinylmagnesium bromide (23.60 mL, 1.0 M in THF, 23.6 mmol) in THF (20 mL). The mixture was stirred until jet black (5 min) and promptly cooled to -78°C. 2-Cyclohexen-1-one (1.00 g, 10.4 mmol) in THF (5 mL) was added dropwise over 5 min. The reaction flask was transferred to a cold bath set at -30°C. The mixture was stirred for 45 min and then cooled to -78°C. Chlorotrimethylsilane (3.20 mL, 25.2 mmol) and triethylamine (4.80 mL, 34.4 mmol) were added and the cooling bath was removed. After 3 h the mixture was partitioned between hexane (100 mL) and saturated aqueous ammonium chloride. The aqueous layer was extracted with ether (2 × 50 mL) and the combined hexane-ether extracts were dried, evaporated, and distilled [Kugelrohr, bp 72°C (3 mm)]. Flash chromatography of the distillate over silica gel (3 × 15 cm) with 12.5% chloroform-hexane and Kugelrohr distillation gave **114**[69] (586 mg, 28%) as a homogeneous (TLC, silica gel, 12.5% chloroform-hexane), colourless liquid: bp 72°C (3 mm) [lit.[69] bp 72°C (3 mm)]; ^{1}H NMR ($CDCl_3$, 80 MHz) δ 0.22 (s), 1.1-2.1 (m, 7H), 2.7-2.98 (br, s, 1H), 4.7-5.1 (m, 2H), 5.58-5.96 (m, 1H).

[(3-Ethenyl-1-cyclopenten-1-yl)oxy]trimethylsilane 115:[76,77]

Vinyllithium (31.30 mL, 1.0 M in ether, 31.3 mmol)

was added to a stirred and cooled (-78°C) suspension of copper(I) cyanide (1.40 g, 15.6 mmol) in ether (20 mL). The reaction vessel was transferred to an ice bath and maintained at ca. 0°C until the solid dissolved (ca. 3 min). The reaction mixture was recooled to -78°C and 2-cyclopenten-1-one (1.00 g, 12.2 mmol) was added. Stirring was continued for 45 min at -78°C, and chlorotrimethylsilane (3.20 mL, 25.2 mmol) and triethylamine (4.80 mL, 34.4 mmol) were injected. The cooling bath was removed and, after 2 h, the mixture was partitioned between hexane (100 mL) and saturated aqueous ammonium chloride (50 mL), the aqueous layer was extracted with ether (2 × 50 mL). The combined hexane-ether etracts were dried, evaporated, and distilled [Kugelrohr, bp 78°C (3 mm)]. Flash chromatography of the distillate over silica gel (3 × 15 cm) with 12.5% chloroform-hexane and Kugelrohr distillation gave 115[76,77] (402 mg, 18%) as a homogeneous (TLC, silica gel, 12.5% chloroform-hexane) colourless liquid: bp 78°C (3 mm); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.22 (s, 9H), 1.58 (m, 1H), 2.1 (m, 1H), 2.28 (m, 2H), 3.25 (br, m, 1H), 4.57 (m, 1H), 4.85 (m, 1H), 4.95 (m, 1H), 5.78 (m, 1H).

trans-2-[1-Hydroxy-2-(phenylseleno)ethyl]-3-(1-methylethenyl)cyclohexanone 116:[71]

Methyllithium (2.60 mL, 1.7 M in ether, 4.42 mmol) was injected at room temperature into a stirred solution of the silyl enol ether **113** (926 mg, 4.41 mmol) in ether (10 mL). After a further period of 1.5 h the mixture was cooled to 0°C and zinc chloride[73] (3.20 mL, 0.69 M in ether, 2.21 mmol) was added dropwise over *ca.* 5 min. The mixture was left for 10 min at 0°C and (phenylseleno)acetaldehyde[68] (880 mg, 4.42 mmol) in ether (5 mL + 1 mL rinse) was injected rapidly (main portion added over *ca.* 3 sec). Stirring was continued for a further 5 min and the reaction was quenched by saturated aqueous ammonium chloride solution (*ca.* 5 mL). The mixture was transferred to a separatory funnel containing more ammonium chloride solution (total used = 30 mL) and extracted with ether (2 × 20 mL). The combined organic extracts were washed with saturated aqueous sodium bicarbonate (30 mL) and with brine (30 mL), and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (5 × 15 cm) with 20% ethyl acetate-hexane gave **116**[71] as two homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oils of combined weight 1.21 g (81%). The material of higher R_f **116a** (835 mg, 56%) had: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.5-1.85 [m, 6H (includes

a singlet at δ1.62)], 1.95-2.1 (m, 2H), 2.2 (m, 1H), 2.6-2.8 (m, 2H), 3.2-3.3 (m, 2H), 3.4 (d, J = 11.5 Hz, 1H), 3.6-3.7 (m, 1H), 4.8 (m, 1H), 4.88 (br, s, 1H), 7.2-7.3 (m, 3H), 7.4-7.5 (m, 2H).

The material of lower R_f **116b** (377 mg, 25%) had: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.6-1.8 [m, 6H (includes a singlet at δ1.68)], 1.95-2.15 (m, 1H), 2.2-2.5 (m, 3H), 2.8 (ddd, J = 11.5, 4, 1 Hz, 1H), 3.02 (dd, J = 12, 3 Hz, 1H), 3.2 (d, J = 9.2 Hz, 1H), 3.34 (dd, J = 12, 10.2 Hz, 1H), 3.8 (m, 1H), 4.7 (m, 2H), 7.2-7.3 (m, 3H), 7.5-7.6 (m, 2H).

trans-3-Ethenyl-2-[1-hydroxy-2-(phenylseleno)ethyl]cyclohexanone 117:[69]

The reaction was carried out exactly as described for the preparation of **116** using methyllithium (0.72 mL, 1.76 M in ether, 1.27 mmol), silyl enol ether **114** (249 mg, 1.27 mmol) in ether (5 mL), zinc chloride (0.92 mL, 0.69 M in ether, 0.63 mmol), and (phenylseleno)acetaldehyde (250 mg, 1.26 mmol) in ether (3 mL + 1 mL rinse). Flash chromatography over silica gel (3 x 15 cm) with 20% ethyl acetate-hexane gave **117**[69] as two separate and homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oils of combined weight 334 mg (81%). The material of higher R_f **117a** (231 mg, 56%) had: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.5-1.75 (m, 2H), 1.8-2.18 (m, 3H), 2.2-2.3 (m, 1H), 2.6-2.7

(m, 2H), 3.18 (dd, J = 12.5, 9 Hz, 1H), 3.3 (dd, J = 12.5, 6 Hz, 1H), 3.35 (d, J = 11 Hz, 1H), 3.7-3.85 (m, 1H), 4.95-5.1 (m, 2H), 5.5-5.6 (m, 1H), 7.2-7.3 (m, 3H), 7.45-7.55 (m, 2H).

The material of lower R_f **117b** (103 mg, 25%) had: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.6-1.75 (m, 2H), 1.8-1.9 (m, 1H), 2.0-2.1 (m, 1H), 2.2-2.5 (m, 3H), 2.6-2.7 (ddd, J = 11, 4.5, 2 Hz, 1H), 3.05 (dd, J = 12.5, 3.5 Hz, 1H), 3.12 (d, J = 8.5 Hz, 1H), 3.3 (dd, J = 12.5, 10 Hz, 1H), 3.9-4.0 (m, 1H), 4.9-5.2 (m, 2H), 5.6-5.75 (m, 1H), 7.2-7.3 (m, 3H), 7.5-7.6 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 24.7, 32.0, 32.5, 42.0, 45.4, 58.5, 70.0, 115.8, 127.2, 129.1, 130.0, 133.3, 140.2, 212.9.

trans-3-Ethenyl-2-[1-hydroxy-2-(phenylseleno)ethyl]cyclopentanone 118:

The reaction was carried out exactly as described for the preparation of **116** using methyllithium (0.65 mL, 1.7 M in ether, 1.11 mmol), silyl enol ether **115** (201 mg, 1.11 mmol) in ether (5 mL), zinc chloride (0.80 mL, 0.69 M in ether, 0.55 mmol) and (phenylseleno)acetaldehyde (224 mg, 1.12 mmol) in ether (3 mL + 1 mL rinse). Flash chromatography over silica gel (3 × 15 cm) with 20% ethyl acetate-hexane gave **118** (252 mg, 73%) as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane)

oil: IR (CCl_4 cast) 3440, 1740, 1480, 1440, 1020, 740, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.5-1.7 (m, 1H), 2.1-2.4 (m, 4H), 2.6-2.8 (m, 1H), 3.0-3.3 (m, 3H), 3.85 (m, 0.5H), 4.2 (m, 0.5H), 5.0-5.2 (m, 2H), 5.7-5.9 (m, 1H), 7.2 (m, 3H), 7.5 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 27.9, 28.2, 33.7, 34.2, 38.4, 38.7, 41.5, 44.7, 57.4, 58.0, 69.2, 69.9, 115.6, 116.1, 127.1, 127.4, 129.1, 129.3, 132.8, 133.1, 140.2, 141.7, 218.5, 219.6; exact mass, m/z 310.0472 (calcd for $C_{15}H_{18}SeO_2$, 310.0472). Anal. Calcd for $C_{15}H_{18}SeO_2$: C, 58.26; H, 5.87; O, 10.35. Found: C, 58.00; H, 5.81; O, 10.48.

trans-3-Ethenyl-2[1-hydroxy-2-(phenylseleno)propyl]cyclohexanone 119:

The reaction was carried out exactly as described for the preparation of **116** using methyllithium (1.80 mL, 1.7 M in ether, 3.0 mmol), silyl enol ether **114** (585 mg, 3.0 mmol) in ether (10 mL), zinc chloride (0.16 mL, 0.69 M in ether, 1.5 mmol) and 2-(phenylseleno)propanal[72] (638 mg, 3.0 mmol) in ether (5 mL + 2 mL rinse). Flash chromatography over silica gel (3 x 15 cm) with 20% ethyl acetate-hexane gave **119** as two separate and apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oils of combined weight 844 mg (83%). A mixed fraction of the two materials (150 mg, 15%) was isolated. The material of

higher R_f **119a** (542 mg, 53%) had: IR (CCl_4 cast) 3520, 2920, 1695, 1437, 998, 740, 698 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.45-1.65 [m, 5H (includes a doublet at δ1.55, J = 7 Hz)], 1.7-2.1 (m, 4H), 2.55-2.7 (m, 1H), 2.95 (d, J = 11.5 Hz, 1H), 3.2 (d, J = 11 Hz, 1H), 3.45-3.7 (m, 2H), 5.08-5.2 (m, 2H), 5.6-5.7 (m, 1H), 7.2 (m, 3H), 7.5 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 19.1, 26.5, 32.4, 42.7, 42.9, 47.9, 56.1, 75.5, 116.6, 127.5, 129.2, 129.5, 134.5, 140.0, 215.6; exact mass, m/z 338.0793 (calcd for $C_{17}H_{22}SeO_2$, 338.0785). Anal. Calcd for $C_{17}H_{22}SeO_2$: C, 60.53; H, 6.57; O, 9.48. Found: C, 60.36; H, 6.44; O, 9.68.

The material of lower R_f **119b** (152 mg, 15%) had: IR (CCl_4 cast) 3520, 2920, 1692, 1477, 1436, 1022, 999, 740, 692 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.2-2.1 (m, 8H), 2.25-3.9 (m, 6H), 5.0-5.2 (m, 2H), 5.5-5.7 (m, 1H), 7.2-7.35 (m, 3H), 7.4-7.6 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 14.1, 14.9, 15.6, 16.7, 19.3, 19.4, 19.5, 20.9, 21.0, 22.7, 22.9, 29.6, 30.1, 30.6, 31.6, 31.7, 31.9, 32.1, 32.2, 41.7, 42.3, 42.6, 42.8, 42.9, 43.0, 43.8, 43.9, 44.5, 44.9, 48.3, 48.5, 48.7, 54.1, 54.4, 55.4, 55.5, 55.7, 56.3, 56.8, 56.9, 71.4, 73.2, 74.0, 74.1, 74.3, 74.7, 75.5, 75.6, 117.0, 127.5, 127.6, 127.7, 127.8, 128.1, 128.5, 128.9, 129.1, 129.2, 129.4, 129.5, 134.6, 134.7, 135.4, 136.1, 139.3, 139.5, 139.6, 216.9, 217.2, 218.1,

218.6; exact mass, m/z 338.0780 (calcd for $C_{17}H_{22}SeO_2$, 338.0785).

8α,8aα,4aβ-Decahydro-8-hydroxy-5-methylnaphthalene-1-one 120 and 3α,3aα,7aβ-Octahydro-1,1-dimethyl-3-hydroxy-1H-inden-4-one 121:

The general procedure for radical cyclization was followed using selenide **116a** (363 mg, 1.08 mmol) in benzene (30 mL), triphenyltin hydride (466 mg, 1.33 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 over silica gel (3 × 15 cm) with 20% ethyl acetate-hexane followed by 30% ethyl acetate-hexane and then 50% ethyl acetate-hexane gave **120** and **121** as two separate and apparently homogeneous (TLC, silica gel, 30% ethyl acetate-hexane) fractions of combined weight 136 mg (69%). The material of higher R_f (57 mg, 29%) **120** had: IR (CCl_4 cast) 3540, 2930, 2865, 1698, 1056 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.94 (d, J = 6.5 Hz, 1.92H), 0.98 (d, J = 7 Hz, 1.08H), 1.0-1.8 (m, 7H), 1.9-2.4 (m, 6H), 3.64 (d, J = 4 Hz, 0.61H), 3.68 (d, J = 4 Hz, 0.39H), 3.8 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 12.4, 19.6, 26.0, 26.1, 26.7, 29.1, 29.4, 30.5, 32.0, 32.2, 32.7, 37.8, 41.9, 42.0, 45.1, 48.7, 55.6, 61.5, 69.1, 70.0, 215.0; exact mass, m/z 182.1303 (calcd for

$C_{11}H_{18}O_2$, 182.1307). Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95. Found: C, 72.43; H, 10.05.

The material of lower R_f (79 mg, 40%) **121** had: IR (CCl_4 cast) 3420, 2950, 2864, 1716, 1464, 1357, 1302, 1165, 1024 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0 [s, 6H (includes two singlets)], 1.4-1.6 (m, 4H), 1.75-1.95 (m, 2H), 2.1-2.4 (m, 4H), 2.55 (ddd, J = 13.5, 8, 1 Hz, 1H), 4.45 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 24.5, 25.1, 27.2, 29.0, 38.5, 41.2, 48.1, 55.2, 62.5, 69.0, 211.8; exact mass, m/z 182.1299 (calcd for $C_{11}H_{18}O_2$, 182.1307). Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95. Found: C, 72.41; H, 9.88.

4aα,8α,8aα-Decahydro-8-hydroxy-6-methylnaphthalen-1-one 122 and 3α,3aβ,7aα-Octahydro-1,1-dimethyl-3-hydroxy-1H-inden-4-one 123:

The general procedure for radical cyclization was followed using selenide **116b** (278 mg, 0.83 mmol) in benzene (20 mL), triphenyltin hydride (407 mg, 1.16 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 over silica gel (3 × 15 cm) with 20% ethyl acetate-hexane followed by 30% ethyl acetate-hexane and then 50% ethyl acetate-hexane gave **122** and **123** (123 mg, 81%) as an inseparable mixture of isomers

that were pure by TLC, silica gel, 50% ethyl acetate-hexane: IR (CCl_4 cast) 3520, 2929, 2868, 1701, 1340, 1040 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.85 (s, 1H), 0.98 (d, J = 6.5 Hz), 0.99 (d, J = 7 Hz), [the signals at δ0.98 and 0.99 correspond to 2H], 1.1 (s, 1H), 1.2-2.4 (m, 12H), 3.12 (t, J = 2 Hz, 0.19H), 3.15 (t, J = 2 Hz, 0.42H), 3.54 (s, 0.39H), 4.3 (m, 0.6H), 4.5 (m, 0.4H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 12.0, 19.9, 24.5, 25.2, 25.7, 26.3, 26.4, 26.5, 27.1, 28.6, 29.2, 29.4, 29.8, 31.1, 32.0, 38.4, 39.0, 40.4, 41.9, 42.1, 42.5, 44.7, 49.1, 52.4, 52.9, 58.4, 59.0, 64.3, 70.2, 214.5, 215.2; exact mass, m/z 182.1306 (calcd for $C_{11}H_{18}O_2$, 182.1307). Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95. Found: C, 72.51; H, 10.05.

2-[(1-Hydroxy)ethyl]-3-ethenylcyclopentane 124 and Octahydro-4-hydroxy-1H-inden-3-one 125:

The general procedure for the radical cyclization was followed using selenides **118** (193 mg, 0.62 mmol) in benzene (15 mL), triphenyltin hydride (297 mg, 0.85 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 over silica gel (2 x 15 cm) with 25% ethyl acetate-hexane gave three major fractions: fraction 1, which corresponds to one isomer of the starting material (8 mg, 4%), as a homogeneous (TLC,

silica gel, 25% ethyl acetate-hexane) oil; fraction 2, which corresponds to one isomer of **124** (8 mg, 8%), as a homogeneous (TLC, silica gel, 25% ethyl acetate-hexane) oil; fraction 3, which was a chromatographically homogeneous, but unresolvable (TLC, silica gel, 25% ethyl acetate-hexane) mixture (^{1}H NMR) of the other isomer of **124** (6 mg, 6%; calculated from ^{1}H NMR spectrum) and **125** (33 mg, 34%; calculated from ^{1}H NMR spectrum).

Fraction 1 had: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.5-1.7 (m, 1H), 2.1-2.4 (m, 4H), 2.6-2.8 (m, 1H), 3.21 (d, J = 4 Hz, 1H), 3.26 (dd, J = 13, 6 Hz, 1H), 3.32 (dd, J = 13, 7 Hz, 1H), 3.85 (m, 1H), 5.0-5.2 (m, 2H), 5.7-5.9 (m, 1H), 7.2 (m, 3H), 7.5 (m, 2H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 27.8, 33.7, 38.6, 44.7, 57.4, 69.9, 116.1, 127.1, 129.1, 132.8, 140.2, 219.6; exact mass, m/z 310.0476 (calcd for $C_{15}H_{18}O_2Se$, 310.0472).

Fraction 2 had: IR (CCl_4 cast) 3440, 2860, 2820, 1737, 1400, 1280, 1090, 910 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.25 (d, J = 6.5 Hz, 3H), 1.55-1.7 (m, 2H), 1.98 (ddd, J = 11, 7, 1.5 Hz, 1H), 2.1-2.48 (m, 2H), 2.55-2.7 (m, 1H), 3.55 (d, J = 3 Hz, 1H), 3.9 (m, 1H), 5.0-5.2 (m, 2H), 5.75-5.9 (m, 1H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 21.7, 28.1, 38.2, 44.5, 59.9, 68.1, 115.7, 141.0; exact mass, m/z 154.0981 (calcd for $C_9H_{14}O_2$, 154.0994).

Fraction 3 had: IR (CCl_4 cast) 3480, 2920, 2850,

1730, 1400, 1280, 1160, 1010 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.1-2.5 (m, 12H), 3.45 (s, 1H), 3.75 (ddd, J = 10.5, 9.5, 4.5 Hz, 1H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 24.5, 27.2, 31.4, 33.6, 37.7, 41.2, 60.9, 70.2, 220.0; exact mass, m/z 154.0994 (calcd for $C_9H_{14}O_2$, 154.0994).

Octahydro-1,2-dimethyl-3-hydroxy-1H-inden-4-one 126:

The general procedure for radical cyclization was followed using selenide **119a** (201 mg, 0.60 mmol) in benzene (15 mL), triphenyltin hydride (256 mg, 0.71 mmol) in benzene (10 mL), and AIBN (6 mg, 0.04 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 20% ethyl acetate-hexane followed by 40% ethyl acetate-hexane gave **126** as two separate and apparently homogeneous (TLC, silica gel, 40% ethyl acetate-hexane) fractions of combined weight 58 mg (53%). The material of higher R_f **126a** (2 mg, 2%) had: IR (CCl_4 cast) 3520, 2950, 2929, 2871, 1711, 1440, 1370, 1240 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.85 (d, J = 7 Hz, 3H), 0.95 (d, J = 6.5 Hz, 3H), 1.2-2.5 (m, 9H), 2.85 (dd, J = 8, 6 Hz, 1H), 3.48 (d, J = 6 Hz, 1H), 3.95 (dd, J = 10, 6 Hz, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 12.7, 14.7, 22.3, 27.5, 39.0, 41.6, 43.1, 45.3, 54.4, 81.0; exact mass, m/z 182.1302 (calcd for $C_{11}H_{18}O_2$, 182.1307).

The material of lower R_f **126b** (56 mg, 51%) had: IR (CCl_4 cast) 3400, 2958, 2929, 1714 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.9 (d, J = 7 Hz, 3H), 1.0 [d, J = 7 Hz, 3H (includes two doubelts of J = 7 Hz)], 1.2-1.7 (m, 4H), 1.9-2.55 (m, 7H), 3.85 (dd, J = 9, 5.5 Hz, 0.71H), 4.42 (br, t, J = 9 Hz, 0.29H); ^{13}C ($CDCl_3$, 75.7 MHz) δ 13.3, 13.7, 14.7, 16.8, 27.3, 27.5, 28.9, 29.3, 39.6, 41.3, 41.6, 43.6, 47.1, 51.1, 51.5, 63.3, 64.5, 69.4, 77.6, 211.4; exact mass, m/z 182.1303 (calcd for $C_{11}H_{18}O_2$, 182.1307). Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95. Found: C, 72.26; H, 9.93.

3α,3aα,7aβ-Octahydro-3-hydroxy-1-methyl-1H-inden-4-one 127:

The general procedure for radical cyclization was followed using selenide **117a** (466 mg, 1.44 mmol) in benzene (30 mL), triphenyltin hydride (690 mg, 1.97 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 over silica gel (3 x 15 cm) with 20% ethyl acetate-hexane followed by 30% ethyl acetate-hexane, and then 50% ethyl acetate-hexane gave **127** as an apparently homogeneous (TLC, silica gel, 30% ethyl acetate-hexane) oil consisting of two isomers (142 mg, 58%): mp. 86-90°C (after recrystallization from ether);

IR (CCl_4 cast) 3245, 2937, 2840, 1713 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0 [d, J = 6.5 Hz, 3H (includes another minor doublet δ1.01, J = 7 Hz)], 1.15-1.3 (m, 1H), 1.3-1.48 (m, 1H), 1.5-1.7 (m, 2H), 1.8-2.4 (m, 7H), 2.45 (d, J = 3 Hz, 1H), 4.5 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 17.4, 18.4, 26.8, 27.3, 29.0, 32.6, 37.9, 40.3, 40.7, 41.1, 41.3, 48.0, 53.3, 60.4, 65.2, 68.7, 70.3, 210.92; exact mass, m/z 168.1148 (calcd for $C_{10}H_{16}O_2$, 168.1150). Anal. Calcd for $C_{10}H_{16}O_2$: C, 71.39; H, 9.59. Found: C, 71.61; H, 9.58.

3α,3aβ,7aα-Octahydro-3-hydroxy-1-methyl-1H-inden-4-one 128:

The general procedure for radical cyclization was followed using selenide **117b** (380 mg, 1.18 mmol) in benzene (30 mL), triphenyltin hydride (515 mg, 1.47 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 over silica gel (3 x 15 cm) with 20% ethyl acetate-hexane followed by 30% ethyl acetate-hexane, and then 50% ethyl acetate-hexane gave **128** as an apparently homogeneous (TLC, silica gel, 30% ethyl acetate-hexane) oil (110 mg, 56%) consisting of two isomers: IR (CCl_4 cast) 3520, 2950, 2927, 1698, 409 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.9 (d, J = 7 Hz, 0.3H), 1.1 (d,

J = 6.5 Hz, 2.7H), 1.15-1.4 (m, 2H), 1.55-1.95 (m, 3H), 2.05-2.4 (m, 6H), 3.42 (s, 0.1H), 3.55 (s, 0.9H), 4.32 (br, m, 0.1H), 4.5 (m, 0.9H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 17.1, 18.6, 26.7, 27.4, 29.1, 32.8, 39.1, 41.6, 41.9, 42.0, 46.4, 50.7, 57.9, 61.5, 64.1, 70.1, 70.7, 213.75; exact mass, m/z 168.1143 (calcd for $C_{10}H_{16}O_2$, 168.1151). Anal. Calcd for $C_{10}H_{16}O_2$: C, 71.39; H, 9.59. Found: C, 71.14; H, 9.62.

8α,8aα,4aβ-Decahydro-8-(3,5-dinitrobenzoyloxy)-5-methyl-naphthalen-1-one 129:

3,5-Dinitrobenzoyl chloride (85 mg, 0.37 mmol) and pyridine (0.03 mL, 0.37 mmol) were added to a stirred solution of **120** (40 mg, 0.22 mmol) in benzene (3 mL). One crystal of DMAP was added as a catalyst and the mixture was stirred at room temperature for 2 h. It was then quenched with dilute hydrochloric acid (10 mL, 1 M). The organic phase was extracted with ether (3 x 20 mL) and the combined extracts were washed with saturated aqueous sodium bicarbonate (20 mL) and brine (20 mL), and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (2 x 15 cm) with 20% ethyl acetate-hexane gave **129** (58 mg, 70%) as an apparently homogeneous solid (TLC, silica gel, 20% ethyl acetate-hexane) consisting of two isomers: mp. 144-150°C; IR

($CHCl_3$ cast) 1724, 1710, 1543, 1344, 1278, 1164, 730, 720 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0 (d, J = 7 Hz, 1.95H), 1.1 (d, J = 7 Hz, 1.05H), 1.2-1.85 (m, 7H), 1.95-2.5 (m, 5H), 2.62 (t, J = 11 Hz, 0.63H), 2.76 (t, J = 11 Hz, 0.37H), 5.4 (td, J = 11, 4.9 Hz, 1H), 9.1 (m, 2H), 9.2 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 12.6, 19.7, 25.2, 27.1, 27.2, 30.0, 30.3, 30.5, 30.8, 31.7, 32.5, 37.8, 42.3, 42.5, 46.8, 50.5, 52.6, 58.5, 73.2, 73.6, 122.3, 129.8, 134.8, 148.8, 162.0, 209.7, 210.4; exact mass, m/z 376.1268 (calcd for $C_{18}H_{20}N_2O_7$, 376.1270). Anal. Calcd for $C_{18}H_{20}N_2O_7$: C, 57.44; H, 5.36; N, 7.44. Found: C, 57.27; H, 5.30; N, 7.44.

4,5,6,7,7a,1-Hexahydro-1,1-dimethyl-2H-inden-4-one 130 and 3α,3aα,7aβ-Octahydro-1,1-dimethyl-3-(3,5-dinitrobenzoyloxy)-1H-inden-4-one 131:

The reaction was carried out exactly as described for the preparation of **129** using 3,5-dinitrobenzoyl chloride (140 mg, 0.61 mmol), pyridine (0.05 mL, 0.62 mmol), a crystal of DMAP, and keto alcohol **121** (54 mg, 0.30 mmol) in benzene (3 mL). Flash chromatography over silica gel (2 × 15 cm) with 20% ethyl acetate-hexane gave **130** (2 mg, 4%) and **131** (95 mg, 84%) each as a pure (TLC, silica gel, 20% ethyl acetate-hexane) oil. Compound **130** had: IR (CCl_4 cast) 2955, 2933, 2869, 1731, 1671 cm^{-1}; ^1H NMR

($CDCl_3$, 300 MHz) δ 0.9 (s, 3H), 1.2 (s, 3H), 1.25-1.4 (m, 1H), 1.6-1.85 (m, 2H), 2.0-2.4 (m, 4H), 2.45-2.65 (m, 2H), 6.65 (dd, J = 6, 3 Hz, 1H); exact mass, m/z 164.1201 (calcd for $C_{11}H_{16}O$, 164.1202).

Compound **131** had: IR ($CHCl_3$ cast) 1720, 1540, 1340, 1276, 1156, 726, 716 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.1 (s, 6H), 1.5-1.7 (m, 4H), 1.9-2.0 (m, 1H), 2.15-2.5 (m, 4H), 3.1 (dd, J = 13, 7.5 Hz, 1H), 5.65 (m, 1H), 9.1 (d, J = 2 Hz, 2H), 9.2 (t, J = 2 Hz, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 23.2, 25.3, 27.3, 28.0, 39.8, 41.3, 47.1, 55.7, 59.7, 73.6, 122.3, 129.4, 134.1, 148.6, 162.0, 208.2; exact mass, m/z 376.1257 (calcd for $C_{18}H_{20}N_2O_7$, 376.1271). Anal. Calcd for $C_{18}H_{20}N_2O_7$: C, 57.44; H, 5.36; N, 7.44. Found: C, 57.43; H, 5.30; N, 7.54.

4,5,6,7,7a,1-Hexahydro-1,1-dimethyl-2H-inden-4-one 130, 1,2,3,4,4a,5,6,7-Octahydro-5-methyl-naphthalen-1-one 132, 4aα,8α,8aα-Decahydro-8-(3,5-dinitrobenzoyloxy)-6-methyl naphthalen-1-one 133 and 3α,3aβ,7aα-Octahydro-1,1-dimethyl-3-(3,5-dinitrobenzoyloxy)-1H-inden-4-one 134:

The reaction was carried out exactly as described for the preparation of **129** using 3,5-dinitrobenzoyl chloride (210 mg, 0.91 mmol), pyridine (0.07 mL, 0.86 mmol), a crystal of DMAP, and the mixture of keto alcohols **122** and **123** (78 mg, 0.43 mmol) in benzene (6 mL). Flash

chromatography over silica gel (2 × 15 cm) with 20% ethyl acetate-hexane gave **130** and **132** (24 mg, 33%) and **133** and **134** (27 mg, 28%), each as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil. The sample of **130** and **132** consists of three isomers: IR (CCl_4 cast) 2920, 1680, 1618, 1540, 1458, 1260, 1220 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.9 (s, 1H), 1.4 (d, J = 6 Hz, 2H), 1.12-1.4 [m, 4H (including a singlet at δ1.2)], 1.6-2.3 (m, 7H), 2.45-2.6 (m, 1H), 6.65-6.8 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 13.1, 20.1, 22.5, 23.6, 23.8, 23.9, 26.0, 27.6, 28.4, 28.8, 30.5, 34.8, 40.0, 44.0, 44.8, 47.7, 55.1, 122.3, 129.4, 135.7, 136.0, 137.8, 139.7, 201.5; exact mass, m/z 164.1202 (calcd for $C_{11}H_{16}O$, 164.1201).

The sample of **133** and **134** consists of three isomers: IR (CCl_4 cast) 1725, 1710, 1540, 1340, 1280, 1160, 715 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0 (s, 0.8H), 1.06 [d, J = 7 Hz, 2.4H (includes another doublet J = 6 Hz)], 1.21 (s, 0.8H), 1.5-2.5 (m, 12H), 5.7 (m, 1H), 9.0 (m, 2H), 9.2 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 12.0, 19.8, 24.2, 24.4, 25.5, 25.2, 25.4, 26.5, 27.3, 29.1, 29.3, 29.4, 29.6, 31.6, 38.1, 38.8, 41.0, 41.4, 41.8, 42.0, 45.1, 48.0, 50.15, 54.2, 56.4, 56.8, 70.0, 70.1, 74.18, 122.1, 129.3, 129.5, 134.7, 148.6, 161.7, 208.9; exact mass, m/z 376.1273 (calcd for $C_{18}H_{20}N_2O_7$, 376.1270).

3α,3aα,7aβ-Octahydro-3-(3,5-dinitrobenzoyloxy)-1-methyl-1H-inden-4-one 135:

The reaction was carried out exactly as described for the preparation of **129** using 3,5-dinitrobenzoyl chloride (80 mg, 0.35 mmol), pyridine (0.03 mL, 0.37 mmol), a crystal of DMAP, and keto alcohols **127** (24 mg, 0.15 mmol) in toluene (2.0 mL). Flash chromatography over silica gel (1 × 15 cm) with 20% ethyl acetate-hexane gave **135** (57 mg, 106%) as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) solid; mp. 167-168°C; IR (CCl_4 cast) 1725, 1715, 1540, 1340, 1280, 1160, 720 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.05 (d, J = 6 Hz, 3H), 1.2-1.8 (m, 3H), 1.9-2.1 (m, 3H), 2.15-2.3 (m, 2H), 2.38-2.5 (m, 2H), 2.9 (dd, J = 13, 8 Hz, 1H), 5.6 (dt, J = 8, 6.5 Hz, 1H), 9.1 (d, J = 2 Hz, 2H), 9.2 (t, J = 2 Hz, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 17.6, 27.3, 29.0, 38.7, 40.0, 41.2, 53.5, 62.0, 73.5, 122.3, 129.4, 134.1, 148.6, 162.0, 207.5; exact mass, m/z 151.1085 [calcd for ($C_{17}H_{18}N_2O_7$-$C_7H_3N_2O_6$), 151.1123]. Anal. Calcd for $C_{17}H_{18}N_2O_7$: C, 56.35; H, 5.00; N, 7.73. Found: C, 56.20; H, 5.01; N, 7.94. X-ray crystal structure analysis of **135** gives a computer generated perspective drawing of **135** from the final X-ray coordinates showing the relative stereochemistry.

3α,3aβ,7aα-Octahydro-3-(3,5-dinitrobenzoyloxy)-1-methyl-1H-inden-4-one 137:

The reaction was carried out exactly as described for the preparation of **129** using 3,5-dinitrobenzoyl chloride (180 mg, 0.78 mmol), pyridine (0.06 mL, 0.74 mmol), a crystal of DMAP, and keto alcohols **128** (65 mg, 0.39 mmol) in benzene (5 mL). Flash chromatography over silica gel (2 × 1[illegible] with 20% ethyl acetate-hexane gave **136** (31 mg, 51%) and **137** (9 mg, 6%), each as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil consisting of two isomers. **136** had: IR (CCl_4 cast) 2910, 1710, 1450 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.86-1.3 [m, 4H (includes a doublet at δ0.87, J = 7 Hz and at δ0.99, J = 7 Hz)], 1.65-1.85 (m, 1H), 2.0-2.3 (m, 5H), 2.35-2.6 (m, 3H), 6.6 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 18.0, 23.8, 29.9, 39.9, 40.0, 43.9, 52.6, 138.05, 144.64, 199.22; exact mass, m/z 150.1045 (calcd for $C_{10}H_{14}O$, 150.1045).

137 had: IR (CCl_4 cast) 1730, 1710, 1545, 1340, 1280, 1160, 720 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0 (d, J = 7 Hz, 3H), 1.4-2.6 (m, 11H), 5.82 (m, 0.57H), 5.95 (m, 0.43H), 9.08 (m, 2H), 9.2 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 16.8, 20.2, 25.3, 26.6, 26.7, 30.0, 32.4, 32.5, 33.3, 38.9, 40.5, 41.67, 42.00, 47.3, 55.7, 56.6, 69.7, 74.6, 122.0, 122.1, 129.3, 129.5, 134.6, 148.6, 161.7, 208.0; exact mass, m/z 362.1118 (calcd for $C_{17}H_{18}N_2O$, 362.1114).

5-Hydroxy-6-(phenylseleno)-hex-1-en-3-one 138:

The reaction was carried out exactly as described for the preparation of **116** using methyllithium (2.46 mL, 1.55 M in ether, 3.81 mmol), 2-(trimethylsiloxy)-1,3-butadiene (545 mg, 3.84 mmol), zinc chloride (2.78 mL, 0.69 M in ether, 1.92 mmol) and (phenylseleno)acetaldehyde (760 mg, 3.82 mmol) in ether (8 mL + 2 mL rinse). Flash chromatography over silica gel (3 x 15 cm) with 20% ethyl acetate-hexane gave recovered (phenylseleno)acetaldehyde (161 mg, 21%) and **138** (166 mg, 20%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4 cast) 3440, 1676, 1478, 1402, 1022, 737, 692 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.85 (dd, J = 18, 8 Hz, 1H), 2.9 (dd, J = 18, 4 Hz, 1H), 3.05 (dd, J = 13, 6.5 Hz, 1H), 3.1 (dd, J = 12.5, 6 Hz, 1H), 3.32 (d, J = 3.5 Hz, 1H), 4.25 (m, 1H), 5.88 (dd, J = 10, 1.5 Hz, 1H), 6.2 (dd, J = 18, 1.5 Hz, 1H), 6.3 (dd, J = 18, 10 Hz, 1H), 7.2-7.3 (m, 3H), 7.5-7.6 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 34.7, 44.9, 67.0, 127.2, 129.3, 129.4, 129.5, 132.7, 136.6, 200.2; exact mass, m/z 270.0152 (calcd for $C_{12}H_{14}SeO_2$, 270.0159). Anal. Calcd for $C_{12}H_{14}SeO_2$: C, 53.54; H, 5.24; O, 11.89. Found: C, 53.37; H, 5.23; O, 12.45. A satisfactory oxygen analysis could not be obtained.

5-Hydroxy-6-(phenylseleno)-1-(triphenylstannio)hexan-3-one 139 and 5-Hydroxy-6-(phenylseleno)hexan-3-one 140:

The general procedure for the radical cyclization was followed using selenide **138** (182 mg, 0.67 mmol) in benzene (16 mL), triphenyltin hydride (315 mg, 0.89 mmol) in benzene (7 mL), and AIBN (7 mg, 0.04 mmol) in benzene (7 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 20% ethyl acetate-hexane gave **139** (97 mg, 23% and **140** (42 mg, 22%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil. Compound **139** had: IR (CCl_4 cast) 3400, 2980, 1710, 1580, 1480, 1428, 1080, 1020, 728, 699 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.5 (td, J = 7, 2 Hz, 2H), 1.58 (s, 1H), 2.4 (dd, J = 17, 5 Hz, 1H), 2.47 (dd, J = 16, 7 Hz, 1H), 2.78-2.85 (m, 4H), 3.9 (m, 1H), 7.2-7.6 (m, 20H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 3.7, 34.6, 40.4, 47.6, 67.0, 127.2, 128.2, 128.5, 128.8, 128.9, 129.0, 129.2, 129.6, 132.7, 136.9, 137.1, 137.3, 139.1, 211.5; m/z 543 [calcd for $[C_{30}H_{30}O_2SnSe-C_6H_5)$, 543].

Compound **140** had: IR (CCl_4 cast) 3440, 1707, 1480, 1440, 1070, 1010, 740, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.02 (t, J = 7 Hz, 3H), 2.4 (q, J = 7 Hz, 2H), 2.66 (dd, J = 18, 7.5 Hz, 1H), 2.75 (dd, J = 17.5, 4 Hz, 1H), 3.01 (dd, J = 13, 7 Hz, 1H), 3.08 (dd, J = 13, 6 Hz, 1H), 3.27 (d, J = 4 Hz, 1H), 4.2 (m, 1H), 7.2-7.3 (m, 3H), 7.5-7.6

(m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 7.4, 34.6, 36.7, 47.5, 66.9, 127.2, 129.2, 129.4, 132.7, 137.0, 211.3; exact mass, m/z 272.0305 (calcd for $C_{12}H_{16}SeO_2$, 272.0315).

5-Phenylpent-4-yn-1-ol 142:[78]

n-Butyllithium (70.0 mL, 1.55 M in hexanes, 108.5 mmol) was added dropwise to a stirred and cooled (-78°C) solution of phenylacetylene (11.95 g, 116.99 mmol) in THF (200 mL). After 10 min, a solution of oxetane (2.14 g, 36.90 mmol) in THF (10 mL) was added dropwise followed by boron trifluoride etherate (14.0 mL, 113.8 mmol) and stirring was continued for 1 h. The reaction mixture was warmed to room temperature, quenched with saturated ammonium chloride solution (100 mL), and extracted with ether (3 x 150 mL). The combined organic extracts were washed with water (100 mL), and with brine (50 mL), and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (5 x 15 cm) with 10% ethyl acetate-hexane followed by 20% ethyl acetate-hexane gave **142**[78] (4.94 g, 83%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4) 3640, 3340, 3082, 2940, 2880, 1600, 1490, 1440, 1330, 1060, 914, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.85 (m, 3H), 2.5 (t, J = 6 Hz, 2H), 3.8 (t, J = 6 Hz, 2H), 7.2-7.5 (m, 5H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 15.7, 31.0, 61.5,

80.8, 89.0, 123.4, 127.3, 127.9, 131.2; exact mass, m/z 160.0893 (calcd for $C_{11}H_{12}O$, 160.0888).

6-Phenyl-5-hexyn-2-ol 143:[101]

The procedure employed for **142** was followed using 2-methyloxetane[86] (2.20 g, 30.61 mmol), phenylacetylene (7.01 g, 68.66 mmol), n-butyllithium (46.0 mL, 149 M in hexanes, 68.54 mmol), and boron trifluoride etherate (8.50 mL, 69.11 mmol). Evaporation of the solvent and flash chromatography of the residue over silica gel (5 x 15 cm) with 20% ethyl acetate-hexane and then 30% ethyl acetate-hexane gave **143**[101] (1.36 g, 25%) as a homogeneous (TLC, silica gel, 30% ethyl acetate-hexane) oil: IR (Neat) 3360, 2960, 2940, 1490, 1370, 1130, 760, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.15 (d, J = 6 Hz, 3H), 1.7 (q, J = 7 Hz, 2H), 2.0 (br, s, 1H), 2.5 (t, J = 7 Hz, 2H), 4.0 (m, 1H), 7.2-7.45 (m, 5H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 15.9, 22.6, 23.4, 37.6, 67.1, 81.0, 89.5, 123.7, 127.6, 128.2, 131.5; exact mass, m/z 174.1046 (calcd for $C_{12}H_{14}O$, 174.1045).

trans-2-[3-[Tri(1-methylethyl)silyl]prop-2-ynyl]cyclohexan-1-ol 144:[85]

n-Butyllithium (9.57 mL, 1.41 M in hexanes, 13.49 mmol) was added dropwise to a stirred and cooled (-20°C) solution of alkyne **194** (2.65 g, 13.50 mmol) in THF (10

mL). After 15 min, a solution of cyclohexene oxide (1.32 g, 13.49 mmol) in THF (3 mL) was added dropwise, the cold bath was removed, and stirred for 1 h. The mixture was quenched with water (30 mL), extracted with ether (3 × 40 mL) and the combined extracts were washed with brine (20 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (5 × 15 cm) with 20% ethyl acetate-hexane gave **144**[85] (1.94 g, 48%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4) 3620, 3540, 2940, 2860, 2165, 1460, 1445, 1050, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.9-2.0 [m, 30H (includes a doublet at δ1.05, J = 4 Hz)], 2.3-2.6 (m, 2H), 3.3-3.5 (br, m, 1H), 3.68 (br, s, 1H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 11.4, 18.7, 23.6, 24.9, 25.5, 30.6, 35.4, 44.4, 73.9; exact mass, m/z 251.1826 [calcd for ($C_{18}H_{34}OSi$-C_3H_7), 251.1831]. Anal. Calcd for $C_{18}H_{34}OSi$: C, 73.40; H, 11.54. Found: C, 73.54; H, 11.75.

5-[Tri(1-methylethyl)silyl]pent-4-yn-1-ol 145:

The procedure employed for **144** was followed using ethylene oxide (1.0 mL), alkyne **194**[85] (2.62 g, 13.38 mmol), and n-butyllithium (8.60 mL, 1.55 M in hexanes, 13.33 mmol) in THF (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (5 × 15 cm) with 10% ethyl acetate-hexane gave **145** (1.74 g,

54%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3630, 3560, 2940, 2860, 2164, 1460, 1280, 1060, 1045, 920, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.0-1.35 [m, 21H (includes a doublet at δ1.1, J = 4 Hz)], 1.65 (br, s, 1H), 1.82 (q', J = 6 Hz, 2H), 2.4 (t, J = 6 Hz, 2H), 3.8 (q, J = 6 Hz, 2H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 12.0, 17.3, 19.3, 32.2, 62.6, 81.8, 108.9; exact mass, m/z 197.1362 [calcd for ($C_{14}H_{28}OSi-C_3H_{21}$), 197.1362]. Anal. Calcd for $C_{14}H_{28}OSi$: C, 69.93; H, 11.74. Found: C, 69.48; H, 11.62.

trans-2-[3-[Tri(1-methylethyl)silyl]prop-2-ynyl]cyclopentan-1-ol 146:

The procedure employed for **144** was followed using cyclopentene oxide (964 mg, 11.46 mmol), alkyne **194**[85] (2.68 g, 13.66 mmol), and n-butyllithium (9.70 mL, 1.41 M in hexanes, 13.67 mmol) in THF (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (5 × 15 cm) with 10% ethyl acetate-hexane gave **146** (2.04 g, 53%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3620, 3560, 2940, 2860, 2160, 1460, 1380, 1070, 1010, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 0.9-1.1 [m, 21H (includes a doublet at δ1.02, J = 4 Hz)], 1.3 (m, 1H), 1.5-1.6 (m, 2H), 1.6-1.75 (m, 1H), 1.85-2.0 (m, 4H), 2.25 (dd, J = 17, 7.5 Hz, 1H),

2.4 (dd, J = 17, 5.5 Hz, 1H), 4.0 (m, 1H); ^{13}C ($CDCl_3$, 100.6 Hz) δ 11.3, 18.6, 21.5, 23.4, 29.7, 34.3, 46.9, 78.4, 81.5, 107.5; exact mass, m/z 237.1678 [calcd for ($C_{17}H_{32}OSi-C_3H_7$), 237.1674]. Anal. Calcd for $C_{17}H_{32}OSi$: C, 72.78; H, 11.49. Found: C, 72.71; H, 11.53.

2-Bromo-1-[3-[tri(1-methylethyl)silyl]prop-2-ynyl]cyclohexan-1-ol 147:

n-Butyllithium (2.2 mL, 1.6 M in hexanes, 3.52 mmol) was added dropwise to a stirred and cooled (-78°C) solution of alkyne **194**[85] (685 mg, 3.50 mmol) in THF (10 mL). After 15 min, a solution of 2-bromocyclohexanone[87] (647 mg, 3.65 mmol) in THF (5 mL + 2 mL rinse) was added dropwise and stirring was continued for a further 6 h. The reaction mixture was quenched with saturated aqueous ammonium chloride (30 mL) and extracted with ether (3 x 40 mL). The combined organic extracts were washed with brine (20 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (3 x 15 cm) with 10% ethyl acetate-hexane gave **147** (803 mg, 61%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4) 3550, 2940, 2860, 2165, 1440, 1350, 1180, 1120, 1065, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0-1.2 [m, 21H (includes a doublet at δ1.05, J = 4 Hz)], 1.2-1.4 (m, 1H), 1.5-2.2 (m, 8H), 2.45 (d, J = 16.5 Hz, 1H), 2.7

(d, J = 16.5 Hz, 1H), 4.6 (m, 1H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 11.2, 18.6, 20.8, 27.3, 33.8, 34.9, 35.1, 62.7, 72.8, 83.8, 104.0; exact mass, m/z 374.1468, 372.1483 (calcd for $C_{18}H_{33}BrSi$, 374.1463, 372.1483). Anal. Calcd for $C_{18}H_{33}BrSi$: C, 57.89; H, 8.91; Br, 21.40. Found: C, 57.95; H, 8.95; Br, 21.54.

5-Bromo-1-phenyl-1-hexyne 148:

Bromine (0.15 mL, 2.89 mmol) was added dropwise to a stirred and cooled (0°C) solution of triphenyl phosphite[79] (1.34 g, 4.33 mmol) in ether (20 mL). After 15 min, the reaction mixture was cooled to -10°C and a solution of alcohol **143** (0.50 g, 2.87 mmol) and pyridine (0.23 mL, 2.89 mmol) in ether (5 mL) was injected, stirring was continued at room temperature for 3 h. The mixture was quenched with water (10 mL) and extracted with ether (3 x 30 mL). The combined organic extracts were washed with brine (20 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (2 x 15 cm) with hexane gave **148** (413 mg, 60%) as a homogeneous (TLC, silica gel, hexane) oil: IR (CCl_4) 3080, 2960, 2920, 1475, 1440, 1375, 1210, 1160, 1030, 910, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.8 (d, J = 7 Hz, 3H), 2.0-2.15 (m, 2H), 2.6 (t, J = 7 Hz, 2H), 4.28-4.4 (m, 1H), 7.2-7.3 (m, 3H), 7.3-7.45 (m, 2H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 17.7,

25.7, 39.2, 49.4, 80.8, 87.7, 127.2, 127.63, 131.0; exact mass, m/z 238.0181, 236.0201 (calcd for $C_{12}H_{13}Br$, 238.0181, 236.0202). Anal. Calcd for $C_{12}H_{13}Br$: C, 60.78; H, 5.53. Found: C, 60.47; H, 5.48.

5-Bromo-1-phenyl-1-pentyne 149:

The procedure employed for **148** was followed using alcohol **142** (847 mg, 5.3 mmol), triphenyl phosphite (1.98 g, 6.4 mmol), bromine (0.33 mL, 6.4 mmol), and pyridine (0.43 mL, 5.3 mmol). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with hexane gave **149** (1.06 g, 89%) as a homogeneous (TLC, silica gel, hexane) oil: IR (CCl_4) 3080, 2970, 1660, 1490, 1445, 1430, 1270, 1250, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.1 (q, J = 6.5 Hz, 2H), 2.6 (t, J = 6.5 Hz, 2H), 3.6 (t, J = 6.5 Hz, 2H), 7.2-7.3 (m, 3H), 7.3-7.45 (m, 2H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 18.2, 31.6, 32.5, 81.7, 87.9, 123.6, 127.8, 128.3, 131.62; exact mass, m/z 224.0023, 222.0047 (calcd for $C_{11}H_{11}Br$, 224.0025, 222.0045). Anal. Calcd for $C_{11}H_{11}Br$: C, 59.22; H, 4.97. Found: C, 59.31; H, 4.98.

5-Bromo-1-[tri(1-methylethyl)silyl]-1-pentyne 150:

The procedure employed for **148** was followed using alcohol **145** (2.12 g, 9.80 mmol), triphenyl phosphite (3.77

g, 11.76 mmol), bromine (0.60 mL, 11.76 mmol), and pyridine (0.79 mL, 9.80 mmol) in ether (30 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (5 x 15 cm) with hexane gave **150** (2.15 g, 80%) as a homogeneous (TLC, silica gel, hexane) oil: IR (CCl_4 cast) 2940, 2850, 2160, 1460, 1260, 1100, 1020, 800 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.9-1.3 [m, 21H (includes a doublet at δ1.05, J = 4 Hz)], 2.1 (q', J = 6 Hz, 2H), 2.45 (t, J = 6 Hz, 2H), 3.55 (t, J = 6 Hz, 2H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 11.2, 18.6, 31.6, 32.3, 81.7, 106.6; exact mass, m/z 304.1053, 302.1068 (calcd for $C_{14}H_{27}SiBr$, 304.1045, 302.1065). Anal. Calcd for $C_{14}H_{27}SiBr$: C, 55.43; H, 8.97; Br, 26.34. Found: C, 55.51; H, 8.77; Br, 26.13.

1-Phenyl-5-(phenylseleno)-1-pentyne 151:

Solutions of alcohol **142** (322 mg, 2.01 mmol) in THF (5 mL) and of tributylphosphine (494 mg, 2.45 mmol) in THF (5 mL) were added to a stirred and cooled (0°C) solution of N-(phenylseleno)phthalimide[80] (871 mg, 2.55 mmol) in THF (10 mL). The cold bath was removed and stirring was continued for 12 h. Evaporation of the solvent and flash chromatography of the residue over silica gel (3 x 15 cm) with 10% ethyl acetate-hexane gave **151** (485 mg, 80%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane)

oil: IR (CCl_4) 3080, 3060, 2940, 1570, 1485, 1470, 1430, 1340, 1230, 1070, 1020, 910, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 2.0 (q', J = 8 Hz, 2H), 2.55 (t, J = 8 Hz, 2H), 3.05 (t, J = 8 Hz, 2H), 7.2-7.3 (m, 3H), 7.35 (m, 2H), 7.5 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 20.2, 27.5, 30.0, 82.1, 89.6, 124.5, 127.5, 128.4, 128.9, 129.8, 130.8, 132.3, 133.3; exact mass, m/z 300.0418 (calcd for $C_{17}H_{16}Se$, 300.0418). Anal. Calcd for $C_{17}H_{16}Se$: C, 68.23; H, 5.39. Found: C, 68.20; H, 5.33.

5-Iodo-1-[tri(1-methylethyl)silyl]-2-pentyne 152:

A mixture of bromide **150** (333 mg, 1.1 mmol) and sodium iodide (1.25 g, 8.34 mmol) in dry acetone (30 mL) was relfux for 24 h. The solvent was evaporated and the residue was diluted with ether (50 mL), washed with water (20 mL) and brine (10 mL) and dried. Evaporation of the solvent gave **152** (294 mg, 76%) as a homogeneous (TLC, silica gel, hexane) oil: ^1H NMR ($CDCl_3$, 80 MHz) δ 0.75-1.5 [m, 21H (includes a doublet at δ1.1, J = 4 Hz)], 1.75-2.2 (m, 2H), 2.4 (t, J = 7 Hz, 2H), 3.3 (t, J = 7 Hz, 2H).

3-[2-(Phenylseleno)cyclopentyl]-1-[tri(1-methylethyl)-silyl]-1-propyne 153:

Solution of alcohol **146** (209 mg, 0.75 mmol) in THF (5 mL) and tributylphosphine (183 mg, 0.90 mmol) in THF (5

mL) were added to a stirred solution of benzeneseleno-cyanide[88] (160 mg, 0.88 mmol) in THF (5 mL). Stirring was continued for 3 days. Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 10% ethyl acetate-hexane gave **153** (158 mg, 50%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3065, 3060, 2940, 2860, 2165, 1470, 1460, 1030, 1020, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.95-1.15 [m, 21H (includes a doublet at δ1.05, J = 4 Hz)], 1.6-1.75 (m, 2H), 1.8-1.95 (m, 3H), 2.05-2.2 (m, 1H), 2.25-2.4 (m, 2H), 2.45-2.6 (m, 1H), 3.75 (dd, J = 10, 6 Hz, 1H), 7.2-7.3 (m, 3H), 7.5-7.6 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 11.4, 18.7, 22.4, 23.7, 29.8, 33.5, 44.4, 49.8, 80.8, 108.3, 126.9, 129.0, 133.7; exact mass, m/z 420.1750 (calcd for $C_{23}H_{36}SeSi$, 420.1751). Anal. Calcd for $C_{23}H_{36}SeSi$: C, 65.84; H, 8.58. Found: C, 65.73; H, 8.40.

Methyl <u>trans</u>-cyclohexyl-2-[3-[tri(1-methylethyl)silyl]-2-propynyl] oxalate 154:

Oxalyl chloride (0.30 mL, 3.44 mmol) was added to a stirred solution of alcohol **144** (415 mg, 1.41 mmol) at room temperature.[89] After 2 h, methanol (3 mL) was added, stirring was continued for 12 h. Evaporation of the solvent and flash chromatography of the residue over

silica gel (3 × 15 cm) with 5% ethyl acetate-hexane gave **154** (31 mg, 57%) as a homogeneous (TLC, silica gel, 5% ethyl acetate-hexane) oil: IR (CCl_4) 2940, 2860, 2170, 1770, 1740, 1460, 1450, 1320, 1305, 1170, 960, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.95-1.15 [m, 21H (includes a doublet at δ1.05, J = 4 Hz)], 1.2-1.5 (m, 4H), 1.7-1.9 (m, 3H), 1.95-2.2 (m, 2H), 2.3-2.5 (m, 2H), 3.9 (s, 3H), 4.8 (ddd, J = 11, 10, 4 Hz, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 11.2, 18.6, 22.8, 24.4, 24.9, 29.9, 31.0, 40.7, 53.4, 79.0, 82.5, 105.3, 156.9, 158.4; exact mass, m/z 337.1835 [calcd for ($C_{21}H_{36}O_4Si-C_3H_7$), 337.1835]. Anal. Calcd for $C_{21}H_{36}O_4Si$: C, 66.27; H, 9.46. Found: C, 66.14; H, 9.51.

2-Bromo-α-(phenylethynyl)benzenemethanol 155:

n-Butyllithium (1.20 mL, 1.55 M in hexanes, 1.86 mmol) was added dropwise to a stirred and cooled (-78°C) solution of phenylacetylene (190 mg, 1.86 mmol) in THF (20 mL). After 10 min, a solution of 2-bromobenzaldehyde (350 mg, 1.89 mmol) in THF (5 mL + 2 mL rinse) was injected dropwise and stirring was continued for 1 h. The cold bath was removed and when the mixture had warmed to room temperature, it was quenched with water (30 mL). The aqueous layer was extracted with ether (3 × 30 mL) and the combined organic extracts were washed with brine (20 mL)

and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (3 x 15 cm) with 15% ethyl acetate-hexane gave **155** (276 mg, 50%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4 cast) 3360, 1490, 1460, 1440, 1380, 1025, 755, 743, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.68 (d, J = 6 Hz, 1H), 6.0 (d, J = 6 Hz, 1H), 7.15-7.55 (m, 7H), 7.6 (m, 1H), 7.85 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 64.6, 86.7, 87.6, 122.2, 122.7, 127.9, 128.2, 128.6, 129.9, 131.7, 133.0, 139.5; exact mass, m/z 285.9990 (calcd for $C_{15}H_{11}OBr$, 286.9993). Anal. Calcd for $C_{15}H_{11}OBr$: C, 62.74; H, 3.86; O, 5.57. Found: C, 62.50; H, 3.86; O, 5.87.

General Procedure for Radical Annulation

The experiments were performed with anhydrous solvents and oven dried apparatus. [AIBN (Eastman material) was used without purification.] The substrate (0.5-1.0 mmol) and Michael acceptor (5-15 mmol) were placed in a 100 mL round-bottomed flask containing a Teflon coated magnetic stirring bar and equipped with a reflux condenser closed by a rubber septum. The system was purged with argon for 5 min and benzene (15-30 mL) was injected into the flask which was then immersed in an oil bath preheated to 80°C. Benzene solutions of triphenyltin

hydride (1.2 equiv., 0.05-0.07 M) and of AIBN (0.1 equiv., 0.01 M) were then injected simultaneously over 10 h by means of a double syringe pump. During this period the reaction mixture was stirred magnetically and maintained under a slight static pressure of argon. Refluxing was continued for a further arbitrary period of 2 h. The mixture was then cooled and evaporated under water pump vacuum. The residue was processed as described for the individual examples.

2-(Phenylmethylene)-1-cyclohexanecarbonitrile 156:

The general procedure for radical annulation was followed using acrylonitrile (1.26 g, 23.77 mmol), bromide **149** (672 mg, 3.01 mmol) in benzene (40 mL), triphenyltin hydride (1.15 g, 3.27 mmol) in benzene (10 mL), and AIBN (38 mg, 0.23 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 5% ethyl acetate-hexane gave **156** as two separate and homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) fractions of combined weight 196 mg (33%). The material of higher R_f **156a** (103 mg, 17.5%) had: IR ($CHCl_3$ cast) 2940, 2238, 1420, 920, 740, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.3-1.6 (m, 2H), 1.75-2.1 (m, 4H), 2.3-2.7 (m, 2H), 4.0 (br, t, J = 2 Hz, 1H), 6.5 (s, 1H), 7.15-7.42 (m, 5H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 22.4,

27.3, 30.0, 33.3, 120.5, 126.7, 127.1, 128.2, 128.5, 135.3, 136.1; exact mass, m/z 197.1200 (calcd for $C_{14}H_{15}N$; 197.1204). Anal. Calcd for $C_{14}H_{15}N$: C, 85.23; H, 7.66. Found: C, 85.43; H, 7.59.

The material of lower R_f **156b** (93 mg, 15.6%) had: IR ($CHCl_3$ cast) 2940, 2860, 2240, 1440, 740, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.55-1.7 (m, 3H), 1.85-2.0 (m, 2H), 2.02-2.14 (m, 1H), 2.2-2.3 (m, 1H), 2.6-2.7 (td, J = 13.5, 6 Hz, 1H), 3.8-4.5 (dd, J = 7.5, 4Hz, 1H), 6.7 (s, 1H), 7.2-7.3 (m, 3H), 7.3-7.4 (m, 2H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 24.2, 26.9, 27.6, 32.3, 37.4, 120.1, 125.6, 126.9, 128.2, 128.8, 135.6, 136.5; exact mass, m/z 197.1209 (calcd for $C_{14}H_{15}N$, 197.1204). Anal. Calcd for $C_{14}H_{15}N$: C, 85.23; H, 7.66. Found: C, 85.37; H, 7.49.

Methyl 2-(phenylmethylene)-1-cyclohexanecarboxylate 157:

The general procedure for radical annulation was followed using methyl acrylate (2.47 g, 28.39 mmol), bromide **149** (550 mg, 2.47 mmol) in benzene (40 mL), triphenyltin hydride (950 mg, 2.71 mmol) in benzene (10 mL), and AIBN (35 mg, 0.21 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 x 15 cm) with 5% ethyl acetate-hexane gave **157** (120 mg, 21%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that

consisted of two isomers: IR (Neat) 2934, 1731, 1432, 1199, 1165, 1130, 1007, 740, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.3-1.9 (m, 5H), 2.0-2.5 (m, 3H), 3.22 (m, 0.36H), 3.68 (s, 0.99H), 3.71 (s, 2.01H), 3.78 (m, 0.64H), 6.19 (s, 0.38H), 6.35 (s, 0.62H), 7.1-7.35 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 22.9, 23.6, 27.3, 27.8, 28.1, 29.7, 30.5, 34.9, 43.2, 50.9, 51.6, 51.8, 124.9, 125.6, 126.3, 126.4, 128.0, 128.2, 128.6, 129.0, 137.5, 137.6, 139.5, 139.8, 174.1, 174.2; exact mass, m/z 230.1304 (calcd for $C_{15}H_{18}O_2$, 230.1307). Anal. Calcd for $C_{15}H_{18}O_2$: C, 78.23; H, 7.88. Found: C, 78.53; H, 7.85.

Annulation of 149 with acrylonitrile, 1-Methyl-2-(phenylmethylene)-1-cyclohexanecarbonitrile 158:

The general procedure for radical annulation was followed using methacrylonitrile (1.44 g, 21.45 mmol), bromide **149** (658 mg, 2.95 mmol) in benzene (40 mL), triphenyltin hydride (1.42 g, 4.04 mmol) in benzene (10 mL), and AIBN (25 mg, 0.15 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane gave **158** (439 mg, 70%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (Neat) 2940, 2860, 2230, 1448, 1080, 750, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.35 (s, 3H), 1.57-2.5 (m, 6H), 2.3-2.5

(m, 2H), 6.6 (s, 1H), 7.18-7.4 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 22.4, 26.3, 27.1, 35.3, 41.0, 76.9, 123.6, 127.1, 127.3, 127.8, 128.9, 137.8, 138.2; exact mass, m/z 211.1366 (calcd for $C_{15}H_{17}N$, 211.1361). Anal. Calcd for $C_{15}H_{17}N$: C, 85.26; H, 8.11. Found: C, 85.16; H, 8.08.

Methyl 1-methyl-2-(phenylmethylene)-1-cyclohexanecarboxylate 159:

The general procedure for radical annulation was followed using methyl methacrylate (1.89 g, 18.91 mmol), bromide **149** (571 mg, 2.56 mmol) in benzene (40 mL), triphenyltin hydride (1.09 g, 3.10 mmol) in benzene (10 mL), and AIBN (20 mg, 0.12 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (4 x 15 cm) with 5% ethyl acetate-hexane and then 10% ethyl acetate-hexane gave **159** (209 mg, 33%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4 cast) 2940, 1730, 1450, 1240, 1160, 1110, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.37 (s, 2.7H), 1.43 (s, 0.3H), 1.5 (m, 1H), 1.6-1.8 (m, 4H), 1.96-2.05 (m, 1H), 2.25-2.5 (m, 2H), 3.1 (s, 2.7H), 3.72 (s, 0.3H), 6.4 (s, 0.2H), 6.48 (s, 0.8H), 7.15-7.35 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 22.0, 23.6, 24.3, 27.1, 27.7, 28.1, 36.1, 38.7, 48.4, 51.3, 122.7, 125.2, 126.2, 127.6, 128.0,

128.8, 129.0, 138.5, 141.6, 176.8; exact mass, m/z 244.1460 (calcd for $C_{16}H_{20}O_2$, 244.1463). Anal. Calcd for $C_{16}H_{20}O_2$: C, 78.65; H, 8.25. Found: C, 78.88; H, 8.10.

Annulation of 151 with acrylonitrile, 1-Methyl-2-(phenylmethylene)-1-cyclohexanecarbonitrile 158:

The general procedure for radical annulation was followed using methacrylonitrile (189 mg, 2.82 mmol), selenide **151** (137 mg, 0.46 mmol) in benzene (15 mL), triphenyltin hydride (277 mg, 0.79 mmol) in benzene (6 mL), and AIBN (10 mg, 0.06 mmol) in benzene (6 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 10% ethyl acetate-hexane gave **158** (64 mg, 66%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR ($CHCl_3$ cast) 2937, 2840, 2220, 1444, 1060, 746, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.35 (s, 3H), 1.55-1.88 (m, 5H), 1.9-2.2 (m, 1H), 2.3-2.5 (m, 2H), 6.58 (s, 1H), 7.18-7.20 (m, 5H); ^{13}C ($CDCl_3$; 75.5 MHz) δ 22.9, 26.7, 27.6, 35.8, 41.5, 124.1, 127.6, 127.8, 128.3, 129.4, 138.2, 138.6; exact mass, m/z 211.1359 (calcd for $C_{15}H_{17}N$, 211.1362).

5-Methyl-2-(phenylmethylene)-1-cyclohexanecarbonitrile 160:

The general procedure for radical annulation was

followed using acrylonitrile (1.73 g, 32.66 mmol), bromide **148** (588 mg, 2.07 mmol) in benzene (50 mL), triphenyltin hydride (911 mg, 2.60 mmol) in benzene (10 mL), and AIBN (42 mg, 0.26 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (4 × 15 cm) with 5% ethyl acetate-hexane gave **160** as three separate fractions of combined weight 168 mg (38%). All appeared to be homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) but the slowest running fraction consisted (NMR) of two isomers. The fraction of highest R_f **160a** (43 mg, 9.8%) had: IR ($CHCl_3$ cast) 2951, 2927, 2120, 1456, 1444, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 0.98 (d, J = 6 Hz, 3H), 1.08-1.27 (m, 2H), 1.9-2.1 (m, 3H), 2.4 (m, 1H), 2.6 (dddd, J = 15, 14.5, 4.5, 2 Hz, 1H), 4.0 (m, 1H), 6.5 (s, 1H), 7.2 (m, 2H), 7.3 (m, 1H), 7.4 (m, 2H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 21.4, 28.9, 29.8, 33.1, 35.7, 38.2, 126.9, 127.10, 127.4, 128.5, 128.8, 134.9, 136.2; exact mass, m/z 211.1363 (calcd for $C_{15}H_{17}N$, 211.1361). Anal. Calcd for $C_{15}H_{17}N$: C, 85.26; H, 8.11. Found: C, 85.43; H, 7.98.

The fraction of intermediate R_f **160b** (44 mg, 10.2%) had: IR (CCl_4 cast) 2952, 2925, 2240, 1444, 739, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.32 (d, J = 7 Hz, 3H), 1.6-1.9 (m, 4H), 2.02-2.12 (m, 1H), 2.25 (dt, J = 14, 4 Hz, 1H), 2.75 (dddd, J = 14, 12, 5, 2 Hz, 1H), 3.8 (t, J =

5 Hz, 1H), 6.54 (s, 1H), 7.2-7.32 (m, 3H); 7.4 (m, 2H); ^{13}C ($CDCl_3$, 60.3 MHz) δ 18.9, 27.3, 27.6, 29.4, 33.0, 35.8, 121.8, 127.2, 127.3, 128.5, 128.6, 135.3, 136.3; exact mass, m/z 211.1361 (calcd for $C_{15}H_{17}N$, 211.1361). Anal. Calcd for $C_{15}H_{17}N$: C, 85.26; H, 8.11. Found: C, 85.34; H, 7.88.

The fraction of lower R_f **160c** (72 mg, 16.4%) had: IR (CCl_4 cast) 2953, 2926, 2240, 1456, 740, 701 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.0-1.2 [m, 4H (includes a doublet at δ1.05, J = 6 Hz)], 1.3-1.6 (m, 1H), 1.7-2.4 (m, 4H), 2.8-3.1 (m, 1H), 3.3-3.45 (m, 0.27H), 3.55 (br, s, 0.73H), 6.48 (s, 0.73H), 6.85 (s, 0.27H), 7.2-7.45 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 15.1, 21.0, 21.3, 25.6, 28.2, 28.7, 32.2, 35.0, 35.1, 37.2, 39.0, 40.5, 119.6, 120.5, 124.5, 126.7, 126.9, 127.1, 128.2, 128.4, 128.7, 128.8, 134.9, 135.6, 136.3, 136.7; exact mass, m/z 211.1362 (calcd for $C_{15}H_{17}N$, 211.1361). Anal. Calcd for $C_{15}H_{17}N$: C, 85.26; H, 8.11. Found: C, 85.39; H, 8.01.

Methyl 5-methyl-2-(phenylmethylene)-1-cyclohexanecarboxylate 161:

The general procedure for radical annulation was followed using methyl acrylate (2.0 g, 23.26 mmol), bromide **148** (442 mg, 1.56 mmol) in benzene (40 mL), triphenyltin hydride (653 mg, 1.85 mmol) in benzene (10

mL), and AIBN (18 mg, 0.11 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (4 x 15 cm) with 10% ethyl acetate-hexane gave **161** (97 mg, 25%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of three isomers: IR (CCl_4 cast) 2940, 2920, 1732, 1430, 1190, 1170, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.93-1.11 [s, 3H (includes three singlets at δ0.95, 0.97 and 0.98)], 1.5 (m, 1H), 1.7-1.95 (m, 4H), 2.15-2.28 (m, 1H), 2.57-2.7 (m, 1H), 3.5 (s, 3.4H), 3.7 (s, 0.3H), 3.76 (s, 0.3H), 6.08 (s, 0.07H), 6.38 (s, 0.07H), 6.48 (s, 0.86H), 7.1-7.38 (m, 5H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 19.5, 21.8, 22.0, 28.7, 28.8, 29.0, 29.2, 31.8, 32.5, 34.2, 34.7, 35.5, 35.8, 36.3, 36.4, 37.7, 38.1, 39.0, 43.3, 51.0, 51.5, 122.1, 125.4, 125.8, 126.3, 126.4, 126.5, 128.1, 128.2, 128.6, 129.0, 137.4, 139.1, 174.8; exact mass, m/z 244.1463 (calcd for $C_{16}H_{20}O_2$, 244.1463). Anal. Calcd for $C_{16}H_{20}O_2$: C, 78.65; H, 8.25. Found: C, 78.72; H, 8.25.

2-[[Tri(1-methylethyl)silyl]methylene]-1-cyclohexanecarbonitrile 162:

The general procedure for radical annulation was followed using acrylonitrile (387 mg, 7.30 mmol), bromide **150** (301 mg, 0.99 mmol) in benzene (40 mL), tributyltin

hydride (377 mg, 1.30 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). After evaporation of the solvent, benzyl chloride (111 mg, 0.87 mmol) was added to the residue and the resulting mixture was examined by ^{1}H NMR ($CDCl_3$, 300 MHz) to measure the yield (52%). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 5% ethyl acetate-hexane gave **162** as three fractions of combined weight 159 mg. Each fraction appeared to be homogeneous by TLC (10% ethyl acetate-hexane) but the middle fraction was actually a mixture of the two other fractions. The material of higher R_f **162a** (38 mg, 13%) had: IR (CCl_4) 2970, 2870, 2240, 1620, 1460, 1450, 885 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.7-2.0 [m, 26H (includes a doublet at δ1.1, J = 4 Hz)], 2.02-2.68 (m, 3H), 3.55 (br, s, 1H), 5.02 (s, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 12.2, 18.9, 22.2, 28.2, 31.5, 35.5, 37.4, 120.5, 122.2, 151.9; exact mass, m/z 277.2220 (calcd for $C_{17}H_{31}NSi$, 277.2226).

The material of lower R_f **162b** (51 mg, 18%) had: IR (CCl_4) 2940, 2870, 2250, 1620, 1460, 1450, 870 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.8-1.4 [m, 21H (includes a doublet at δ1.1, J = 4 Hz)], 1.5-2.2 (m, 7H), 2.4-2.6 (m, 1H), 3.35 (dd, J = 16, 8 Hz, 1H), 5.54 (s, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 12.1, 18.9, 24.0, 27.3, 32.6, 33.5, 40.4, 120.4, 150.7; exact mass, m/z 277.2227 (calcd for

$C_{17}H_{31}NSi$, 277.2226).

The middle fraction (70 mg, 25%) consisted (^1H NMR) of the above two isomers.

Octahydro-7a-hydroxy-1-(phenylmethylene)-1H-inden-2-carbonitrile 163:[77]

The general procedure for radical annulation was followed using acrylonitrile (302 mg, 5.69 mmol), bromide **169**[77] (284 mg, 1.02 mmol) in benzene (30 mL), triphenyltin hydride (485 mg, 1.38 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). After evaporation of the solvent, the residue was stirred for ca. 2 min with potassium fluoride (260 mg, 2.76 mmol) in water (10 mL). The aqueous layer was extracted with ether (3 × 30 mL) and the combined extracts were washed with brine (20 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 20% ethyl acetate-hexane gave **163**[77] (194 mg, 73%) as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil that consisted of seven isomers: IR (CCl_4 cast) 3480, 2933, 2858, 2240, 1490, 1440, 960, 760, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0-1.8 (m, 9H), 1.9-2.3 (m, 3H), 3.48-3.92 (m, 1H), 6.56 (d, J = 2 Hz, 0.07H), 6.65 (d, J = 2.5 Hz, 0.07H), 6.67 (d, J = 2 Hz, 0.07H), 6.71 (d, J = 2.5 Hz, 0.07H), 6.79 (d, J = 2.5 Hz, 0.13H),

6.85 (d, J = 2 Hz, 0.4H), 6.89 (d, J = 2 Hz, 0.2H), 7.2-7.5 (m, 5H); exact mass, m/z 253.1475 (calcd for $C_{17}H_{19}NO$, 253.1467). Anal. Calcd for $C_{17}H_{19}NO$: C, 80.60; H, 7.56; N, 5.53. Found: C, 80.75; H, 7.49; N, 5.18.

Octahydro-7a-hydroxy-2-methyl-1-(phenylmethylene)-1H-inden-2-carbonitrile 164:

The general procedure for radical annulation was followed using methacrylonitrile (251 mg, 5.75 mmol), bromide **169**[77] (182 mg, 0.65 mmol) in benzene (15 mL), triphenyltin hydride (296 mg, 0.84 mmol) in benzene (10 mL), and AIBN (6 mg, 0.04 mmol) in benzene (10 mL). After evaporation of the solvent, the residue was worked up and chromatographed over silica gel (2 x 15 cm) with 20% ethyl acetate-hexane, as described for **163** to give **164** (148 mg, 85%) as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil which consisted of seven isomers: IR (CCl_4) 3480, 2933, 2860, 2240, 1440, 750, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0-2.4 [m, 15H (includes seven singlets at δ 1.34, 1.44, 1.48, 1.6, 1.65, 1.69, 1.7)], 6.63 (s, 0.14H), 6.71 (s, 0.14H), 6.76 (s, 0.14H), 6.79 (s, 0.14H), 6.82 (s, 0.14H), 6.85 (s, 0.14H), 6.88 (s, 0.14H), 7.2-7.6 (m, 5H); exact mass, m/z 267.1623 (calcd for $C_{18}H_{21}NO$, 267.1624). Anal. Calcd for $C_{18}H_{21}NO$: C, 80.86; H, 7.92; N, 5.24. Found: C, 80.60;

H, 7.75; N, 5.12.

Methyl octahydro-7a-hydroxy-1-(phenylmethylene)-1H-inden-2-carboxylate 165:

The general procedure for radical annulation was followed using methyl acrylate (525 mg, 6.09 mmol), bromide **169**[77] (307 mg, 1.10 mmol) in benzene (30 mL), triphenyltin hydride (573 mg, 1.63 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). After evaporation of the solvent the residue was worked up and chromatographed over silica gel (3 x 15 cm) with 20% ethyl acetate-hexane as described for **163** to give **165** (132 mg, 41%) as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil which consisted of six isomers: IR (CCl_4 cast) 3440, 2934, 1735, 1440, 1167, 780, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0-2.4 (m, 11H), 2.5-2.9 (m, 1H), 3.4-3.7 (m, 1H), 3.75-3.8 [s, 3H (includes five singlets at δ 3.74, 3.75, 3.76, 3.77, 3.78)], 6.2 (d, J = 1.5 Hz, 0.07H), 6.56 (br, s, 0.15H), 6.6 (d, J = 2.5 Hz, 0.1H), 6.63 (d, J = 2 Hz, 0.37H), 6.7 (d, J = 2 Hz, 0.18H), 6.74 (d, J = 2 Hz, 0.15H), 7.2-7.5 (m, 5H); exact mass, m/z 286.1572 (calcd for $C_{18}H_{22}O_3$, 286.1569). Anal. Calcd for $C_{18}H_{22}O_3$: C, 75.50; H, 7.74. Found: C, 75.08; H, 7.69.

Attempted annulation of 154 with acrylonitrile in benzene:

The general procedure for radical annulation was followed using acrylonitrile (167 mg, 3.14 mmol), ester **154** (202 mg, 0.53 mmol) in benzene (15 mL), triphenyltin hydride (300 mg, 0.85 mmol), and AIBN (6 mg, 0.04 mmol). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane gave the starting material **154** (107 mg, 52%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 2940, 2860, 2170, 1770, 1740, 1460, 1380, 1310, 1200, 1160, 1120, 910, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.0-1.2 [m, 21H (includes a doublet at δ1.05, J = 4 Hz)], 1.25-1.45 (m, 4H), 1.7-1.9 (m, 3H), 2.0-2.2 (m, 2H), 2.3-2.45 (m, 2H), 3.9 (s, 3H), 4.75 (m, 1H).

Attempted annulation of 154 with acrylonitrile in toluene:

The general procedure for radical annulation was followed using acrylonitrile (258 mg, 4.87 mmol), ester **154** (258 mg, 0.68 mmol) in toluene (20 mL), triphenyltin hydride (287 mg, 0.82 mmol) in toluene (10 mL), and AIBN (13 mg, 0.07 mmol) in toluene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane gave starting material **154** (108 mg, 41%) as a homogeneous (TLC,

silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 2940, 2860, 2170, 1770, 1740, 1460, 1450, 1320, 1305, 1170, 960, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.95-1.15 [m, 21H (includes a doublet at δ1.05, J = 4 Hz)], 1.2-1.5 (m, 4H), 1.7-1.9 (m, 3H), 1.95-2.2 (m, 2H), 2.3-2.5 (m, 2H), 3.9 (s, 3H), 4.8 (ddd, J = 11, 10, 4 Hz, 1H); ^{13}C ($CDCl_3$, 75.5 Hz) δ 11.2, 18.6, 22.8, 24.4, 24.9, 29.9, 31.0, 40.7, 53.4, 79.0, 82.5, 105.3, 156.9, 158.4; exact mass, m/z 337.1837 [calcd for ($C_{21}H_{36}O_4Si-C_3H_7$), 337.1835].

1-[Tri(1-methylethyl)silyl]-3-cyclopentyl-1-propyne 166:

The general procedure for radical annulation was followed using acrylonitrile (219 mg, 4.14 mmol), selenide **153** (324 mg, 0.77 mmol) in benzene (20 mL), triphenyltin hydride (354 mg, 1.00 mmol) in benzene (10 mL), and AIBN (11 mg, 0.07 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with hexane gave **166** (37 mg, 18%) and an oily mixture of unidentified material. **166** had: IR (CCl_4) 2960, 2860, 2170, 1460, 1380, 1120, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.95-1.15 [m, 21H (includes a doublet at δ1.05, J = 4 Hz)], 1.2-1.4 (m, 2H), 1.5-1.7 (m, 4H), 1.7-1.85 (m, 2H), 2.05 (m, 1H), 2.25 (d, J = 6.5 Hz, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 11.4, 18.7, 25.4, 25.7, 31.9,

39.2, 80.1, 108.6; exact mass, m/z 264.2272 (calcd for $C_{17}H_{32}Si$, 264.2273). Anal. Calcd for $C_{17}H_{32}Si$: C, 77.19; H, 12.19. Found: C, 77.35; H, 12.20.

α-(Phenylethynyl)benzenemethanol 167:[90]

The general procedure for radical annulation was followed using acrylonitrile (353 mg, 6.67 mmol), bromide **155** (328 mg, 1.14 mmol) in benzene (30 mL), triphenyltin hydride (506 mg, 1.44 mmol) in benzene (10 mL), and AIBN (12 mg, 0.07 mmol) in benzene (10 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane gave **167**[90] (84 mg, 35%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4) 3600, 3060, 2980, 2860, 1480, 1468, 1440, 1120, 1030, 910, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.6 (d, J = 5.5 Hz, 1H), 6.0 (d, J = 5.5 Hz, 1H), 7.15-7.5 (m, 8H), 7.6 (m, 1H), 7.85 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 64.7, 86.8, 87.6, 122.8, 127.9, 128.3, 128.7, 130.0, 131.8, 133., 139.5; exact mass, m/z 208.0852 (calcd for $C_{15}H_{12}O$, 208.0888).

1-(Phenylethynyl)-1-cyclohexanol 168:[102]

The general procedure for radical annulation was followed using (ethenylsulphonyl)benzene (558 mg, 3.32 mmol), bromide **169** (185 mg, 0.66 mmol) in benzene (18 mL),

triphenyltin hydride (324 mg, 0.92 mmol) in benzene (10 mL), and AIBN (7 mg, 0.04 mmol) in benzene (10 mL). After evaporation of the solvent, the residue was worked up and chromatographed over silica gel (2 × 15 cm) with 20% ethyl acetate-hexane as described for **163** to give **168**[102] (56 mg, 42%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4 cast) 3340, 2933, 1480, 1440, 1060, 960, 755, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.2-1.38 (m, 1H), 1.55-1.8 (m, 8H), 1.95-2.1 (m, 1H), 2.2 (s, 1H), 7.2-7.35 (m, 3H), 7.4-7.5 (m, 2H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 23.4, 25.2, 40.1, 69.1, 84.4, 92.9, 122.9, 128.1, 128.2, 131.7; exact mass, m/z 200.1195 (calcd for $C_{14}H_{16}O$, 200.1121).

Attempted annulation of 2-Bromo-1-(phenylethynyl)-1-cyclohexanol 169[77] with tributyl germanium hydride:

The general procedure for radical annulation was followed using acrylonitrile (329 mg, 6.2 mmol), bromide **169**[77] (290 mg, 1.04 mmol) in benzene (30 mL), tributyl-germanium hydride (569 mg, 2.32 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 over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane and then 20% ethyl acetate-hexane gave **169**[77] (251 mg, 86%) as a homogeneous (TLC, silica gel, 20%

ethyl acetate-hexane) oil: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.3-1.5 (m, 1H), 1.55-1.95 (m, 4H), 2.1-2.4 (m, 3H), 2.65 (s, 1H), 4.5 (dd, J = 9, 5 Hz, 1H), 7.25-7.38 (m, 3H), 7.4-7.5 (m, 2H).

^{1}H NMR experiment, 1-phenyl-1-pentyne 170:[103]

Bromide **149** (205 mg, 0.92 mmol), triphenyltin hydride (392 mg, 1.12 mmol), and AIBN (10 mg, 0.06 mmol) in benzene (20 mL) were refluxed for 3 h. Evaporation of the solvent and examination of the residue by ^{1}H NMR ($CDCl_3$, 400 MHz) showed signals at δ 1.2 (t, J = 8 Hz, 3H), 1.8 (s', J = 8 Hz, 2H), 2.55 (t, J = 8 Hz, 2H).

^{1}H NMR experiment, Table 14, Entry 1, 2-(Phenylmethylene)-1-cyclohexanecarbonitrile 156:

With the exception that only part of the acrylonitrile (56 mg, 1.06 mmol) was placed in the reaction flask at the beginning of the experiment, the remainder (217 mg, 4.3 mmol) in benzene (10 mL) being added over 10 h, the general procedure for radical annulation was followed using bromide **149** (230 mg, 1.03 mmol) in benzene (30 mL), triphenyltin hydride (451 mg, 1.28 mmol) in benzene (10 mL), and AIBN (9 mg, 0.05 mmol) in benzene (10 mL). Evaporation of the solvent, addition of benzyl chloride (116 mg, 0.91 mmol) as an internal

standard and examination of the material by ^{1}H NMR ($CDCl_3$, 300 MHz) showed that the yield of cyclized material **156** was 55% and the yield of uncyclized reduced material **170** was 20%.

^{1}H NMR experiment, Table 14, Entry 2, 2-(Phenylmethylene)-1-cyclohexanecarbonitrile 156:

With the exception that only part of the acrylonitrile (121 mg, 2.27 mmol) was placed in the reaction flask at the beginning of the experiment, the remainder (170 mg, 3.21 mmol) in benzene (10 mL) being added over 10 h, the general procedure for radical annulation was followed using bromide **149** (227 mg, 1.02 mmol) in benzene (30 mL), triphenyltin hydride (460 mg, 1.31 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Evaporation of the solvent, addition of benzyl chloride (159 mg, 1.26 mmol) as an internal standard and examination of the material by ^{1}H NMR ($CDCl_3$, 200 MHz) showed that the yield of cyclized material **156** was 46% and the yield of uncyclized reduced material **170** was 13%.

^{1}H NMR experiment, Table 14, Entry 3, 2-[Tri(1-methylethyl)silyl]methylene-1-cyclohexanecarbonitrile 162:

With the exception that only part of the acrylonitrile (116 mg, 2.19 mmol) was placed in the reaction

flask at the beginning of the experiment, the remainder (167 mg, 3.15 mmol) in benzene (10 mL) being added over 10 h, the general procedure for radical annulation was followed using bromide **150** (307 mg, 1.01 mmol) in benzene (30 mL), tributyltin hydride (371 mg, 1.27 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Evaporation of the solvent, addition of benzyl chloride (169 mg, 1.33 mmol) as an internal standard and examination of the material by ^{1}H NMR ($CDCl_3$, 300 MHz) showed that the yield of the cyclized material **162** was 24%.

^{1}H NMR experiment, Table 14, Entry 4, 5-Bromo-1-[tri(methylethyl)silyl]-1-pentyne 150:

The general procedure for radical annulation was followed using acrylonitrile (237 mg, 4.47 mmol), bromide **150** (318 mg, 1.05 mmol) in benzene (30 mL), tributylgermanium hydride (319 mg, 1.3 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 over silica gel (3 × 15 cm) with hexane gave **150** (295 mg, 92%) as a homogeneous (TLC, silica gel, hexane) oil: ^{1}H NMR ($CDCl_3$, 80 MHz) δ 0.7-1.2 [m, 21H (includes a doublet at δ1.0)], 2.1 (t, J = 6 Hz, 2H), 2.45 (m, 2H), 3.5 (t, J = 6 Hz, 2H).

^{1}H NMR experiment, Table 14, Entry 5, 2-[Tri(1-methylethyl)silyl]methylene-1-cyclohexanecarbonitrile 162:

The general procedure for radical annulation was followed using acrylonitrile (350 mg, 6.60 mmol), iodide **152** (294 mg, 0.84 mmol) in benzene (30 mL), tributyltin hydride (301 mg, 1.03 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL) at 50°C. Evaporation of solvent, addition of benzyl chloride (113 mg, 0.89 mmol) as an internal standard and examination of the material by ^{1}H NMR ($CDCl_3$, 300 MHz) showed that the yield of the cyclized material **162** was 15%.

^{1}H NMR experiment, Table 14, Entry 6, 2-[Tri(1-methylethyl)silyl]methylene-1-cyclohexanecarbonitrile 162:

The general procedure for radical annulation was followed using acrylonitrile (377 mg, 7.12 mmol), bromide **150** (304 mg, 1.00 mmol) in benzene (30 mL), triphenyltin hydride (435 mg, 1.24 mmol) in benzene (10 mL), and AIBN (10 mg, 0.06 mmol) in benzene (10 mL). Evaporation of solvent, addition of benzyl chloride (117 mg, 0.92 mmol) as an internal standard and examination of the material by ^{1}H NMR ($CDCl_3$, 200 MHz) showed that the yield of the cyclized material **162** was 54%.

1-Methyl-2-oxo-1-cyclohexanecarbonitrile 171:[81]

The procedure employed for **105** was followed using olefin **158** (285 mg, 1.35 mmol) in dry 20% methanol-dichloromethane (10 mL) and for work up dimethylsulphide (0.2 mL, 2.72 mmol). Evaporation of the solvent and examination of the residue by ^{1}H NMR ($CDCl_3$, 400 MHz) showed only one aldehyde signal [at δ10.2 (s)]. Flash chromatography of the total reaction product over silica gel (1 x 15 cm) gave **171**[81] (115 mg, 63%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (CCl_4 cast) 2940, 2860, 2231, 1730, 1440, 1080 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.45 (s, 3H), 1.65-1.8 (m, 2H), 1.85-1.94 (m, 1H), 2.02-2.2 (m, 2H), 2.35 (m, 1H), 2.5 (m, 1H), 2.8-2.9 (m, 1H); ^{13}C ($CDCl_3$, 400 MHz) δ 20.4, 22.3, 27.8, 39.9, 40.3, 46.4, 120.7, 202.9; exact mass, m/z 137.0843 (calcd for $C_8H_{11}NO$, 137.0840).

Methyl 5-methyl-2-oxo-1-cyclohexanecarboxylate 172:[84]

The procedure employed for **105** was followed using olefins **161** (151 mg, 0.62 mmol) in dry 20% methanol-dichloromethane (5 mL) and for work up dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and examination of the residue by ^{1}H NMR ($CDCl_3$, 300 MHz) showed only one aldehyde signal [at δ10.2 (s)]. Flash chromatography of the total reaction product over silica

gel (1 x 15 cm) with 5% ethyl acetate-hexane gave **172**[84] (27 mg, 25%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil that consisted of two isomers: IR (CCl_4) 2960, 1750, 1720, 1655, 1610, 1450, 1280, 1230, 1210 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.0-1.05 [d, J = 6 Hz, 3H (includes two doublets (J = 6 Hz) at δ 1.0 and 1.04)], 1.24-1.38 (m, 1H), 1.6-1.84 (m, 4H), 2.2-2.5 (m, 3H), 3.7-3.8 [s, 3H (includes two singlets)]; ^{13}C ($CDCl_3$, 75.5 MHz) δ 20.4, 21.0, 21.2, 28.5, 28.9, 29.8, 30.7, 35.0, 37.1, 37.7, 41.1, 51.3, 51.9, 56.7, 171.9, 172.9; exact mass, m/z 170.0942 (calcd for $C_9H_{14}O_3$, 170.0943). Anal. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29. Found: C, 63.33; H, 8.29.

Methyl 1-methyl-2-oxo-1-cyclohexanecarboxylate 173:[82]

The procedure employed for **105** was followed using olefin **159** (260 mg, 1.06 mmol) in dry 20% methanol-dichloromethane (5 mL) and for work up dimethylsulphide (0.2 mL, 2.72 mmol). Evaporation of the solvent and examination of the residue by ^1H NMR ($CDCl_3$, 300 MHz) showed only one aldehyde signal [at δ10.2 (s)]. Flash chromatography of the total reaction product over silica gel (2 x 15 cm) with 5% ethyl acetate-hexane and then 10% ethyl acetate-hexane gave **173**[82] (97 mg, 53%) as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane)

oil: IR (CCl_4) 2940, 2865, 1740, 1715, 1450, 1430, 1250, 1210, 1160, 1085 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.3 (s, 3H), 1.4-1.55 (m, 1H), 1.6-1.8 (m, 3H), 1.96-2.1 (m, 1H), 2.4-2.57 (m, 3H), 3.77 (s, 3H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 21.3, 22.6, 27.5, 38.2, 40.6, 52.4, 57.1, 173.6, 208.2; exact mass, m/z 170.0943 (calcd for $C_9H_{14}O_3$, 170.0943). Anal. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29. Found: C, 63.26; H, 8.32.

^1H NMR experiment on ozonolysis of 156a, 2-Oxo-1-cyclohexanecarbonitrile 174:

The procedure employed for **105** was followed using olefin **156a** (107 mg, 0.47 mmol) in dry 20% methanol-dichloromethane (5 mL) and for work up dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and examination of the residue by ^1H NMR ($CDCl_3$, 400 MHz) gave only one aldehyde signal [at δ10.02 (s)].

^1H NMR experiment on ozonolysis of 156b, 2-Oxo-1-cyclohexanecarbonitrile 174:

The procedure employed for **105** was followed using olefin **156b** (40 mg, 0.17 mmol) in dry 20% methanol-dichloromethane (5 mL) and for work up dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and examination of the residue by ^1H NMR ($CDCl_3$, 400 MHz)

showed only one aldehyde signal [at δ10.02 (s)].

^{1}H NMR experiment on ozonolysis of 157, Methyl 2-oxo-1-cyclohexanecarboxylate 175:

The procedure employed for **105** was followed using olefins **157** (102 mg, 0.44 mmol) in dry 20% methanol-dichloromethane (5 mL) and for work up dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and examination of the residue by ^{1}H NMR ($CDCl_3$, 400 MHz) showed only one aldehyde signal [at δ10.02 (s)]. The mass spectrum of a portion of the reaction mixture showed a peak with exact mass, m/z 156.0791 (calcd for $C_8H_{12}O_3$, 156.183).

^{1}H NMR experiment on ozonolysis of 160a, 5-Methyl-2-oxo-1-cyclohexanecarbonitrile 176:

The procedure employed for **105** was followed using olefin **160a** (66 mg, 0.31 mmol) in dry 20% methanol-dichloromethane (5 mL), and for work up, dimethylsulphide (0.2 mL, 2.72 mmol). Evaporation of the solvent and examination of the residue by ^{1}H NMR ($CDCl_3$, 400 MHz) showed only one aldehyde signal [at δ10.02 (s)].

^{1}H NMR experiment on ozonolysis of 160b, 5-Methyl-2-oxo-1-cyclohexanecarbonitrile 176:

The procedure employed for **105** was followed using olefin **160b** (27 mg, 0.13 mmol) in dry 20% methanol-dichloromethane (5 mL), and for work up, dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and examination of the residue by ^{1}H NMR ($CDCl_3$, 400 MHz) gave only one aldehyde signal [at δ10.02 (s)].

^{1}H NMR experiment on ozonolysis of 160c, 5-Methyl-2-oxo-1-cyclohexanecarbonitrile 176:

The procedure employed for **105** was followed using olefins **160c** (58 mg, 0.28 mmol) in dry 20% methanol-dichloromethane (5 mL), and for work up, dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and examination of the residue by ^{1}H NMR ($CDCl_3$, 400 MHz) showed only one aldehyde signal [at δ10.02 (s)].

Ozonolysis of 163 fraction 1, Octahydro-7a-hydroxy-1-oxo-1H-inden-2-carbonitrile 177a:

The procedure employed for **105** was followed using olefins **163** (64 mg, 0.25 mmol) in 20% methanol-dichloromethane (5 mL), and for work up, dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and flash chromatography of the residue over silica gel (1 x 15 cm)

with 10% ethyl acetate-hexane gave **177a** (27 mg, 59%) as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil that consisted (^{1}H NMR) of two isomers; IR (CCl_4 cast) 3440, 2930, 2240, 1760, 1440, 1190, 1140, 980, 950 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.2-2.4 (m, 12H), 3.09 (dd, J = 10, 8 Hz, 0.58H), 3.69 (dd, J = 10, 2.5 Hz, 0.42H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 19.2, 20.3, 24.1, 24.5, 25.3, 25.4, 29.8, 29.9, 30.3, 32.2, 34.7, 35.5, 43.8, 43.9, 75.1, 75.3, 117.2, 117.8, 203.7, 204.1; exact mass, m/z 179.0940 (calcd for $C_{10}H_{13}NO_2$, 179.0947).

Ozonolysis of 163 fraction 2:

The procedure employed for **105** was followed using olefins **163** (38 mg, 0.15 mmol) in 20% methanol-dichloromethane (5 mL), and for work up, dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and flash chromatography of the residue over silica gel (1 x 15 cm) with 20% ethyl acetate-hexane gave **177a** (18 mg, 68%) as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil that consisted (^{1}H NMR) of two isomers; IR (CCl_4 cast) 3441, 2938, 2862, 2245, 1766, 1450, 1252, 1194, 985, 955 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.2-2.4 (m, 12H), 3.09 (dd, J = 10, 8.5 Hz, 0.45H), 3.69 (dd, J = 10, 2.5 Hz, 0.44H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 20.3, 24.1, 24.4, 25.3, 25.4, 29.8, 30.0, 35.5, 43.7, 75.0,

75.3, 117.2, 117.8, 203.7, 204.1; exact mass, m/z 178.0866 [calcd for ($C_{10}H_{13}NO_2$-H), 178.0868].

Ozonolysis of 163 fraction 3:

The procedure employed for **105** was followed using olefins **163** (90 mg, 0.36 mmol) in 20% methanol-dichloromethane (5 mL), and for work up, dimethylsulphide (0.1 mL, 1.36 mmol). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 20% ethyl acetate-hexane and then 40% ethyl acetate-hexane gave **177a** (9 mg, 11%) and **177b** (18 mg, 28%) each as an apparently homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil. The material of higher R_f **177a** consisted (^{1}H NMR) of two isomers and the material of lower R_f **177b** consisted (^{1}H NMR) of two isomers. **177a** had: IR (CCl_4 cast) 3440, 2928, 2240, 1763, 1288, 116, 1074 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.2-2.7 (m, 12H), 3.08 (dd, J = 10, 8 Hz, 0.47H), 3.69 (dd, J = 9.5, 2.5 Hz, 0.53H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 20.2, 24.1, 24.4, 25.2, 25.3, 29.7, 30.0, 30.4, 34.7, 35.5, 43.7, 75.0, 117.1; exact mass, m/z 179.0910 (calcd for $C_{10}H_{13}NO_2$, 179.0947).

177b had: IR (CCl_4 cast) 3440, 2940, 2850, 2240, 1760, 1460, 1380, 1120, 1070, 940 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.4-2.5 (m, 12H), 3.3-3.42 (m, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 20.6, 20.7, 21.7, 21.9, 24.3, 26.1, 27.3,

28.0, 29.5, 29.6, 33.6, 34.3, 39.4, 40.0, 116.7, 207.1; exact mass, m/z 179.0919 (calcd for $C_{10}H_{13}NO_2$, 179.0946).

N-[1β,4α,4aα,8aα-Decahydro-4-(phenylseleno)naphthyl]acetamide 179:

Diphenyl diselenide (254 mg, 0.82 mmol) in dry acetonitrile (5 mL + 2 mL rinse) was injected into a stirred solution of (1Z,5E)-cyclodeca-1,5-diene (102 mg, 0.75 mmol) in acetonitrile (5 mL). Then iodine (218 mg, 0.86 mmol) in acetonitrile (5 mL + 2 mL rinse) was added and stirring was continued for 1.5 h. Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane and then 85% ethyl acetate-hexane yielded the crude product which was recrystallized from hexane to give **179** (174 mg, 66%) as a homogeneous (TLC, silica gel, 90% ethyl acetate-hexane) solid: mp. 125-127°C; IR (CCl_3) 3440, 2930, 2860, 1720, 1500, 1450, 1370 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.2-1.7 (m, 9H), 1.72-1.85 (m, 2H), 1.9 (s, 3H), 2.02-2.2 (m, 2H), 2.3-2.4 (m, 1H), 3.35 (td, J = 12, 4 Hz, 1H), 3.9 (m, 1H), 5.4 (br, d, J = 7 Hz, 1H), 7.2-7.35 (m, 3H), 7.5-7.6 (m, 2H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 20.3, 20.7, 23.5, 26.2, 28.4, 30.2, 34.5, 41.0, 41.3, 52.3, 127.8, 128.9,

186.2, 169.0; exact mass, m/z 351.1100 (calcd for $C_{18}H_{25}NOSe$, 351.1101).

N-[1α,5α,4aβ,8aβ-Decahydro-5-(phenylseleno)naphthyl]acetamide 180:

The procedure employed for **179** was followed using (1E-6E)-cyclodeca-1,6-diene (187 mg, 1.38 mmol) in dry acetonitrile (5 mL), diphenyl diselenide (442 mg, 1.41 mmol) in acetonitrile (15 mL + 1 mL rinse), and iodine (390 mg, 1.54 mmol) in acetonitrile (20 mL + 1 mL rinse). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 90% ethyl acetate-hexane and then 100% ethyl acetate-hexane gave **180** (308 mg, 63%) as a homogeneous (TLC, silica gel, ethyl acetate-hexane) solid: mp. 134-136°C; IR (CCl_4) 3440, 2940, 2860, 1680, 1500, 1470, 1440 cm^{-1}; ^1H NMR ($CDCl_3$, 100 MHz) δ 1.2-1.2 [m, 17H (includes a singlet at δ1.95)], 3.2-3.5 (m, 1H), 3.7-4.0 (m, 1H), 5.25-5.5 (m, 1H), 7.2-7.5 (m, 3H), 7.5-7.7 (m, 2H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 18.8, 20.8, 23.4, 24.8, 27.0, 27.1, 29.2, 41.2, 41.6, 49.2, 51.5, 127.3, 129.1, 129.8, 134.3, 169.1; exact mass, m/z 351.1103 (calcd for $C_{18}H_{25}NOSe$, 351.1101). Anal. Calcd for $C_{18}H_{25}NOSe$: C, 61.71; H, 7.19; N, 4.00. Found: C, 61.32; H, 7.17; N, 4.14.

Homolysis (C-Se) cleavage of 179, N-(1α,4aβ,8aβ-Decahydro-1-naphthyl)acetamide 181:[108]

Solutions of tributyltin hydride (433 mg, 1.49 mmol) in benzene (6 mL + 1 mL rinse) and AIBN (18 mg, 0.11 mmol) in benzene (6 mL + 1 mL rinse) were injected consecutively into a stirred solution of selenide **179** (403 mg, 1.15 mmol) in benzene (4 mL). The mixture was refluxed for 3 h, cooled to room temperature and evaporated. Flash chromatography of the residue over silica gel (3 × 15 cm) with 90% ethyl acetate-hexane and then ethyl acetate gave **181** (194 mg, 86%) as a homogeneous (TLC, silica gel, ethyl acetate) solid: mp. 174-178°C; IR (NUJOL) 3255, 2922, 2854, 1640, 1555, 1462, 1435, 1370, 1210, 1105 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.2-2.0 [m, 19H (includes a singlet at δ2.0)], 3.9 (m, 1H), 5.4 (br, s, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 19.8, 21.2, 23.5, 24.4, 25.2, 26.3, 26.9, 31.8, 35.9, 39.7, 51.7, 169.0; exact mass, m/z 195.1622 (calcd for $C_{12}H_{21}NO$, 195.1622).

Homolysis (C-Se) cleavage of 180, N-(1α,4aβ,8aβ-Decahydro-1-naphthyl)acetamide 181a:[108]

The procedure employed for **181** was followed using selenide **180** (178 mg, 0.51 mmol) in benzene (3 mL), triphenyltin hydride (234 mg, 0.67 mmol) in benzene (3 mL + 1 mL rinse), and AIBN (6 mg, 0.04 mmol) in benzene (3 mL

+ 1 mL rinse). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 60% ethyl acetate-hexane and then ethyl acetate gave **181a**[108] (88 mg, 89%) as a homogeneous (TLC, silica gel, ethyl acetate) solid: mp. 178-180°C; IR (NUJOL) 3255, 2922, 2854, 1640, 1555, 1462, 1435, 1370, 1210, 1105 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.2-2.0 [m, 19H (includes a singlet at δ2.0)], 3.9 (m, 1H), 5.4 (br, s, 1H); ^{13}C ($CDCl_3$, 75.5 MHz) δ 18.8, 21.2, 23.5, 24.4, 25.2, 26.3, 26.9, 31.8, 35.9, 39.7, 51.7, 169.0; exact mass, m/z 195.1622 (calcd for $C_{12}H_{21}NO$, 195.1622). Anal. Calcd for $C_{12}H_{21}NO$: C, 73.80; H, 10.84; N, 7.17. Found: C, 73.69; H, 10.89; N, 7.29.

1α,4aβ,5α,8aβ-Decahydro-5-(phenylseleno)-1-naphth[illegible]ol acetate 182:

Phenylselenyl chloride (642 mg, 3.35 mmol) in acetic acid (15 mL + 4 mL rinse) was added dropwise over 15 min to a stirred solution of sodium acetate (287 mg, 3.50 mmol) and (1E,6E)-cyclodeca-1,6-diene (411 mg, 3.02 mmol) in acetic acid (15 mL). The mixture was stirred at room temperature for 20 min, and was then evaporated. The residue was treated with aqueous saturated sodium bicarbonate (50 mL) and extracted with ether (3 × 50 mL). The combined organic extracts were washed with brine

(20 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (3 x 15 cm) with 5% ethyl acetate-hexane and then 10% ethyl acetate-hexane gave **182** (577 mg, 54%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (Neat) 3070, 3060, 2940, 2860, 1730, 1475, 1450, 1370, 1360, 1240, 1030, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.2-2.1 [m, 18H (includes a singlet at δ2.0)], 3.35 (dt, J = 13, 4 Hz, 1H), 4.7 (dt, J = 12, 4 Hz, 1H), 7.2-7.3 (m, 3H), 7.5-7.6 (m, 1H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 18.8, 20.7, 21.3, 23.7, 25.9, 27.0, 29.3, 40.8, 41.8, 49.0, 75.3, 122.0, 127.3, 129.0, 134.2, 167.2; exact mass, m/z 352.0938 (calcd for $C_{18}H_{24}O_2Se$, 352.0941). Anal. Calcd for $C_{18}H_{24}O_2Se$: C, 61.53; H, 6.88; O, 9.11. Found; C, 61.39; H, 6.81; O, 8.74.

1α,4β,4aβ,8aβ-Decahydro-4-(phenylseleno)-1-naphthalenol acetate 183:

The procedure employed for **182** was followed using (1E,5Z)-cyclodeca-1,5-diene (538 mg, 3.95 mmol) in acetic acid (2 mL), sodium acetate (329 mg, 4.01 mmol) in acetic acid (8 mL + 1 mL rinse), and phenylselenenyl chloride (761 mg, 3.98 mmol) in acetic acid (10 mL + 1 mL rinse). Flash chromatography over silica gel (3 x 15 cm) with 5% ethyl acetate-hexane and then 10% ethyl acetate-hexane

gave **183** (859 mg, 61%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (Neat) 3070, 3050, 2940, 2860, 1730, 1480, 1450, 1440, 1380, 1360, 1240, 1050, 1030, 750, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.2-1.7 (m, 9H), 1.7-1.8 (m, 2H), 2.0 (s, 3H), 2.05-2.2 (m, 2H), 2.3-2.4 (m, 1H), 3.35 (td, J = 12, 4 Hz, 1H), 4.7 (dt, J = 10, 5 Hz, 1H), 7.2-7.3 (m, 3H), 7.5-7.6 (m, 2H); exact mass, m/z 352.0943 (calcd for $C_{18}H_{24}O_2Se$, 352.0941). Anal. Calcd for $C_{18}H_{24}O_2Se$: C, 61.53; H, 6.88; O, 9.11. Found: C, 61.66; H, 6.81; O, 8.86.

1α,4β,4aβ,8aβ-Decahydro-4-(phenylseleno)-1-naphthalenol 184:

(1E,5Z)-Cyclodeca-1,5-diene (205 mg, 1.51 mmol) was added to a stirred solution of sodium acetate (121 mg, 1.47 mmol) in acetic acid (21 mL). Then a solution of phenylselenenyl chloride (256 mg, 1.34 mmol) in acetic acid (20 mL) was added over 5 min and stirring was continued for 20 min. The solvent was evaporated and the residue was treated with aqueous sodium bicarbonate solution (50 mL) and extracted with ether. The combined organic extracts were washed with brine (20 mL) and dried. The solvent was evaporated and the residue was stirred for 12 h with potassium carbonate (210 mg, 1.52 mmol), methanol (15 mL), and water (3 mL). The solvent

was evaporated and water (20 mL) was added. The mixture was extracted with ether (3 × 50 mL) and the combined ether extracts were washed with brine (20 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 10% ethyl acetate-hexane and then 20% ethyl acetate-hexane gave **184** (277 mg, 58%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) solid; mp. 75-77°C; IR (CCl_4) 3640, 3078, 3060, 2940, 2860, 1550, 1450, 1250, 1060, 1020 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.2-1.85 (m, 12H), 2.0 (m, 1H), 2.1 (m, 1H), 2.3 (m, 1H), 3.4 (td, J = 12, 4 Hz, 1H), 3.7 (dt, J = 11, 5 Hz, 1H), 7.2-7.4 (m, 3H), 7.5-7.65 (m, 2H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 19.5, 21.1, 26.1, 30.3, 30.7, 33.7, 40.9, 41.5, 44.2, 72.6, 127.6, 128.4, 128.8, 135.8; exact mass, m/z 310.0834 (calcd for $C_{16}H_{22}OSe$, 310.0836).

1α,4aβ,5α,8aβ-Decahydro-5-(phenylseleno)-1-naphthalenol 185:

The procedure employed for **184** was followed using (1E,6E)-cyclodeca-1,6-diene (159 mg, 1.17 mmol), sodium acetate (108 mg, 1.32 mmol) in acetic acid (10 mL), phenylselenenyl chloride (233 mg, 1.22 mmol) in acetic acid (5 mL + 2 mL rinse), and for hydrolysis, potassium carbonate (160 mg, 1.16 mmol) in methanol (10 mL) and water (1.7 mL). Flash chromatography over silica gel (3 ×

15 cm) with 20% ethyl acetate-hexane gave **185** (196 mg, 54%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) solid: mp. 106-107°C; IR ($CHCl_3$) 3600, 3440, 2940, 2860, 1580, 1470, 1450, 1440, 1140, 965 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.2-2 (m, 15H), 3.4 (dt, J = 13, 4 Hz, 1H), 3.65 (dt, J = 11, 5 Hz, 1H), 7.2-7.3 (m, 3H), 7.5-7.6 (m, 2H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 18.0, 20.9, 24.0, 27.2, 29.6, 29.7, 41.4, 45.1, 49.4, 73.0, 127.2, 129.0, 134.2; exact mass, m/z 310.0837 (calcd for $C_{16}H_{22}OSe$, 310.0837). Anal. Calcd for $C_{16}H_{22}OSe$: C, 62.13; H, 7.17. Found: C, 62.20; H, 7.20.

Homolysis (C-Se) cleavage of 184, 1α,4aβ,8aβ-Decahydro-1-naphthalenol 186:[91]

The procedure employed for **181** was followed using selenide **184** (670 mg, 2.17 mmol) in toluene (6 mL), triphenyltin hydride (1.02 g, 2.89 mmol) in toluene (4 mL + 2 mL rinse), and AIBN (20 mg, 0.12 mmol) in toluene (4 mL + 2 mL rinse). Evaporation of the solvent and flash chromatography of the residue over silica gel (3 × 15 cm) with 20% ethyl acetate-hexane gave **186**[91] (291 mg, 87%) as a homogeneous (~~TLC~~, silica gel, 20% ethyl acetate-hexane) solid: mp. 85-90°C; IR ($CHCl_3$) 3600, 2920, 2860, 1460, 1445, 1050, 1020, 940 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.15-1.9 (m, 17H), 3.7 (dt, J = 11.5, 5 Hz, 1H); ^{13}C

($CDCl_3$, 100.6 Hz) δ 19.0, 21.7, 24.4, 24.6, 26.4, 29.6, 31.9, 35.9, 43.1, 73.7;

Homolysis (C-Se) cleavage of 185, 1α,4aβ,8aβ-Decahydro-1-naphthalenol 186a:[91]

The procedure employed for **181** was followed using selenide **185** (130 mg, 0.42 mmol) in benzene (4 mL), triphenyltin hydride (206 mg, 0.59 mmol) in benzene (3 mL + 1 mL rinse), and AIBN (10 mg, 0.06 mmol) in benzene (3 mL + 1 mL rinse). Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 20% ethyl acetate-hexane gave **186a**[91] (57 mg, 87%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) solid: mp. 86-90°C; IR (CCl_4) 3620, 2920, 2860, 1465, 1445, 1090, 1050, 1030, 940 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.1-1.9 (m, 17H), 3.65 (dt, J = 11, 5 Hz, 1H); ^{13}C ($CDCl_3$, 50.3 MHz) δ 19.0, 21.6, 24.4, 24.5, 26.4, 29.5, 31.9, 35.9, 43.1, 73.6; exact mass, m/z 154.1356 (calcd for $C_{10}H_{18}O$, 154.1358).

Authentic sample of 1α,4aβ,8aβ-Decahydro-1-naphthalenol 186:[91]

An authentic sample was prepared as described in the literature.[91] IR (CCl_4) 3620, 2920, 2860, 1465, 1445, 1090, 1055, 1030, 940 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.1-

1.9 (m, 17H), 3.7 (dt, J = 11, 5 Hz, 1H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 19.0, 21.6, 24.4, 24.5, 26.4, 29.5, 31.9, 35.9, 43.1, 73.6; exact mass, m/z 154.1357 (calcd for $C_{10}H_{18}O$, 154.1357).

Acetylation of 186, 1α,4aβ,8aβ-Decahydro-1-naphthalenol acetate 187:[107]

Acetic anhydride (5.0 mL, 52.99 mmol) was added to a solution of alcohol **186** (277 mg, 1.80 mmol) in pyridine (5.0 mL, 61.82 mmol). The mixture was stirred for 12 h, quenched with cold 10% hydrochloric acid (30 mL) and extracted with ether (3 × 30 mL). The combined organic extracts were washed with aqueous sodium bicarbonate (30 mL) and brine (20 mL), and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (2 × 15 cm) with 3% ethyl acetate-hexane gave **187**[107] (220 mg, 62%) as a homogeneous (TLC, silica gel, 5% ethyl acetate-hexane) oil: IR (Neat) 2930, 2860, 1730, 1470, 1450, 1360, 1240, 1205, 1050, 1030 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ1.1-2.05 [m, 19H (includes a singlet at δ2.05)], 4.75 (dt, J = 11.25, 6 Hz, 1H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 19.7, 21.2, 24.0, 24.3, 25.8, 26.0, 31.5, 35.3, 39.7, 75.8, 170.3; exact mass, m/z 137.1292 [calcd for ($C_{12}H_{20}O_2$-$C_2H_3O_2$), 137.1331].

Acetylation of 186a, 1α,4aβ,8aβ-Decahydro-1-naphthalenol acetate 187a.[107]

The procedure employed for **187** was followed using alcohol **186a** (81 mg, 0.53 mmol), acetic anhydride (3.0 mL, 31.79 mmol), and pyridine (2.6 mL, 32.15 mmol). After work up, evaporation of the solvent gave **187a**[107] (100 mg, 97%) directly as a homogeneous (TLC, silica gel, 5% ethyl acetate-hexane) oil: IR (CCl_4) 2930, 2860, 1740, 1470, 1460, 1360, 1240, 1030 cm^{-1}; ^1H NMR ($CDCl_3$, 100 MHz) δ 1.1-2.1 [m, 19H (includes a singlet at δ2.05)], 4.8 (dt, J = 10, 5 Hz, 1H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 19.9, 21.4, 24.1, 24.5, 26.0, 26.1, 31.6, 35.5, 40.0, 76.0, 170.5; exact mass, m/z 137.1318 [calcd for ($C_{12}H_{20}O_2$-$C_2H_3O_2$), 137.1331].

Authentic sample of 1α,4aβ,8aβ-Decahydro-1-naphthalenol acetate 187:[107]

The procedure employed for **186** was followed using alcohol **186** (290 mg, 1.88 mmol), acetic anhydride (3.5 mL, 37.09 mmol), and pyridine (3.0 mL, 37.09 mmol). After work up, evaporation of the solvent gave **187**[107] (310 mg, 84%) directly as a homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil: IR (Neat) 2920, 2860, 1735, 1450, 1360, 1240, 1210, 1045, 1030 cm^{-1}; ^1H NMR ($CDCl_3$, 100 MHz) δ 1.1-2.1 [m, 19H (includes a singlet at δ2.05)], 4.8 (dt,

J = 10, 5 Hz, 1H); ^{13}C ($CDCl_3$, 22.6 MHz) δ19.7, 21.2, 23.9, 24.3, 25.9, 26.0, 31.4, 35.3, 39.8, 75.8, 170.3; exact mass, m/z 137.1301 [calcd for ($C_{12}H_{20}O_2$-$C_2H_3O_2$), 137.1331].

trans-Octahydro-1(2H)-naphthalenone 188:[105]

Alcohol **186** was added to a solution of commercial pyridinium chlorochromate (12.43 g, 57.6 mmol) in dry dichloromethane (30 mL) and the mixture was stirred for 2 h. Ice cold hexane (100 mL) was added, stirring was continued for 10 min and the mixture was passed through a short column of Florisil with hexane (300 mL). Evaporation of the solvent and flash chromatography of the residue over silica gel (4 × 15 cm) with 10% ethyl acetate-hexane and Kugelrohr distillation (bp 100°C, 1.0 mm) gave **188**[105] (2.16 g, 82%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4) 2960, 2860, 1710, 1440, 1205, 1170, 905, 805 cm^{-1}; ^{13}C ($CDCl_3$, 22.6 MHz) δ 25.1, 25.5, 25.8, 26.9, 33.1, 34.4, 41.8, 45.0, 55.1, 212.7; exact mass, m/z 152.1198 (calcd for $C_{10}H_{16}O$, 152.1201).

cis-Octahydro-1(2H)-naphthalenone 189:[105]

The procedure employed for **188** was followed using alcohol **186** (1.88 g, 12.2 mmol), pyridinium chlorochromate

(3.24 g, 15.03 mmol, prepared as in the literature[104]) in dichloromethane (30 mL). Evaporation of the solvent and Kugelrohr distillation (bp 50°C, 0.05 mm) gave **189**[105] (1.47 g, 79%) as a homogeneous (TLC, silica gel, 20% ethyl acetate-hexane) oil: IR (CCl_4) 2940, 2860, 1700, 1450, 1240, 1230, 1155, 1005, 945 cm^{-1}; ^{13}C NMR ($CDCl_3$, 22.6 MHz) δ 23.2, 23.6, 24.7, 25.3, 29.2, 29.3, 39.3, 40.7, 50.8, 213.6; exact mass, m/z 152.1199 (calcd for $C_{10}H_{16}O$, 152.1201).

cis- and trans-Decahydro-1-methylene-naphthalene 190 and 191:[106]

n-Butyllithium (0.41 mL, 1.6 M in hexanes, 0.66 mmol) was added dropwise into a solution of methyl triphenylphosphonium bromide (302 mg, 0.84 mmol) in THF (10 mL). Stirring was continued for 15 min and a solution of ketone **189** (100 mg, 0.66 mmol) in THF (4 mL + 1 mL rinse) was added dropwise. After a further 1 h, the mixture was refluxed for 3 h, cooled to room temperature, quenched with 10% hydrochloric acid (10 mL) and extracted with ether (3 × 20 mL). The combined organic extracts were washed with brine (10 mL) and dried. Evaporation of the solvent and flash chromatography of the residue over silica gel (1 × 10 cm) with hexane gave **190** and **191** (15 mg, 15%) as an apparently homogeneous (TLC, silica gel,

hexane) oil that consisted (^{13}C NMR) of the cis and trans isomers of **190**: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.0-2.4 (m, 16H), 4.45-6.2 (m, 2H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 26.4, 26.5, 27.5, 28.2, 29.1, 34.6, 34.8, 37.2, 37.9, 44.9, 47.5, 103.8, 104.8, 105.0, 106.6.

trans-Decahydro-1-methylene-naphthalene 191:[106]

The procedure employed for **190** was followed using ketone **188** (104 mg, 0.68 mmol), methyl triphenylphosphonium bromide (295 mg, 0.82 mmol), and n-butyllithium (0.43 mL, 1.6 M in hexanes, 0.68 mmol) in THF (15 mL). Flash chromatography over silica gel (1 × 15 cm) with hexane gave **191** (15 mg, 15%) as a homogeneous (TLC, silica gel, hexane) oil: IR (Neat) 2940, 2860, 1645, 1450, 895, 885 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.0-2.0 (m, 14H), 2.0-2.1 (m, 1H), 2.3-2.14 (m, 1H), 4.54 (s, 1H), 4.65 (s, 1H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 26.5, 26.6, 28.2, 29.1, 34.5, 34.8, 37.1, 44.8, 47.4, 103.8, 153.6.

cis-trans-Decahydro-(E)- and (Z)-1-(phenylmethylene)-naphthalene 192 and 193:

The procedure employed for **190** was followed using benzyl triphenylphosphonium chloride (358 mg, 0.92 mmol) in THF (5 mL), n-butyllithium (0.46 mL, 1.6 M in hexanes, 0.75 mmol), and ketone **189** (113 mg, 0.75 mmol) in THF (4

mL). Work up and flash chromatography over silica gel (1 × 15 cm) with hexane gave **188** (37 mg, 33%) and **192** and **193** (17 mg, 15%) as an apparently homogeneous (TLC, silica gel, hexane) oil. **188** had: IR (Neat) 2940, 2850, 1705, 1450, 1205, 1170, 905, 805 cm^{-1}; ^{13}C ($CDCl_3$, 22.6 MHz) δ 25.2, 25.4, 25.7, 26.4, 33.0, 34.3, 41.8, 44.9, 55.0, 212.7.

192 and **193** had: ^{1}H NMR ($CDCl_3$, 400 MHz) δ1.0-1.4 (m, 7H), 1.6-1.9 (m, 8H), 2.15-2.3 (m, 0.48H), 2.85-2.95 (m, 0.52H), 6.12 (s, 0.48H), 6.58 (s, 0.52H), 7.1-7.3 (m, 5H); ^{13}C ($CDCl_3$, 100.6 MHz) δ 26.4, 26.7, 28.0, 29.1, 30.5, 34.8, 35.1, 45.2, 48.5, 119.1, 125.7, 127.1, 128.0, 128.2, 128.9, 129.1, 130.3, 137.4, 139.3.

trans-Decahydro-(E) and (Z)-1-phenylmethylene naphthalene 193:

The procedure employed for **190** was followed using benzyl triphenylphosphonium chloride (455 mg, 1.17 mmol) in THF (5 mL), n-butyllithium (0.55 mL, 1.6 M in hexanes, 0.88 mmol), and ketone **188** (134 mg, 0.88 mmol) in THF (4 mL + 1 mL rinse). Work up and flash chromatography over silica gel (1 × 15 cm) with hexane gave **188** (84 mg, 63%) and **193** (48 mg, 24%) as an apparently homogeneous (TLC, silica gel, 10% ethyl acetate-hexane) oil. **188** had: IR (Neat) 2920, 2860, 1715, 1450, 1205, 1170, 905, 805 cm^{-1};

^{13}C ($CDCl_3$, 22.6 MHz) δ 25.1, 25.5, 25.8, 26.5, 33.1, 34.4, 41.8, 45.0, 55.1, 212.8.

193 had: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.2-1.4 (m, 7H), 1.6-2.0 (m, 8H), 1.95 (m, 1H), 6.16 (s, 1H), 7.15-7.35 (m, 5H); ^{13}C ($CDCl_3$, 22.6 MHz) δ 26.3, 26.6, 27.8, 29.0, 30.4, 34.7, 35.0, 45.1, 48.4, 119.0, 125.6, 128.0, 129.0, 146.7; exact mass, m/z 226.1723 (calcd for $C_{17}H_{22}$, 226.1721).

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