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The synthesis and study of tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene; an important member of a homologous series of pyramidalized olefins

Smith, Joseph Michael, Ph.D.

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U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

The Synthesis and Study of Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene; an Important Member of a Homologous Series of Pyramidalized Olefins

by

JOSEPH M. SMITH

A dissertation submitted in partial fulfillment

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(Chairperson of Supervisory Comittee)

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Doctoral Dissertation

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Abstract

The Synthesis and Study of Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene; an Important Member of a Homologous Series of Pyramidalized Olefins

by Joseph Michael Smith

Chairperson of Supervisory Committee: Professor Weston Thatcher Borden

Department of Chemistry

This dissertation describes the 17-step synthesis and study of tricyclo[3.3.3.$0^{3,7}$]-undec-3(7)-ene. It is, indeed, a very important member of a homologous series of pyramidalized olefins, because, unlike lower members of this series, it can be isolated and studied at room temperature. The stability of this olefin has allowed its ^{13}C NMR spectrum to be obtained, and the spectrum shows unequivocally that pyramidalization results in a downfield shift of the resonance for the olefinic carbons. The temperature dependence of both the ^{13}C and ^{1}H NMR spectra indicate that the olefin undergoes a dynamic conformational change that involves flipping of the trimethylene bridge. The same process is

evident in the NMR spectra of several precursors of the olefin; and the values of $\Delta G^{\neq}$ that are measured and the results of molecular mechanics calculations both indicate that twisting about the C_3-C_7 bond facilitates this conformational change. The photoelectron and electron transmission spectra of the olefin confirm the computational prediction that pyramidalization lowers the energy of the lowest unoccupied orbital of an olefin much more than it raises the energy of the highest occupied orbital. Not only is the synthesis of the olefin significant for the new information about the effects of olefin pyramidalization that it has already furnished, it is also important because of the future studies of this molecule that its successful preparation has made possible.

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Acknowledgements

With sincere appreciation, I thank Professor Borden for his guidance, patience, and encouragement throughout this research project. I am also indebted to Dr. David Hrovat for his help in solving many of the problems I encountered in this project. I also thank my friends and people in the chemistry department for all their help. Finally, my love and deepest thanks go to my wonderful family for all the love and support they have given me.

Dedication

I dedicate this dissertation to my parents, Mr. Joseph R. and Mrs. Mary I. Smith, only by whose love and sacrifices made it possible for me to successfully pursue and obtain a Ph.D. degree in chemistry.

I. Introduction

A. Pyramidalized Alkenes

A pyramidalized alkene is a molecule in which at least one of the olefinic carbon atoms does not lie in the plane defined by the three substituents attached to it. The amount of pyramidalization at a doubly bonded carbon can be specified by a pyramidalization angle, ϕ, which is defined as the angle between the plane containing the carbon and the two substituents connected to it and a line colinear with the two doubly bonded atoms.

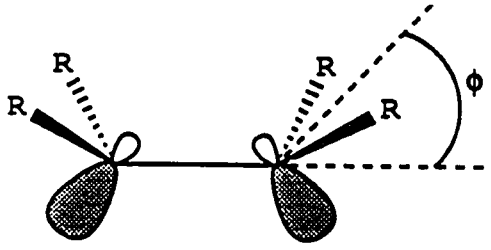
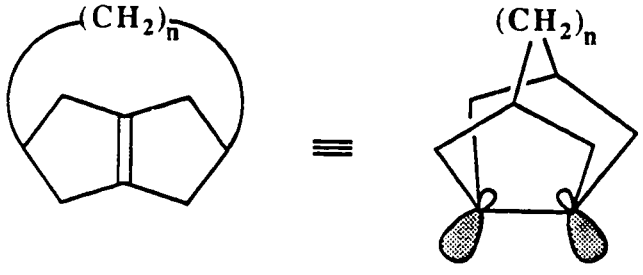


Figure IA.1 **Pyramidalization Angle (ϕ) in a Pyramidalized Olefin.**

The experimental study of highly pyramidalized olefins has a relatively short history. Synthesis of the first highly pyramidalized alkene, 9,9'-didehydrodianthracene, was reported twenty four years ago by Weinshenker and Greene.[1] The subsequent literature on pyramidalized alkenes through 1988 has been reviewed.[2]

In the series of pyramidalized alkenes (**1**) that is the subject of this thesis the amount of pyramidalization at the doubly bonded carbons can be systematically varied. As the number, n, of methylene groups that bridge the bicyclo[3.3.0]oct-1(5)-ene moiety in **1** is decreased, the four allylic carbons will increasingly be pulled out of the plane of the doubly bonded carbons, thus resulting in the doubly bonded carbons becoming increasingly pyramidalized. As a result of this pyramidalization, the overlap between the atomic orbitals comprising the "π" bond will decrease, thus weakening this bond. Research in Professor Borden's group in recent years has been focused on the synthesis of the lower members (n = 0-3) of this series of pyramidalized tricyclo[3.3.n.$0^{3,7}$]alk-3(7)-enes and the study of their structures, chemistry, and spectroscopy.

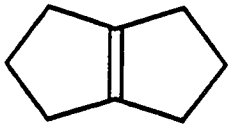


1a, n = 3
1b, n = 2
1c, n = 1
1d, n = 0

Figure IA.2 A Homologous Series of Highly Pyramidalized Olefins (**1**).

B. Results of Calculations on Tricyclo[3.3.n.0^{3,7}]alk-3(7)-enes

Ab initio calculations have been performed on **1a-d**, as well as on bicyclo[3.3.0]oct-1(5)-ene, **2**, which serves as the reference compound for this homologous series of olefins.[3] The calculations predict that, as the number of



2

Figure IB.1 **The Unbridged Reference Olefin (2).**

methylene carbons, n, in **1** is decreased from n=3 to n=0, the pyramidalization angle and the C-C double bond length will both increase; and the C-C double bond stretching frequency will decrease.[4] The HOMO-LUMO energy gap is also predicted to decrease. The chief contributer to the shrinking in the HOMO-LUMO gap is computed to be lowering of the energy of the LUMO, rather than raising of the energy of the HOMO. Finally, the olefin strain energy (OSE), -- the difference between the hydrogenation energies of the pyramidalized olefins (**1**) and the unbridged olefin (**2**) -- is calculated to increase along the series **1a-d**. Some of the calculated properties of **1a-d** and **2** are given in Table IB.1.

Table IB.1. Calculated[3] RHF/3-21G Properties of Tricyclo[3.3.n.$0^{3,7}$]alk-3(7)-enes (**1**) and Bicyclo[3.3.0]oct-1(5)-ene (**2**).

Olefin		**1a**	**1b**	**1c**	**1d**	**2**
Pyramidalization. angle ϕ (°)		25.2 25.0	40.8	52.8	61.2	-3.6
C=C bond length (Å)[a]		1.344	1.361	1.389	1.434	1.334
C=C stretch freq. (cm^{-1}):	MNDO[b]	1617	1597	1540	1482	1675
	ab initio[c]	1634	1599	1538	1455	1675
ΔE LUMO (eV)[d]		-0.79	-1.38	-2.04	-2.91	0
ΔE HOMO (eV)[d]		0.24	0.33	0.44	0.28	0
OSE (kcal/mol)[d,e]		17.7	37.4	52.3	72.8	0

[a] Calculated at the TCSCF/3-21G level. [b]Calculated frequencies scaled by 0.943 to fit experimental value (1675 cm^{-1})[2] of olefin **2**. [c]Calculated RHF/3-21G frequencies scaled by 0.883 to fit experimental value (1675 cm^{-1}) of olefin **2**. [d] Relative to **2**. [e] Calculated at the TCSCF/3-21G* level.

In order to test these computational predictions, alkenes **1a-d** must not only be synthesized; but they must also be generated under conditions where their properties can be

measured, before these highly reactive alkenes dimerize. As discussed in the next chapter, the high reactivity of **1b-d** has severely limited the amount of structural and spectroscopic information about these alkenes that has been obtained. The limited amount of information available about **1b-d** prompted the synthesis of **1a** in the hope that its less highly pyramidalized geometry would reduce its reactivity, so that detailed information could be obtained about its structure, spectroscopy, and chemistry.

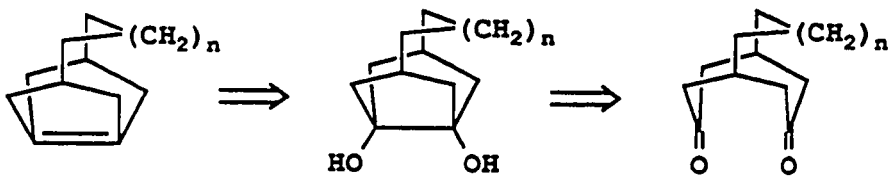
The synthesis and study of tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene (**1a**) which is described in Chapter III, was the focus of most of the research that is contained in this thesis. However, the preparation of the $(Ph_3P)_2Pt$ complex of **1a** and of the n=2 alkene (**1b**) is also described in Chapter III. The spectroscopic properties of the $(Ph_3P)_2Pt$ complexes of **1a** and **1b** are compared with those previously obtained for the $(Ph_3P)_2Pt$ complexes of **1c**[5] and ethylene.

C. Synthesis, Chemistry, and Spectroscopic Properties of Some Tricyclo[3.3.n.$0^{3,7}$]alk-3(7)-enes and Other Pyramidalized Derivatives of Bicyclo[3.3.0]oct-1(5)-ene -- A Brief Review of Previous Work

1. Synthetic Strategy

In order to assure that the double bond in **1** is introduced between the two bridgehead atoms, C-3 and C-7, it is necessary to perform a bifunctional elimination reaction, rather than eliminating the elements of HX from a bridgehead monohalide. A

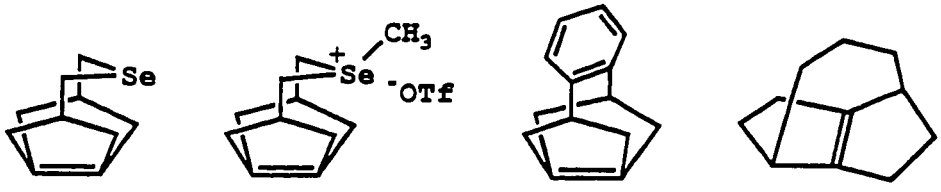
variety of methods are available for the conversion of vicinal diols into olefins,[6] and the diol precursors of **1** could be synthesized by transannular reductive ring closure of diketones **4**.[7]



1 **3** **4**

Figure IC.1 **A Synthetic Methodology for the Generation of Olefins 1 from Diketones 4 via Diols 3.**

The Borden group has successfully used this route to prepare the 10-selena derivative (**5a**) of **1a**[8] and a derivative (**6**) of **1b** in which a benzo group replaces the two bridging methylene groups.[9] A torsionally strained alkene (**7**), related to trans-cycloheptene, has also been prepared by this pathway,[10] and a synthesis of the unbridged olefin (**2**), as a model for the synthesis of pyramidalized olefins **1**, was performed by this route.[7]



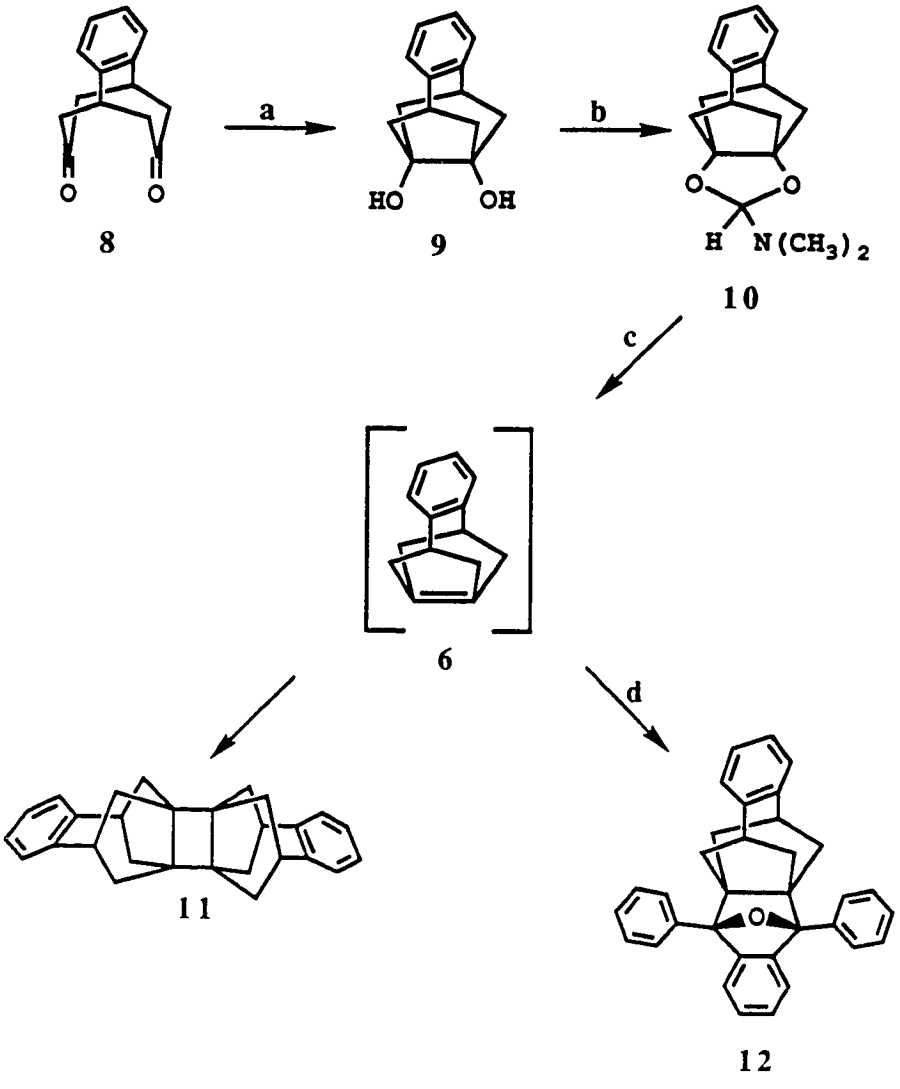
5a 5b 6 7

Figure IC.2 **Pyramidalized Olefins 5a, 5b, 6, and Torsionally Strained Olefin 7.**

2. Synthesis of Alkene 6

The benzo bridged derivative (**6**) of the n=2 olefin (**1b**) was the first pryamidalized olefin to be prepared by this route.[9] As shown in Figure IC.3, diol **9** was obtained via transannular reductive ring closure of diketone **8**, using zinc amalgam in aqueous hydrochloric acid.[7] Diketone **8** was in turn prepared in two steps, starting with phthalic dicarboxaldehyde and dimethyl 1,3-acetonedicarboxylate.[11]

A number of attempts to prepare **6** from diol **9** were unsuccessful. For example, there was no evidence of formation of **6** when the thionocarbonate derivative of diol **9** was heated in triethyl phosphite, despite the success of this reaction[6a] in preparing **2** from its diol precursor.[7,9] However, as shown in Figure IC.3, refluxing the dimethylaminodioxolane derivative of diol **9** in the presence of several different Lewis acids in tetraglyme gave



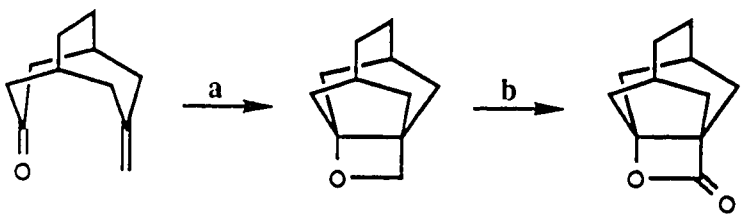
8 9 10 6 11 12

Figure IC.3 Synthesis and Chemistry of Olefin 6. a) Zn/Hg, H_3O^+, CH_3OH. b) $HC(OCH_3)_2N(CH_3)_2$, p-TsOH, C_6H_6. c) tetraglyme, HOAc, Δ. d) DPIBF.

dimer (**11**). When the reaction was performed in the presence of diphenylisobenzofuran (DPIBF), alkene **6** could be chemically trapped as a Diels-Alder adduct (**12**). Unfortunately, the reaction conditions required to generate **6** from **10** are so harsh that they preclude the isolation and study of the alkene.

3. Synthesis of Alkene 1b

The first successful generation of the n=2 olefin (**1b**), under conditions where it could be studied spectroscopically, used as the precursor, not derivatives of diol **3b**, but β-lactone **15**. The β-lactone was prepared by the route shown in Figure IC.4, starting from 7-methylenebicyclo[3.3.2]decane-3-one (**13**).[12] Transannular photochemical ring closure of **13**, followed by ruthenium tetroxide oxidation of the resulting oxetane (**14**) gave **15**.[13]



13 14 15

Figure IC.4 Synthesis of β-Lactone 15. a) hυ. b) RuO_4.

As shown in Figure IC.5, pyrolysis of **15** in refluxing tetraglyme in the presence of DPIBF gave the Diels-Alder adduct **16**; whereas, dimer **17** was found when no DPIBF was present.[13] Flash vacuum pyrolysis (FVP) of **15** and matrix isolation of **1b** at low temperature allowed the olefin to be studied spectroscopically.[14]

The C-C double bond stretch in **1b** appeared at 1557 cm^{-1} as a weak band in the IR and the strongest band in the Raman spectrum. The polarization of the IR absorption was found to be perpendicular, rather then parallel, to the C-C double bond. The UV absorption spectrum of **1b** showed a λ_{max} at around 245 nm. A very recent photoelectron spectrum of **1b** shows that this long wavelength absorption cannot be due primarily to a raising of the HOMO energy, since as predicted,[3] the ionization energy of **1b** is only 0.3-0.4 eV lower than that of **2**.[15]

Photolysis of **1b** in the matrix or pyrolysis of **1b** at temperatures slightly above that required for its formation from **15** cause the olefin to rearrange to **18**.[16] This vinylcyclopropane itself rearranges to **19** at still higher temperatures or by exposure to traces of acid.

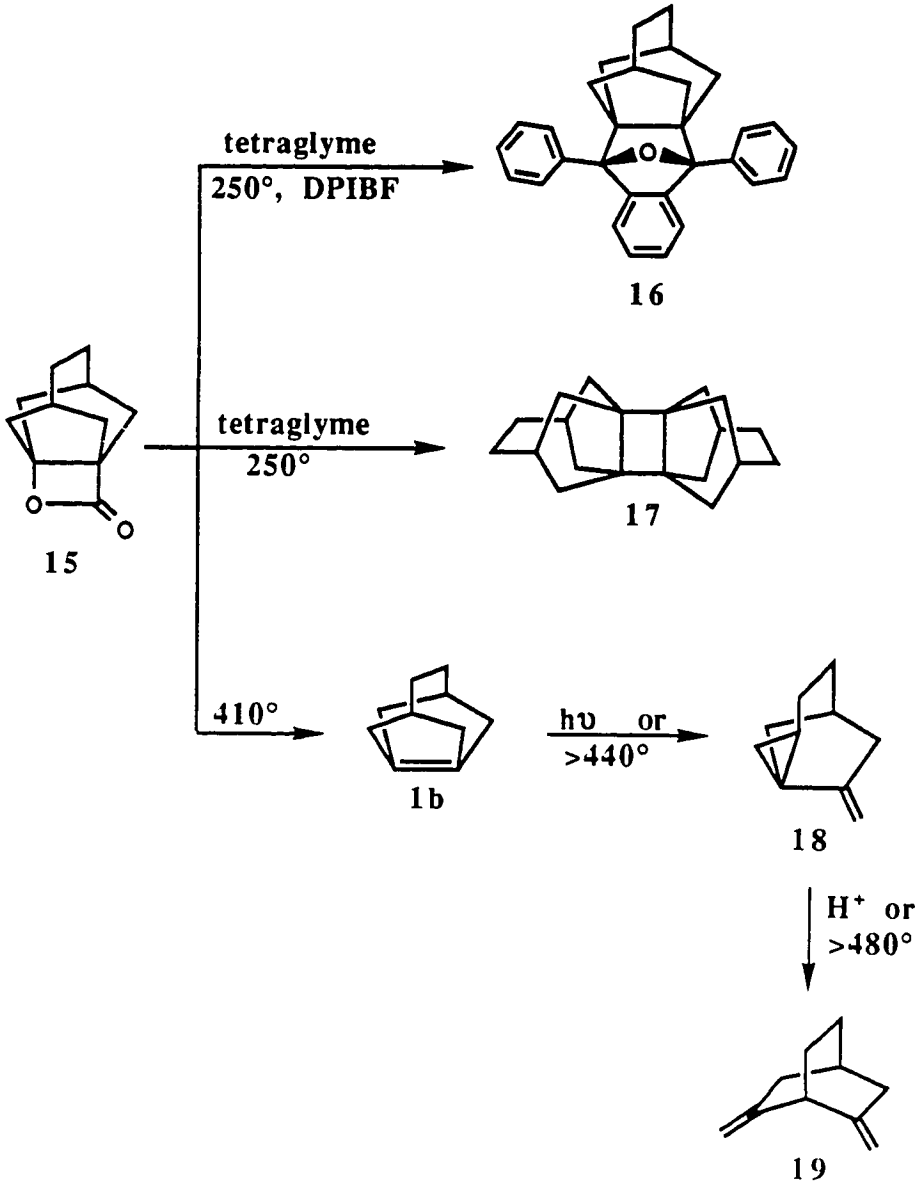


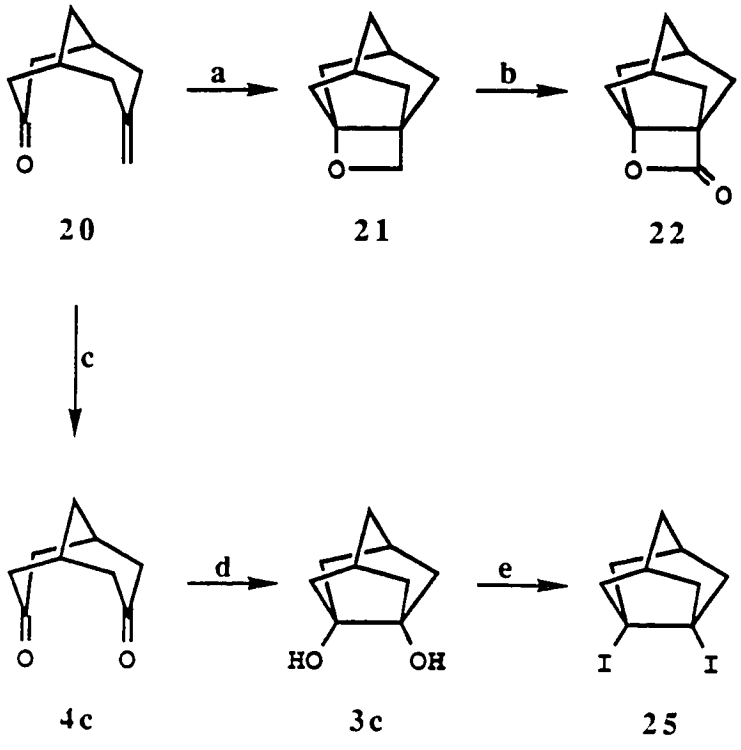
Figure IC.5 Some Chemistry of the n=2 Olefin (1b).

4. Synthesis of Alkene 1c

As shown in Figure IC.6, β-lactone **22**, a potential precursor of **1c**, was prepared from 7-methylenebicyclo[3.3.1]nonane-3-one (**20**),[17] by transannular photochemical ring closure, followed by ruthenium tetroxide oxidation of the resulting oxetane (**21**).[13] However, as shown in Figure IC.7, FVP of **22** at 550° gave, not **1c**, but ketoketene **26** and unreacted starting material.[18] At higher temperatures, formation of **1c** probably does take place, because a small amount of dimer **27** was detected. Nevertheless, the major product isolated was the rearrangement product **29**.[14,18] Presumably, most of the olefin **1c** that is formed rearranges to the vinylcyclopropane isomer **28**, which, under the pyrolysis conditions, itself rearranges to **29**.

Alkene **1c** was successfully generated at lower temperature by another route.[18] Diol **3c**, prepared by transannular ring closure of diketone **4c**,[6b] using zinc amalgam in aqueous hydrochloric acid,[10] was, as shown in Figure IC.6, converted to diiodide **25** by heating with 95% phosphoric acid and sodium iodide.[18] Treating **25** with one equivalent of butyllithium in THF at -78° gave dimer **27** in almost quantitative yield. When **1c** was generated in the presence of DPIBF, the corresponding Diels-Alder adduct **30** was also isolated in almost quantitative yield. These reactions are shown in Figure IC.8.

Olefin **1c** has recently been matrix isolated at low temperature by reduction of **25** with potassium vapor in the gas phase.[19] The C-C double bond stretching frequency was observed at 1496 cm^{-1} by IR. Photolysis of matrix-isolated **1c** converted it to the vinylcyclopropane isomer **28**.



20 21 22

4c 3c 25

Figure IC.6 Syntheses of β-Lactone 22 and Diiodide 25. a) hυ. b) RuO_4. c) O_3. d) Zn/Hg, H_3O^+, CH_3OH. e) I_2, H_3PO_4.

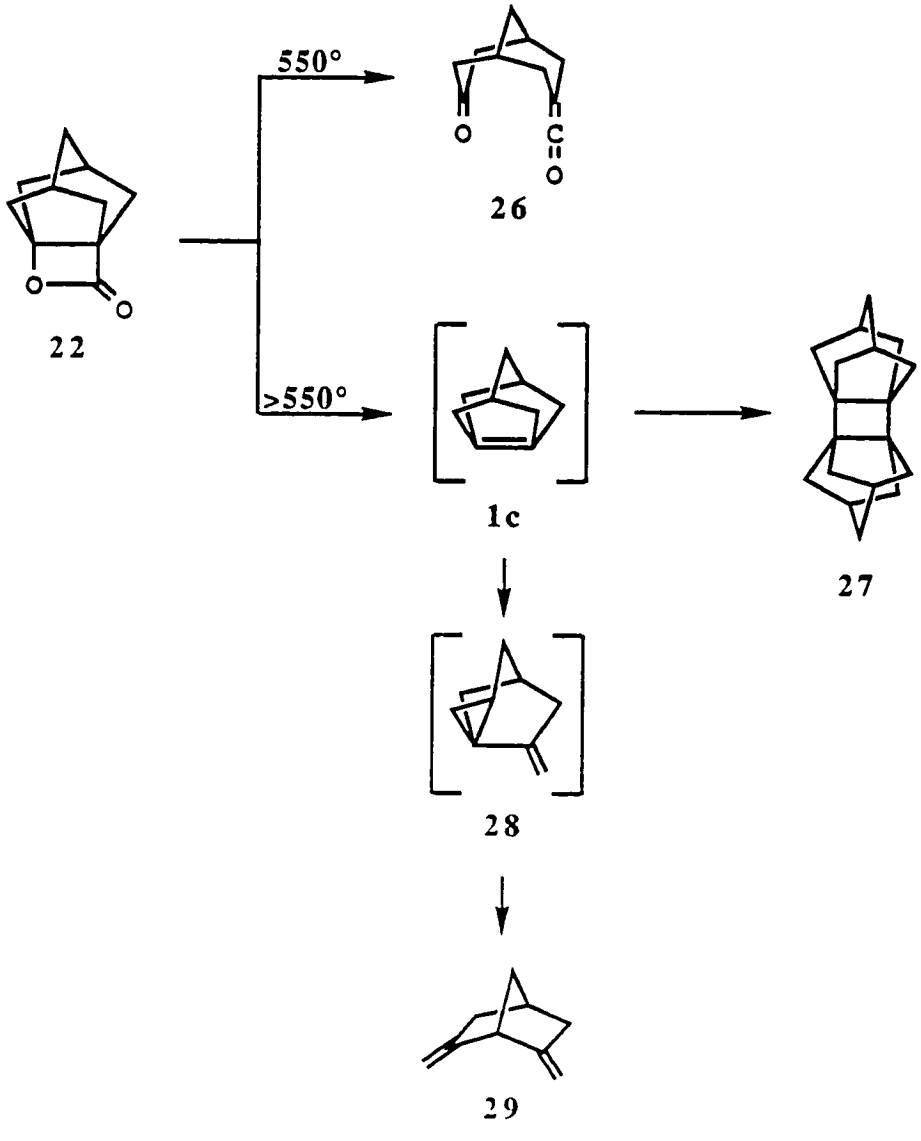


Figure IC.7 Results of Pyrolyzing β-Lactone 22.

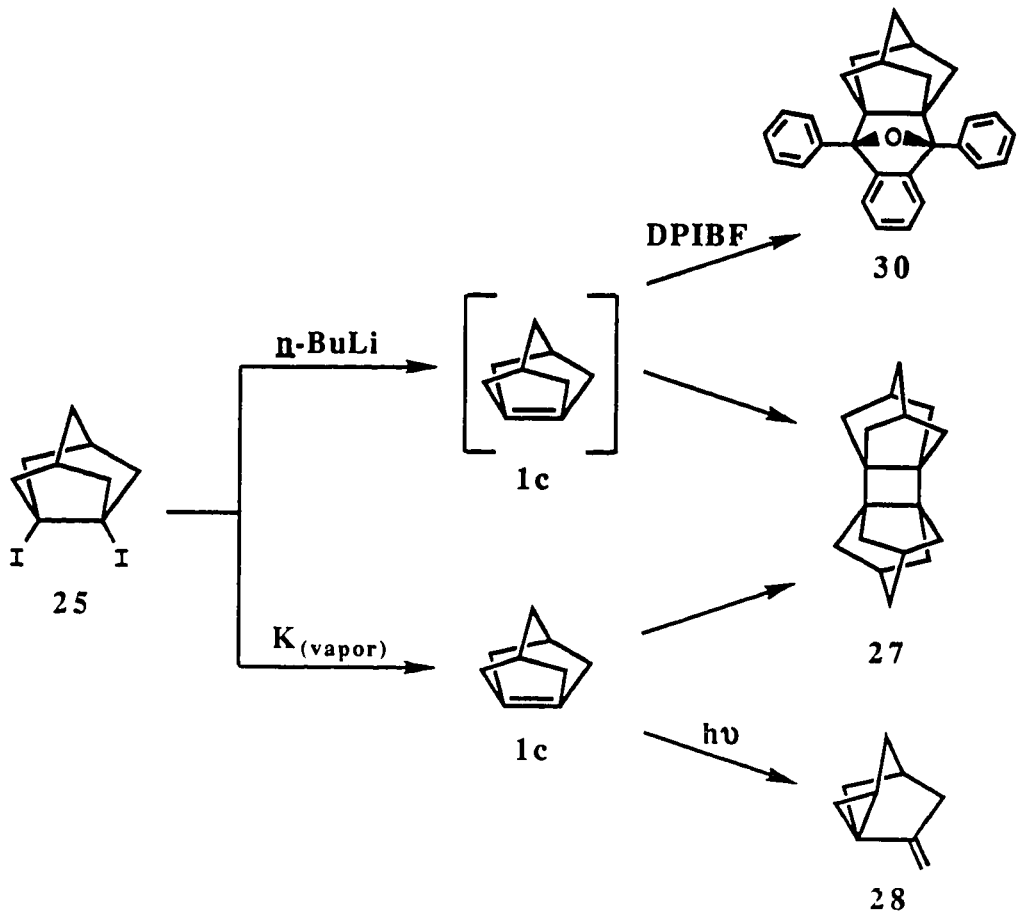
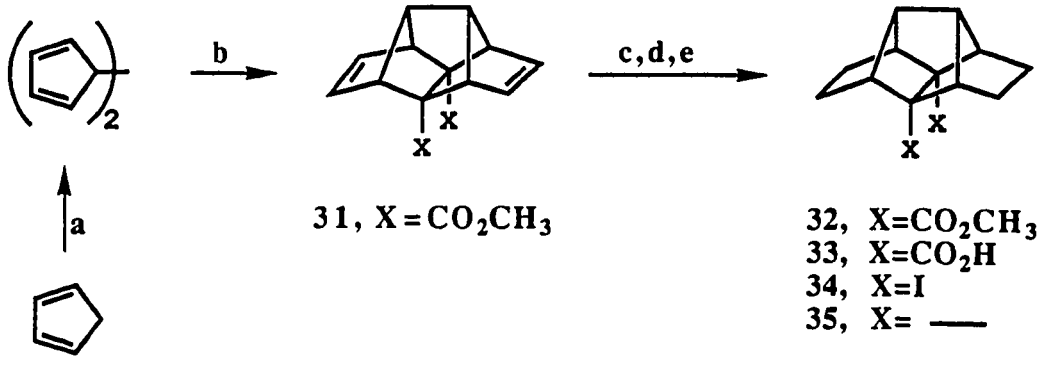


Figure IC.8 Some Chemistry of the n=1 Olefin (1c).

Stirring diiodide **25** and sodium amalgam in diethyl ether under argon at -78° also gives dimer **27**. Evidence for the intermediacy of olefin **1c** in this reaction comes from trapping of **1c** with bis(triphenylphosphine)platinum (0) to form a stable $(Ph_3P)_2Pt$ complex.[5] This complex of **1c** and those of **1a** and **1b** are discussed in Chapter III.

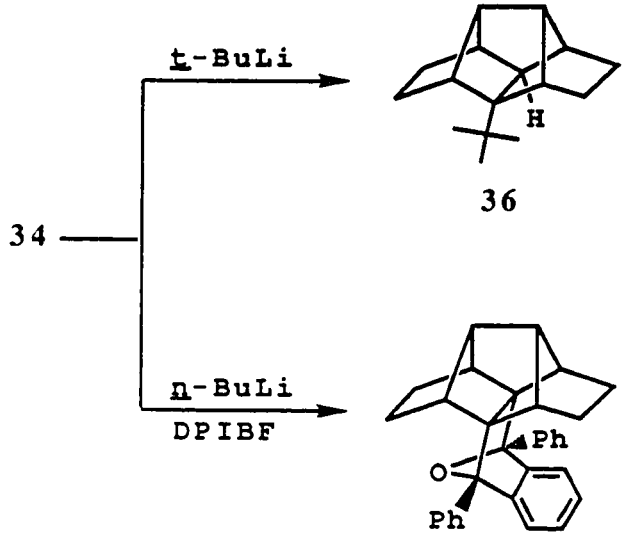
5. Synthesis of Alkene 35

Although the n=0 olefin (**1d**) is still unknown, the synthesis, shown in Figure IC.9, of a bis(ethano)bridged derivative (**35**) of **1d** has been carried out.[20] Reaction of diiodide **34** with excess tert-butyllithium leads to the addition product **36**, presumably via the intermediacy of **35**. Formation of olefin **35** in the reaction of diiodide **34** with alkyllithiums has been confirmed by trapping **35** with DPIBF as the Diels-Alder adduct (**37**) in quantitative yield. No spectroscopic information on olefin **35** has yet been obtained.



31, $X=CO_2CH_3$

32, $X=CO_2CH_3$
33, $X=CO_2H$
34, X=I
35, X= ——



36

37

Figure IC.9 Synthesis and Chemistry of Olefin 35. a) 1) NaH, 2) I_2. b) dimethyl acetylenedicarboxylate. c) H_2, PtO. d) H_2SO_4. e) HgO, I_2, $MgSO_4$, hυ.

6. Synthesis of Alkene 5a

Synthesis of the Se bridged derivative, (**5a**), of the n=3 olefin, (**1a**), has been accomplished via a 13 step reaction sequence, starting with phthalic dicarboxaldehyde and dimethyl 1,3-acetonedicarboxylate and proceding through diol **9**.[8] Protection of the diol as the acetonide, followed by oxidation of the benzene ring with either ruthenium tetroxide or ozone, gave diacid **38**. As shown in Figure IC.10, reduction of **38** to diol **39**, and its conversion to diiodide **41**, allowed the introduction of the bridging selenium atom and ring closure of **42** to give **43**. Deprotection of **43**, conversion of diol **44** to the dimesylate **45**, and reduction of dimesylate **45**, using sodium naphthalide in THF, afforded **5a**, which was isolable. Though much less reactive toward dimerization than olefins **1b**, **1c**, **6**, or **7**, olefin **5a** was found to form epoxide **46** upon attempted purification by preparative thick layer chromatography in the air.

Olefin **5a** showed a C-C double bond stretching frequency at 1625 cm^{-1}. A UV spectrum showed end absorption around 210 nm. The olefinic carbons in the room temperature ^{13}C NMR spectrum appeared as one resonance at 150.7 ppm. An X-ray structural analysis of the methylselenonium triflate salt, (**5b**), of **5a**, showed **5b** to have pyramidalization angles of 12.3° and 20.3° and a C-C double bond length of 1.338 Å. The large difference between the two pyramidalization angles in **5b** may be due to an attraction between the positively charged selenonium group and the π electrons of the double bond.[2] Consistent with this hypothesis is the fact that the carbon of the double bond in **5b** that is nearer the selenonium group is the less pyramidalized of the two.

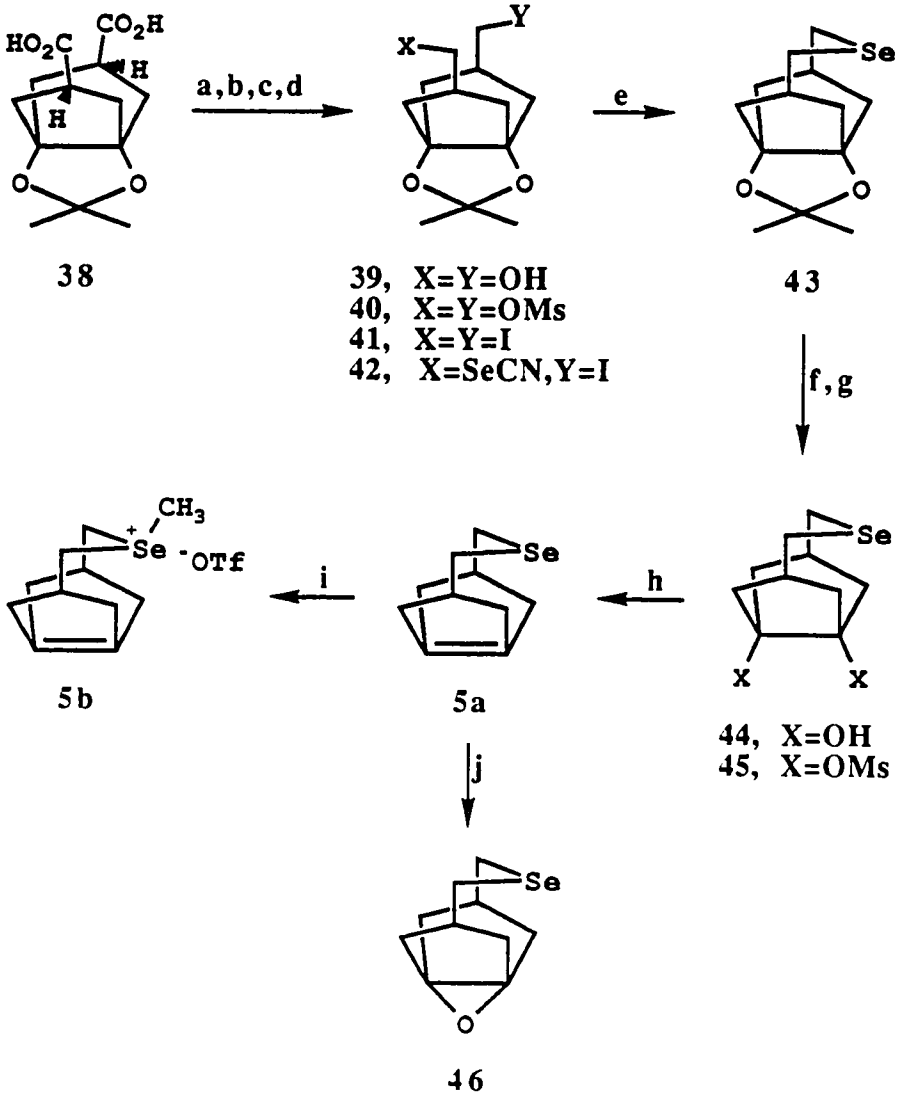


Figure IC.10 Syntheses of Olefins 5a and 5b and Some Chemistry of Olefin 5a. a) LAH. b) MsCl, Et_3N. c) NaI. d) KSeCN. e) $NaBH_4$. f) H_3O^+. g) MsCl, Et_3N. h) Na/naphthalene. i) CH_3OTf. j) O_2.

7. Attempted Synthesis of 1a and Preparation of 7

The strategy used in the first attempt to synthesize the n=3 olefin (**1a**) involved transannular ring closure of diketone **4**, n=3, and conversion of the resulting diol (**3**, n=3) to **1a**.[10] One conceivable way to generate the required diketone **4**, (n=3), would be from double ring expansion of the known diketone **47**.[21] As shown in Figure IC.11, double ring expansion was achieved in **47** by addition of isocyanomethyllithium, followed by hydrolysis of the bis-adduct to the bis-aminoalcohol (**48**), and subsequent Tiffeneau-Demjanov ring expansion. However, the major product was not **4**, n=3, but diketone **49**, which results from methylene, not bridgehead, migration.

Although **49** could not be used to prepare **1a**, it was employed for the synthesis and study of torsionally strained olefin **7**,[10] which is also shown in Figure IC.11. Transannular ring closure of diketone **49**, using zinc amalgam in aqueous hydrochloric acid, gave diol **50**. Heating the thionocarbonate derivative (**51**) of diol **50** in triethyl phosphite gave a dimer which spectral analysis showed to be **52**, the product of an ene type reaction between two molecules of **7**. In the presence of DPIBF, **7** was trapped as the Diels-Alder adduct (**53**).

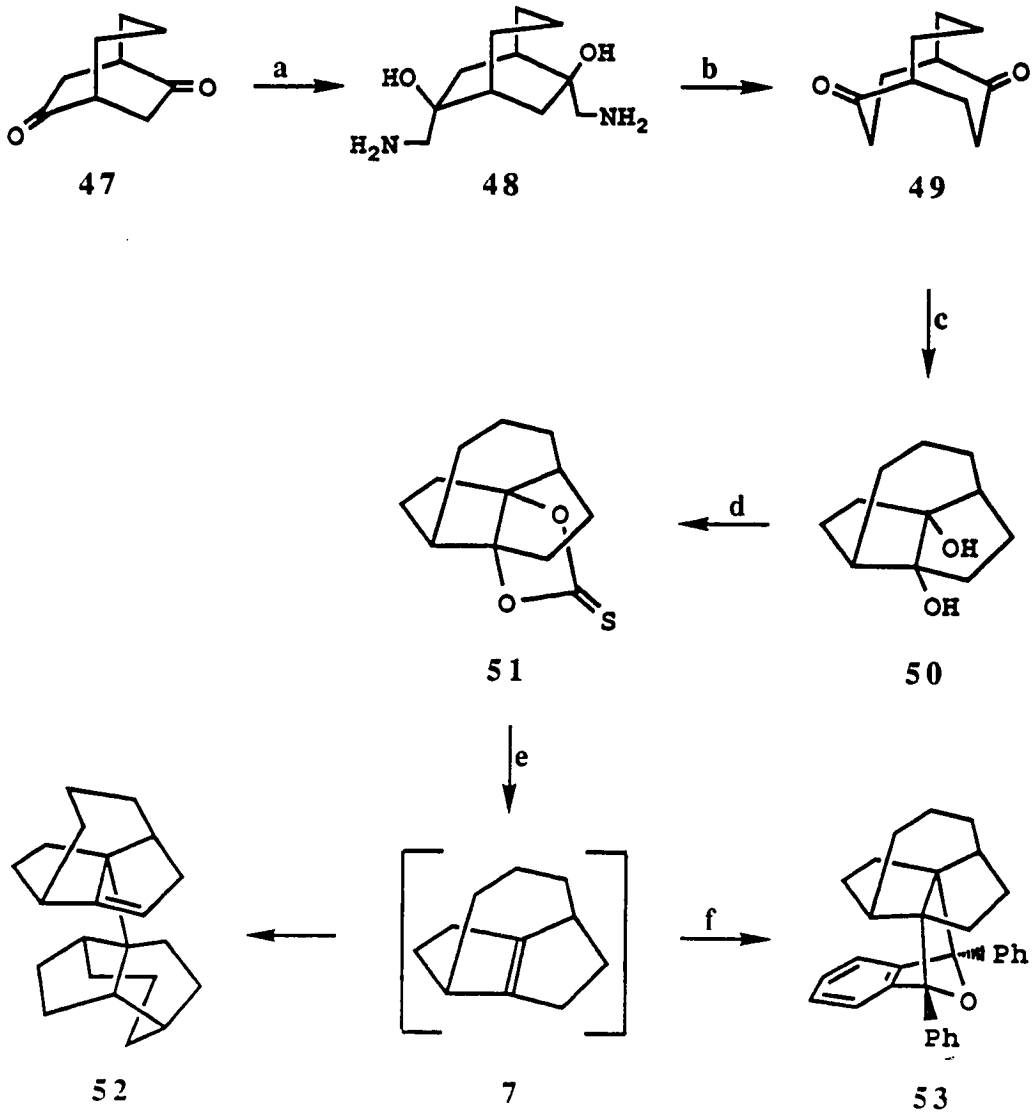


Figure IC.11 Synthesis and Chemistry of Olefin 7. a) 1) $LiCH_2NC$, 2) H_3O^+. b) HONO. c) Zn/Hg, H_3O^+. d) 1) n-BuLi, 2) thiocarbonyl-diimidazole. e) $P(OEt)_3$, Δ. f) DPIBF.

For reasons discussed in the first section of the next chapter, the synthesis of **1a** has, in the years since this first unsuccessful attempt,[10] acquired increasing importance. This provided the motivation for again attempting the synthesis of **1a**. Two more unsuccessful attempts are described briefly in the second and third sections of Chapter II, and the successful preparation of olefin **1a** is described in the first section of Chapter III.

II. Unsuccessful Attempts to Synthesize Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene

A. Motivation for the Synthesis of Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene

Although some spectral data have been obtained for matrix isolated samples of **1b**[14] and **1c**,[19] these highly pyramidalized olefins are so reactive that on thawing the argon matrices, the olefins dimerize. The high reactivity of these alkenes has precluded some very important experimental studies of them. For example, although their geometries have been calculated,[3] there is no experimental information regarding how pyramidalized these alkenes actually are.

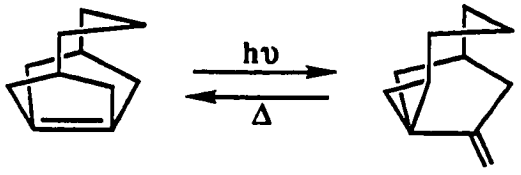
Because the OSE calculated for **1a** is much smaller than that computed for **1b** or **1c** (see Table IB.1), it is conceivable that **1a** would be stable enough to be isolated at room temprerature, thus allowing a thorough study of its structure, spectroscopy, and chemistry. A structure determination would be of particular importance, since it would permit a direct comparison between the calculated and the observed pyramidalization angles and C-C double bond lengths in **1a**. If close agreement were found, one could be more confident that the calculated structures of the more highly pyramidalized members of this homologous series (e.g. **1b** and **1c**) are also correct.

Previous attempts to obtain crystals of the 10-selena derivative (**5a**) of **1a**, suitable for an X-ray analysis, were unsuccessful.[8] Reaction of **5a** with methyl triflate gave the methylselenonium triflate salt (**5b**) of **5a**, which did form crystals suitable for an X-ray structural analysis. As noted in Chapter I, a C-C double bond length of 1.338 Å and pyramidalization angles of 12.3° and 20.3° were found. The smaller angle was for the carbon syn to the Se bridge.

Calculations at the RHF/3-21G level predict **1a** to have a C-C double bond length of 1.320 Å and nearly identical pyramidalization angles of 25.0° and 25.2°.[3] At the GVB/3-21G level, which allows for correlation of the pair of electrons in the "π" bond, calculations predict **1a** to have a C-C double bond length of 1.344 Å and pyramidalization angles of 28.7° and 29.2°.[4] At either level, the predicted size of the two pyramidalization angles in **1a** is much larger and the difference between them much smaller than that found experimentally in **5b**. These results indicate that the long carbon-selenium bonds and positively charged selenium in **5b**[3] cause it not to be a very good model for olefin **1a**. The best model for **1a** would obviously be **1a** itself.

If **1a** proved isolable, another computational prediction could be tested. MP2/6-31G*//RHF/3-21G calculations[22] predict **1a** to be approximately 6 kcal/mol more stable than its retrograde vinylcyclopropane rearrangement product (**54**), which is shown in Figure IIA.1. If **1a** were, in fact, isolable and found to be resistant to thermal isomerization to **54**, an interesting experiment would be to photolyze **1a**. Based on analogy with the photochemistry of **1b**[16] and **1c**,[19] photolysis of **1a** should lead to **54**. The photoproduct (**54**) could then be pyrolyzed in order to test the prediction that it should revert to the thermodynamically more stable **1a**.

As discussed in Chapter I, calculations also predict that, upon pyramidalization of the carbons forming the double bond, the increase in the energy of the HOMO is much less than the size of the decrease in the energy of the LUMO. If isolable, **1a** would allow this prediction to be tested by measuring its photoelectron (PE) and electron transmission (ET) spectra.



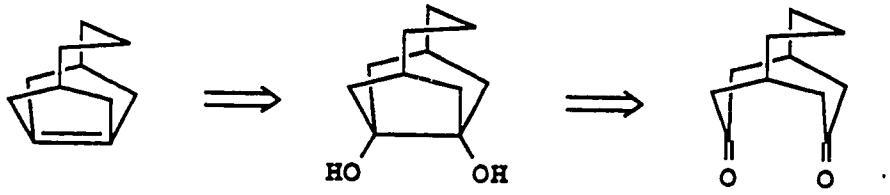
1a **54**

Figure IIA.1 Interconversion Between Olefin 1a and Its Vinylcyclopropane Isomer 54.

Thus, although **1a** is predicted to be less highly pyramidalized than **1b-d**, there are a number of different reasons why its successful synthesis would be important to the studies of this homologous series of pyramidalized alkenes. The importance of **1a** motivated the attempts to synthesize this pyramidalized alkene that are described in this and the succeeding chapter.

B. Attempts to Synthesize Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene by Routes Involving Ring Expansion Reactions

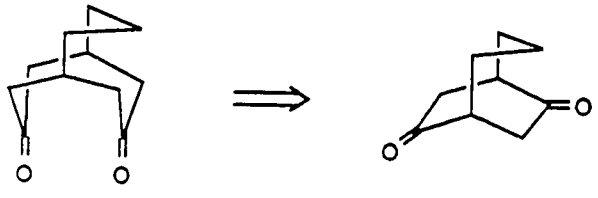
As discussed in Chapter I, one possible synthetic route to the n=3 olefin (**1a**) would be transannular reductive ring closure of diketone **4a**, followed by transformation of the resulting diol (**3a**) to the desired olefin (**1a**). Also as discussed in section IC, one



1a 3a 4a

Figure IIB.1 **Diketone 4a as a Possible Precursor of Olefin 1a.**

way of obtaining diketone **4a** would be a double ring expansion of diketone **47**.



4a 47

Figure IIB.2 Diketone 47 as a Possible Precursor of Diketone 4a.

A number of attempts to form the bisamino alcohol **48** from diketone **47** using diazomethane, hydrogen cyanide, and nitromethane were unsuccessful.[10] Although **48** was obtained by forming the diepoxide with either dimethylsulfonium or dimethylsulfoxonium methylide, followed by ring opening with ammonia, reaction with isocyanomethyllithium, followed by hydrolysis proved to be superior.[10] Subsequently, it was found that reaction of diketone **47** with trimethylsilyl cyanide, followed by fluorodesilylation, also proved effective in generating **48**. Unfortunately, as shown in Figure IIB.3, Tiffeneau-Demjanov reaction of **48** gave, instead of **4a**, **49**, the product of migration of the two methylene, rather than the two bridgehead, carbons.

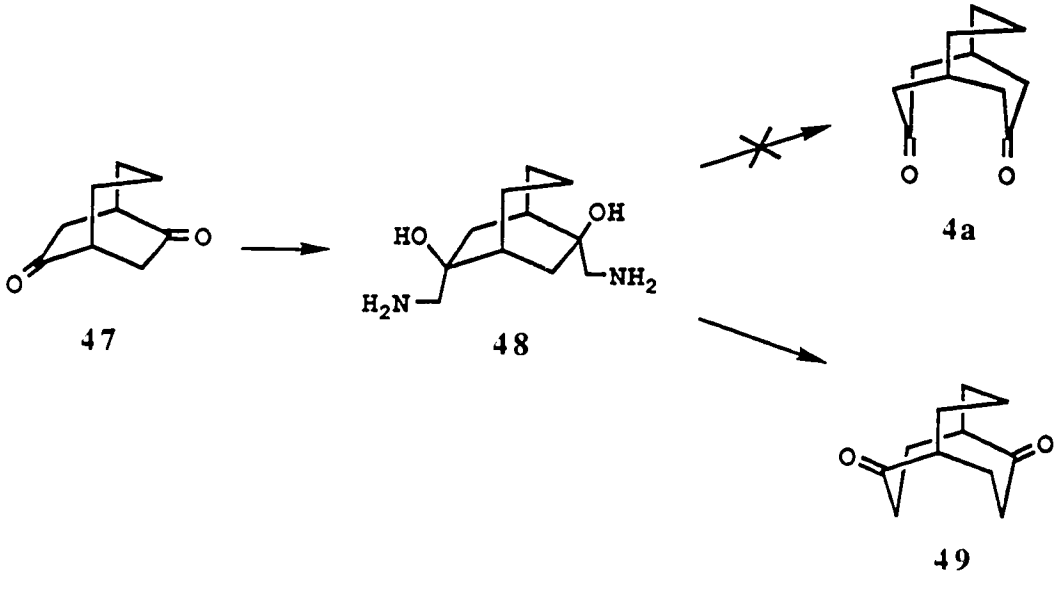


Figure IIB.3 Tiffeneau-Demjanov Ring Expansion of Diketone 47.

Knapp and coworkers found that bridgehead carbon migration can be effected in the ring expansion of norbornanone (**55**), as well as in a number of other ketones, by a tetrakis(acetonitrile)copper(I) tetrafluoroborate catalyzed reaction of the corresponding tris(methylthio)methyl carbinol (**56**) to the corresponding dithioketal (**57**).[23a] As shown in Figure IIB.4, the carbinol (**56**) was formed by reaction of **55** with tris(methylthio)-methyllithium. Following ring expansion, subsequent dissolved metal reduction of the resulting dithioketal (**57**) gave the ring expanded ketone, bicyclo[3.2.1]octan-3-one (**58**).

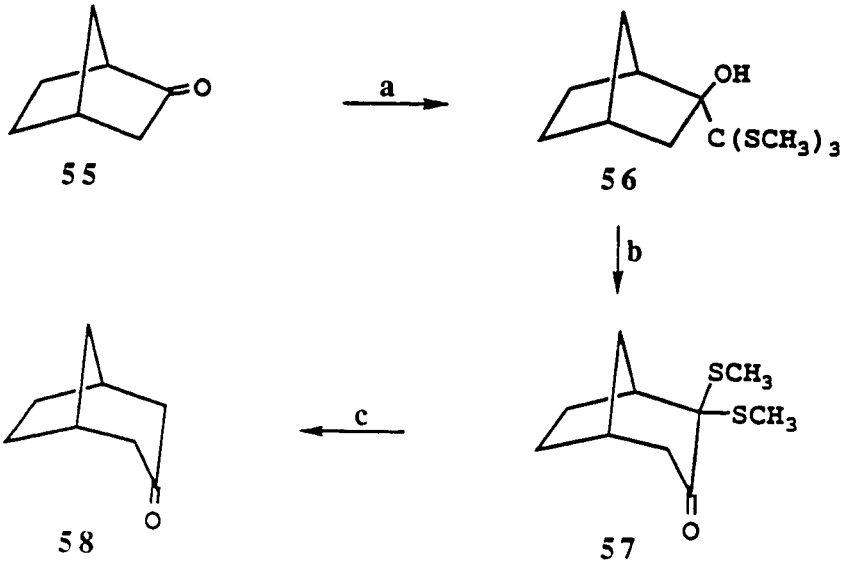
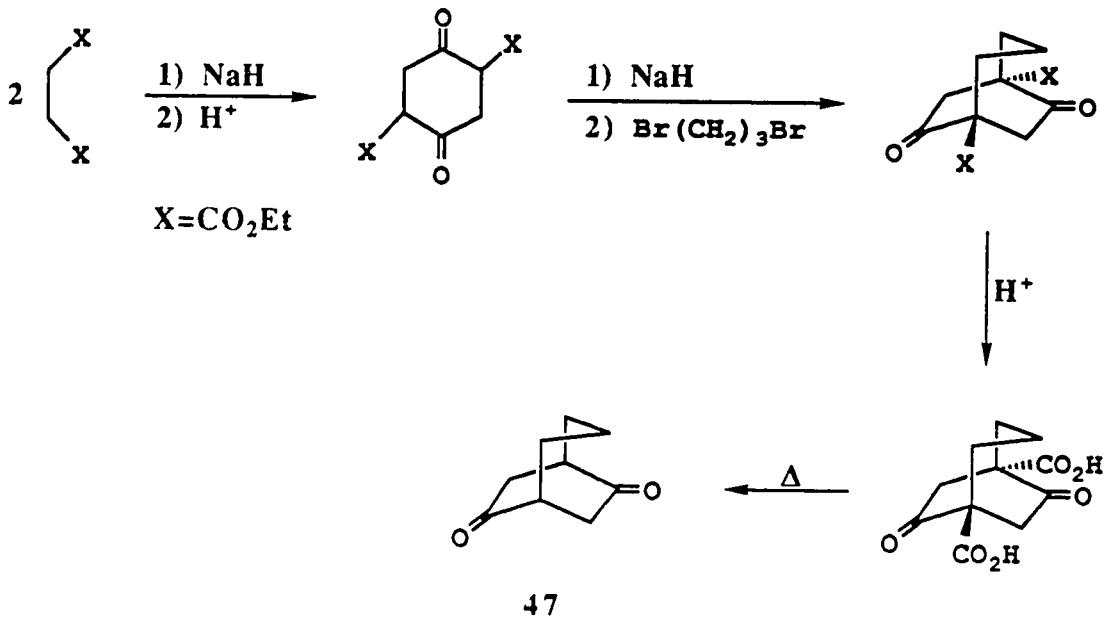


Figure IIB.4 Ring Expansion of Norbornanone (55) using Tris(methylthio)methane and Tetrakis(acetonitrile)copper(I) Tetrafluoroborate. a) 1) $LiC(CH_3)_3$, 2) H^+. b) 1) n-BuLi, 2) $CuBF_4 \cdot 4CH_3CN$. c) Zn, HOAc.

This method appears attractive because of its high regioselectivity and because enolate formation does not seriously interfere with the initial addition reaction. Therefore, we attempted to apply it to the ring expansion of **47** to **4a**.

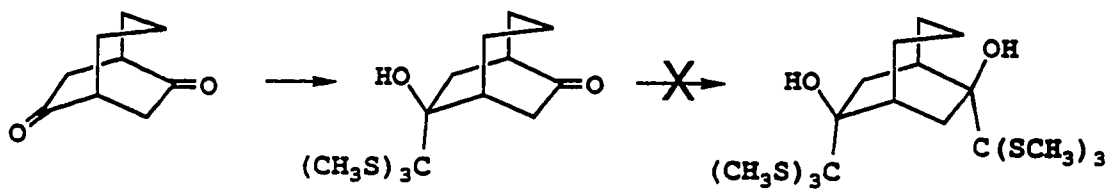
Diketone **47**,[21] was prepared in four steps, starting from commercially available diethyl succinate, by the route shown in Figure IIB.5.



47

Figure IIB.5 Synthesis of Diketone 47.

We discovered that tris(methylthio)methyllithium readily adds to diketone **47**; but unfortunately, only the monoadduct (**59**) was detected, even when the reaction was carried out with a large excess of tris(methylthio)methyllithium.



47 **59** **60**

Figure IIB.6 Reaction of Diketone 47 with Tris(methylthio)methyllithium.

One possible reason that addition to both carbonyls is not observed is that the energy barrier for addition of tris(methylthio)methyllithium to the monoadduct (**59**) is significantly greater than the energy barrier for addition of tris(methylthio)methyllithium to diketone **47**. Presumably, initial addition occurs from the bottom face of one of the carbonyl groups, since the approach of a bulky nucleophile like tris(methylthio)-methyllithium is very likely to be sensitive to steric effects; and the bottom faces of the carbonyl groups of diketone **47** appear to be less sterically hindered than the top faces. After one mole of tris(methylthio)methyllithium adds to one carbonyl group, there are likely to be significant increases in van der Waals repulsions between the trimethylene bridge and the encroaching alkoxy group, as indicated in **59'** in Figure IIB.7. Conformation **59''** is, therefore, probably favored, so that addition of tris(methylthio)-

methyllithium to **47** actually occurs at the carbonyl that is anti to the trimethylene bridge to form **59''**, rather than **59'**. However, addition of tris(methylthio)methyllithium to **59''** must necessarily occur at the syn carbonyl; and this reaction may have a larger energy barrier than that for addition to the anti carbonyl group in **47**.

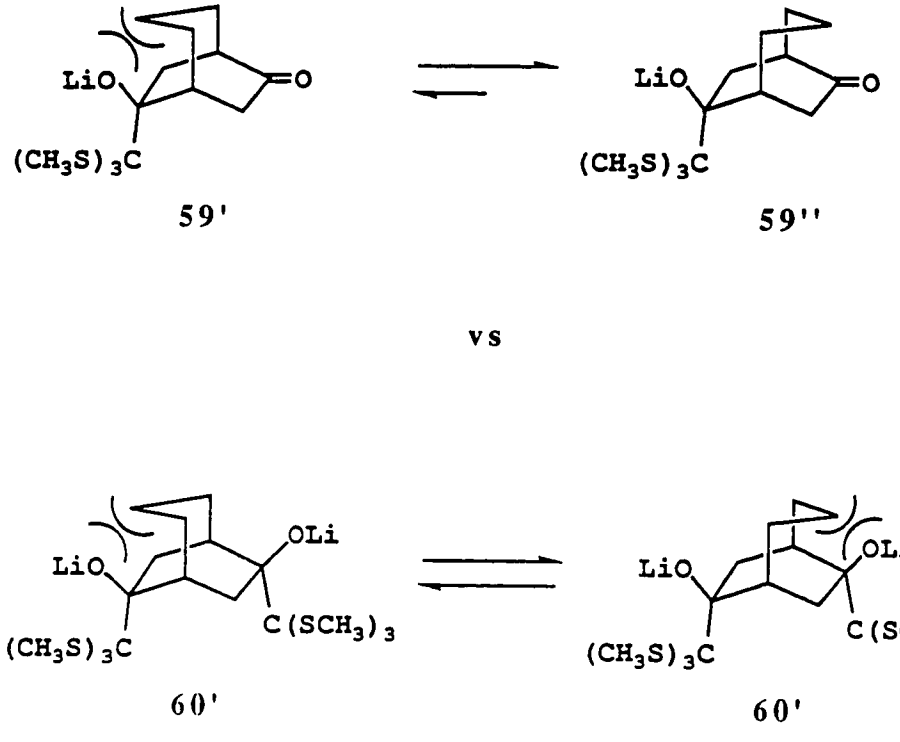


Figure IIB.7 Conformational Equilibria Between Monoadduct Conformers 59' and 59'' and Between the Two Equivalent Conformers of Diadduct 60.

Moreover, whereas the monoadduct (**59**) can avoid steric compression between the trimethylene bridge and the alkoxy group by adopting conformation **59''**, the diadduct (**60**) can not avoid this van der Waals interaction.Thus, even if addition of tris(methylthio)-methyllithium to both carbonyl groups is kinetically accessible, perhaps the addition to the monoadduct (**59**) is reversible; and any **60** that does form simply equilibrates back to tris(methylthio)methyllithium and **59**.

C. Attempts to Synthesize Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene by Routes Involving Ring Closure Reactions

Rather than continuing to pursue ring expansion of **47** to diketone **4a** via **60**, we instead investigated a route to diol **3a** that utilized the ring-closure approach, developed to synthesize the selenium-bridged n=3 olefin, **5a**.[8] However, instead of using a selenide nucleophile to displace both iodines in **41**, in order to prepare **5a**, we needed to use a nucleophilic carbon. We envisioned that in a first reaction, an equivalent of a doubly activated carbanion, $X_2HC:^-$, would be added to the diiodide **41** to form **61**. Subsequently, the monoalkylation product (**61**) would be deprotonated in dilute solution to induce ring closure. The two activating groups would then be replaced with hydrogens and the acetonide protecting group removed to give diol **3a**.

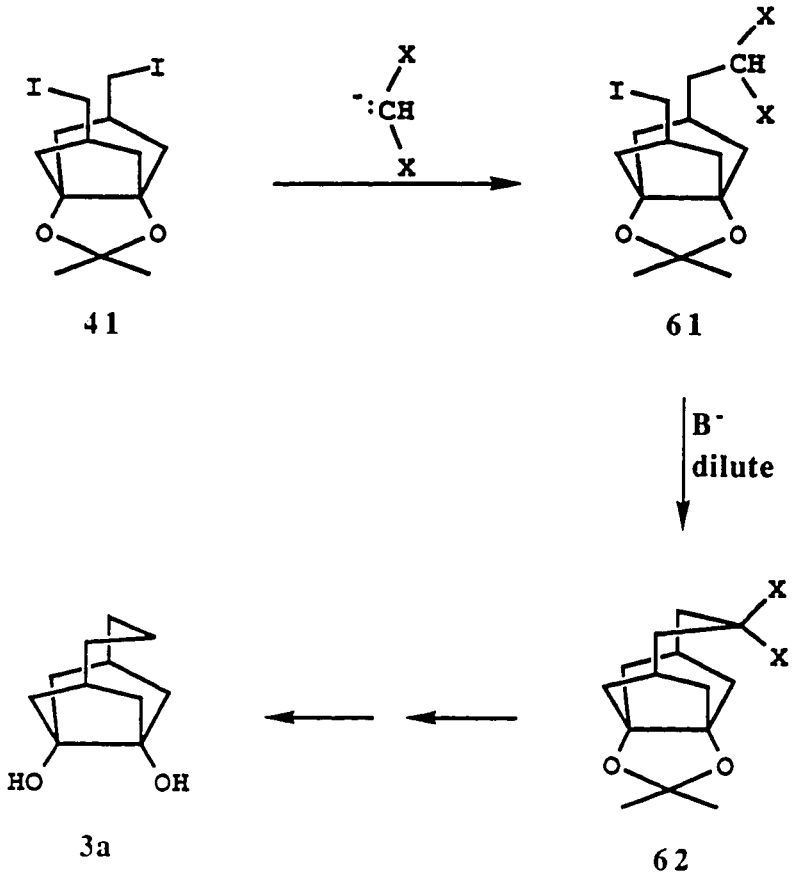


Figure IIB.8 Proposed Synthesis of 3a by Monoalkylation of Diiodide 41 and Ring Closure with a Doubly Activated Nucleophile.

Corey and Seebach have shown that, starting with a dihalide, dithiane can be used to effect this type of ring formation in reasonable yields.[24] The dithioketal moiety in the cyclized product can then be converted into a methylene group via hydrogenation over

Raney nickel.[25] Therefore, we investigated reaction with dithiane and subsequent ring closure as a possible route for transforming diiodide **41** to diol **3a**.

Diiodide **41**[8] was prepared by way of an eight-step synthesis, shown in Figure IIB.9, starting from phthalic dicarboxaldehyde and dimethyl 1,3-acetonedicarboxylate.

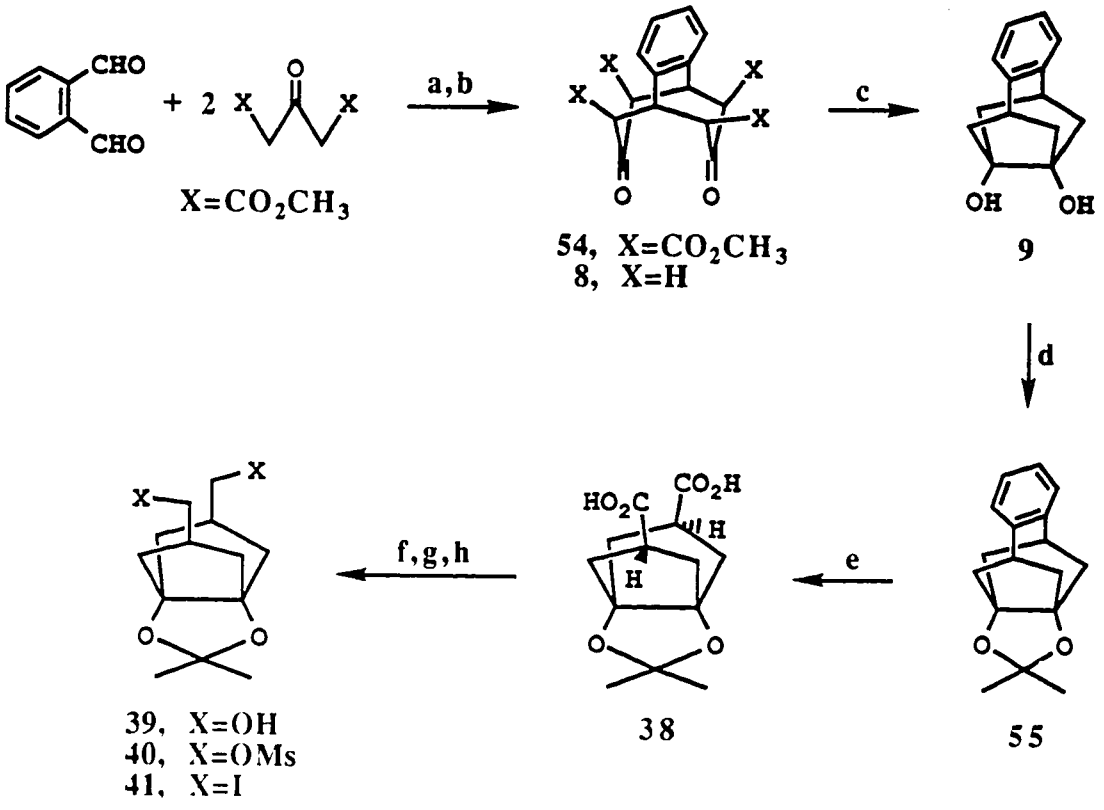


Figure IIB.9 Synthesis of Diiodide 41. a) piperidine. b) HOAc, HCl, Δ. c) Zn/Hg, H_3O^+, CH_3OH. d) acetone, H^+. e) RuO_4. f) LAH. g) MsCl, Et_3N. h) NaI.

A solution of the lithium salt of 1,3-dithiane was prepared by treatment of 1,3-dithiane in THF at -20° with n-butyllithium. Slow addition of 1.0 equivalent of the dithiane anion solution to a solution of diiodide **41** in THF gave a mixture containing the desired monoalkylation product **65**, as well as some dialkylation product **66** and unreacted diiodide **41**. The monoadduct (**65**) could be separated from **41** and **66** by flash chromatography on silica, using ethyl acetate:hexane (1:8) as the eluent; and **65** was isolated in 38% yield.

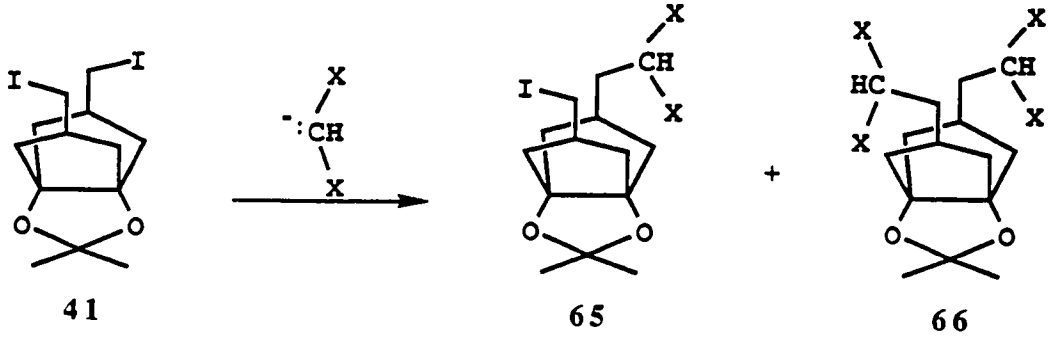
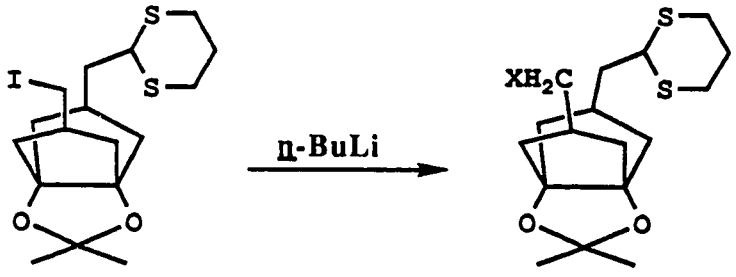


Figure IIB.10 **Reaction of Diiodide 41 with Dithiane Anion.**

Unfortunately, when a dilute solution of iododithiane **65** in THF was treated with 1.1 equivalents of n-butyllithium, instead of ring closure, transmetallation to form **67** apparently occured; for on addition of water, **68** was isolated. Product mixtures were quite clean, generally consisting of only **68** (25-40% by GC) and unreacted iododithiane **65**.



65

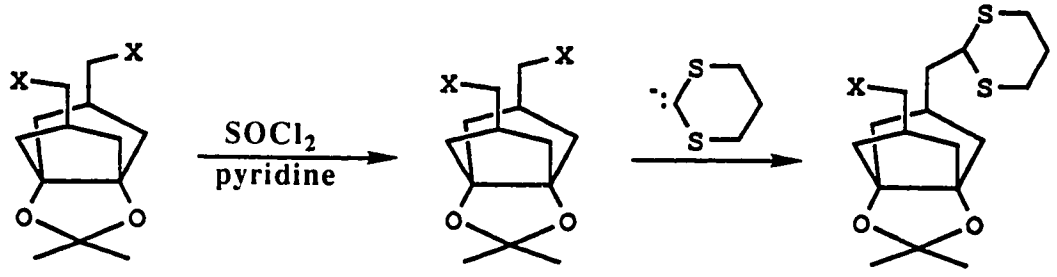
67, X=Li
68, X=H

Figure IIB.11 **Reaction of Iododithiane 65 with n-BuLi.**

Since n-butyllithium was apparently too nucleophilic, we looked for a base that would not transmetallate **65** but would still be strong enough to deprotonate the dithiane moiety in it. To this end, lithium diisopropylamine (LDA) was generated by treating a solution of diisopropylamine in THF with n-butyllithium. 1.05 equivalents of LDA were added to a dilute solution of **65** in THF. Aliquots were quenched with D_2O after 3 and 6 hours of reaction time. Both aliquots consisted of only recovered starting material, the NMR spectrum of which showed no evidence of deuterium incorporation. Thus, under these conditions, LDA does not appear to deprotonate **65**.

We thought that substituting a leaving group, less good than iodide, in compound **65** might alter the reactivity with n-butyllithium such that deprotonation would occur faster

than transmetallation. For example, Corey and Seebach have successfully ring closed dichlorides using 1,3-dithiane.[24] We found the diol precursor (**39**) of diiodide (**41**)[8] was easily converted to dichloride **69** in 70% yield, using thionyl chloride and pyridine. However, reaction of dithiane anion with **69** gave monoalkylation product **70** in only 1-2% yield. Chloride appears to be too poor a leaving group for the S_N2 reaction of **69** to occur at a reasonable rate.



39, X=OH **69, X=Cl** **70, X=Cl**

Figure IIB.12 Preparation of Dichloride 69 and Its Reaction with Dithiane Anion.

Seebach, Willert, Beck, and Grobel[26,27] have shown that not only can trans-metallation of tin be used to generate dithiane anion, but subsequent cyclization reactions can be made to ensue. Seebach et al. generated 2,2-bis(tributylstannyl)-1,3-dithiane, (**71**), by first adding one equivalent of n-butyllithium to 1,3-dithiane, followed by addition of one equivalent of tri-n-butylstannylchloride. To this reaction mixture they added one

equivalent of LDA, followed by addition of another equivalent of tri-n-butylstannylchloride to form 2,2-bis(tributylstannyl)-1,3-dithiane, (**71**). One equivalent of n-butyllithium was then added to **71** to generate the 2-(tributylstannyl)-1,3-dithiane anion, which displaced bromide when added to **72**. Transmetallation of **73** by n-butyllithium resulted in epoxide opening and formation of the six-membered ring in **74**.

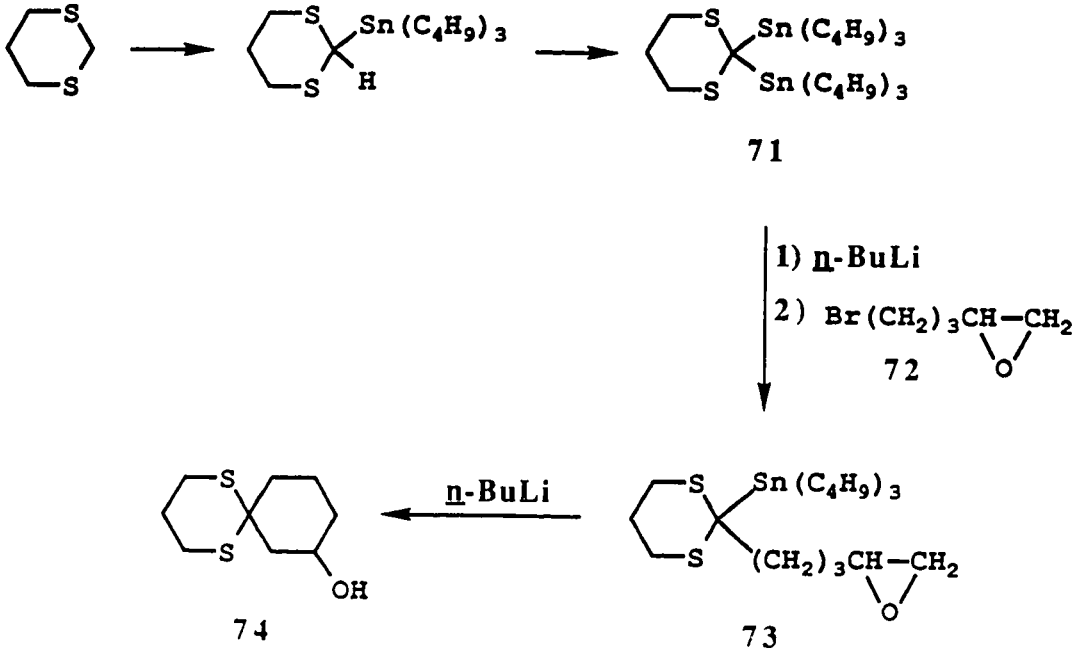
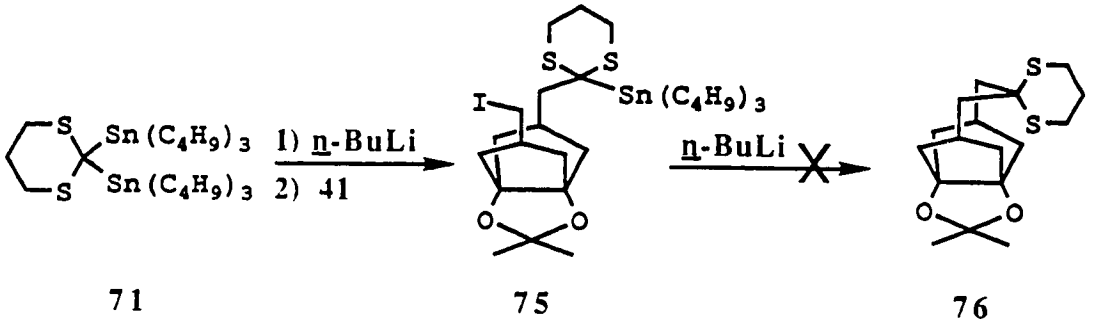


Figure IIB.13 Preparation of and Ring Formation Using 2,2-Bis(tributylstannyl)-1,3-dithiane (71).[26,27]

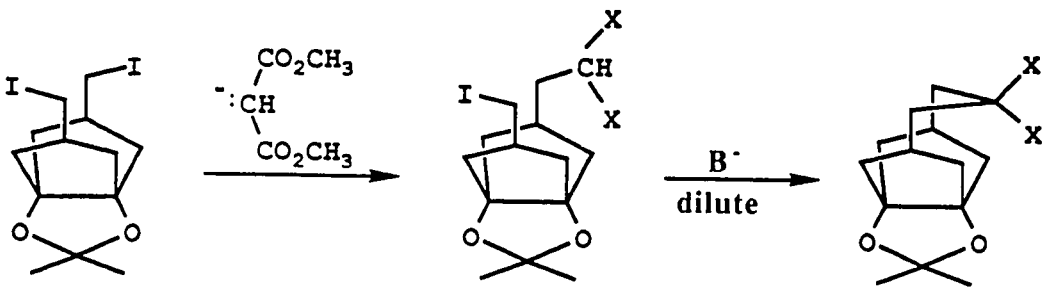
For use as a possible reagent in the preparation of **76**, 2,2-bis(tributylstannyl)-1,3-dithiane (**71**) was synthesized as described above and purified using flash chromatography. A solution of 2-(tributylstannyl)-1,3-dithiane anion was generated by adding 1.1 equivalents n-butyllithium to a solution of **71** in THF under nitrogen at -78°. Addition of this solution to a solution of diiodide **41** in THF, gave monoalkylation product **75**, which was purified using both flash and preparative thick layer chromatography. Better yields (≈30%) of monoalkylation product **75** were obtained when diiodide **41** was added to the solution of 2-(tributylstannyl)-1,3-dithiane anion, as compared to slow addition of 2-(tributylstannyl)-1,3-dithiane anion to diiodide **41**. Unfortunately, analysis of product mixtures, resulting from treatment of monoalkylation product **75** with n-butyllithium, showed no evidence that ring closure had taken place to form **76**. Instead, complex mixtures were obtained.



71 75 76

Figure IIB.14 Attempted Ring Closure of Diiodide 41, Utilizing Some Tin/Dithiane Chemistry.

Because attempts to effect ring closure of **65** or **75**, using a thianyl anion as a nucleophile had been unsuccessful, we decided to try a different nucleophile. A malonate ester anion[28] seemed to be a good candidate for a number of reasons. Malonate esters are acidic enough to be deprotonated by bases much weaker than n-butyllithium, thus avoiding the problem of transmetallation that was encountered when n-butyllithium was allowed to react with iododithiane **65**. After cyclization, the ring-closed product (**78**) could then be converted to the acetonide (**79**) of **3a**, using conventional methods for functional group removal. For example, hydrolysis of **78** at elevated temperatures should lead to decarboxylation and give the monoacid, whose decarboxylation, for instance, by the methodology developed by Barton,[29] would afford acetonide **79**.



41 77, X=CO_2CH_3 78, X=CO_2CH_3 79, X=H

Figure IIB.15 Proposed Route from Diiodide 41 to Acetonide 79, Utilizing Dimethyl Malonate Anion.

A solution of sodiomalonic ester was prepared by adding dimethylmalonate to a refluxing solution of sodium methoxide in dry methanol under nitrogen. Refluxing a methanolic solution of diiodide **41** with 1.0 equivalent of sodiomalonic ester for 4 days under nitrogen gave alkylated malonate ester **77** in 28% yield. Some dimalonate **80** was formed too, and unreacted diiodide **41** was also present in the reaction mixture.

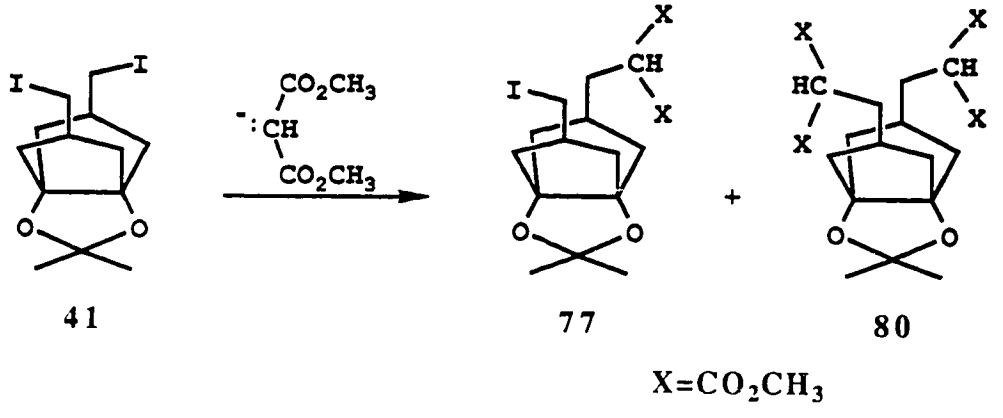


Figure IIB.16 **Reaction of Diiodide 41 with Dimethyl Malonate Anion.**

A dilute solution of iodomalonate **77** in methanol was refluxed for 3 days under nitrogen in the presence of 1.1 equivalents of sodium methoxide. Analysis of the product mixture showed the presence of mostly unreacted starting material **77**. As shown in Figure IIB.17, small amounts of substitution (**81**) and elimination (**82**) products were formed; but there was no evidence of formation of the desired, ring-closed product **78**.

It is possibile that methoxide is not strong enough a base to deprotonate enough iodomalonate **77** at equilibrium to allow ring closure to ensue at a reasonable rate. Therefore, we decided to use a much stronger base, sodium dimsylate,[30] to deprotonate **77**. A dilute solution of iodomalonate **77** in DMSO was refluxed for 1 day under nitrogen in the presence of 1.1 equivalents of sodium dimsylate, generated by refluxing sodium hydride in dry DMSO. Again, analysis of the product mixture showed the presence of some elimination product **82**, as well as starting material **77**; but there was no evidence of the desired, ring-closed product **78**.

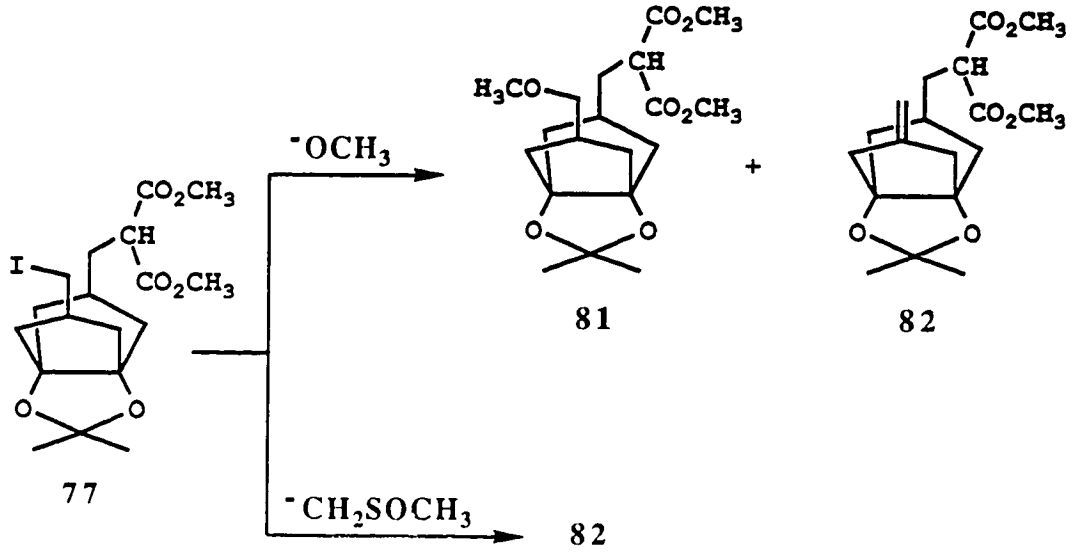
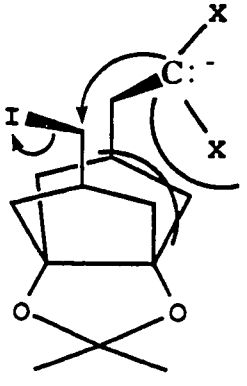


Figure IIB.17 Reactions of Iodomalonate 77 with Methoxide and Dimsylate Anions.

One possible explaination for our failure to observe ring closure in either the iodomalonate (**77**) or iododithiane (**65**) is that the nucleophile is too bulky. As depicted schematically in Figure IIB.18, models suggest that steric interactions between the nucleophilic moiety in the anions formed from both **65** and **77** and the five-membered ring to which the nucleophile is attached could be preventing these anions (**61**) from attaining the stereoelectronic orientation that is required for the desired transannular S_N2 reaction to take place.



61a, X-X=S-$(CH_2)_3$-S
b, X=CO_2CH_3

Figure IIB.18 Representation of Steric Congestion Within the Anions (61), Formed From Monoalkylation Products 65 and 77, Preventing Ring Closure.

However, in iododithiane **65**, we realized that we were one transformation away from a molecule that offered a mode of ring closure that should be free of these stereo-electronic difficulties. Hydrolysis of the dithiane moiety in **65** would yield iodoaldehyde **83**. Ring closure in **83** would involve transforming the CH_2I group into a nucleophilic carbon which would add to the aldehyde carbonyl group, to afford the alcohol **84**, which could be converted to acetonide **79** by a number of methods.

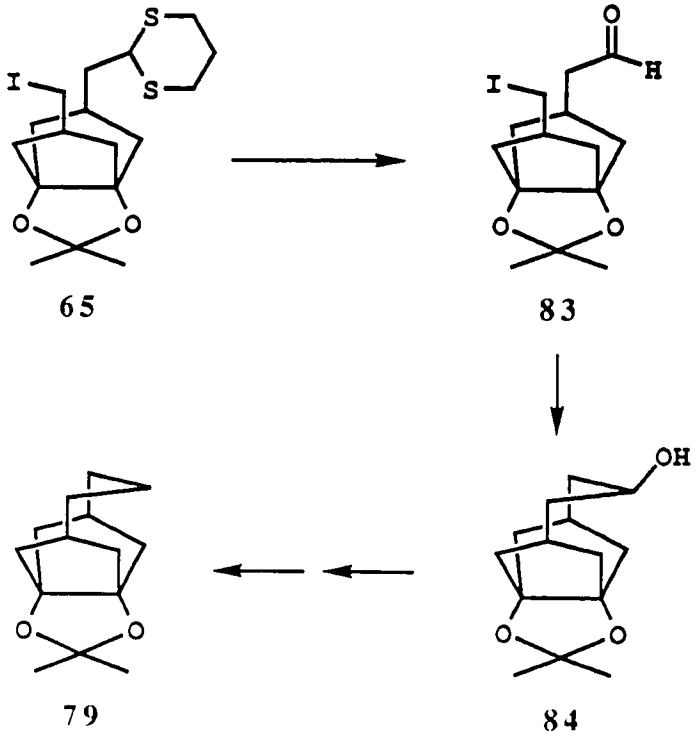
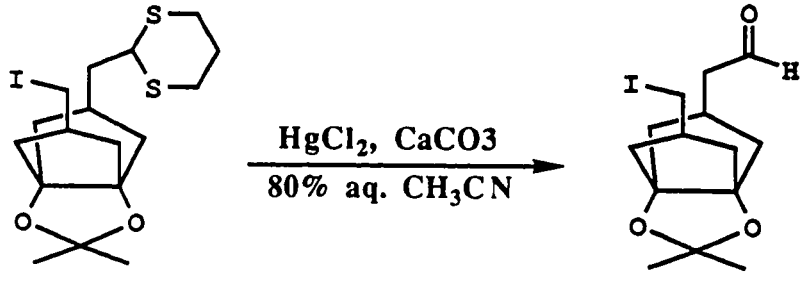


Figure IIB.19 Proposed Formation and Ring Closure of Iodoaldehyde 83.

Iododithiane **65** was hydrolyzed to iodoaldehyde **83**, using four different methods. The first method we tried was that described by Corey and Erickson,[31] which uses a mercuric chloride catalyst. Two other methods, also described by Corey and Erickson, using NBS and NCS, were also assayed. The fourth method we tried, described by Stork and Zhao,[32] uses bis-(trifluoroacetoxy)iodobenzene. We found the mercuric chloride method to be by far the best of the four, giving a 48% isolated yield of the iodoaldehyde (**83**). The other three methods gave much poorer yields.



65 **83**

Figure IIB.20 **Conversion of Iododithiane 65 to Iodoaldehyde 83 with Mercuric Chloride and Calcium Carbonate.**

Cooke and Houpis[33] have demonstrated that cycloalkanols can be generated through metal-halogen exchange-initiated cyclization of iodocarbonyl compounds. Although competing reactions, such as the alkyllithium reagent adding to the carbonyl group, were a problem, they were able to find conditions which favored the ring-closure pathway.

Reaction of iodoaldehyde **83** with 1.2 equivalents of n-butyllithium at -78° in THF gave predominantly carbonyl addition product **85**, a small amount of starting material, and a very small amount of the product (**86**) expected from transmetallation, followed by proton capture on work-up. None of the desired ring-closed product **84** was detected. Reaction of iodoaldehyde **83** with 2.2 equivalents of t-butyllithium at -95° in THF gave predominantly starting material, again some **86**, and a small amount of carbonyl addition product **87**. Again, no ring closed product **84** was detected.

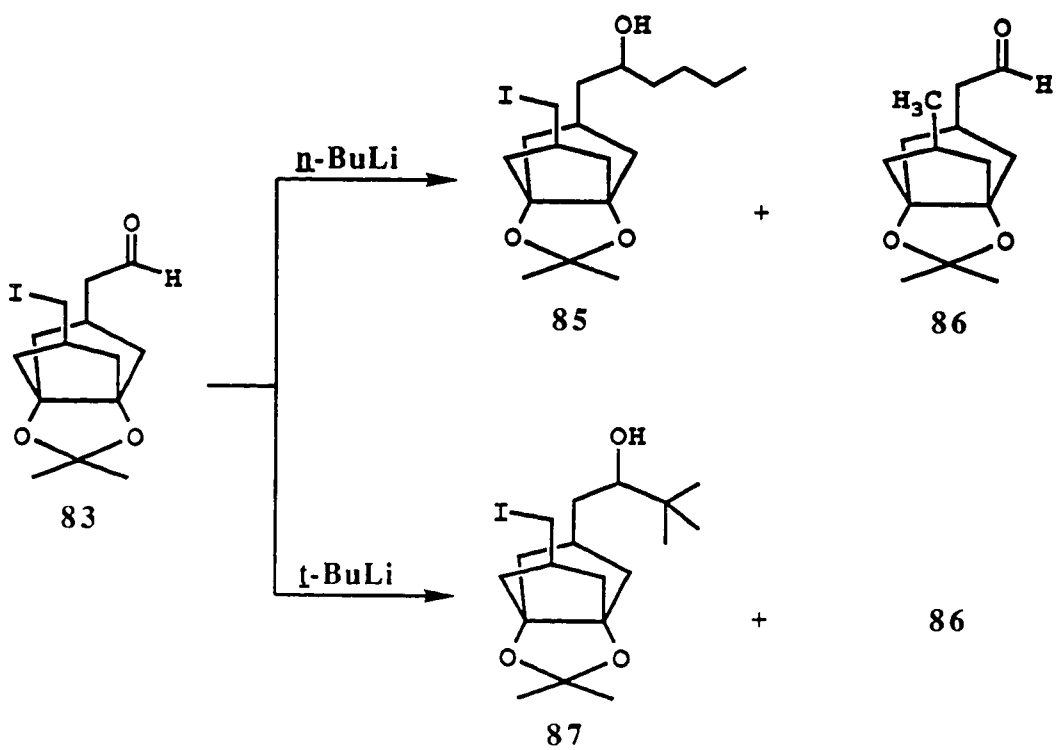
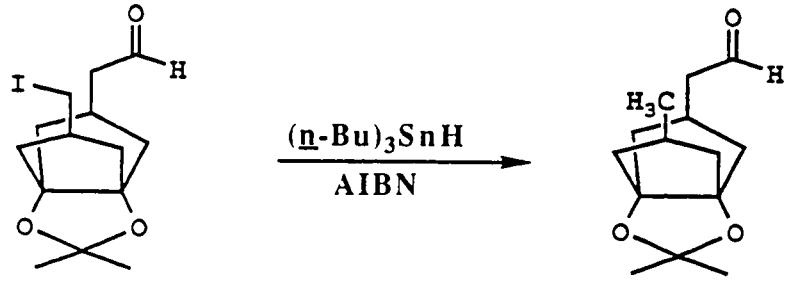


Figure IIB.21 Reactions of Iodoaldehyde 83 with n-BuLi and t-BuLi.

Tsang and Fraser-Reid[34] have demonstrated that cycloalkanols can be generated in good yield via intramolecular addition of carbon radicals to carbonyl groups. Of particular interest was that the examples they reported undergoing cyclization are molecules containing aldehyde and primary iodide moieties. A typical reaction involved refluxing the iodoaldehyde in benzene under argon in the presence of 1.0 equivalent of tri-n-butyltin hydride and a catalytic amount of AIBN. Presumably, the primary radical, formed by loss of iodine to the tri-n-butyltin radical, attacks the aldehyde carbon, thus forming an alkoxy radical, which abstracts hydrogen from tri-n-butyltin hydride to form the cycloalkanol and regenerates the tri-n-butyltin radical.

Unfortunately, reaction of iodoaldehyde **83** under the conditions described by Tsang and Fraser-Reid, gave only reduction product **86** in 66% yield. Once again no evidence was found for formation of the desired, tricyclic alcohol **84**.

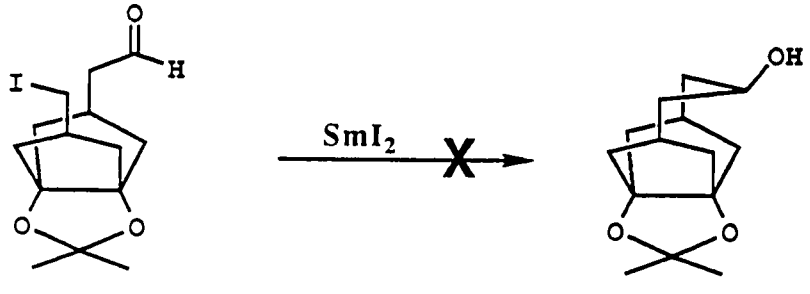


83 86

Figure IIB.22 Reaction of Iodoaldehyde 83 with Tri-n-butyltin Hydride and AIBN.

Molander and Etter[35] have developed a method for cyclizing iodoalkanones in excellent yield utilizing samarium diiodide. Typically, a 2:1 molar mixture of samarium diiodide and substrate iodoketone are stirred in THF at room temperature for an hour in the presence of a catalytic amount of iron(III)tris(dibenzoylmethane). Presumably, samarium diiodide forms a radical at the carbon bearing iodide and reduces the carbonyl group to a ketyl radical anion. The radical and ketyl couple forming an alkoxide anion, which is protonated upon work-up to give the cycloalkanol.

We found that reaction of iodoaldehyde **83**, under the conditions described by Molander and Etter, gave predominantly one product. Although it was clearly not the desired ring-closed product **84**, we were unable to establish unequivocally the identity of this product.



83 84

Figure IIB.23 Reaction of Iodoaldehyde 83 with Samarium Diiodide.

The failure of iodoaldehyde **83** to afford the tricyclic alcohol (**84**) under a variety of reaction conditions is probably attributable to the fact that the ring that we were attempting to close contains eight carbons, not the five or six carbons in the products of successful iodoaldehyde cyclizations. Eight-membered rings are notoriously difficult to close for both entropic and enthalpic reasons.[36] Although the bicyclo[3.3.0]octane ring system in iodoaldehyde **83** reduces the entropic unfavorability by partially restricting some rotations about C-C single bonds in the reactant, the enthalpic unfavorability is not similarly reduced.

III. Synthesis, Spectroscopy, and Chemistry of Tricyclo[3.3.3.$0^{3,7}$]-undec-3(7)-ene

A. Successful Synthesis of Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene

In a purely formal sense, oxidative cleavage of the benzene ring in diol **9**, followed by formation of a bond between a methylene group synthon and each of the two benzenoid carbons that are retained in **38**, provides a route to diol **3a**, a promising precursor of olefin **1a**. However, as described in the previous chapter, all our attempts to prepare **3a** by this type of route, which is shown schematically in Figure IIB.10, were unsuccessful. Our inability to effect formation of the second C-C bond to the methylene group equivalent, which requires closure of an eight-membered ring, caused us to consider other methods for inserting a methylene group between the two carboxylic carbons in **38**.

As shown in Figure IIIA.1, another way to insert a methylene group between these two carbons in **38** would be first to effect ring closure between them and then perform a one-carbon ring expansion. The acyloin condensation[37] is a well-known synthetic method for forming C-C bonds, including those that result in closure of medium-sized rings. The diester that is required for this reaction should be available by reaction of diacid **38**[8] with diazomethane.[38] After reductive removal of the hydroxyl group from the product of the acyloin reaction, the resulting ketone could then be ring expanded.[23b]

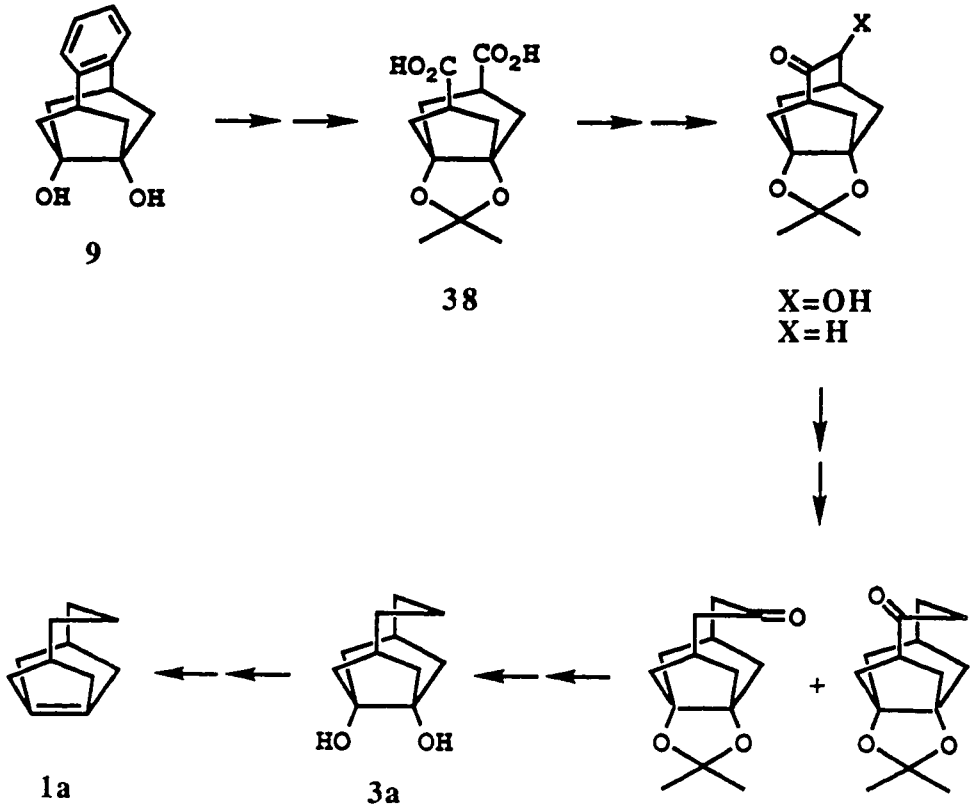


Figure IIIA.1 Strategy for the Synthesis of Olefin 1a by Ring Expansion, Starting from Diol 9.

As in Leonard and Coll's synthesis of bicyclo[3.3.3]undecane (manxane),[39] but unlike the case in the previous attempt to prepare bicyclo[3.3.3]undecane-3,7-dione (**4a**) by ring expansion of bicyclo[3.2.2]nonane-6,8-dione (**47**),[10] the regiochemistry of the ring expansion reaction in Figure IIIA.1 would be unimportant. Whether this reaction favored bridgehead or methylene migration or a mixture of the two, both product ketones should undergo Wolff-Kishner reduction[40] to form the acetonide of diol **3a**. Following removal of the acetonide protecting group, transformation of **3a** to olefin **1a** could then be undertaken.

A 17 step synthesis of tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene (**1a**), based on the route outlined in Figure IIIA.1, was eventually developed. Starting from commercially available phthalic dicarboxaldehyde and dimethyl 1,3-acetonedicarboxylate, the synthesis proceeds in 2-3% overall yield.

The first five reactions which produce **38**, an intermediate in the syntheses of olefins **5a** and **5b**,[8] are shown in Figure IIB.9. Reaction between phthalic dicarboxaldehyde and dimethyl 1,3-acetonedicarboxylate in methanol in the presence of piperidine gave tetramethyl 9,10-benzobicyclo[3.3.2]dec-9(10)-en-3,7-dione-2,4,6,8-tetracarboxylate (**63**)[11] in 81% yield. Hydrolysis and decarboxylation of **63** in refluxing acetic acid and hydrochloric acid afforded a 99% yield of 9,10-benzobicyclo[3.3.2]dec-9(10)-en-3,7-dione (**8**).[11] Transannular reductive ring closure was accomplished by vigorous stirring of **8** and zinc amalgam in methanol, water, and hydrochloric acid to give a 98% yield of 9,10-benzotricyclo[3.3.2.$0^{3,7}$]dec-9(10)-en-3,7-diol (**9**).[7,41] Protection of the vicinal diol moiety of **9** as the acetonide (**64**) was carried out in 84% yield by heating **9** in refluxing acetone in the presence of a catalytic amount of acid.[8] Oxidative cleavage of the benzene ring in **64**, giving bicyclo[3.3.0]octane-3,7-dicarboxylate-1,5-diol acetonide (**38**), was

effected in 53% by vigorously stirring a heterogeneous mixture of **64**, ruthenium dioxide monohydrate, sodium periodate, carbon tetrachloride, acetonitrile, and water over a period of 2-4 days.[8,42] Alternatively, this reaction can be effected via ozonolysis, followed by an oxidative work-up,[43] to afford the diacid in a comparable yield.[44]

The new chemistry, developed for the synthesis of **1a**, is shown in Figure IIIA.2 on page 58 and began with **38**. Methylation of **38** using diazomethane[38] in diethyl ether gave dimethyl bicyclo[3.3.0]octane-3,7-dicarboxylate-1,5-diol acetonide (**88**) as a clear oil and in 96% yield. Diester **88** could be crystallized from either diethyl ether and pentane or ethyl acetate and pentane.

The acyloin reaction to effect ring closure of **88** was carried out by vigorously stirring a heterogeneous mixture of diester **88**, sodium metal, and trimethylsilylchloride in refluxing toluene under argon for 5-6 hours.[45] During the reaction, the appearance of the reaction mixture slowly changed from a translucent light purple to an opaque dark brown color. It was observed that unreacted dimethylester was present in the product mixture if the amount of trimethylsilylchloride used was less than the amount prescribed in the experimental section. A 67% yield of 9,10-bis(trimethylsiloxy)tricyclo[3.3.2.0^{3,7}]dec-9(10)-en-3,7-diol acetonide (**89**) was obtained.

Hydrolysis of the bis-trimethylsilylenol ether to the corresponding α-hydroxy ketone, tricyclo[3.3.2.0^{3,7}]decan-3,7,10-triol-9-one acetonide (**90**), was performed in 84% yield by stirring **89** in refluxing, deoxygenated methanol under argon for 4 days.[37] To facilitate the reductive removal of the hydroxyl group from **90**, it was esterified in 82% yield by stirring in a solution of acetyl chloride and 4-dimethylaminopyridine in methylene chloride for 2 hours. The resulting α-acetoxy ketone, 10-ethanoyloxytricyclo[3.3.2.0^{3,7}]-

decane-3,7-diol-9-one acetonide (**91**), was reduced by stirring a solution of **91**, samarium diiodide,[46] and methanol in THF under argon for 1 hour to give a 91% yield of tricyclo-[3.3.2.$0^{3,7}$]decan-3,7-diol-9-one acetonide (**92**).

Ring expansion of ketone **92** was carried out by slowly adding ethyl diazoacetate to a stirring solution of **92** and triethyloxonium tetrafluoroborate in methylene chloride under nitrogen.[47,48] A 3:2 mixture of regioisomeric β-keto esters, 9-ethoxycarbonyltricyclo-[3.3.3.$0^{3,7}$]undecane-3,7-diol-10-one acetonide (**93a**) and 10-ethoxycarbonyltricyclo-[3.3.3.$0^{3,7}$]undecane-3,7-diol-9-one acetonide (**93b**), was obtained in 45% yield. Subsequent hydrolysis of β-keto esters **93a** and **93b** to the corresponding β-keto acids (**94a**) and (**94b**) was carried out in 98% yield by stirring the mixture of **93a** and **93b** in 5% aqueous sodium hydroxide at room temperature for 15 hours. Decarboxylation of the β-keto acids was accomplished by heating the mixture of **94a** and **94b** in refluxing dioxane for 8 hours. A 82% yield of a mixture of tricyclo[3.3.3.$0^{3,7}$]undecan-3,7-diol-10-one acetonide (**95a**) and tricyclo[3.3.3.$0^{3,7}$]undecan-3,7-diol-9-one acetonide (**95b**) was obtained. In a separate experiment, a 63% overall yield (based on ketone **92**) of a 1:1 mixture of ketones **95a** and **95b** was obtained by carrying out the three successive reactions -- ring expansion of ketone **92**, hydrolysis of β-keto esters **93a** and **93b**, and decarboxylation of β-keto acids **94a** and **94b** -- and purifying the products (**95a** and **95b**) only after the last step.

Wolff-Kishner reduction of the mixture of regioisomeric ketones (**95a** and **95b**), by heating with sodium hydroxide, and hydrazine monohydrate in refluxing diethylene glycol under nitrogen for 24 hours,[40,49] gave a single product, tricyclo[3.3.3.$0^{3,7}$]-undecane-3,7-diol acetonide (**79**), in 78% yield. Deprotection of **79**, brought about by

stirring it in 20% aqueous acetic acid at 85° for 48 hours, gave a 81% yield of tricyclo-[3.3.3 $0^{3,7}$]undecane-3,7-diol (**3a**).

Of the many methods available for transforming vicinal diols into olefins,[6] dimesylate reduction was chosen for generating **1a** from **3a**, since this method had been used to generate successfully the Se bridged n=3 olefin (**5a**).[8] Dimesylate **96** was prepared via the dilithio salt of **3a**, which was formed by adding 1.5 equivalents of methyllithium to a solution of diol **3a** in THF under nitrogen at 0°. Subsequent addition of 1.1 equivalents of methanesulfonyl chloride gave tricyclo[3.3.3.$0^{3,7}$]undecane-3,7-dimesylate (**96**) in 55% yield.

The generation of **1a** from dimesylate **96** has been carried out using two different methods. The first successful generation of **1a** was effected by sodium naphthalide reduction of **96**.[50] A solution of sodium naphthalide in THF was added to a stirring solution of dimesylate **96** in THF at 0° under argon. Care was taken to dry and deoxygenate the THF by distilling it from sodium/benzophenone ketyl. Despite the fact that two moles of sodium naphthalide should be sufficient to reduce one mole of **96** to **1a**, it was found that only after 3.5-4.0 moles had been added did the dark blue color of sodium naphthalide persist. Work-up was accomplished by quenching the reaction mixture with deoxygenated, aqueous ammonium chloride, followed by extraction with deoxygenated methylene chloride. Evaporation of the solvent afforded approximately a 1:4 mixture of **1a** and naphthalene. A crude separation of **1a** from naphthalene was carried out by flash chromatography. Deoxygenated solvent and an inert atmosphere were used; since, as described in section IIIC, it was found that **1a** reacts rapidly with oxygen.

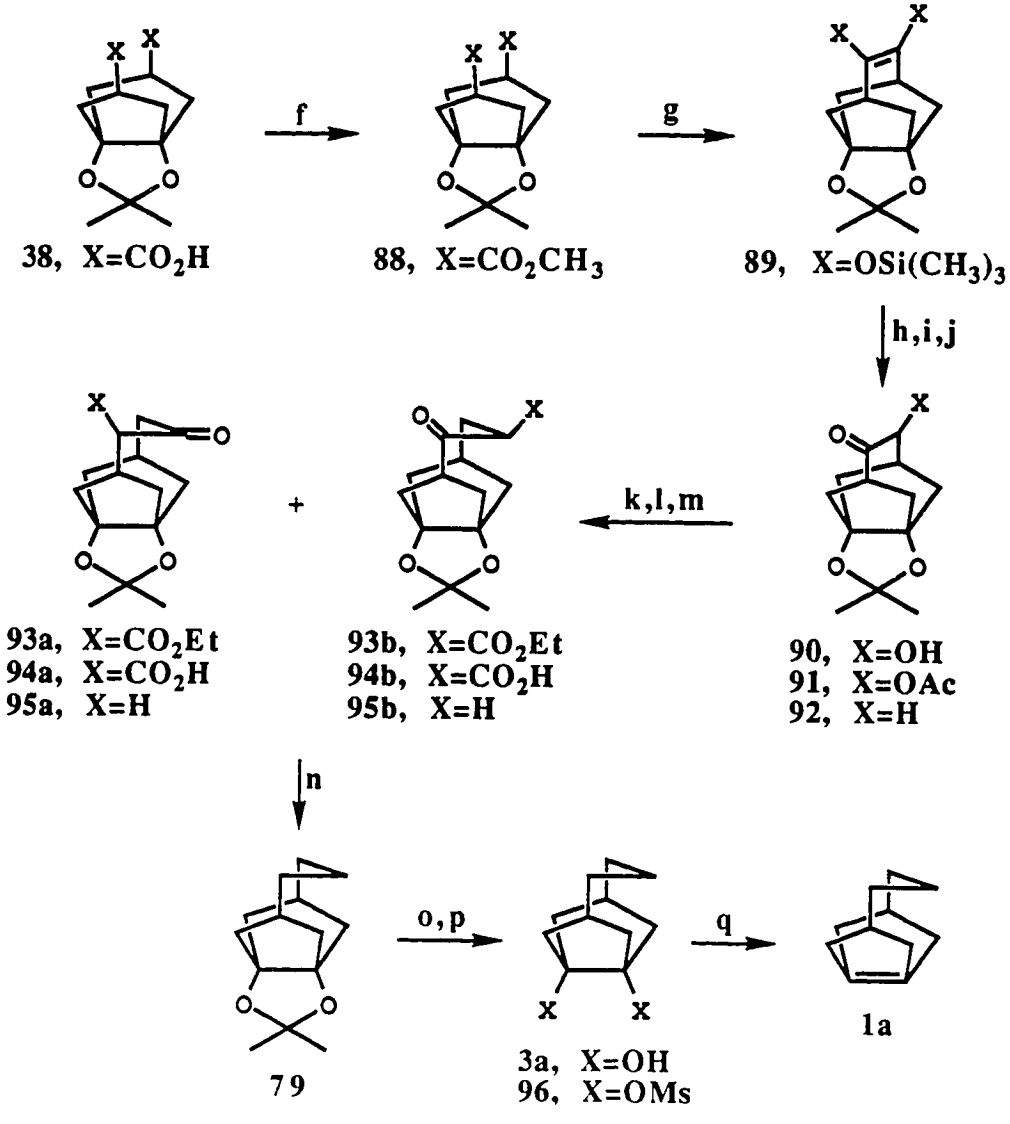


Figure IIIA.2 Synthesis of the n=3 Olefin (1a): f) CH_2N_2, ether, 96%. g) Na, TMSCl, toluene, 67%. h) CH_3OH, 84%. i) acetyl chloride, DMAP, CH_2CL_2, 82%. j) SmI_2, THF, 91%. k) OEt_3BF_4, ethyl diazoacetate, CH_2CL_2, 45%. l) 5% NaOH, 98%. m) Δ, p-dioxane, 82%. n) N_2H_4, NaOH, diethylene glycol, 78%. o) H_3O^+, 81%. p) 1) CH_3Li, THF, 2) MsCl, 55%. q) Na/Hg, ether or Na/naphthalene, THF, 100%.

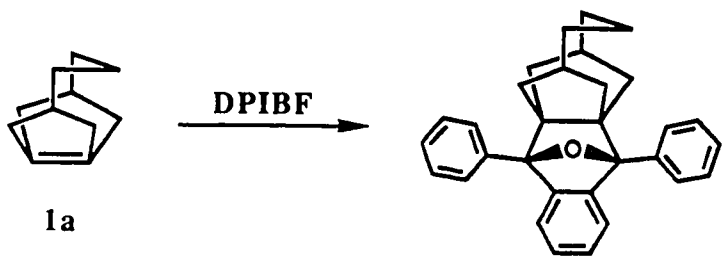
Because sodium naphthalide reduction of **96** results in a mixture of **1a** and naphthalene, from which it is difficult to separate the pure alkene, another method for generating **1a** from dimesylate **96** was sought. It was found that reduction of **96** could be brought about by vigorously stirring a heterogeneous mixture of **96** and 0.4% sodium amalgam in dry, deoxygenated diethyl ether under argon for 20 hours at room temperature. Passage of the liquid phase through a celite bed to remove any residual amalgam afforded a solution of pure **1a** in diethyl ether in what appears to be nearly quantitative yield. The high volatility and reactivity of **1a** toward oxygen precluded us from obtaining a precise yield of isolated product.

When the ether solvent is removed by careful distillation, pure **1a** is obtained as a volatile oil, which has resisted all attempts at recrystallization. As discussed in section IIIC, **1a** is highly reactive toward oxygen, so that **1a** must be stored under an inert atmosphere and only dissolved in deoxygenated solvents.

However, in contrast to olefins **1b** and **1c**, olefin **1a** is stable toward dimerization at room temperature and shows no sign of dimerizing, even upon heating. When a concentrated NMR sample of **1a** in toluene-d_8 and was heated at 100° under argon overnight, the ^1H and ^{13}C NMR spectra of the sample were found to be unchanged. Solutions of **1a** have remained unchanged for months, so long as oxygen is excluded. The stability of **1a** has allowed its spectroscopic characterization, which is described in the next section.

B. Spectroscopic Characterization of Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene and of Its Diels-Alder Adduct with DPIBF

Because of the volatility and reactivity toward oxygen of the n=3 olefin (**1a**), it was initially characterized as the Diels-Alder adduct (**97**) with diphenylisobenzofuran (DPIBF). A dilute, deoxygenated solution of about 25 mg of olefin **1a** and 45 mg of DPIBF in 4 ml methylene chloride was allowed to stir overnight. Subsequent analysis showed the absence of any olefin **1a** and the presence of adduct **97**. Pure **97**, mp 202-203°, was obtained after chromatography and recrystallization from ethanol.



1a

97

Figure IIIB.1 Formation of Diels-Alder Adduct 97 by Reaction of Olefin 1a with Diphenylisobenzofuran (DPIBF).

Spectroscopic and high resolution mass spectrographic analyses were consistent with the adduct being the product (**97**) of a [$_{\pi}4_{s} + _{\pi}2_{s}$] cycloaddition reaction between DPIBF and olefin **1a**. Of particular interest were the ^{1}H NMR and ^{13}C NMR spectra of the adduct. The room temperature ^{13}C NMR spectrum of **97**, taken in $CDCl_3$, is shown on page 109.

The spectrum shows fourteen peaks. Fourteen is two less than the minimum number expected, even if flipping of the three carbon bridge is so fast that **97** has an effective plane of symmetry on the NMR timescale. A clue as to why the room temperature ^{13}C NMR spectrum of **97** is missing two peaks comes from the broadness of the resonance at δ 73. Its breadth suggests that **97** is undergoing a dynamic process which at room temperature results in site exchange at a rate intermediate between the slow and fast exchange limits. Presumably, two more peaks are so broad at room temperature that they cannot be seen, because they are buried in the base line. In fact, it was found that the ^{13}C NMR spectra of **97** do show the expected numbers of peaks, if the spectra are taken at the low or high temperature limits.

At 209 K, the ^{13}C NMR spectrum of **97** (shown on page 110) has thirteen resonances in the aliphatic region (< 100 ppm). This is the number of resonances expected in this region for adduct **97** at the low temperature limit, where trimethylene bridge flipping is sufficiently slow that separate resonances are observed for all the aliphatic carbons. Fourteen resonances are anticipated in the aromatic region at low temperatures, but only eleven are observed. A DEPT 135 ^{13}C NMR experiment, carried out at 254 K, showed that three of the observed aromatic signals are due to quaternary carbon atoms while eight are due to tertiary carbon atoms. Thus, one quaternary and two tertiary carbon resonances

are either missing or unresolved. This result is consistent with the possibility that, because the benzo moiety in the adduct is so far removed in space from the trimethylene bridge, the two non-equivalent quaternary carbon atoms in the benzo moiety appear as one resonance; and the four non-equivalent tertiary carbon atoms appear as two resonances.

At 343 K, the ^{13}C NMR spectrum of **97** (shown on page 111) has nine resonances in the aliphatic region. This is the number of resonances expected for adduct **97** at the high temperatures limit, where fast conformational change in the trimethylene bridge creates effective equivalence on the NMR timescale among carbons which would actually be equivalent only if **97** had a plane of symmetry. However, even at 343 K, the resonances at δ 43 and 46.5 ppm are still quite broad, indicating that the high temperature limit has not quite been reached. Also consistent with adduct **97** having an effective plane of symmetry on the NMR timescale at this temperature is the observation of resonances for just two types of quaternary and five types of tertiary aromatic carbons.

Although not as easy to analyze as the ^{13}C NMR spectra, the ^{1}H NMR spectra of adduct **97** also exhibit the temperature dependence expected for trimethylene bridge flipping. Shown on page 112 is the ^{1}H NMR spectrum at room temperature. The resonances at δ 2.4 and 2.5 are most likely due to the two non-equivalent bridgehead protons, labelled (A) and (B). The rest of the aliphatic region from δ 1.1-2.3 consists of one inordinately broad resonance. We believe this broad band is due to all the aliphatic methylene protons, which have been labelled as (C).

Shown on page 113 is the ^{1}H NMR spectrum of adduct **97** taken at 217 K. The broad peak from δ 1.1-2.3 in the room temperature spectrum has been replaced by sharp, well-resolved resonances. Apart from the resonances at δ 2.4 and 2.5 for two bridgehead

protons, the rest of the signals in the aliphatic region were left unassigned, since no proton decoupling or NOE experiments were carried out. However, the integration, both within and between the aliphatic and aromatic regions, is that required by the structure (**97**) assigned to the adduct.

Shown on page 114 is the ^1H NMR spectrum of adduct **97** taken at 325 K. The number of peaks in this spectrum is consistent with the existence of an effective plane of symmetry in adduct **97**. Not only does the integration work out well; but also the aliphatic region of the high temperature ^1H NMR spectrum of adduct **97** resembles the room temperature ^1H NMR spectrum of acetonide **79** (vida infra), after allowing for the reduction in symmetry from effective C_{2V} in **79** to effective C_S in **97**.

Like its Diels-Alder adduct (**97**) with DPIBF, olefin **1a** is conformationally mobile, as evidenced by the temperature dependence of its ^{13}C and ^1H NMR spectra. The 50 MHz ^{13}C NMR spectrum of olefin **1a**, taken at room temperature in dry, deoxygenated toluene-d_8, is shown on page 115.[51]

The broad signal at δ 156-158 is due to the two olefinic carbon atoms, 3 and 7, which are labelled (a') and (a''). This broad resonance resolves into two sharp resonances, at δ 156.39 and 157.37 at low temperatures and becomes a single sharp resonance at δ 157.28 at high temperatures. The low (240 K) and high (371 K) temperature ^{13}C NMR spectra of olefin **1a** are shown on pages 116 and 117.

In the room temperature spectrum, the broad signal at δ 43 is due to one of the sets of two equivalent methylenic carbon atoms in the two five-membered rings of **1a**, and the broad signal at δ 35.5 is due to the other. These two broad signals coalesce into a single

signal at δ 39.4, still rather broad in the high temperature spectrum at 371 K; and both resonances sharpen at low temperatures.

The results of a DEPT 135 ^{13}C NMR experiment, carried out at 240 K, showed that the signal at δ 54 is due to the tertiary carbon atoms 1 and 5. The resonance at δ 37 has been assigned to carbon atoms 9 and 11, of the trimethylene bridge, and the resonance at δ 25 has been assigned to carbon atom 10. The latter two assignments were based on the signal intensities and chemical shifts of these two resonances.

One piece of information we sought from the ^{13}C NMR spectrum of olefin **1a** was the chemical shift of the olefinic carbon atoms. The chemical shift of the olefinic carbon atoms of the unbridged olefin, (**2**), is reported at δ 146.0;[52] whereas the chemical shift of the olefinic carbon atoms of the selenium bridged n=3 olefin, (**5a**), is δ 150.74.[7] The ^{13}C NMR spectrum of **1a** provides an opportunity to determine whether the downfield shift of these carbons in **5a** is due primarily to pyramidalization of the olefinic carbon atoms or to the presence of selenium in the three-atom bridge.

The average chemical shift of the olefinic carbon atoms of olefin **1a**, obtained from the high temperature spectrum, in which the olefinic carbon atom resonances have coalesced, is δ 157.28. The monotonic change in chemical shift from δ 146.0 to 150.74 to 157.28, as pyramidalization increases in going from **2** to **5a** to **1a**, indicates that increasing pyramidalization results in a downfield shift of the olefinic carbons and that the effect of the Se atom on the chemical shift of these carbons in **5a** is probably not significant.

It should also be noted that the room temperature ^{13}C NMR spectrum of the selenium-bridged n=3 olefin (**5a**), unlike that of **1a**, corresponds to the high temperature limit (i.e. the existence of an effective plane of symmetry) and does not show any obvious

line broadening.[7] This suggests a lower barrier to bridge flipping in **5a** than in **1a**, which can be attributed to the fact that the C-Se bond lengths in **5a** are about 0.4 Å longer than the corresponding two C-C bond lengths in **1a**. Not only is this difference expected to cause less pyramidalization in **5a** than in **1a**, but it also appears to result in a lower barrier to bridge flipping in **5a** than in **1a**.

A room temperature, 500 MHz ^{1}H NMR spectrum of olefin **1a** is shown on page 118. The signals in the room temperature spectrum are too broad to make any more than a few crude assignments of resonances to the hydrogens of olefin **1a**. However, a complete assignment was made possible by ^{1}H NMR experiments carried out at low temperature.

A low temperature ^{1}H NMR spectrum, taken at 246 K, of olefin **1a** is shown on page 119. A series of homonuclear decoupling experiments, carried out at 246 K in toluene-d_8, as well as homonuclear NOE experiments, carried out in $CDCl_3$ at 213 K, allowed complete assignment of all the resonances in the ^{1}H NMR spectrum of **1a**.

Proton decoupling experiments on olefin **1a** in toluene-d_8 at 246 K showed that there is strong coupling, J = 13.6 Hz, between the resonances at δ 2.78 and δ 1.65, which appear as doublets, in the fully coupled spectrum. Also strongly coupled are the signals at δ 2.55 and δ 2.00, which too appear as doublets with J = 13.4 Hz. The broader resonances at δ 2.78 and δ 2.55 are also weakly coupled to the broad singlet at δ 2.57, which is assigned to the bridgehead protons at carbon atoms 1 and 5. Using the dihedral angles obtained from a molecular model of olefin **1a**, and the Karplus relationship, the doublets at δ 2.78 and δ 2.55 are assigned as *exo* protons on the five-membered rings in **1a**, and the doublets at δ 2.00 and δ 1.65 are assigned as the *endo* protons on these rings.

Strong coupling was also observed between the two-proton multiplets at δ 1.15 and δ 1.73, with the later also showing weak coupling to the bridgehead protons. Finally, strong coupling was observed between the one-proton multiplets at δ 1.50 and δ 1.40, with the former also showing strong coupling to the resonance at δ 1.73. From molecular models and the Karplus relationship, it was possible to use this information to assign these resonances to the protons of the trimethylene bridge in the manner shown on the spectrum on page 119.

However, whether the signals at δ 2.78 and δ 1.65 or those at δ 2.55 and δ 2.00 are due to the methylene protons on the five-membered ring that are *syn* to the central carbon of the trimethylene bridge was still unknown. NOE experiments served to resolve this ambiguity and to confirm the assignments made on the basis of the decoupling experiments.

Based on a molecular model of olefin **1a**, the *endo* proton at C-10 of the trimethyene bridge should be close in space to the two *endo* protons on the *syn* carbons of the five-membered rings. Thus, a strong NOE between the multiplet at δ 1.40 and one of the two doublets at δ 2.00 and δ 1.65 should indicate which doublet corresponds to the *endo* protons that are *syn* to the trimethylene bridge.

The spectrum on page 122 shows that irradiation of the doublet at δ 2.00 (δ 2.07 in $CDCl_3$) gives rise to a very strong NOE for the doublet at δ 2.55 (δ 2.49 in $CDCl_3$). This is expected, since these two resonances correspond to protons that are geminal and, hence, close to each other in space. More important, however, is the NOE that appears for the signal at δ 1.40 (δ 1.47 in $CDCl_3$). This NOE provides good evidence that it is the *endo* protons at δ 2.00 that are *syn* to the trimethylene bridge.

Confirmation of this assignment comes from the spectrum on page 123. It shows that irradiation of the doublet at δ 1.65 (δ 1.69 in $CDCl_3$) gives rise to a very strong NOE for the geminal protons at δ 2.78 (δ 2.70 in $CDCl_3$), but, more importantly, no NOE effect is observed for the proton at δ 1.40 (δ 1.47 in $CDCl_3$). Instead, there is a significant NOE observed at δ 1.17 (δ 1.20 in $CDCl_3$), which corresponds to the pair of protons on the trimethylene bridge that are closest in space to the *anti-endo* methylene protons. What looks like a negative NOE at δ 1.73 (δ 1.79 in $CDCl_3$) probably represents spin transfer from the pair of protons at δ 1.17 to the pair of protons on the trimethylene bridge that are geminal to them.

The assignments shown on the low temperature ^1H NMR spectrum on page 119 are also supported by the changes in the ^1H NMR spectra of **1a** as the temperature is raised. Since in the high temperature limit specific sets of protons become equivalent, one can predict how the appearance of the low temperature spectrum should change as temperature increases. The ^1H NMR spectrum of olefin **1a**, taken in toluene-d_8 at 386 K, is shown on page 121.

Protons A' and A", which are split by protons B' and B", respectively, and appear as two doublets at the low temperature limit, become equivalent and appear as one doublet at δ 2.58 at the high temperature limit. Similarly, protons B' and B", which are split by protons A' and A", respectively, and appear as two doublets at low temperatures, also become equivalent and appear as one doublet at δ 1.79 at the high temperature limit. Protons D' and D", as well as protons E' and E", which are all resolved at lower temperatures, appear as one broad singlet at δ 1.45. Protons C remain equivalent

regardless of the rate of trimethylene bridge flipping and thus appear as a broad singlet around δ 2.55 at either temperature limit.

The UV spectrum of olefin **1a** has been obtained in deoxygenated pentane and is shown on page 124. An absorption maximum appears at about 217 nm with $\varepsilon \approx 10^4$.

The existence of a long-wavelength UV absorption in **1a** is not unexpected. The next lower homologue (**1b**) in matrix isolation shows an absorption at 248 nm.[14] As shown in Table IB.1, ab initio calculations predict that on going from **1b** to **1a** the HOMO-LUMO gap should increase by 0.67 eV as the pyramidalization angle decreases from 40.8° to about 25.1°.[3] If the calculated change in the HOMO-LUMO gap on going from **1b** to **1a** is equated to the expected blue shift of the absorption maximum of 245 nm in **1b**, λ_{max} = 215 nm is predicted for **1a**, in excellent agreement with λ_{max} = 217 nm that is found.

Also as shown by the results in Table IB.1, ab initio calculations further predict that increasing pyramidalization lowers the energy of the LUMO much more than it raises the energy of the HOMO. The stability of **1a** toward dimerization has enabled us to confirm this prediction by obtaining the photoelectron (PE) and electron transmission (ET) spectra of **1a** for comparison with those of the unbridged reference alkene (**2**). The spectra were obtained by the research group of Professor Michael Allan at the University of Fribourg on samples of **1a** and **2** that were provided by us.

The PE spectra of **1a** and **2** are shown on page 143. The ionization energy (IE) of **1a** (7.81eV) is lower than that of **2** (8.12 eV) by 0.31 eV. If, using Koopmans' theorem, the difference in IEs is equated to the difference in HOMO energies, the experimental difference in the IEs of 0.31 eV is close to the calculated difference in HOMO energies of 0.25 eV. The PE spectrum of the n=2 olefin (**1b**) is also shown on page 143.[15] Since it

was obtained by pyrolyzing β-lactone **15** directly into the inlet of the PE spectrometer, the spectrim of **1b** is much noisier than those of either **1a** or **2**. Nevertheless, it is clear from the PE spectrum of **1b** that its adiabatic IE is not shifted much from that of **1a**. If the apparent peak at 7.75 eV corresponds to the adiabatic IE of **1b**, the 0.06 eV difference between the IEs of **1a** and **1b** is in excellent agreement with the calculated difference of 0.07 eV between the energies of their HOMOs.

It has not been possible to obtain the ET spectrum of **1b**, generated as a transient species in the gas-phase by pyrolysis of β-lactone **15**. However, the synthesis of **1a** and its stability toward dimerization have allowed us to obtain its ET spectrum for comparison with that of **2**. Both ET spectra are shown on page 144.

Analysis of these spectra by Allan and co-workers leads to an electron affinity (EA) of -2.44 eV for **2** and -1.66 eV for **1a**. Again, using Koopmans' theorem, the difference of 0.78 eV between these EAs may be equated with the difference between the LUMO energies, which, as shown in Table IB.1, is calculated to be 0.79 eV. The agreement between the measured increase in the EA of **1a**, relative to **2**, and the calculated lowering of the LUMO energy is excellent. Moreover, the finding that on going from **2** to **1a**, the increase in the EA is more than a factor of 2.5 greater than the magnitude of the decrease in the IP confirms the more qualitative prediction that pyramidalization lowers the energy of the LUMO of an alkene much more than it raises the energy of the HOMO.

The IR spectrum of olefin **1a**, also taken in deoxygenated pentane, is shown on page 125. A number of very weak absorptions were found in the region where the C=C stretching vibration of **1a** might be expected, any of which could be due to this vibration. It is not suprising that this IR band would be weak, since the IR absorptions corresponding

to the analogous vibrational mode for olefins **1b**[14] and **1c**[19] are also weak. In all three olefins the C=C transition dipole is expected to be polarized not along but at 90° to the C-C double bond and to depend on the amount of pyramidalization.[14,19] It is likely, therefore, that the change in dipole moment associated with this particular mode would be even smaller for olefin **1a** than for olefins **1b** or **1c**. Therefore, we sought to observe the C=C stretch in **1a** in the Raman spectrum of **1a**.

The most intense peak in the Raman spectrum of olefin **1a**, taken in deoxygenated diethyl ether, occurs at 1611±5 cm^{-1}; and it is assigned to the C-C double bond stretching mode of **1a**. The frequency of this band falls between the double bond stretching frequencies of the Se bridged detivative **5a** at 1625 cm^{-1} [7] and of **1b** at 1557 cm^{-1}.[14] Moreover, since the most intense signal in the Raman spectrum of olefin **1b** was that from the C-C double bond stretching mode; it is reassuring that the signal at 1611 cm^{-1} is also the most intense peak in the Raman spectrum of olefin **1a**.

When an IR spectrum was taken of a very concentrated sample of olefin **1a**, a small peak was found at 1615 cm^{-1}. This same sample was then allowed to react with air; and after GC analysis showed olefin **1a** to be gone, the peak at 1615 cm^{-1} was also absent from the IR spectrum. Since the maximum in the Raman spectrum of **1a** is difficult to locate accurately, the IR band at 1615 cm^{-1} could correspond to the band at 1611±5 cm^{-1} in the Raman spectrum.

The assignment of the C=C stretching frequency of **1a** around 1615 cm^{-1} is supported by the results of ab initio calculations at the RHF/3-21G level, performed by Dr. David Hrovat in our research group. A vibrational analysis at this level on **1a** predicts a C=C stretching frequency of 1851 cm^{-1}; however, calculated quadratic, RHF vibrational

frequencies are always too high and must be scaled to account for anharmonicity and electron correlation effects. For example, the quadratic RHF/3-21G vibrational frequencies for C=C stretching in bicyclo[3.3.0]oct-1(5)-ene (**2**) and in **1b** of, respectively, 1898 and 1811 cm^{-1}, are considerably higher than the experimentally observed frequencies of, respectively, 1685 $(1675)^2$ cm^{-1} and 1557 cm^{-1}.

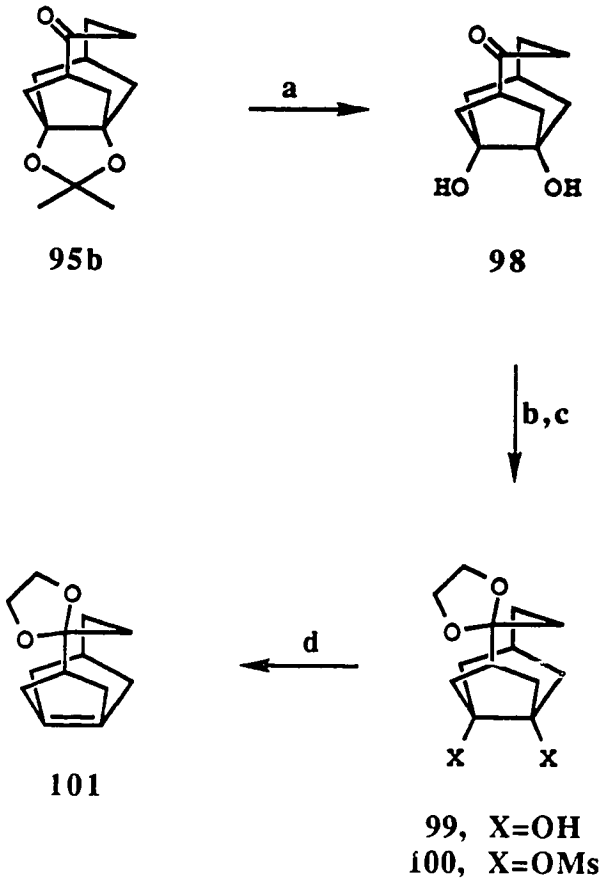
If a single scaling factor is used, the best fit of the calculated C=C stretching frequencies for **2** and **1b** to those found experimentally is obtained with a scaling factor of 0.873. It gives a scaled frequency of 1657 cm^{-1} for **2**, which is 23±5 cm^{-1} too low, and 1581 cm^{-1} for **1b**, which is 24 cm^{-1} too high. Since the amount of pyramidalization in **1a** is intermediate between that in **1b** and in **2**, this scaling factor might be expected to be better for **1a** than for either **1b** or **2** individually. In fact, multiplying the calculated C=C stretching frequency of 1851 cm^{-1} for **1a** by 0.873 gives a scaled frequency of 1616 cm^{-1}, which is in excellent agreement with the experimental assignment of 1615 cm^{-1} as the C=C stretching frequency in **1a**.

Attempts to grow crystals of **1a** for an X-ray study have, unfortunately, not been successful. It seems likely that the presence of a polar substituent would increase the propensity of the n=3 olefin (**1a**) toward crystallizing. However, this substituent must not perturb the double bond in **1a**, and the substituent must be stable to the conditions of the reactions that are utilized in the synthesis of this derivative of **1a**.

Introduction of additional functionality into **1a** might make use of one of the two regioisomeric ketones, (**95a**) or (**95b**), since they each already contain a polar functional group, the carbonyl that is converted to a methylene group in the synthesis of **1a**. We discovered that we could separate ketone **95b** from the mixture of it with the regioisomeric

ketone **95a** that is formed in the ring expansion of **92**. By carrying out five successive recrystallizations from chloroform, **95b** can be obtained in >97% purity. Protection of the carbonyl group of **95b** as a ketal with, for example, ethylene glycol, followed by generation of the olefinic bond between C-3 and C-7, might give a crystalline derivative of **1a**. It is encouraging that acetonide **79**, which also contains a ketal group, forms crystals quite readily.

An outline of this synthetic strategy is given in Figure IIIB.3. Conversion of ketone **95b** to ketodiol **98** could be carried out by hydrolysis of the acetonide group in **95b** in aqueous acid. Protection of the carbonyl group in **98**, by refluxing **98** in acidic ethylene glycol, should give diol **99**. Formation of dimesylate **100** could be carried out by reaction of **99** with methyllithium, followed by addition of methanesulfonyl chloride. Finally, reductive elimination of dimesylate **100** in the presence of sodium amalgam should give olefin **101**. If olefin **101** does not form crystals, it seems likely that it should not be too difficult to find a derivative of **101** that will.



95b

98

101

99, X=OH
100, X=OMs

Figure IIIB.3 Proposed Conversion of Ketone 95b to Olefin 101. a) H_3O^+. b) ethylene glycol, H^+. c) 1) CH_3Li, 2) MsCl. d) Na/Hg.

The importance of obtaining structural data on **1a** or a derivative was discussed in section IIA, as part of the motivation for preparing this olefin. The finding that **1a** is stable toward dimerization now, at least in principle, permits for the first time a direct comparison of the values for the pyramidalization angles and the length of the C-C double bond between those predicted computationally and those found experimentally in a member of the homologous series (**1**) of pyramidalized olefins. The discovery that **1a** is stable to dimerization, thus provides strong motivation for finding a crystalline derivative of **1a** that is suitable for structure determination by X-ray crystallography.

C. Some Chemistry of Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene

1. Reaction of Olefin 1a with Oxygen

When exposed to air, olefin **1a** disappears with concurrent formation of three new compounds. The rate at which **1a** disappears and the three new compounds appear depend upon the extent to which **1a** is exposed to air. When a solution sample of **1a** was intermittently exposed to air, GC analysis showed that the amounts of **1a** and the three new compounds also changed in small increments. The amount of **1a** before exposure to air was roughly equal to the sum of the amounts of **1a** and the three new compounds after exposure to air. The relative amounts of the three new compounds formed, in order of GC elution, were in ratios of approximately 1:1:2. However, these ratios changed with time, since at least one of the three products that were initially formed underwent subsequent reactions.

Analysis by GCMS showed that the first two of these new compounds to elute from the GC column both have a molecular weight of 164. The third new compound was

found to have a molecular weight of 180. These masses correspond, respectively, to that of **1a** plus 16 and **1a** plus 32. It thus seems that **1a** reacts with molecular oxygen to give two new compounds containing one oxygen atom and a third containing two oxygen atoms.

The first oxidation product of **1a** to be eluted from the GC column appears to be epoxide **102**. It decomposed upon attempted purification; so it was not characterized spectroscopically. However, as shown in Figure IIIC.1, olefin **1a** reacts with MCPBA to form a compound that has the same GC retention time as this oxygen addition product, to which we thus assign structure **102**.

The second oxidation product of **1a** to elute from the GC column was tentatively identified as tricyclo[3.3.3.$0^{3,7}$]undec-6,7-en-3-ol, **103**. A relatively pure sample was isolated by flash chromatography on a silica gel column, using 1:2 ethyl acetate:hexane as the eluent, followed by rechromatography under the same set of conditions of the fractions enriched in this product..

Exposure of this sample to air resulted in the disappearance of the oxidation product assigned structure **103** and concommitant formation of several new compounds. However, one of these new compounds was predominant and was isolated by flash chromatography on silica gel, using ethyl acetate:pentane (1:2) as the eluent. This new compound was fully characterized by NMR; and, as shown in Figure IIIC.1, it was identified as 6,7-epoxytricyclo[3.3.3.$0^{3,7}$]undecan-3-ol, **104**, the product of epoxidation of **103**.

A broadband decoupled ^{13}C NMR spectrum of **104** showed eleven signals, which is expected since the structure of **104** lacks any symmetry. Two signals of low intensity at

δ 80.56 and 73.36 and a much more intense signal, at δ 70.36, have been assigned to the three carbon atoms in **104** that have an oxygen atom directly attached to them. A DEPT 135 ^{13}C NMR experiment confirmed that the signal at δ 70.58 was that of a tertiary carbon and that the other two signals were due to quaternary carbons. The remaining eight signals were found between δ 45 and 20. The DEPT 135 experiment also showed that two of these signals, those at δ 36.75 and 31.89, were tertiary carbons and that the remaining six were secondary carbons.

A 500 MHz ^{1}H NMR spectrum in C_6D_6 showed a sharp singlet at δ 2.87, which was assigned to the tertiary hydrogen at C-6 of **104**. The lack of splitting of this signal can be explained, using a molecular model of **104**, which shows that this hydrogen and the adjacent bridgehead hydrogen form a dihedral angle that is close to 90°. Homonuclear proton decoupling experiments were also carried out and tentative assignments made for all sixteen of the non-equivalent hydrogens in **104**. Some of these assignments were ambiguous, but, the integration and splitting patterns found in the ^{1}H NMR spectrum fit structure **104** quite well. Also in agreement with this proposed structure, an IR spectrum showed a free O-H stretching frequency at 3566 cm^{-1} and a hydrogen bonded O-H stretching frequency at 3472 cm^{-1}.

Because of the conversion of **103** to **104** on exposure to oxygen, samples of **103** used for spectral analysis were invariably contaminated with some **104**. Therefore, spectroscopic analysis had to be done on these mixtures. The ^{13}C NMR spectrum of a mixture enriched in **103** showed two resonances in the olefinic region at δ 136 and δ 150. The more intense signal at δ 136 is assigned to the tertiary olefinic carbon atom and the less intense signal at δ 150 to the quaternary olefinic carbon atom. These two signals disappeared at about the same rate as GLC showed **103** to disappear.

As expected from the assignment of structure **103** to this product, the ^{1}H NMR spectra showed a one-proton singlet in the olefinic region, which also disappeared as **103** disappeared. A molecular model of **103** shows that the olefinic hydrogen forms a dihedral angle close to 90° with the adjacent bridgehead hydrogen, thus explaining why there is very little if any observable splitting in the resonance for the olefinic hydrogen.

The IR spectra taken on the mixtures of **103** and **104**, showed absorptions associated with free and hydrogen bonded O-H stretching, alkenic C-H stretching, and C-C double bond stretching. The IR data are thus consistent with the presence of the allylic alcohol moiety that **103** contains.

The bridgehead double bond in **103** is torsionally strained, since it may be viewed as being *trans* in an eight-membered ring. Torsionally strained olefins of this type are known to react readily with oxygen.[53] Thus, the formation of **104** from **103** on exposure to oxygen provides additional evidence that is consistent with the structure (**103**) assigned to the second oxidation product of **1a**.

The third oxidation product of **1a** to elute from the GC column has been unequivocally identified as bicyclo[3.3.3]undecane-3,7-dione (**4a**). The spectra of this product wholly consistent with this assignment. In addition, when treated with zinc amalgam in HCl under the conditions used to effect transannular reductive ring closure of the diketones **4** to the diols **3**,[7] the reduction product obtained exhibited the same TLC R_f value, GC retention time, and ^{1}H NMR spectrum as a sample of diol **3a**, prepared as an intermediate in the synthesis of olefin **1a**.

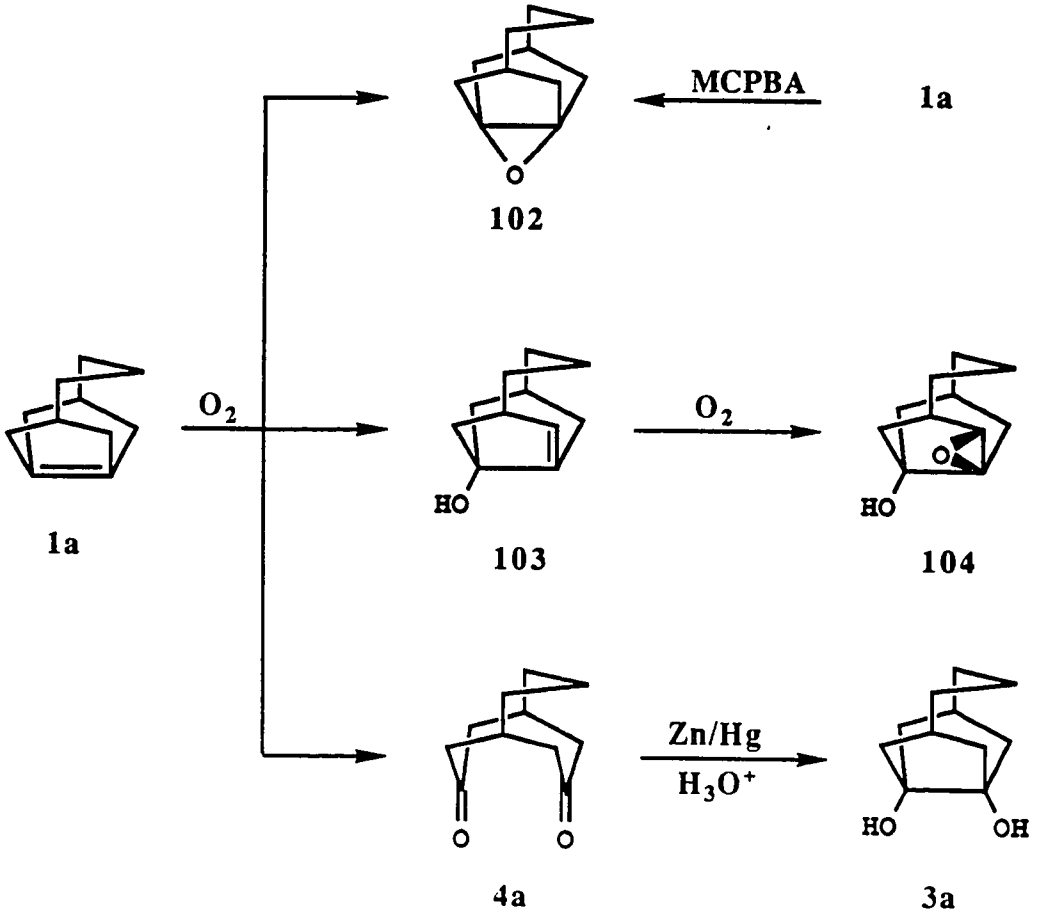


Figure IIIC.1 Products Formed from Olefin 1a in the Presence of Oxygen.

There are now also several examples in the literature of pyramidalized olefins reacting with oxygen to form epoxides, allylic alcohols, and diketones.[54,55] Thus, the formation of **102**, **103**, and **4a** on exposure of **1a** to oxygen has good precedent. However, the formation of allylic alcohol **103** and diketone **4a**, in addition to epoxide **102**, from **1a** is of some interest, because the much slower reaction of the selenium-bridged n=3 olefin (**5a**) with oxygen has been reported to give only an epoxide.[8]

2. Photolysis of 1a

Olefins **1b** and **1c**, under photolysis in matrix isolation, rearrange, respectively, to vinylcyclopropanes **18** and **28**.[14,19] It was of some interest to see whether **1a** would undergo the same rearrangement on photolysis. If it did, the rearrangement product (**54**) could be pyrolyzed to test the prediction[22] that, unlike the case with **18** and **28**,[16] **54** should be less thermodynamically stable that the corresponding pyramidalized alkene (**1a**). A preliminary exploration of the photochemistry of **1a** in solution was therefore undertaken.

A 27.0 mM solution of olefin **1a** in deoxygenated hexane and was photolyzed in a quartz test tube, using a high pressure mercury vapor lamp. After photolyzing for 1 hour, GC analysis showed that all of the olefin (**1a**) was gone; but present were two, large, new peaks. GCMS showed both to have a molecular weight of 296, which is the mass of a dimer of olefin **1a**. Also present in much smaller amounts were two other, new compounds, which GCMS showed to have molecular weights of 148 and 150. These latter two compounds have retention times very close to but not the same as olefin **1a**. The component having a molecular weight of 148 is an isomer of olefin **1a**, and thus could be

9-methylenetricyclo[5.2.1.$0^{1,3}$]decane (**54**), the retrograde vinylcyclopropane rearrangement product of **1a**.

When this same sample was photolyzed for longer periods (up to a total of 15 hours), the component with the mass of dimer and the shorter retention time and the component with the mass of **54** gradually disappeared, as shown by GC. Concurrently, the amount of the component having a molecular weight of 150 increased, and several new compounds, all of which GCMS showed to have molecular weights of 170, were observed. The amount of the second compound with the mass of dimer appeared unchanged. There appeared to be no change in the composition of the sample between periods of photolysis, indicating that all the reactions observed are photochemical, since they do not appear to occur in the dark.

In order to minimize the amount of dimer formed, in another experiment, a hundred-fold more dilute sample of olefin **1a** (~0.27 mM) in pentane was irradiated for short intervals, ranging from 10 seconds to 15 minutes. As hoped, the two compounds with the mass of dimer were present in much smaller amounts, relative to the compounds having molecular weights of 148 and 150, than in the previous experiment. The decrease in the amount of olefin **1a** and the increase in the amounts of the two compounds with molecular weights of 148 and 150 could be followed by GLC.

A sample, containing the compound with mass of rearrangement product **54**, was exposed to air for up to five days. GC analysis of the sample showed that the amount of this compound was unchanged. Thus, if this compound is the rearrangement product **54**, it, like the n=2 vinylcyclopropane (**18**),[16] is much more stable in the presence of oxygen than is olefin **1a**. As discussed in the next section, establishing the identity of this

photoproduct, as well as the identities of the photoproducts with masses of 150, and 296, should have high priority in future explorations of the chemistry of **1a**.

3. Future Experiments

The successful preparation of **1a** opens the way for a thorough exploration of the chemistry and spectroscopy of a pyramidalized olefin that is stable to dimerization. Several experiments immediately suggest themselves.

As discussed above, it is important to obtain an X-ray structure of a derivative of olefin **1a**, in order to provide the first direct comparison between the calculated and the observed pyramidalization angles and C-C double bond lengths for a member of the series of pyramidalized olefins **1**. In addition, the identity of the photoisomer of **1a** should be established. If it is found to be vinylcyclopropane **54**, it should be pyrolyzed, in order to test the computational prediction[22] that **1a** is the more thermodynamically stable of the two isomers.

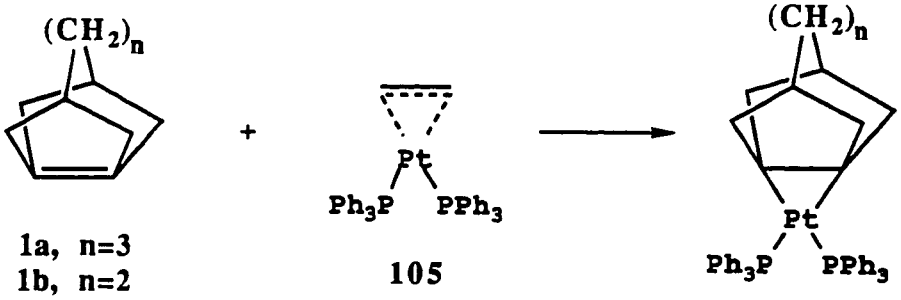
The olefin strain energy (OSE) can be defined as the difference in hydrogenation energies of a strained olefin and an olefin with little or no strain.[3] If a sufficient quantity of olefin **1a** were available, its hydrogenation energy could be measured and compared with that of olefin **2**. An olefin strain energy of 16 kcal/mol has been calculated for **1a**.[3] If the hydrogenation energy of olefin **2** is found to be around -30 kcal/mol, then a hydrogenation energy of around -46 kcal/mol is predicted for olefin **1a**. Measuring the hydrogenation energy of **1a** would provide an indication of the accuracy of the OSE calculations that have been carried out on the other members of the series of olefins **1**.

It would also be interesting to compare the rates of Diels-Alder reactions of olefin **1a** to those of an olefin with little or no olefin strain, such as the unbridged olefin (**2**). The olefin strain energy present in **1a** should cause it to undergo a Diels-Alder reaction much more readily than **2**. Since lowering of the LUMO is predicted to be the primary cause of the increased reactivity of **1a**, one might also expect to see a significantly faster rate of reaction of **1a** with nucleophiles, as compared to olefin **2**.

D. Preparation of Bis(triphenylphosphine)platinum Complexes of Two Tricyclo[3.3.n.$0^{3,7}$]alk-3(7)-enes. NMR and X-Ray Studies of the Complexes

1. Synthesis

Alok Kumar in the Borden group has successfully trapped **1c** as the bis(triphenylphosphine)platinum complex (**106c**) by generating the n=1 olefin in the presence of the bis(triphenylphosphine)platinum complex (**105**) of ethylene.[56] The ^{13}C NMR spectrum of **106c** showed many interesting features when compared with that of the ethylene complex. The synthesis of the n=3 olefin (**1a**) provided the opportunity to investigate how the spectroscopic properties of **106c** might be modified by replacing **1c** with **1a** in the complex. Moreover, one of the synthetic intermediates in the preparation of **1a** could be converted to a precursor of the n=2 olefin (**1b**), so that this olefin too could be generated under conditions where it could be trapped as the bis(triphenylphosphine)platinum complex (**106b**).



1a, n=3
1b, n=2
1c, n=1

105

106a, n=3
106b, n=2
106c, n=1

Figure IIID.1 **Conversion of Olefins 1 to the Corresponding Bis(triphenylphosphine)platinum Complexes (106).**

Preparation of the bis(triphenylphosphine)platinum complex (**106c**) of **1c** was, as shown in Figure IIID.2, carried out by reacting the vicinal diiodide **25**[18] with sodium amalgam in the presence of the ethylene complex (**105**). Under the same conditions, the bis(triphenylphosphine)platinum complex (**106b**) of the n=2 olefin (**1b**) was, as shown in Figure IIID.3, prepared from dimesylate (**108**). The preparation of **108** was made possible by the availability of ketone **92** as an intermediate in the synthesis of **1a**.

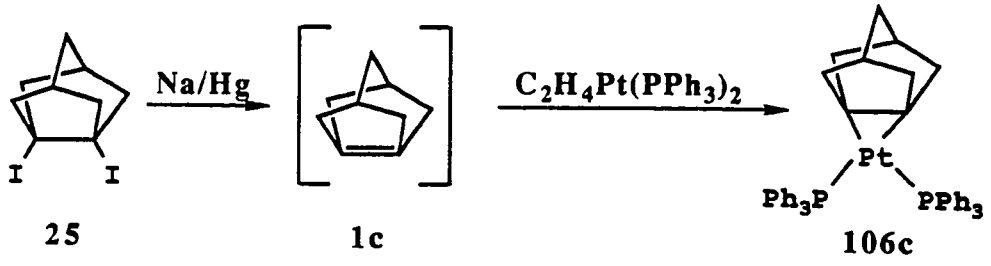


Figure IIID.2 **Conversion of Diiodide 25 to Complex 106c.**

As indicated in Figure IIID.3, Wolff-Kishner reduction of ketone **92**, by heating with sodium hydroxide, and hydrazine monohydrate in refluxing diethylene glycol under nitrogen for 24 hours,[42,49] gave tricyclo[3.3.2.$0^{3,7}$]decane-3,7-diol acetonide (**107**), in 89% yield. The subsequent steps in the synthesis of **108** were analogous to those in the preparation of the dimesylate precursor (**96**) of **1a** from the homolog (**79**) of **107**. Deprotection of **107**, brought about by stirring in 20% aqueous acetic acid at 85° for 48 hours, gave an 83% yield of tricyclo[3.3.2.$0^{3,7}$]decane-3,7-diol (**3b**). Adding 1.6 equivalents of methyllithium to a solution of diol **3b** in THF under nitrogen at 0°, followed by addition of 1.6 equivalents of methanesulfonyl chloride, gave tricyclo[3.3.2.$0^{3,7}$]-decane-3,7-dimesylate (**108**) in 52% yield.

Reduction of **108** with sodium amalgam in the presence of the ethylene complex (**105**) gave **106b** as a yellowish powder. Purification by recrystallization from THF:ethanol (1:3) gave crystals of **106b** (42%) that were not only pure enough for spectroscopic study but were also suitable for structure determination by X-ray crystallography.

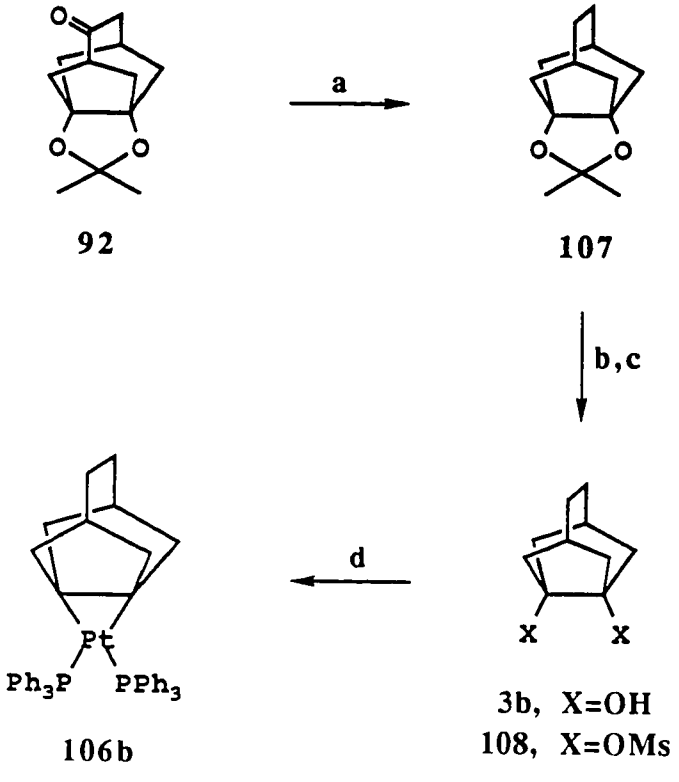
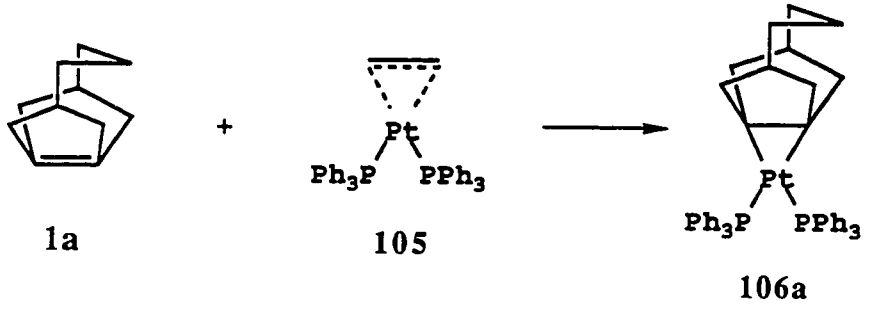


Figure IIID.3 Synthesis of the Bis(triphenylphosphine)platinum Complex (106b) of Olefin 1b from Ketone 92. a) N_2H_4, NaOH. b) H_3O^+. c) 1) CH_3Li, 2) MsCl. d) Na/Hg, $C_2H_4Pt(Ph_3P)_2$.

The preparation and purification of **106a** was closely analogous to that of **106b**, except that the stability of **1a** toward dimerization made it unnecessary to generate the olefin in the presence of the bis(triphenylphosphine)platinum trapping agent. Instead, a solution of **1a** was added to a solution of the bis(triphenylphosphine)platinum complex (**105**) of ethylene; and, once again, recrystallization from THF:ethanol (1:3) gave crystals of **106a** (43%) that were pure enough for spectroscopic study and suitable for X-ray structure determination.



1a **105** **106a**

Figure IIID.4 **Synthesis of the Bis(triphenylphosphine)platinum Complex (106a) of Olefin 1a.**

2. NMR Studies of the Complexes[57]

One of the most useful probes for observing the consequences of increasing pyramidalization of the olefinic ligands in complexes **106a-c** was the measurement of the

magnitude of coupling between the platinum and the olefinic carbon atoms. These coupling constants should depend on the amount of s character in the orbitals of the olefinic carbons,[58] and might therefore give an indication of the degree to which these carbons are pyramidalized in the complexes. Indeed, we found that these coupling constants increase monotonically and double on going from the ethylene complex **105** to **106c**, as shown in Table IIID.1.

As pyramidalization increases, the olefinic carbon atoms are predicted to become increasingly electronegative, and electron density is calculated to be transferred from the highest filled d orbital of the bis(triphenylphosphine)platinum moiety to the LUMO of the olefin.[59] This transfer should increase the donation of electron density from the olefin LUMO into the empty 6s atomic orbital on platinum, at the expense of donation of the phosphine lone pair orbitals into this atomic orbital. In a molecular orbital picture the increase in the interaction between the olefin HOMO and 6s is not only responsible for the dramatic increase in $J_{C\text{-}Pt}$ that is observed but it may also account for the smaller decrease in the magnitude of coupling between the phosphorous and platinum atoms that is observed on going from **105** to **106c**.

Also, as shown in Table IIID.1, the magnitude of the three-bond coupling between the platinum and bridgehead carbon atoms increases along this series. This decrease is probably due to the changes in the dihedral angle between the relevant C-C and C-Pt bonds as pyramidalization increases.

Table IIID.1 Coupling Constants for complexes **105** and **106a-c**.[a]

Complex	J_{Pt-C}[b] (Hz)	J_{Pt-P} (Hz)	J_{Pt-C}[c] (Hz)
105	194	3740	
106a[d]	296	3332	76
106b	343	3115	106
106c	407	2948	107

[a] C_6D_6, 298 K. [b] C-3 and C-7, the olefinic carbons directly attached to Pt. [c] C-1 and C-5, the bridgehead carbons. [d] toluene-d_8, 338 K. Under these conditions the signals for quaternary carbons C-3 and C-7, as well as those for the methylene carbons C-2, C-4, C-6, and C-8, have coalesced.

Not only are the olefinic carbon atoms in complexes **105** and **106a-c** coupled to ^{195}Pt, but they are also coupled to both of the phosphorus atoms. Because each olefinic carbon atom is coupled differently to the cis and trans phosphorus atoms and because these latter two atoms are also coupled to each other, the carbons are observed as a second order, AXX', five-line pattern. This multiplet was simulated using PANIC;[60] and from these simulations the values, shown below in Table IIID.2, were obtained for J_{C-P}cis, J_{C-P}trans, and J_{P-P} in each complex.

Because $J_{C\text{-}P}$(trans) is generally larger than $J_{C\text{-}P}$(cis), the smaller, negative carbon-phosphorus coupling constants have been assigned to $J_{C\text{-}P}$(cis). Apart from the ethylene complex, **105**, the values for $J_{C\text{-}P}$(cis) change very little. However, the other coupling constants, $J_{C\text{-}P}$(trans) and $J_{P\text{-}P}$, both increase (the magnitude of $J_{P\text{-}P}$, which is negative, decreases) as pyramidalization increases in the complexes. These changes can also be accounted for by increasing charge transfer from the highest filled orbital of the $(Ph_3P)_2Pt$ moiety to the olefin LUMO, which should increase $J_{C\text{-}P}$ and decrease $J_{P\text{-}P}$.

Table IIID.2 Coupling Constants for Complexes **105** and **106a-c** Derived By Simulating the ^{13}C NMR Signal of the Olefinic Carbons.

Complex	$J_{C\text{-}P}$trans (Hz)	$J_{C\text{-}P}$cis (Hz)	$J_{P\text{-}P}$ (Hz)
105	27	-3	-58
106a	48	-9	-55
106b	56	-9	-41
106c	67	-10	-27

As shown in Table IIID.3, we also observed a monotonic downfield chemical shift of the olefinic carbon resonances in the ^{13}C NMR spectra of complexes **106a** to **106c**. This is consistent with the predicted increase in the transfer of electron density from the

bis(triphenylphosphine)platinum moiety to these carbons with increasing pyramidalization,[59] as is the generally downfield shift of platinum. However, the upfield shift of phosphorous with increasing olefin pyramidalization is the opposite of what one would have expected. Nevertheless, the same trend is seen in bis(triphenylphosphine)platinum complexes of cyanoethylenes as the number of cyano groups is increased[61] and in bis(triphenylphosphine)platinum complexes of cyclic alkynes as the ring size decreases.[62]

Table IIID.3 Chemical Shifts for Complexes **105** and **106a-c**.[a]

Complex	δ C[b] (ppm)	δ Pt[c] (ppm)	δ P[d] (ppm)	δ C[e] (ppm)
105	39.2	-555	34.1	
106a[f]	78.8	-501	32.2	50.7
106b	74.9	-514	31.1	54.1
106c	66.9	-467	30.5	61.2

[a] C_6D_6, with respect to C_6D_6 (128.0 ppm), 298 K. [b] C-3 and C-7, the olefinic carbons directly attached to Pt. [c] δ Pt in the complexes **106a**, **106b**, and **106c** were measured relative to δ Pt in the ethylene complex **105**, whose value was taken from reference 61. [d]with respect to 85% H_3PO_4. [e] C-1 and C-5, the bridgehead carbons. [f] toluene-d_8, with respect to toluene-d_8, (20.4 ppm), 338 K. Under these conditions the signals for quaternary carbons C-3 and C-7, as well as those for the methylene carbons C-2, C-4, C-6, and C-8, have coalesced.

3. Structure Determinations by X-Ray Crystallography[57]

The preparation, crystallization, and subsequent X-ray structure determination of complexes **106a-c** allowed us to test several predictions about the structures of these complexes.

As pyramidalization of the olefinic carbon atoms increases along the series **1a-c**, the pyramidalization angles in complexes **106a-c** should increase too. In **106a**, unlike the case in the salt (**5b**) of the selenium derivative of olefin **1a**, the non-equivalent pyramidalization angles at carbon atoms 3 and 7 should be nearly the same, based on ab initio calculations on uncomplexed olefin **1a**.[3]

Furthermore, as pyramidalization increases along the series of olefins **1a-c**, the bond between the olefinic carbons should lengthen. This increase should be enhanced in the complexes **106a-c** as back-donation from a filled d orbital on platinum to the π^* orbital also increases with pyramidalization. Increasing back-donation from platinum to carbon should also shorten the Pt-C bond lengths. Both these effects have been seen in the results of ab initio calculations on bis(triphenylphosphine)platinum complexes of ethylene and an ethylene model for **1c**.[59]

The crystal structures of complexes **106a** and **106b** are shown on pages 141 and 142. As shown in Table IIID.4, there is an increase in the pyramidalization angle from **106a** to **106c**. The pyramidalization angles in **106a** differ by 4.0°, but, because of experimental uncertainty, may be nearly the same. Similarly, experimental uncertainty precludes the observation of any trend in the olefinic C=C bond length with changes in

pyramidalization. The Pt-C bond length does appear to decrease as pyramidalization increases, but, there is some uncertainty between complexes **106b** and **106c** since their Pt-C bond lengths are the same within experimental error. Finally, the Pt-P bond lengths for the three complexes appear to be nearly the same and fall within experimental error of each other.

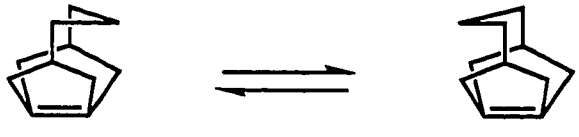
Table IIID.4 Some X-Ray Data Obtained From Complexes 106a-c.

Complex	106a	106b	106c
Pyram. angle, ϕ (°)	50.4 ± 2.1 46.4 ± 2.0[a]	57.1 ± 3.6	62.0 ± 4.2
C=C bond length (Å)	1.46 ± 0.01	1.47 ± 0.02	1.44 ± 0.02
Pt-C bond length (Å)	2.14 ± 0.01	2.09 ± 0.02	2.06 ± 0.01
Pt-P bond length (Å)	2.277 ± 0.002	2.28 ± 0.01	2.29 ± 0.02

[a] This value corresponds to the pyramidalization angle in complex **106a** that is syn to the trimethylene bridge.

E. Studies of the Conformational Dynamics of Tricyclo[3.3.3.$0^{3,7}$]-undec-3(7)-ene and Related Molecules by ^{1}H and ^{13}C NMR and by Molecular Mechanics Calculations

During the course of the synthesis and study of the n=3 olefin (**1a**), interesting features were observed in the ^{1}H and ^{13}C NMR spectra of it and a number of related compounds. As discussed in section IIIB, it was discovered that certain carbon and hydrogen resonances were broad or in some cases "missing" when observed at room temperature. NMR spectra recorded at both higher and lower temperatures were consistent with this broadening being due to a conformational change, involving flipping of the trimethylene bridge, as depicted for **1a** in Figure IIIE.1. Apparently, the barrier to interconversion of conformations **1a'** and **1a''** is large enough that around room temperature, conformational interconversion takes place at a comparitively slow rate on the NMR timescale.



1a' 1a''

Figure IIIE.1 Conformational Interconversion of the Trimethylene Bridge in Olefin 1a.

In order to study this phenomenon in more detail, five compounds -- olefin **1a**, acetonide **79**, dimesylate **96**, Diels-Alder adduct **97**, and the bis(triphenylphosphine)-platinum complex (**106a**) of olefin **1a**, were subjected to a series of variable temperature ^1H NMR and ^{13}C NMR experiments. For each compound the coalescence temperature (T_c)[58] was found for each of the sites being exchanged by trimethylene bridge flipping. Measurement of the frequency difference, $\Delta\nu$, between the sites being exchanged was obtained from NMR spectra at low temperatures. The rate of site exchange at coalescence is given by the formula:[58,63]

$$k_c = \pi\Delta\nu\ (2)^{-1/2} \qquad (1)$$

The free energy of activation at coalescence for the conformational dynamics of the trimethylene bridge that results in site exchange in these four molecules can then be obtained from absolute rate theory, using the formula:

$$k_c = (kT_c/h)e^{-\Delta G^{\neq}/RT_c} \qquad (2)$$

Substituting equation 1 in equation 2 and rearranging gives:

$$\Delta G^{\neq} = -RT_c\ln\{\pi\Delta\nu h\ (2)^{-1/2}/kT_c\} \qquad (3)$$

Equation 3 is applicable because the barriers for the forward and reverse conformational changes in all five molecules studied are equal. The two conformers resulting from bridge flipping in **1a**, **79**, **96**, and **106a** are identical, and the two conformers resulting from bridge flipping of **97** have an enantiomeric relationship.

1. Olefin 1a

Shown on pages 115-117 are a series of ^{13}C NMR spectra of the n=3 olefin, (**1a**), taken in toluene-d_8 at various temperatures. The different numbers of ^{13}C signals associated with olefin **1a**, five resonances at 371 K and seven sharp resonances at 240 K, is attributed to fast flipping of the trimethylene bridge at high temperatures and slow bridge flipping at low temperatures.

At temperatures below 275 K, carbon atoms 3 and 7, the olefinic carbons, are non-equivalent and are seen as two distinct signals, separated by 48.9 Hz; but, at temperatures above 304 K (the experimentally determined coalescence temperature, T_c, for the C-3 and C-7 resonances), these carbons become effectively equivalent on the NMR timescale and are observed as one signal. The same effect is seen for the two sets of methylenic carbon atoms. At temperatures below 310 K, one signal is observed for C-2 and C-4 and another for C-6 and C-8. The two are separated by 386.5 Hz. However, above 328 K (the experimentally determined T_c for these two sets of methylenic carbon atoms) all four methylenic carbon atoms become effectively equivalent on the NMR timescale and appear as one resonance.

The two values calculated from equation 3 for the free energy barrier in **1a**, using the two low temperature, ^{13}C frequency differences and the coalescence temperatures, are

15.0 kcal/mol for the olefinic carbons and 14.9 kcal/mol for the methylenic carbons. The agreement between these two independent measurements of the free energy barrier for flipping of the trimethylene bridge in **1a** is excellent.

The fact that these two values for the barrier to bridge flipping were determined over a temperature range of 24° and are essentially equal suggests that the entropic contribution to the free energy barrier is negligible.

Shown on pages 188-121 are a series of ^{1}H NMR spectra of the n=3 olefin, (**1a**), taken in toluene-d_8 at various temperatures. One can follow the resonances as they broaden and eventually coalesce. Independent values of the free energy of activation for bridge flipping were obtained from the ^{1}H NMR spectra. Using the protons labelled (A') and (A"), for which the frequency difference is 112.0 Hz and the estimated T_c of 308 K, the activation barrier was calculated to be 14.6 kcal/mol. Using protons labelled (B') and (B"), for which the frequency difference is 167.9 Hz, and the estimated T_c of 316 K, the activation barrier was calculated to be 14.8 kcal/mol. The agreement of these two values with each other and with those obtained from the ^{13}C spectra is superb.

Except for small chemical shift differences, the ^{1}H NMR spectrum of olefin **1a** at 386 K closely resembles that of the selenium-bridged n=3 olefin (**5a**) at room temperature which is shown on page 126.[64] However, it should be noted that olefin **1a** must be heated to 386 K before its ^{1}H NMR spectrum sharpens and becomes like that of olefin **5a** at 300 K. The barrier to flipping of the trimethylene bridge in olefin **1a** is apparently much greater than that for flipping the selenium bridge in **5a**. Unfortunately, site exchange in **5a** has not been frozen out, so a more quantitative comparison is not possible.

2. Acetonide 79

Shown on pages 127-130 are a series of ^{13}C NMR spectra of the n=3 acetonide, (**79**), taken in toluene-d_8 at various temperatures. The number of ^{13}C signals associated with acetonide **79**, seven resonances at high temperatures and nine resonances at low temperatures, is, as in the case of olefin **1a**, attributed to slow flipping of the trimethylene bridge at low temperatures and fast flipping at higher temperatures.

At temperatures below 215 K, the quaternary carbon atoms, 3 and 7, are non-equivalent and are seen as two distinct signals, separated by 66.5 Hz; but, at temperatures above 227.5 K (the experimentally determined T_c, for C-3 and C-7), the carbons become effectively equivalent on the NMR timescale and are observed as one signal. The same effect is seen between two sets of methylenic carbon atoms. At temperatures below 240 K, C-2 and C-4 appear as one signal and C-6 and C-8 as another. The two resonances are separated by 423.0 Hz. However, above 247.5 K (the experimentally determined T_c, for the two sets of methylenic carbon atoms) all four methylenic carbon atoms become effectively equivalent on the NMR timescale and appear as one resonance.

The two values, calculated for the energy barrier to bridge flipping, using coalescence temperatures of the quaternary and methylenic carbon atoms are 10.9 kcal/mol and 11.0 kcal/mol, respectively. These values not only agree well with each other, but they also agree well with the barrier heights obtained from the ^1H NMR spectra of **79**.

Shown on pages 131-134 are a series of ^1H NMR spectra of the n=3 acetonide, (**79**), taken in $CDCl_3$ at various temperatures. Once again, one can follow the resonances as they broaden and eventually coalesce. Using the protons labelled (A') and (A''), a

frequency difference of 158.1 Hz, and an estimated T_c of 236 K, the activation barrier was found to be 11.0 kcal/mol. Using the protons labelled (B') and (B"), a frequency difference of 193.4 Hz, and an estimated T_c of 238 K, the activation barrier was also found to be 11.0 kcal/mol. This value is in excellent agreement with the two values determined using ^{13}C NMR. Comparison of the barriers obtained from ^{13}C NMR in toluene-d_8 and ^1H NMR experiments in $CDCl_3$ seems justified, because the ^{13}C spectra obtained using either $CDCl_3$ or toluene-d_8 are essentially identical.

3. Dimesylate 96

The energy barrier to bridge flipping in dimesylate **96** was determined to be even lower than that of acetonide **79**. A barrier height of 8.98 kcal/mol was found using ^{13}C NMR, a frequency difference of 872.8 Hz, and a T_c of 210 K by observing coalescence of the methylenic sets of carbons in the two five-membered rings. The sample froze at lower temperatures, thus precluding us from obtaining the barrier to bridge flipping by observing coalescence of the two quaternary carbon atoms.

A barrier height of 8.89 kcal/mol was found using ^1H NMR, a frequency difference of 265.5 Hz, and a T_c of 198 K by observing coalescence of the two sets of methylenic protons on carbon atoms 9 and 11 in the trimethylene bridge. These two values for the free energy of activation for bridge flipping that were found using both ^1H and ^{13}C NMR are in very good agreement with each other.

4. MM2 Calculations

The ^1H and ^{13}C dynamic NMR studies of olefin **1a**, acetonide **79**, and dimesylate **96** establish clearly that there is a decrease in the free energy barrier heights for

trimethylene bridge flipping along this series. In order to try to understand why the barrier height in **1a** is 66% larger than that in **96**, we undertook molecular mechanics calculations, using the MM2 Force Field of Allinger.[65]

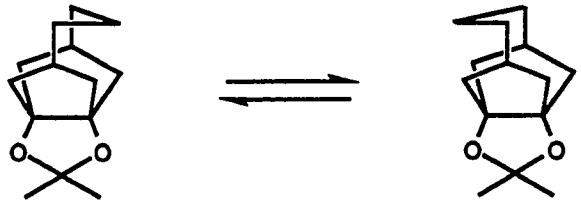
Optimization of the geometry of **1a** in C_S symmetry gave a calculated strain energy of 40.4 kcal/mol. The transition state for bridge flipping was located by imposing C_{2V} symmetry on the olefin. Reducing this symmetry constraint to C_2 resulted in no change, so that the transition state does appear to have C_{2V} symmetry. Relaxing the symmetry constraint to C_S led smoothly to the equilibrium geometry of **1a**. The transition state was calculatd to 14.4 kcal/mol higher in energy, in good agreement with the measured free energy of activation of 14.8±0.2 kcal/mol for bridge flipping in **1a**.

Similar calculations on acetonide **79** and dimesylate **96** were also performed. The strain energy of the ground state geometry in C_S symmetry was calculated to be 22.1 kcal/mol for **79** and 41.1 kcal/mol for **96**, which was modeled as the hydrogenation product (**109**) of olefin **1a**. When C_{2V} symmetry was imposed on the transition state geometry, MM2 calculated a barrier height of 14.5 kcal/mol for **79** and 14.5 kcal/mol for **96**. However, when only C_2 symmetry was imposed on the transition state geometries, MM2 calculated an energy barrier to bridge flipping of 11.9 kcal/mol for **79**, which is 2.6 kcal/mol smaller than the value predicted when C_{2V} symmetry is imposed on the transition state geometry and in better agreement with the measured free energy of activation of 11.0 kcal/mol for **79**. The reduction in the calculated barrier height for **96** is even larger, amounting to 5.8 kcal/mol, which brings the calculated value of 8.7 kcal/mol into reasonable agreement with the free energy barrier height of 9.0 kcal/mol that is measured. The calculated and experimental barrier heights are compared in Table IIIE.3.

These results suggest that, unlike the case in olefin **1a**, when trimethylene bridge flipping takes place in acetonide **79** and dimesylate **96**, the molecules maintain only C_2 symmetry. The ability of **79** and **96** to twist about the C_3-C_7 bond and thus utilize a transition state geometry of only C_2 symmetry accounts for the result, found both experimentally and computationally, that the barrier to trimethylene bridge flipping in acetonide **79** is smaller than that in olefin **1a** and that in **96** smaller still.

The preference of **79** and **96** for transition state geometries with C_2 symmetry, rather than C_{2V} symmetry, is also evident from molecular models. It is much more difficult to force the trimethylene bridge from conformation **64'** to conformation **64''** when the molecule is forced to maintain C_{2V} symmetry than when the molecule is allowed to twist about the C_3-C_7 bond and relax to C_2 symmetry. The substitution of the C-C double bond in olefin **1a** for the C_3-C_7 single bonds in **79** and **96** prevents the olefin from twisting about the C_3-C_7 bond and forces it to pass through a higher energy transition state, which maintains C_{2V} symmetry.

The presence of the additional ring in acetonide **79** that is absent in dimesylate **96** partially restricts rotation about the C_3-C_7 bond in **79** and thus accounts for the fact that the barrier to bridge flipping is higher in **79** than in **96**. Indeed, the dihedral angle of 19.5° between the two C-O bonds in the transition state for bridge flipping in **79** is computed to be 4.0° smaller than the analogous dihedral angle in the reduced olefin (**109**) model for **96**.



79' 79''

Figure IIIE.2 Conformational Interconversion of the Trimethylene Bridge in Acetonide 79.

An additional indication of the effect of twisting about the C_3-C_7 bond on the barrier to bridge flipping was obtained by carrying out MM2 calculations on the hydrogenation product (**109**) of olefin **1a**. Once again, the energy difference between the ground state conformation (strain energy = 30.4 kcal/mol) and the C_{2V} transition state for trimethylene bridge flipping was calculated to be 14.5 kcal/mol. However, a calculation, carried out with only C_2 symmetry enforced on the transition state predicted an energy barrier of only 9.9 kcal/mol, very similar to that computed for the reduced olefin model for dimesylate **96**. Synthesis of **109**, by hydrogenation of **1a**, and investigation of its dynamic NMR behavior would provide an experimental test of the computational prediction of similar barriers to bridge flipping in **109** and in **96**.

5. Diels-Alder Adduct (97) of the n=3 Olefin (1a)

The hypothesis that the ability of the tricyclo[3.3.3.$0^{3,7}$]undecane ring system to rotate about the C_3-C_7 bond affects the barrier to trimethylene bridge flipping was given an additional experimental test by measuring the barrier height in the Diels-Alder adduct (**97**) of **1a**. Molecular models suggest that incorporation of the C_3-C_7 bond into the 7-oxa-bicyclo[2.2.1]heptene ring system, present in **97**, should restrict rotation about this bond and thus raise the barrier height above that found in acetonide **79**.

Shown on pages 109-111 are a series of ^{13}C NMR spectra of the Diels-Alder adduct (**97**) of the n=3 olefin (**1a**), taken in $CDCl_3$ at various temperatures. As was the case for olefin **1a** and acetonide **79**, there are a greater number of resonances observed in the low temperature ^{13}C NMR spectra of adduct **97** than there are observed in the high temperature ^{13}C NMR spectra. The coalescence of four sets of resonances -- (i', i''), (a', a''), (b', b''), and (c', c'') -- that are observed in the aliphatic region of the 209 K spectrum can be followed. Since the non-equivalence engendered upon these pairs of carbons at low temperatures is due to the conformational flipping of the trimethylene bridge, it is interesting to note that the frequency differences between and, hence, the coalescence temperatures of the four pairs of resonances increase with the proximity to the trimethylene bridge of the carbons to which they correspond. The frequency difference for the resonances labelled b' and b'' is nearly equal to that for the resonances labelled c' and c'', presumably because these two pairs of carbons are approximately the same distance from the trimethylene bridge.

The three values obtained for the free energy barrier in **97**, using the frequency differences (114.9, 489.9, and 440.3 Hz) and the coalescence temperatures (292, 304, and

306 K) for the three pairs of ^{13}C resonances -- (a', a"), (b', b"), and (c', c") -- are 13.9, 13.9, and 14.0 kcal/mol, respectively. This is 3.0 kcal/mol greater than the barrier in acetonide **79** and only 1.0 kcal/mol less than that in olefin **1a**.

The transition state for bridge flipping in **97** can have at most C_S symmetry. When C_S symmetry was imposed on **97** to find the transition state geometry, MM2 calculations predicted an enthalpy of activation of 14.1 kcal/mol, very close to the value of 14.4 kcal/mol calculated for bridge flipping in **1a**. The results of the ^{13}C NMR experiments, thus, suggest that rotation about the C_3-C_7 bond in **97** is strongly inhibited during bridge flipping and that the lowest energy transition state geometry may even have a plane of symmetry.

Shown on pages 112-114 are three ^1H NMR spectra of adduct **97**, taken in $CDCl_3$ at 217, 298, and 325 K, respectively. Although one can see coalescence taking place, a complete assignment of the aliphatic protons in **97** was not carried out. Therefore, verification of the value of the free energy of activation for bridge flipping that was determined, using the ^{13}C NMR spectra was not performed using the ^1H NMR spectra of adduct **97**.

6. Bis(triphenylphosphine)platinum Complex (106a) of Olefin 1a

The bis(triphenylphosphine)platinum complex (**106a**) of olefin **1a** would also be expected to be prevented from rotating about the C_3-C_7 bond; and so, like the uncomplexed olefin (**1a**), **106a** would be predicted to have a barrier of around 14.8 kcal/mol to flipping of the trimethylene bridge.

Shown on pages 135-137 are a series of ^{13}C NMR spectra of the bis(triphenylphosphine)platinum complex (**106a**) of the n=3 olefin (**1a**), taken in toluene-d_8 at various temperatures. Apart from the presence of the aromatic signals and splitting due to couplings to ^{195}Pt and ^{31}P, the spectra are very similar in appearance to the corresponding spectra of olefin **1a**. This is due in part to many of the carbons in complex **106a** having chemical shifts that are similar to those in olefin **1a** and also to the fact that, as discussed below, **106a** was found to have a barrier to bridge flipping that is very close to that in olefin **1a**.

For example, the room temperature spectrum of **106a** has two very broad resonances at δ 42 and 52, which corresponds to a frequency difference of 536.7 Hz. These signals have been assigned to the two sets of methylene carbon atoms labelled (b') and (b''). No NOE experiments have been carried out to distinguish which set of equivalent methylene carbons corresponds to which of the two broad signals. The coalescence of these two resonances at 329 K corresponds to a free energy barrier to bridge flipping of 14.7 kcal/mol. This value is close to that in olefin **1a** and Diels-Alder adduct **97** and suggests that, as expected, the three membered ring in **106a** restricts the freedom of the molecule to rotate about the C_3-C_7 bond and thus utilize a lower energy transition state.

As a check on the value of the free energy barrier for bridge flipping in **106a**, determined by ^{13}C NMR, the barrier was also determined using ^{1}H NMR. Shown on pages 138-140 are a series of ^{1}H NMR spectra of the n=3 platinum complex (**106a**), taken in toluene-d_8 at various temperatures. Once again, one can follow the resonances as they broaden and eventually coalesce with increasing temperature.

Other than some chemical shift differences, these ^1H spectra are also similar to those of the n=3 olefin. The major difference is that the pseudo-equatorial protons labelled (A') and (A") in **106a** show significant coupling to ^{195}Pt (J = 80.6 Hz) and thus appear as triplet-like patterns. Smaller couplings to ^{195}Pt (J = 20.1 Hz) are observed for the pseudo-axial protons, (B') and (B"). The broadness of these resonances makes the accurate determination of a coalescence temperature difficult. However, an estimated coalescence temperature of 301 K for protons A' and A" (frequency difference = 171.7 Hz) gives a value of 14.1 kcal/mol for the free energy barrier to bridge flipping. Coalescence of protons B' and B" (frequency difference = 126.6 Hz) at 305 K gives a value of 14.4 kcal/mol. Given the uncertainties in determining T_c accurately in the ^1H NMR spectrum of **106a**, the agreement between the barrier heights determined from the ^{13}C and ^1H dynamic NMR studies is certainly satisfactory.

7. Summary

The results of the dynamic NMR studies on **1a**, **79**, **96**, **97**, and **106a** are summarized in Tables IIIE.1 and IIIE.2 which give for each compound the frequency difference between each of the sites that are exchanged by bridge flipping, the coalescence temperature, and the value of $\Delta G^{\neq}$ derived from this experimental data. Also given for each compound are the average value of $\Delta G^{\neq}$ obtained from the individual ^{13}C NMR measurements and the energy barriers calculated by MM2. Both the measurements and the calculations agree that the barrier to flipping of the trimethylene bridge in the tricyclo-[3.3.3.$0^{3,7}$]undecane ring system decreases as freedom to twist about the C_3-C_7 bond increases. Thus, in addition to providing access to an important member of the homologous series of pyramidalized alkenes (**1**), the synthesis of **1a** serendipitously provided detailed information about the stereodynamics of this ring system.

Table IIIE.1. Some Experimental Dynamic ^{13}C NMR Data for Olefin **1a**, the $(Ph_3P)_2Pt$ Complex **106a**, Diels-Alder Adduct **97**, Acetonide **79**, and Dimesylate **96**.

Compound	Site Exchanged[a]	$\Delta\nu$ (Hz)	T_c (K)	$\Delta G^{\neq}$ (kcal/mol)
1a	a', a''	48.9	304	15.0
	b', b''	386.5	328	14.9
106a	b', b''	536.7	329	14.7
97	a', a''	114.9	292	13.9
	b', b''	489.9	304	13.9
	c', c''	440.3	306	14.0
79	a', a''	66.5	228	10.9
	b', b''	423.0	248	11.0
96	b', b''	872.8	210	8.98

[a] See the relavent NMR spectra for the keys to these labels.

Table IIIE.2. Some Experimental Dynamic ^1H NMR Data for Olefin **1a**, the $(Ph_3P)_2Pt$ Complex **106a**, Acetonide **79**, and Dimesylate **96**.

Compound	Site Exchanged[a]	$\Delta\nu$ (Hz)	T_c (K)	$\Delta G^{\neq}$ (kcal/mol)
1a	A', A''	112.0	308	14.6
	B', B''	167.9	316	14.8
106a	A', A''	171.7	301	14.1
	B', B''	126.6	305	14.4
79	A', A''	158.1	236	11.0
	B', B''	193.4	238	11.0
96	D', D''	265.5	198	8.89

[a] See the relavent NMR spectra for the keys to these labels.

Table IIIE.3. Experimental (NMR) and Calculated (MM2) Values for the Free Energy Barrier to Bridge Flipping (kcal/mol).

	$\Delta G^{\neq}$ exp[a]	$\Delta E^{\neq}$ calc	
		(C_{2v}) TS[b]	(C_2) TS[c]
n=3 olefin (1a)	14.9 ± 0.1	14.4	14.4
acetonide (79)	11.0 ± 0.1	14.5	11.9
n=3 olefin/H_2 (109)	-----	14.5	9.9
dimesylate (96)	9.0 ± 0.1	-----	-----
Pt complex (106a)	14.7 ± 0.1	-----	-----

[a] Average of experimental free energy barriers to bridge flipping found by using ^{13}C NMR. [b] C_{2v} symmetry imposed on the transition state. [c] C_2 symmetry imposed on the transition state.

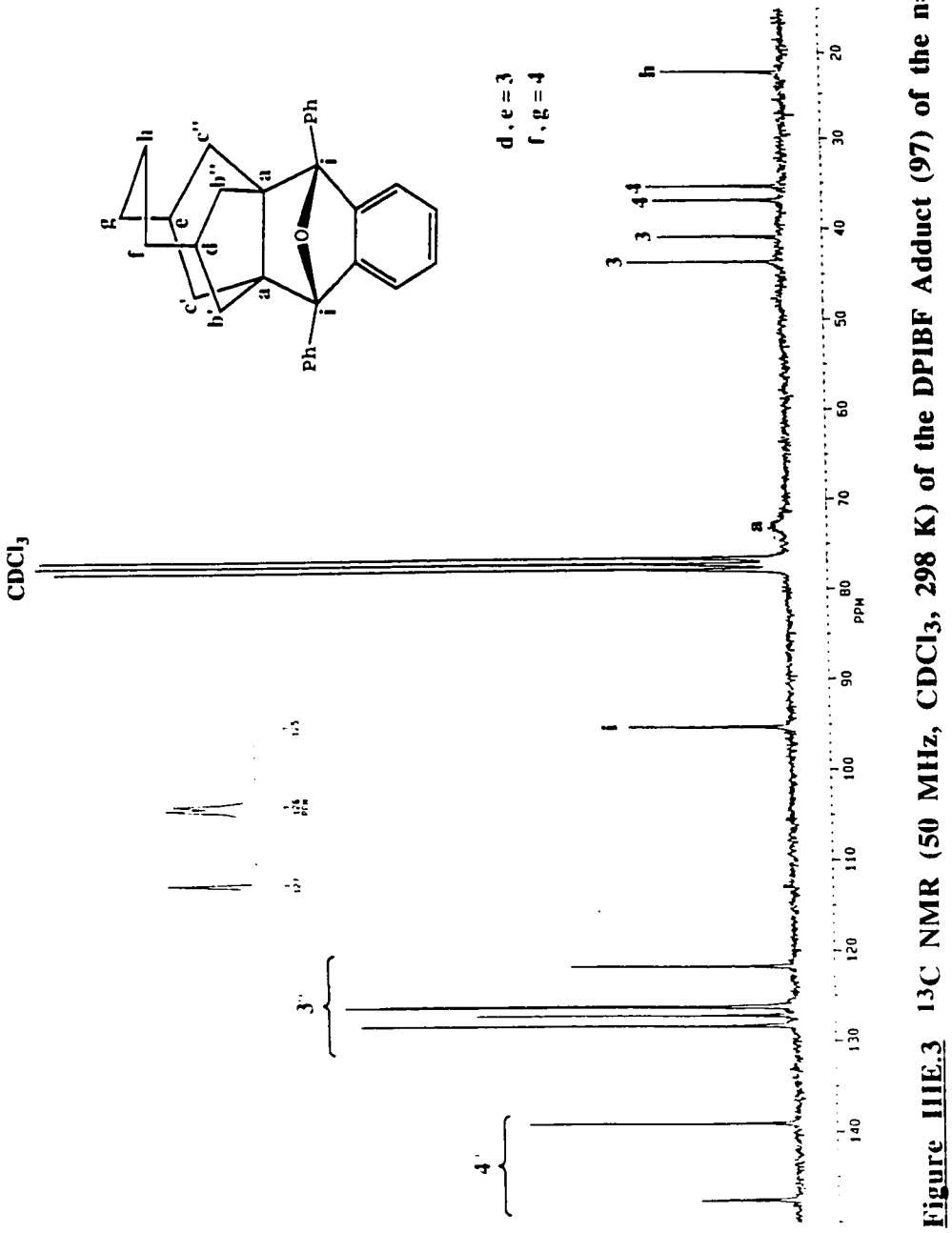


Figure IIIE.3 ^{13}C NMR (50 MHz, $CDCl_3$, 298 K) of the DPIBF Adduct (97) of the n=3 Olefin (1a).

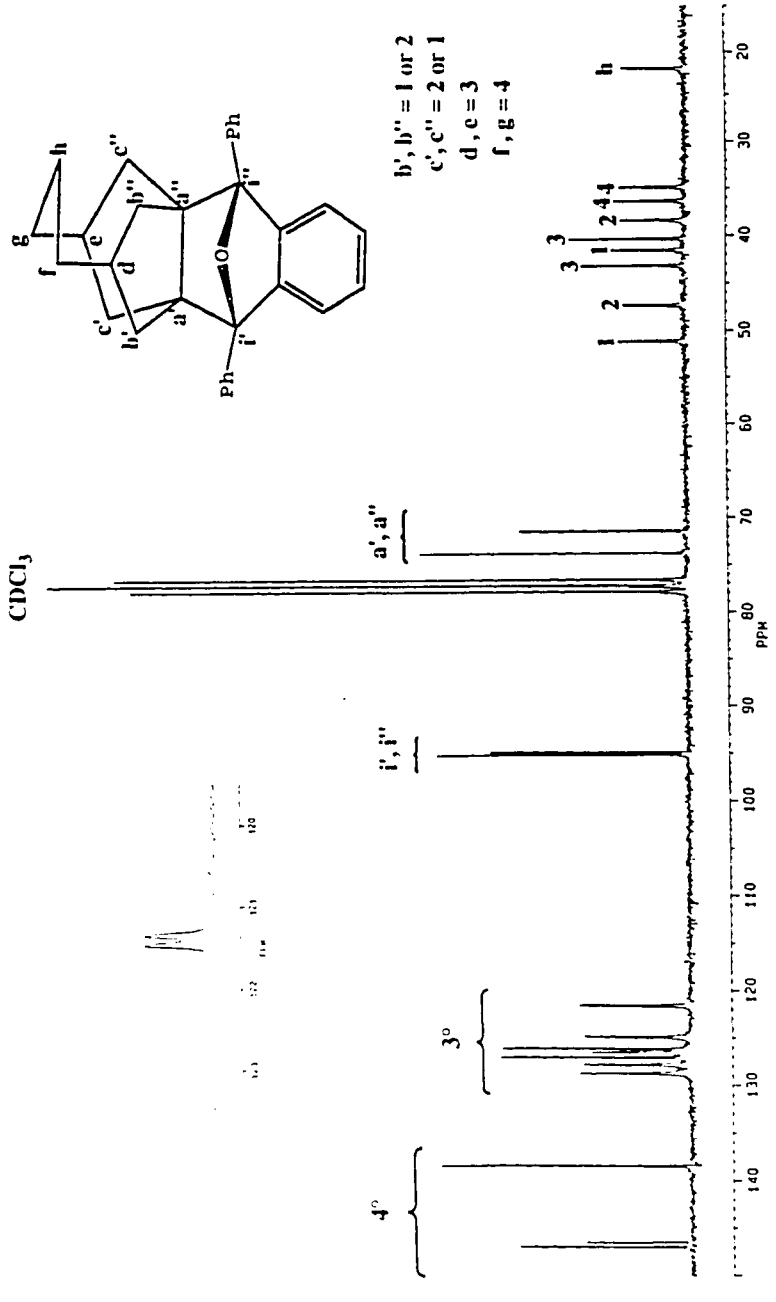


Figure IIIE.4 ^{13}C NMR (50 MHz, $CDCl_3$, 209 K) of the DPIBF Adduct (97) of the n=3 Olefin (1a).

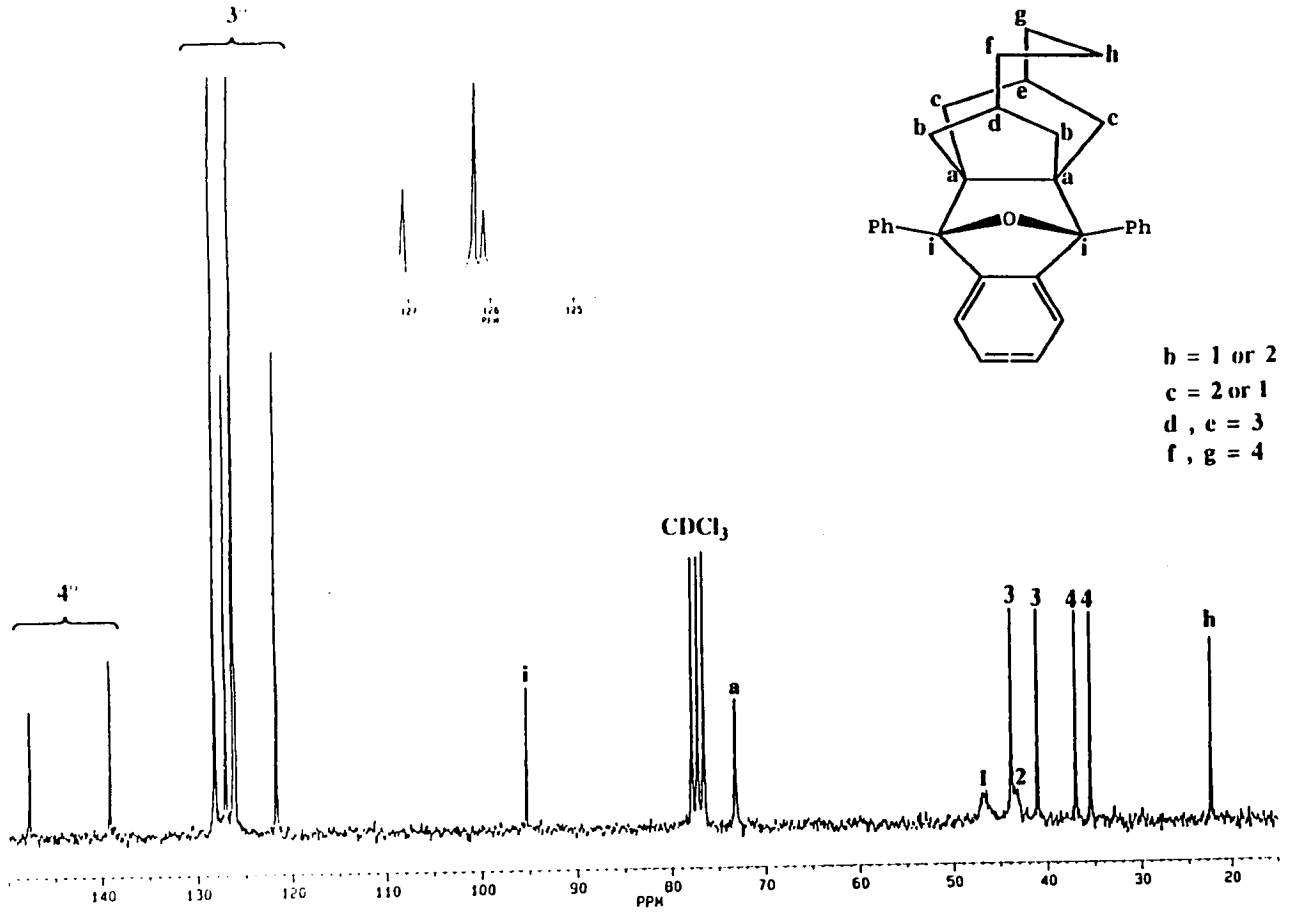


Figure IIIE.5 ^{13}C NMR (50 MHz, $CDCl_3$, 343 K) of the DPIBF Adduct (97) of the n=3 Olefin (1a).

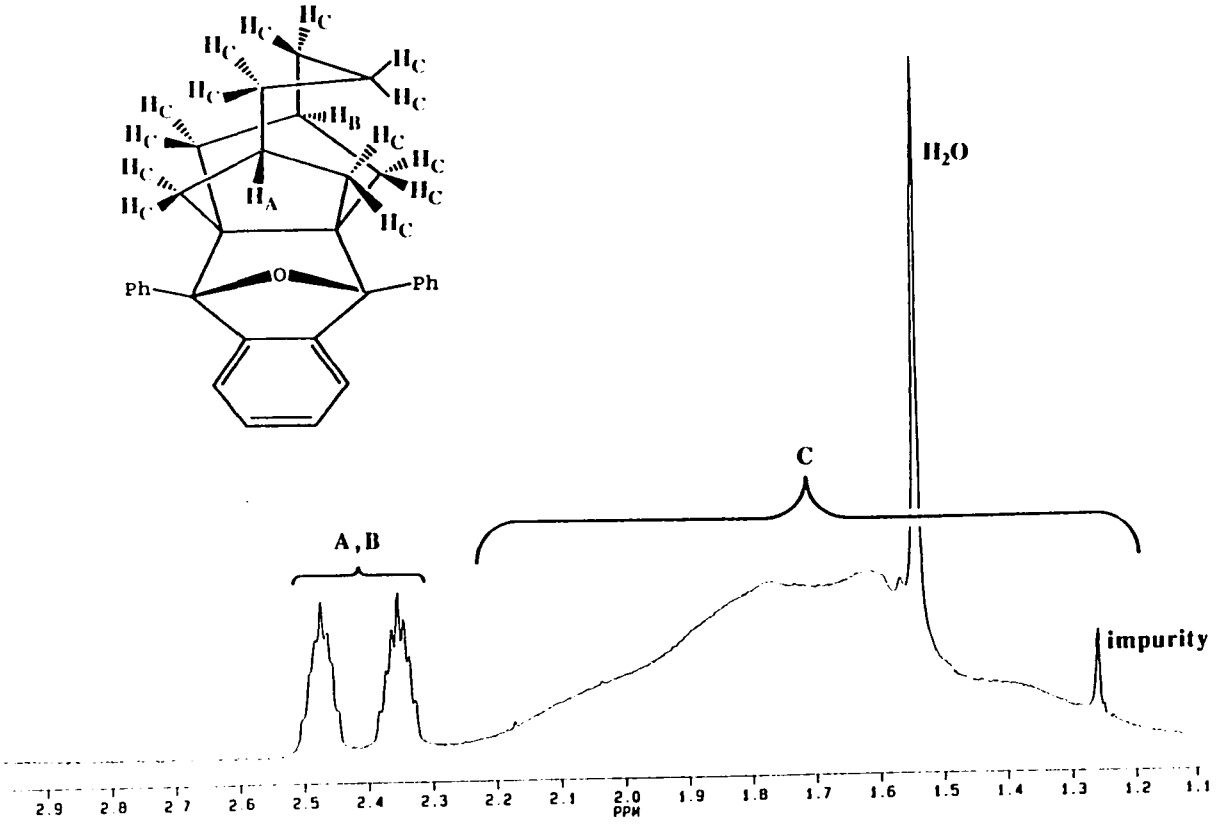


Figure IIIE.6 ^1H NMR (500 MHz, $CDCl_3$, 298 K) of the DPIBF Adduct (97) of the n=3 Olefin (1a).

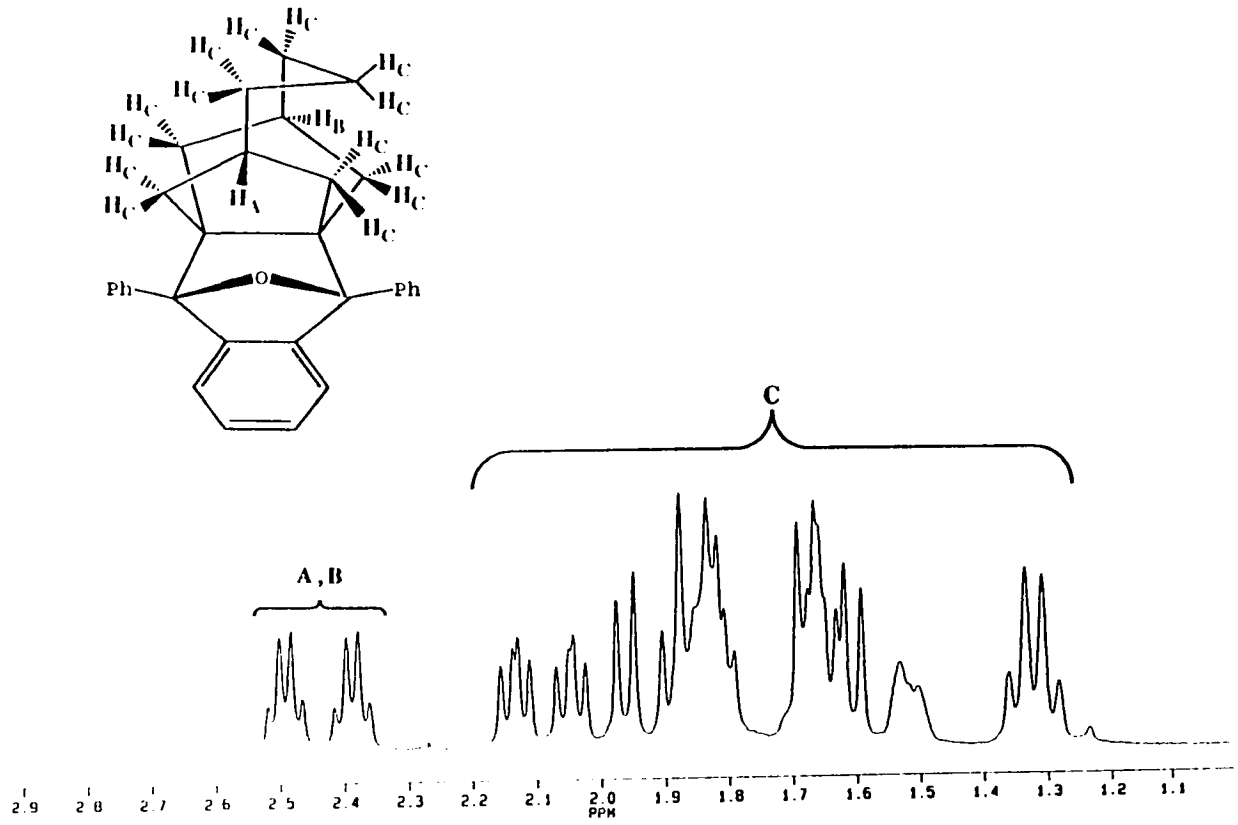


Figure IIIE.7 ^{1}H NMR (500 MHz, $CDCl_3$, 217 K) of the DPIBF Adduct (97) of the n=3 Olefin (1a).

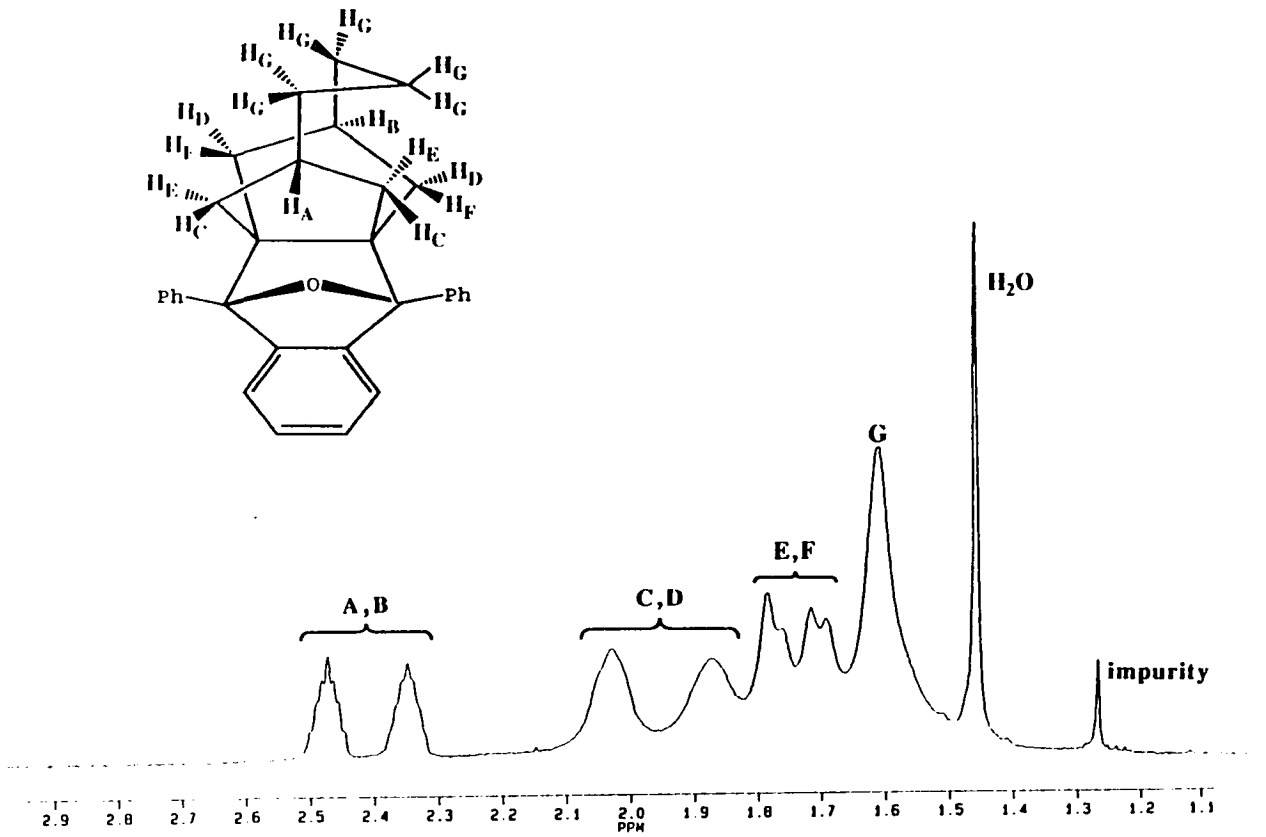


Figure IIIE.8 ^{1}H NMR (500 MHz, $CDCl_3$, 325 K) of the DPIBF Adduct (97) of the n=3 Olefin (1a).

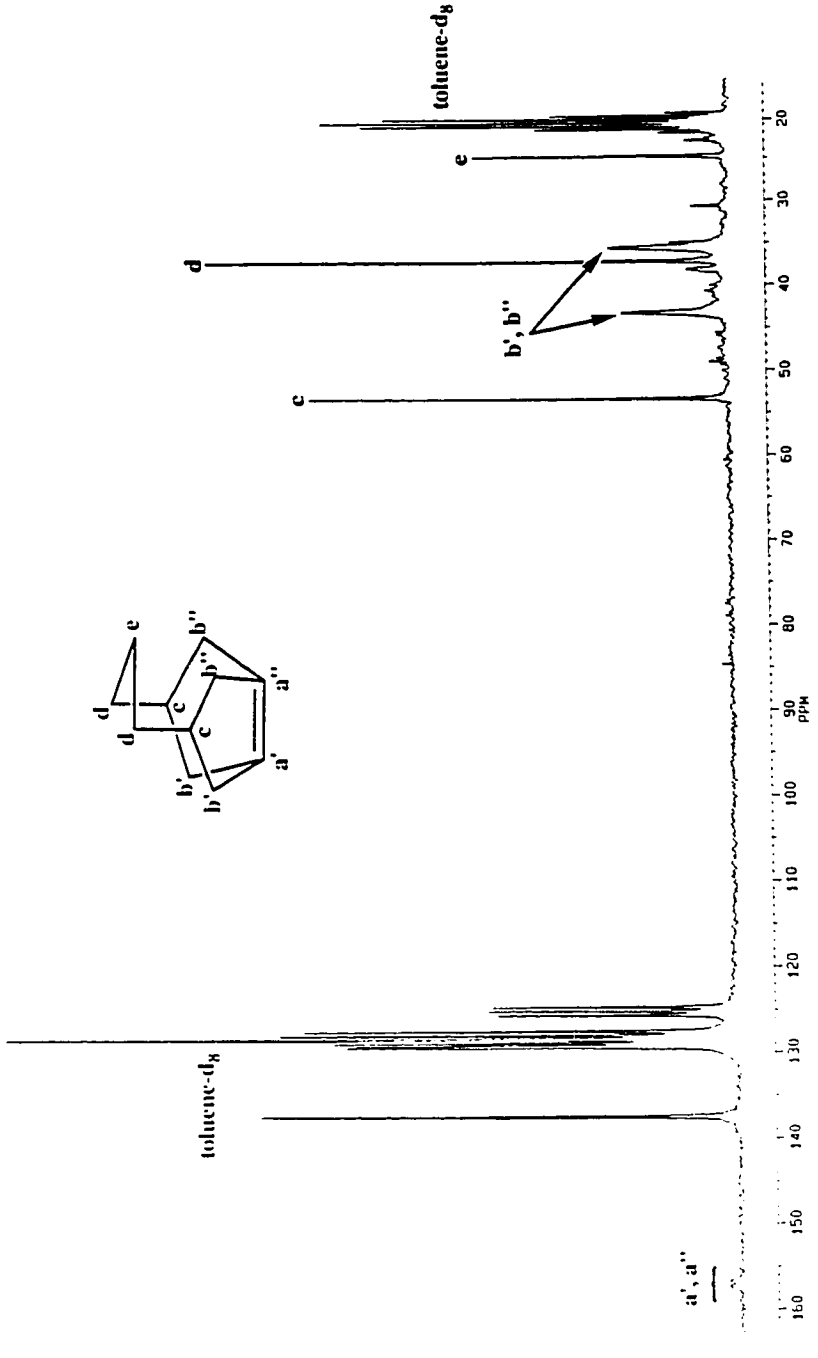


Figure IIIE.9 ^{13}C NMR (50 MHz, Toluene-d_8, 298 K) of the n=3 Olefin (1a).

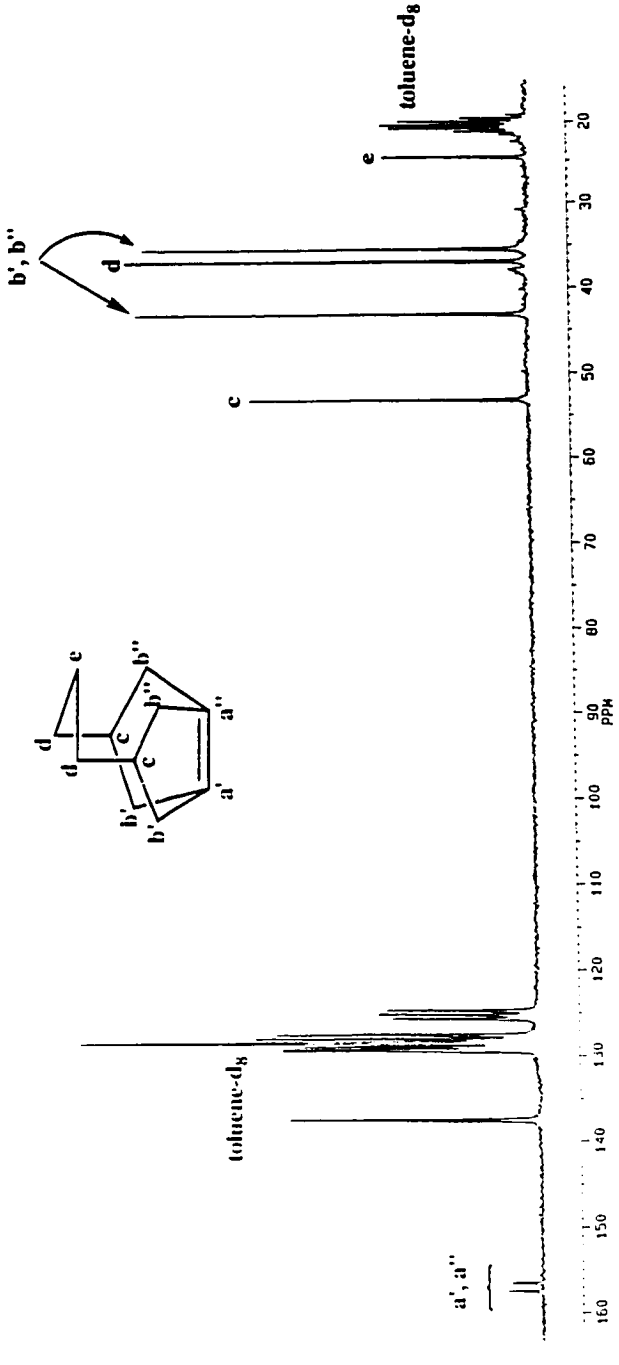


Figure IIIE.1() ^{13}C NMR (50 MHz, Toluene-d_8, 240 K) of the n=3 Olefin (1a).

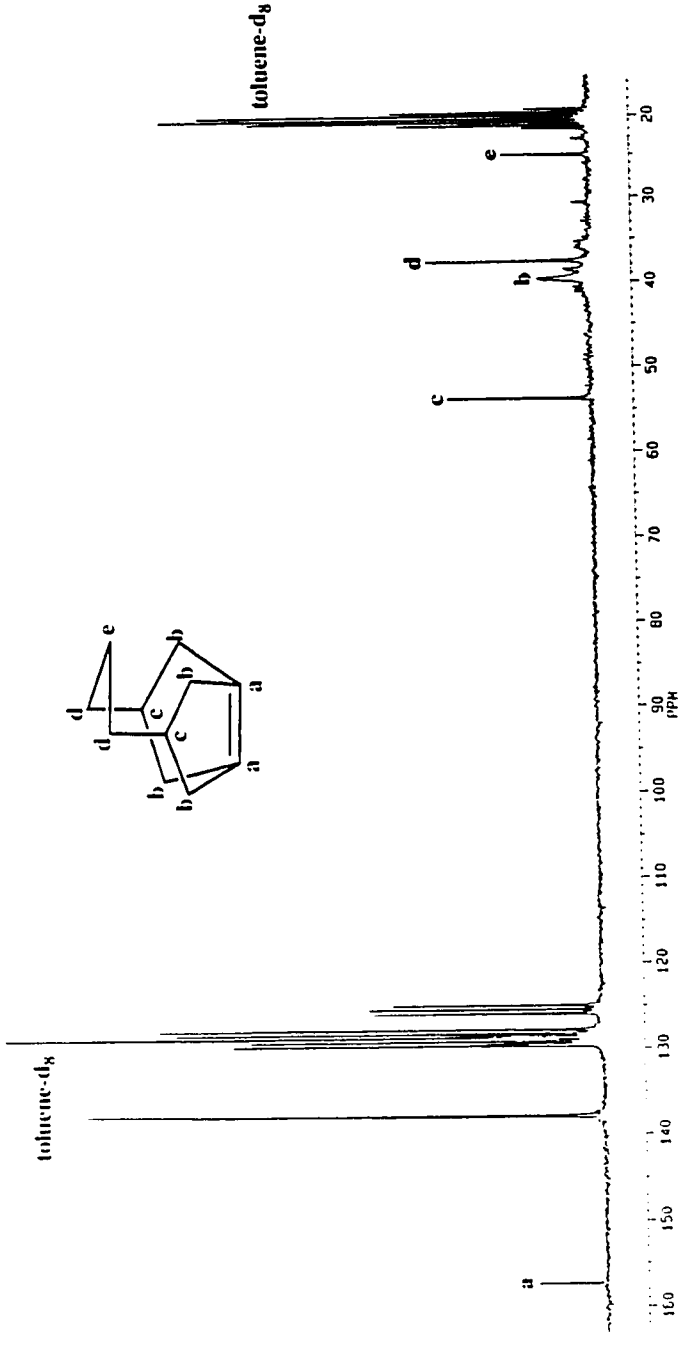


Figure IIIE.11 ^{13}C NMR (50 MHz, Toluene-d_8, 371 K) of the n=3 Olefin (1a).

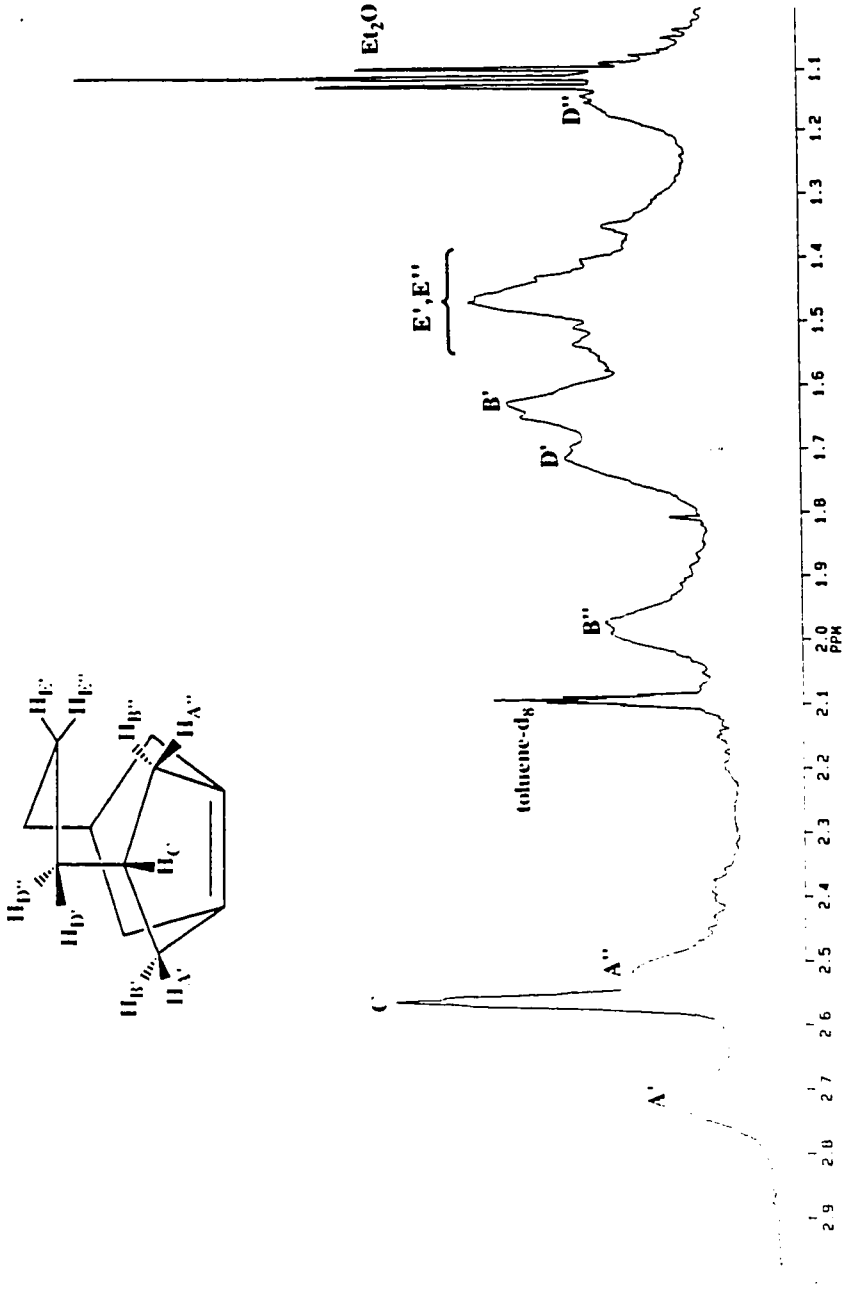
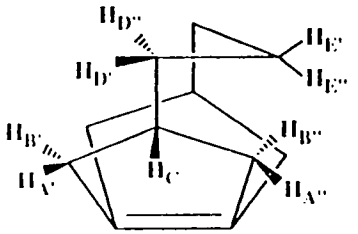


Figure IIIE.12 ^{1}H NMR (500 MHz, Toluene-d$_8$, 298 K) of the n=3 Olefin (1a).



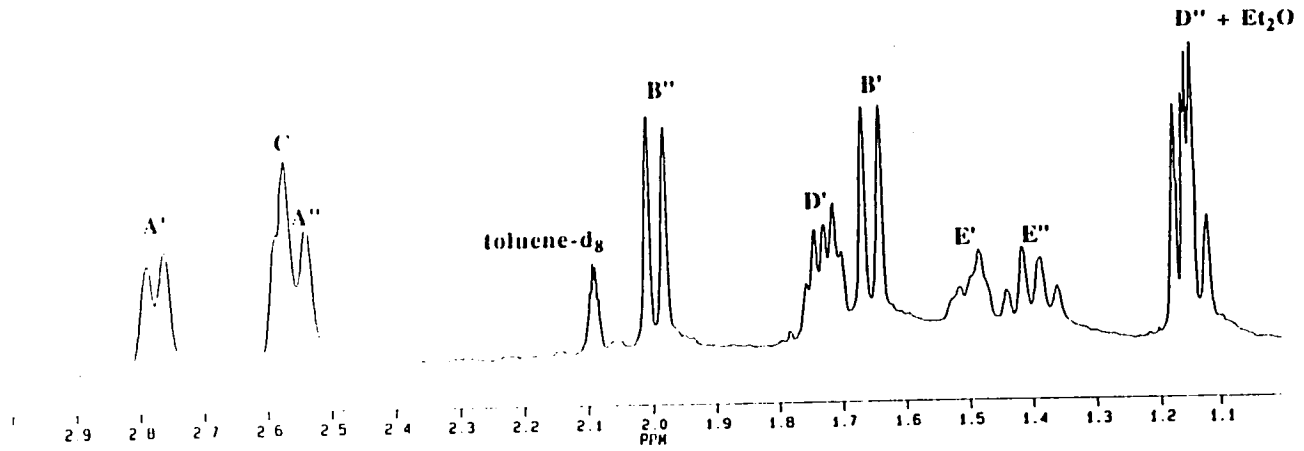


Figure IIIE.13 **^{1}H NMR (500 MHz, Toluene-d_8, 246 K) of the n=3 Olefin (1a).**

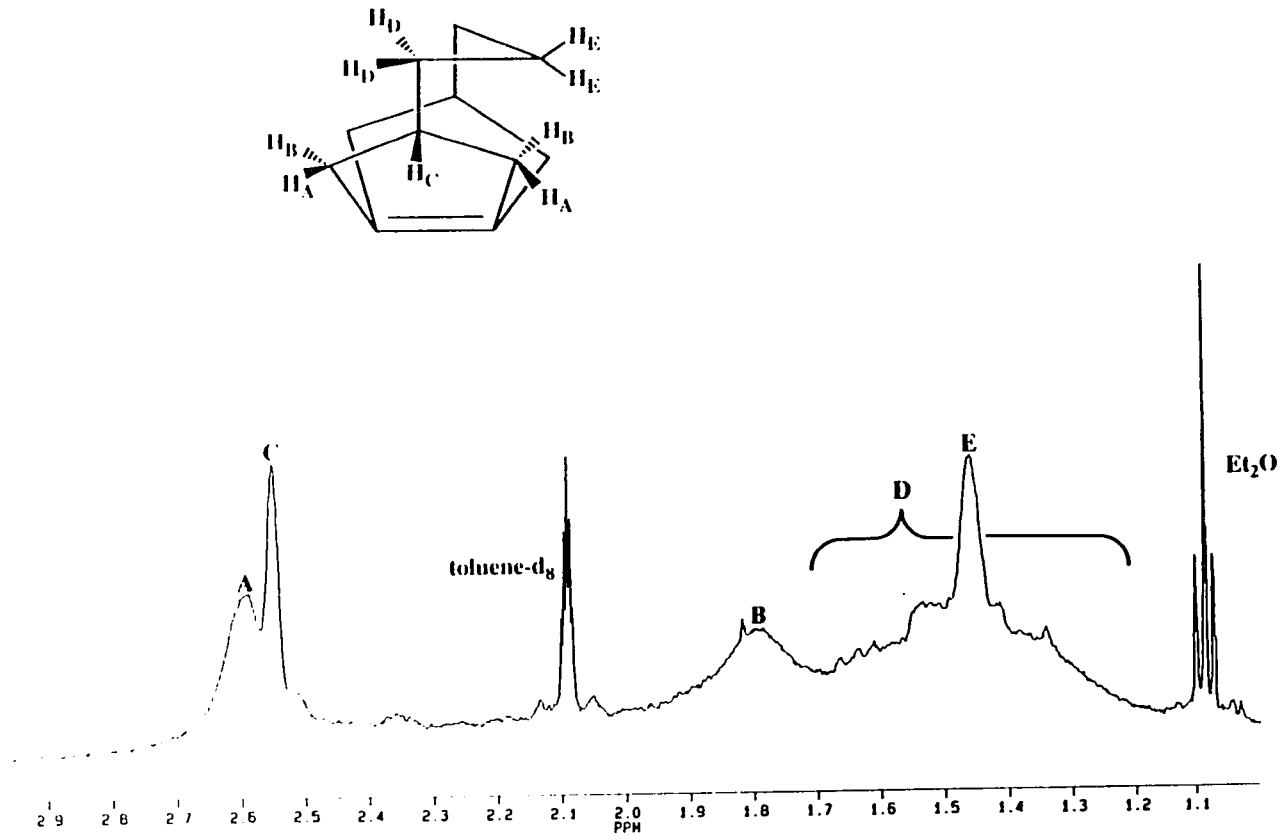


Figure IIIE.14 ^{1}H NMR (500 MHz, Toluene-d_8, 332 K) of the n=3 Olefin (1a).

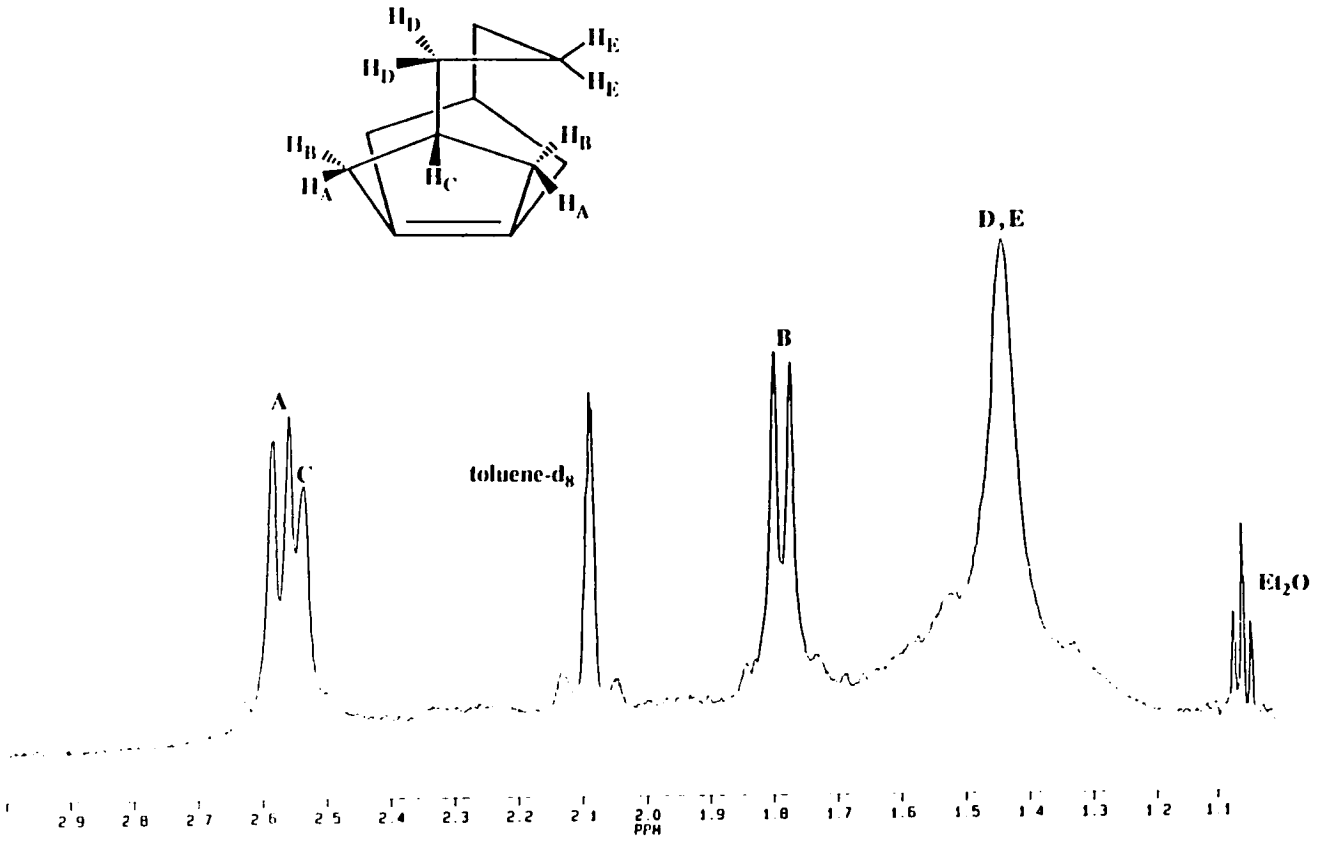


Figure IIIE.15 ^{1}H NMR (500 MHz, Toluene-d_8, 386 K) of the n=3 Olefin (1a).

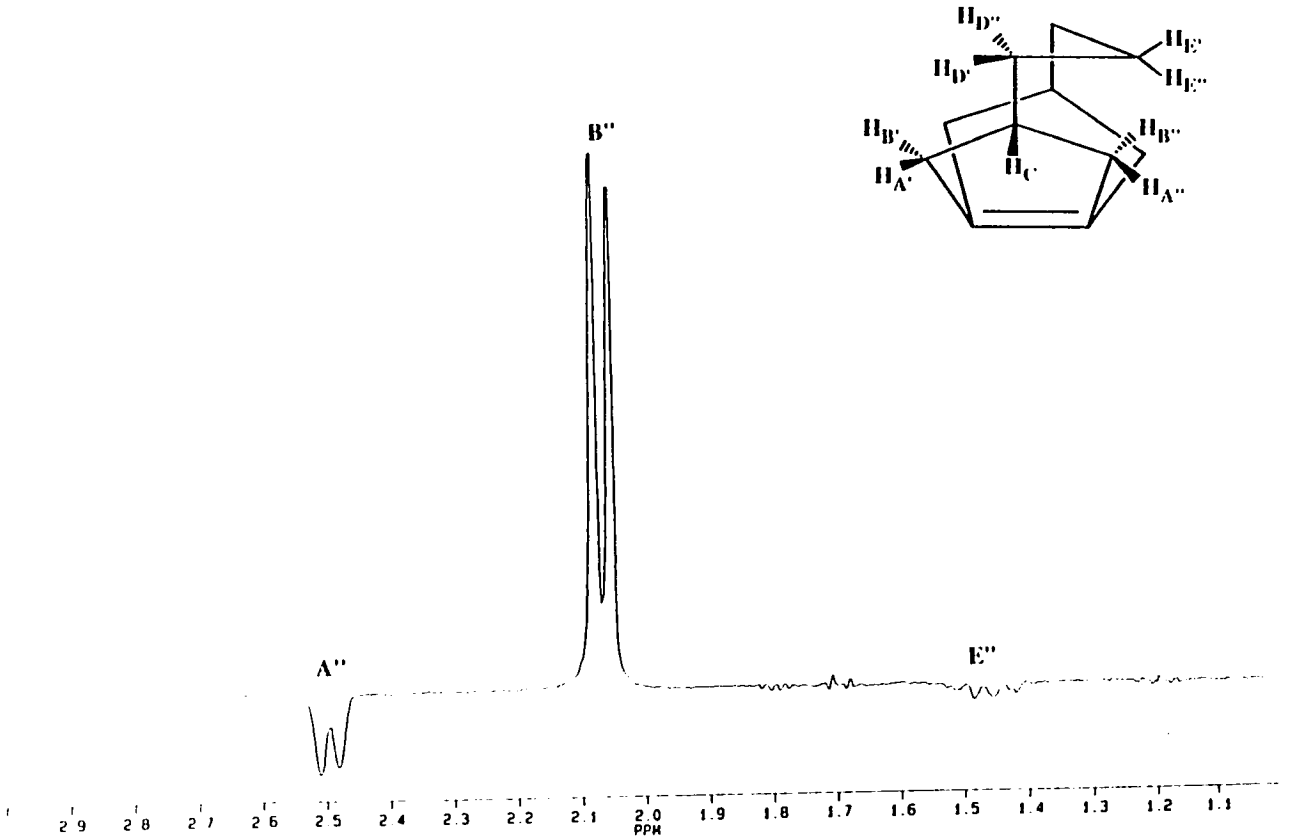


Figure IIIE.16 ^{1}H NMR-1D NOE (500 MHz, $CDCl_3$, 213 K, irrad. at δ 2.07) of the n=3 Olefin (1a).

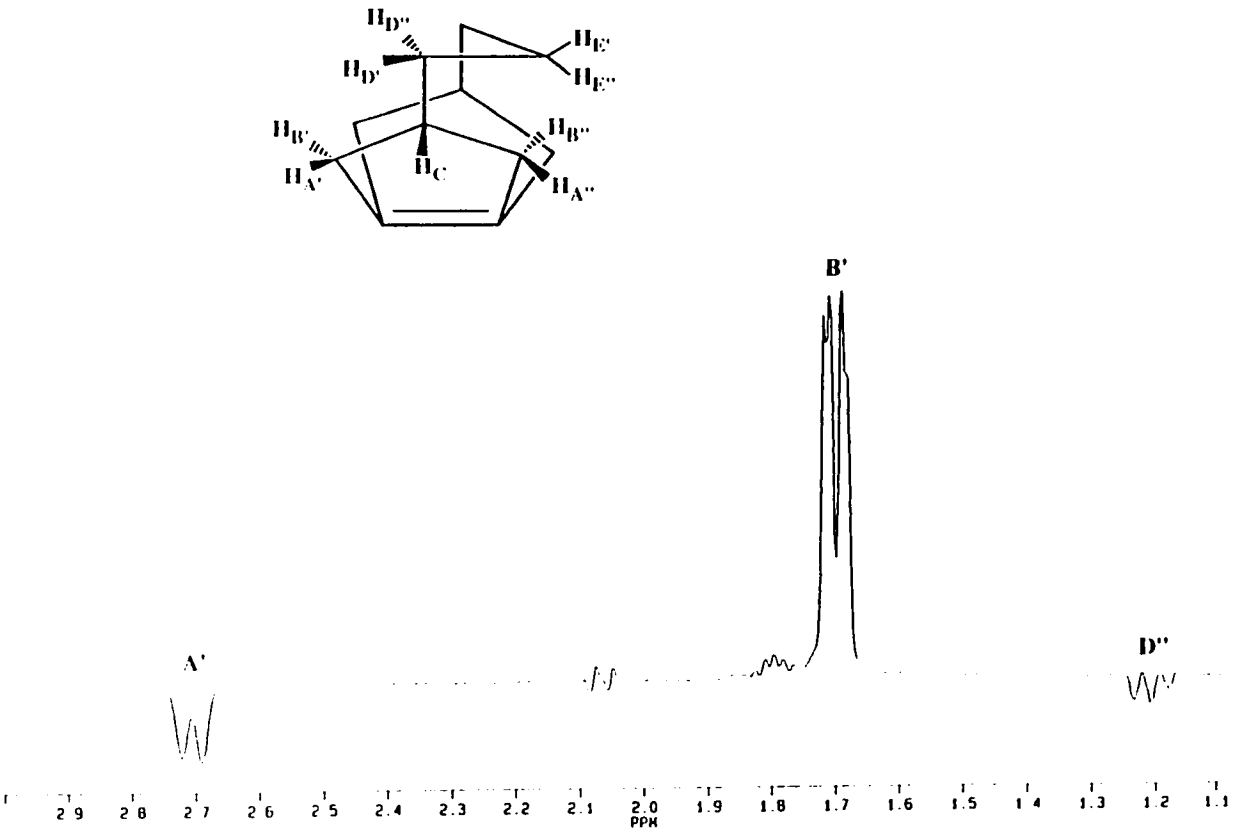


Figure IIIE.17 **^{1}H NMR-1D NOE (500 MHz, $CDCl_3$, 213 K, irrad. at δ 1.69) of the n=3 Olefin (1a).**

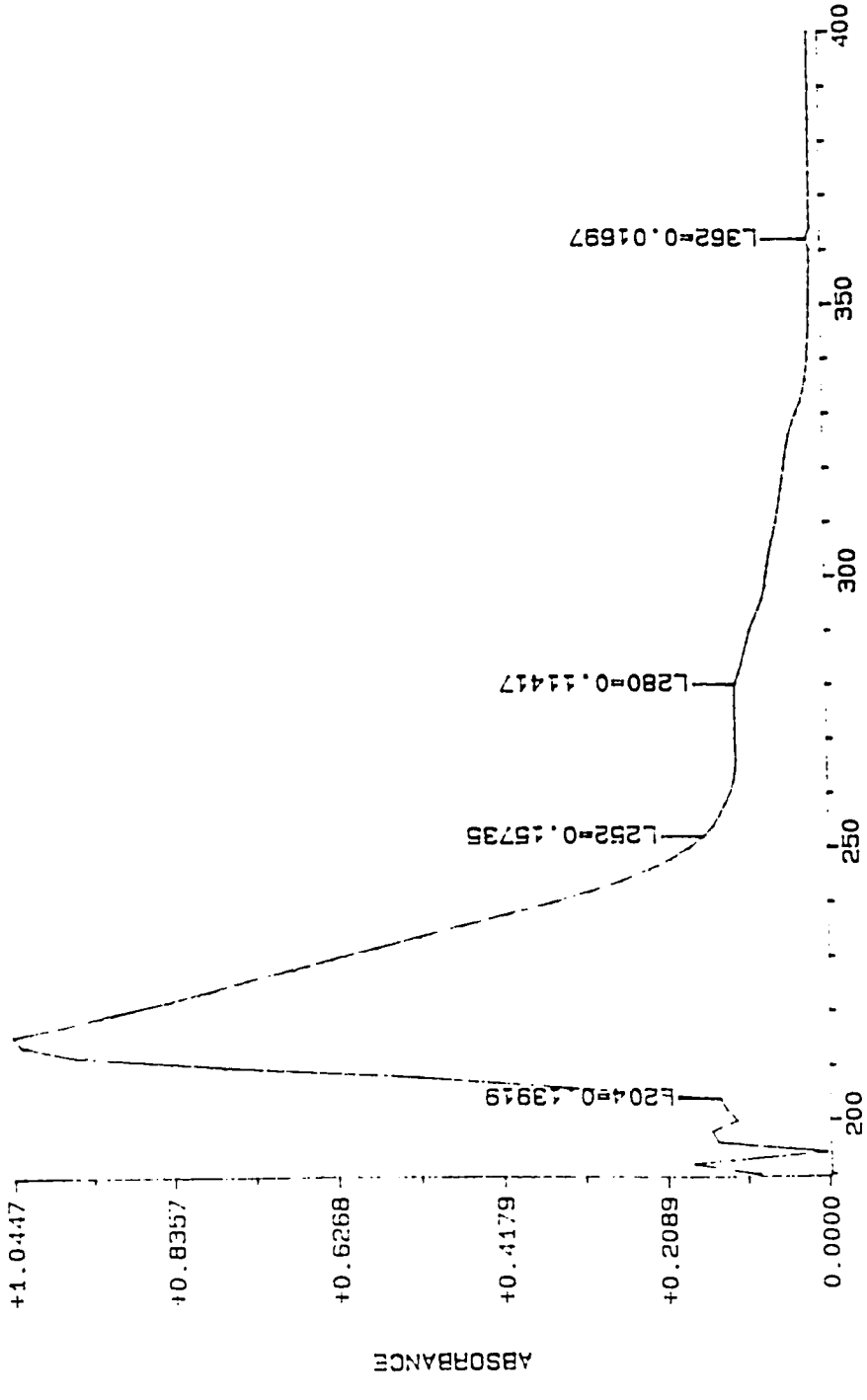


Figure IIIE.18 UV Spectrum of the n=3 Olefin (1a) in Pentane.

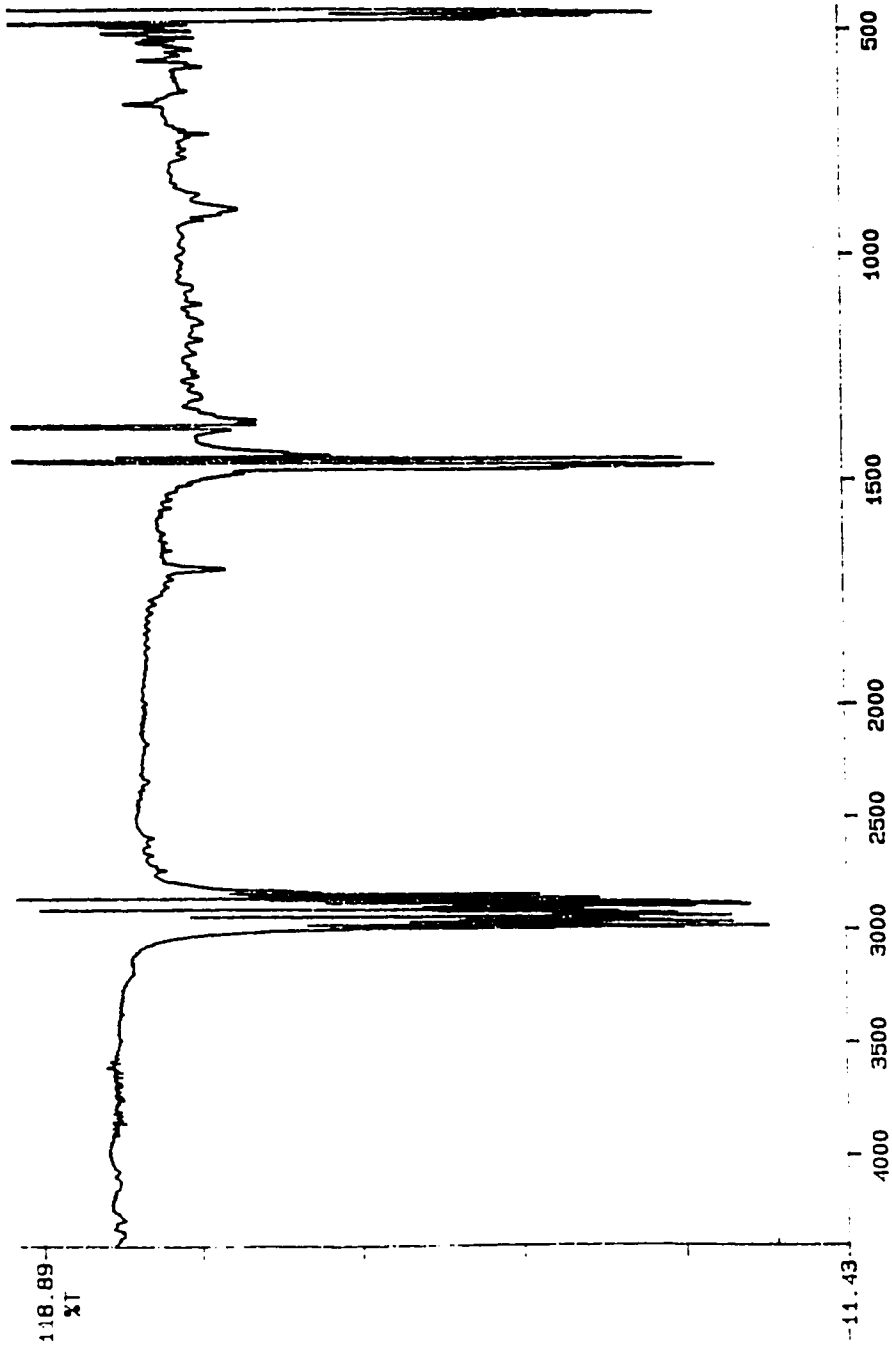


Figure IIIE.19 **IR Spectrum of the n=3 Olefin (1a) in Pentane.**

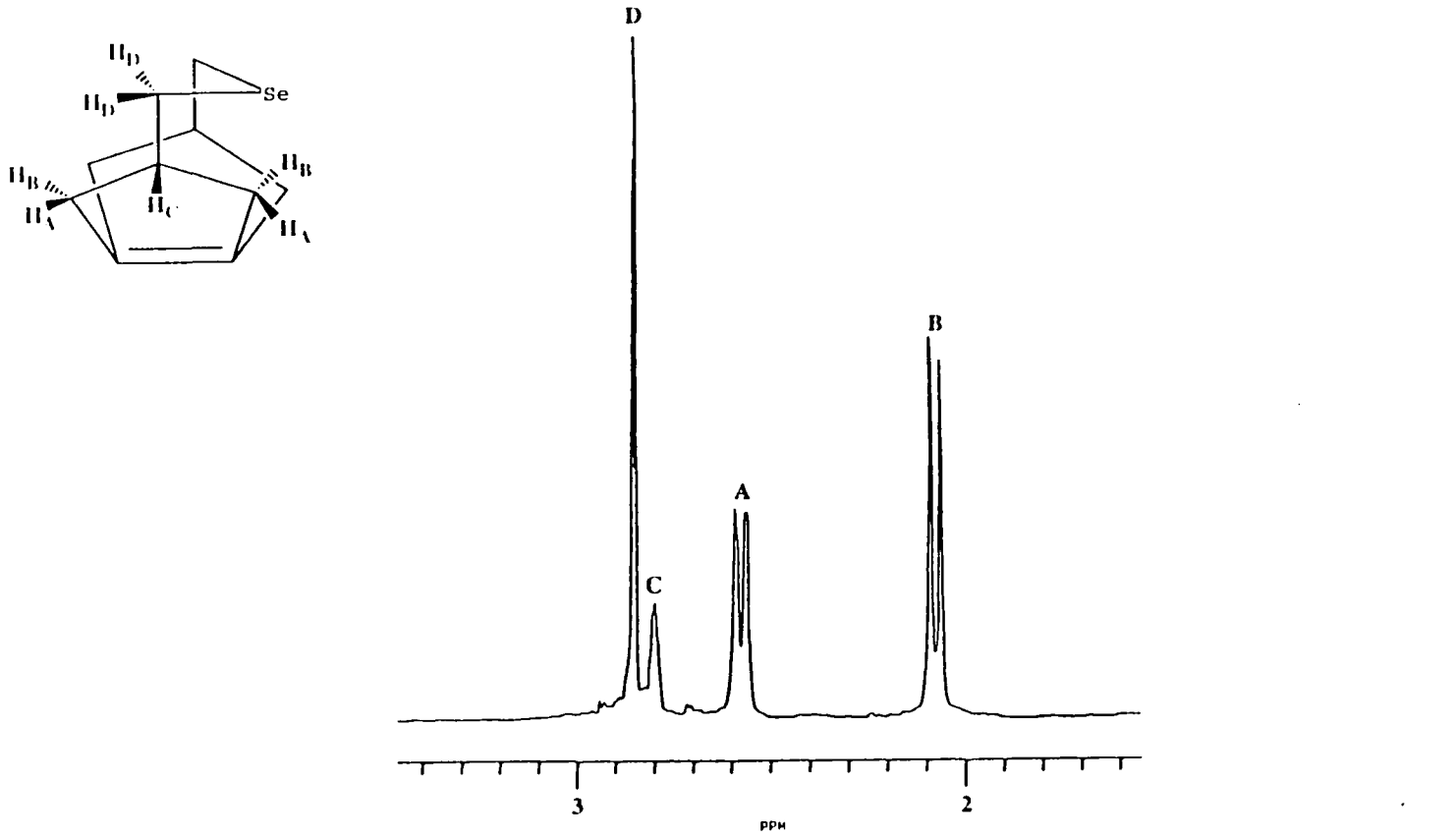


Figure IIIE.20 **^{1}H NMR (500 MHz, $CDCl_3$, 298 K) of the Se Bridged n=3 Olefin (5a).**

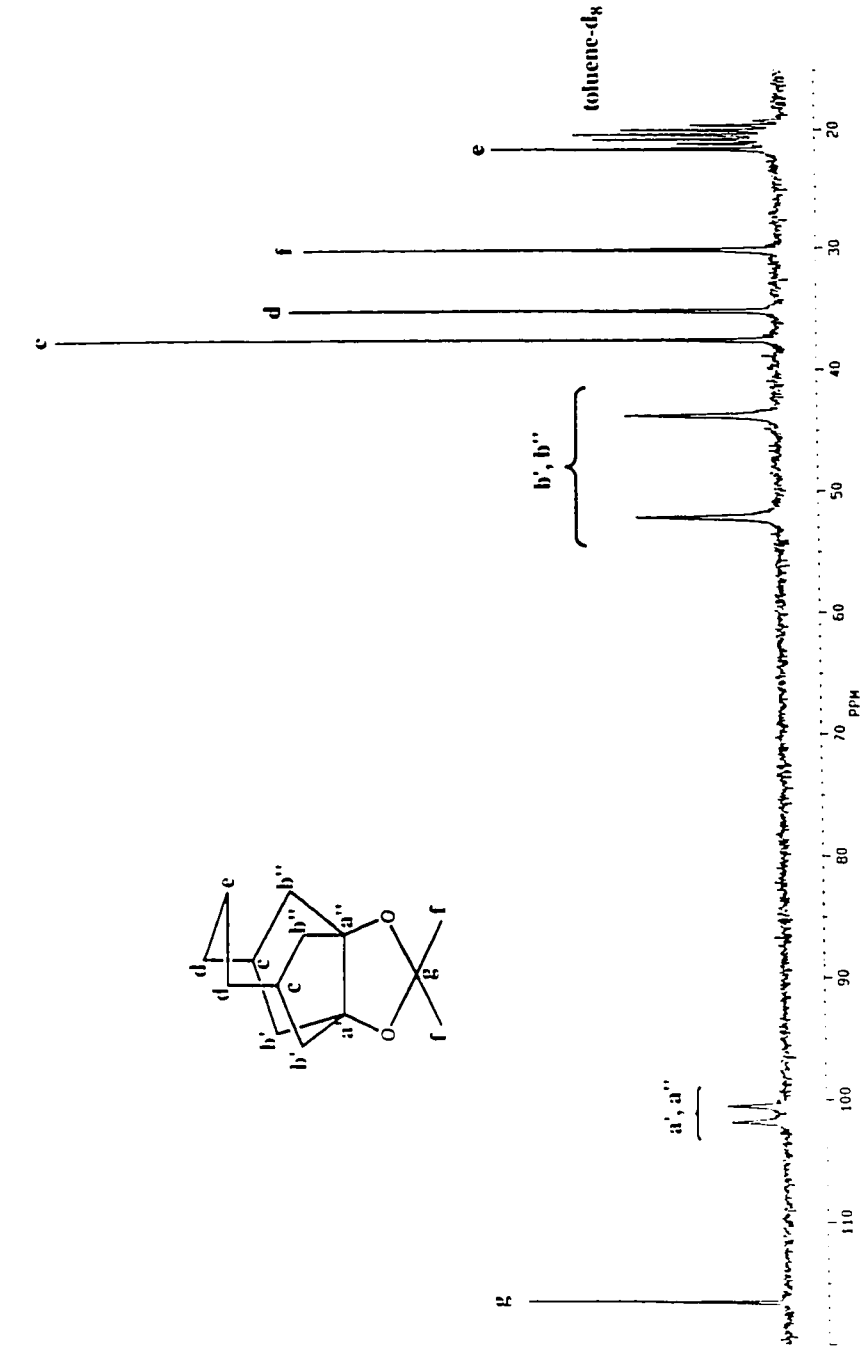


Figure IIIE.21 ^{13}C NMR (50 MHz, Toluene-d_8, 215 K) of Acetonide 79.

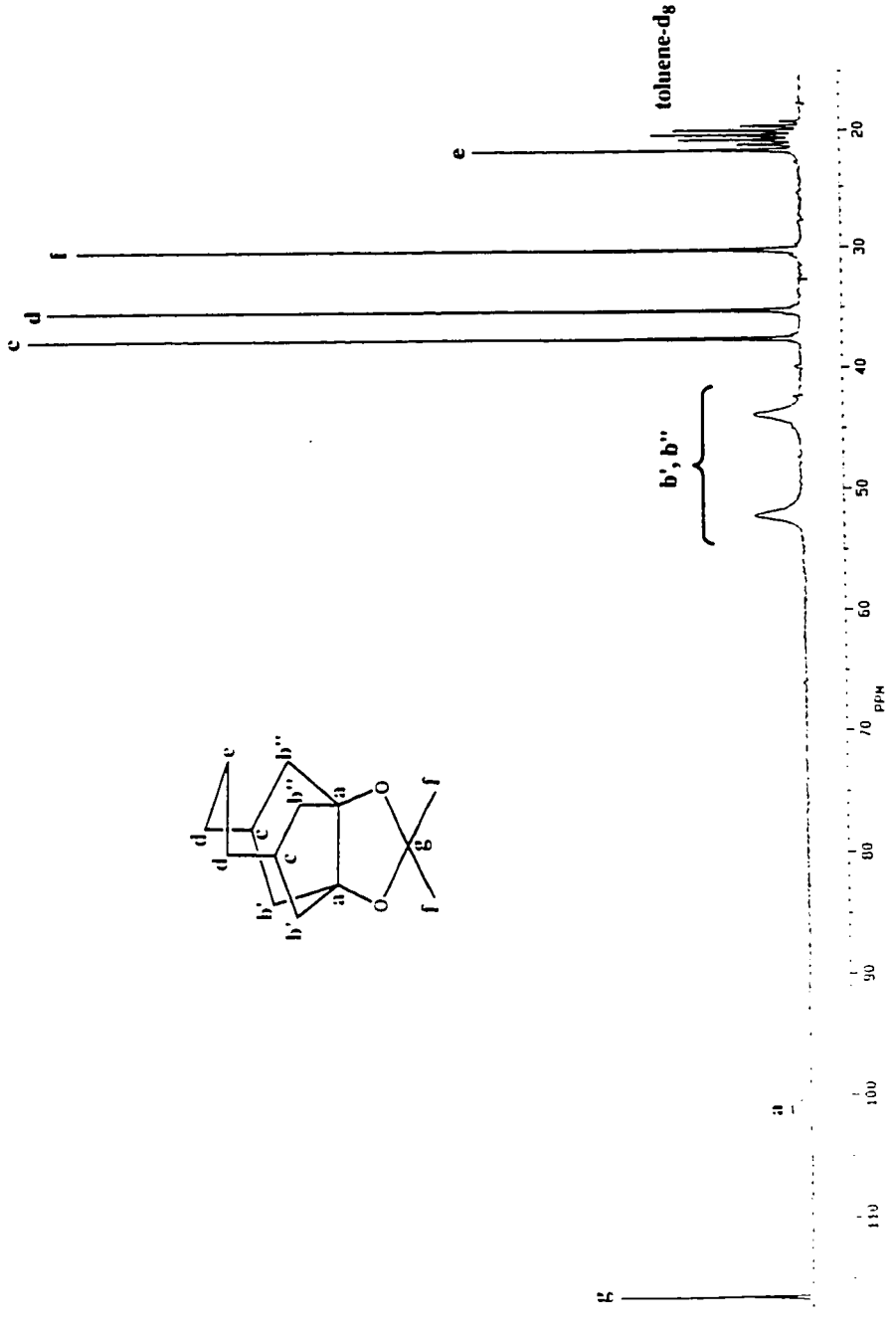


Figure IIIE.22 ^{13}C NMR (50 MHz, Toluene-d_8, 228 K) of Acetonide 79.

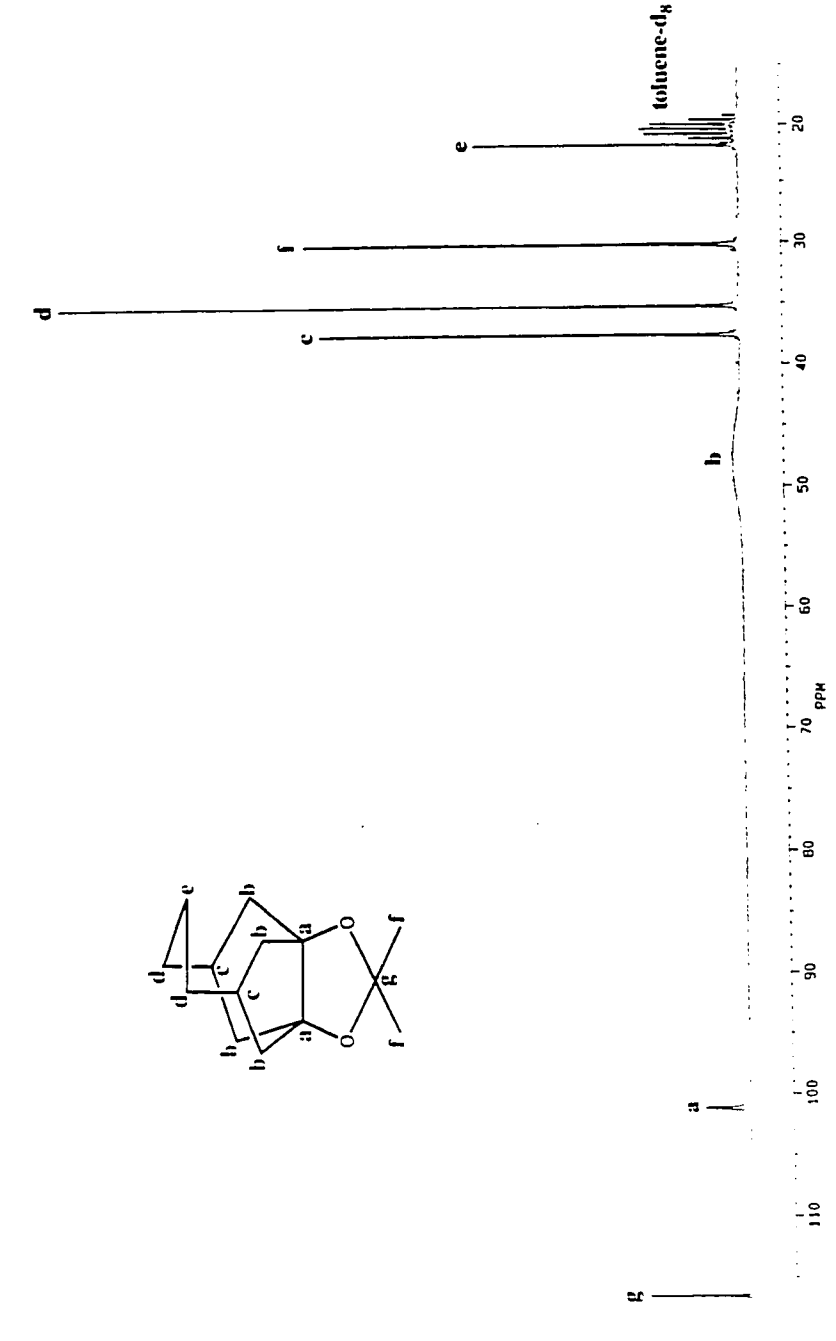


Figure IIIE.23 ^{13}C NMR (50 MHz, Toluene-d8, 248 K) of Acetonide 79.

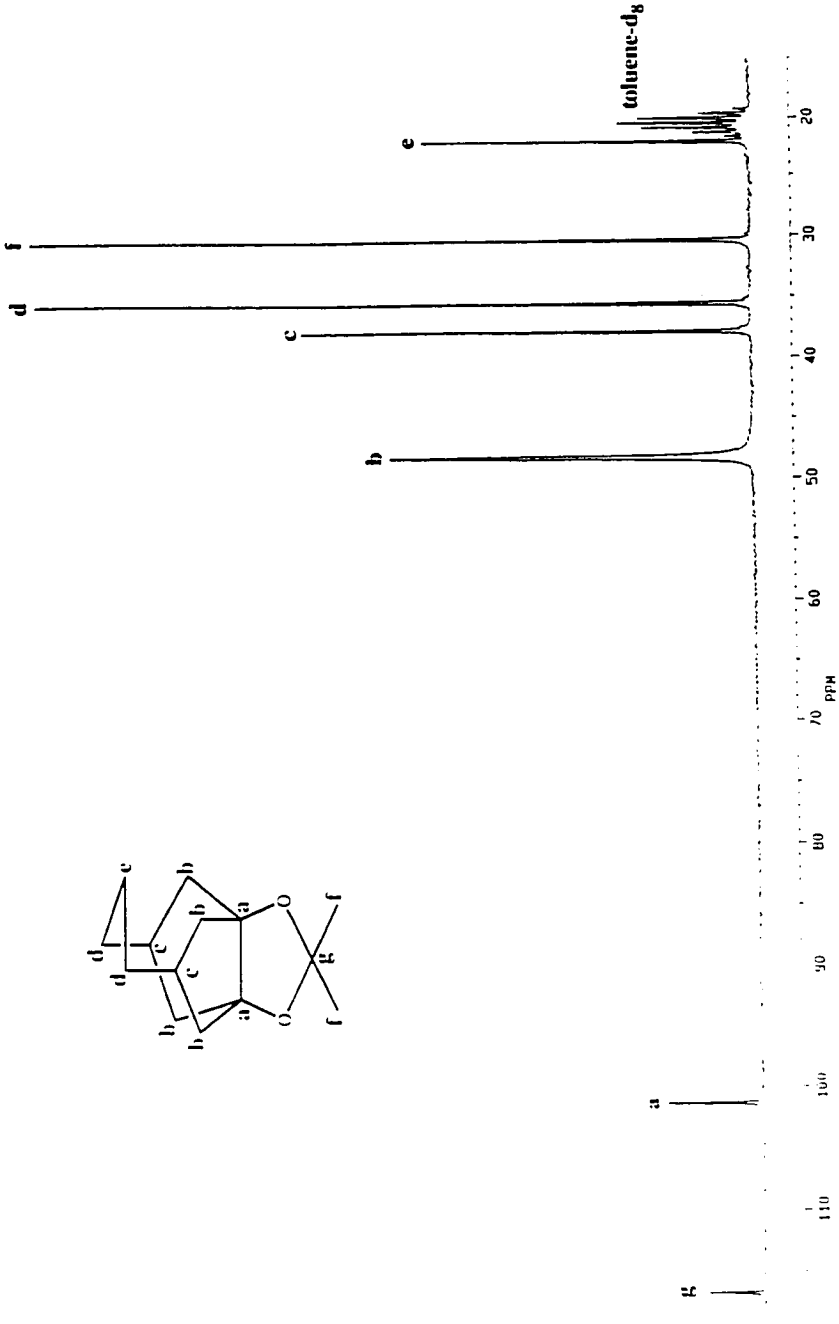


Figure IIIE.24 ^{13}C NMR (50 MHz, Toluene-d_8, 298 K) of Acetonide 79.

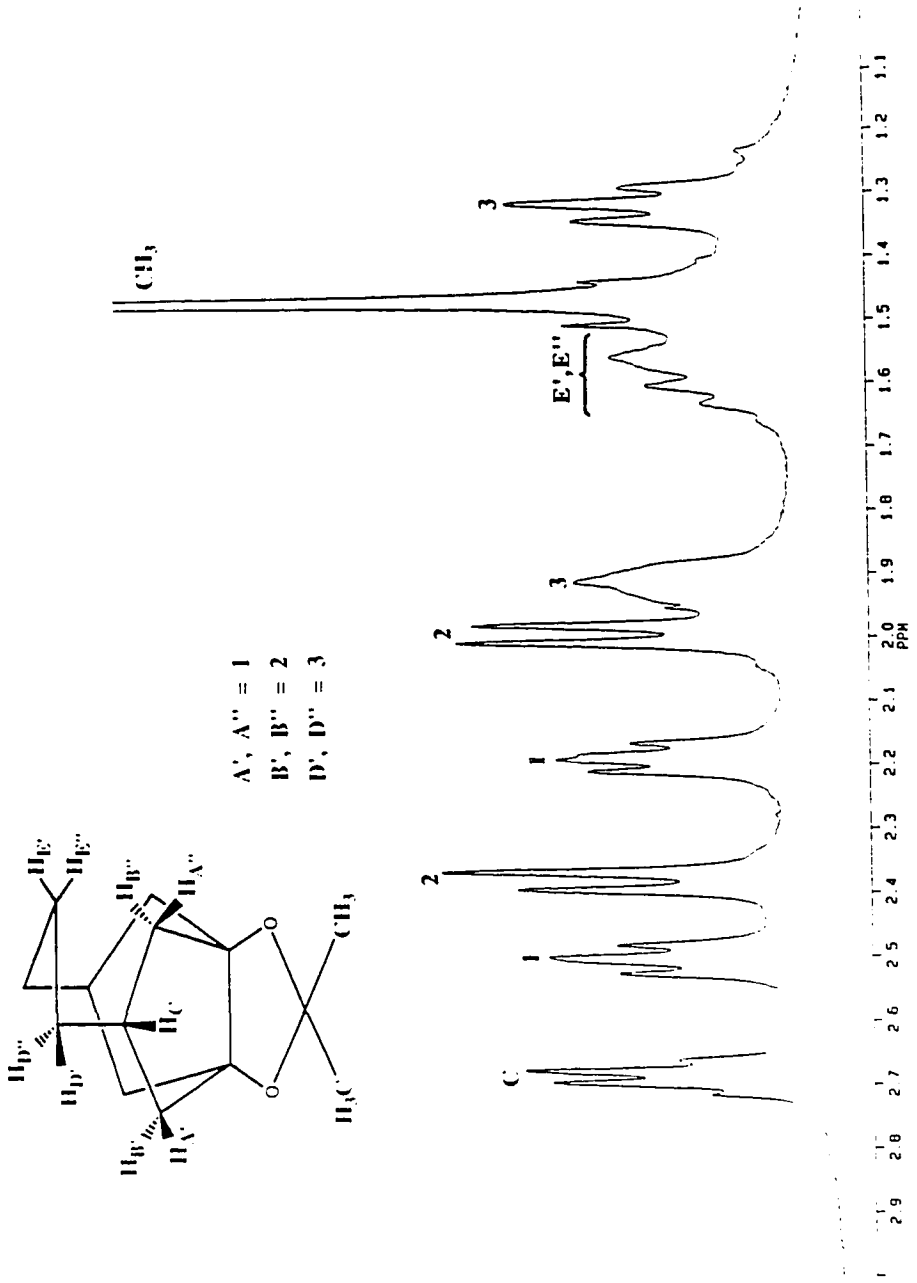


Figure IIIE.25 ^{1}H NMR (500 MHz, $CDCl_3$, 208 K) of Acetonide 79.

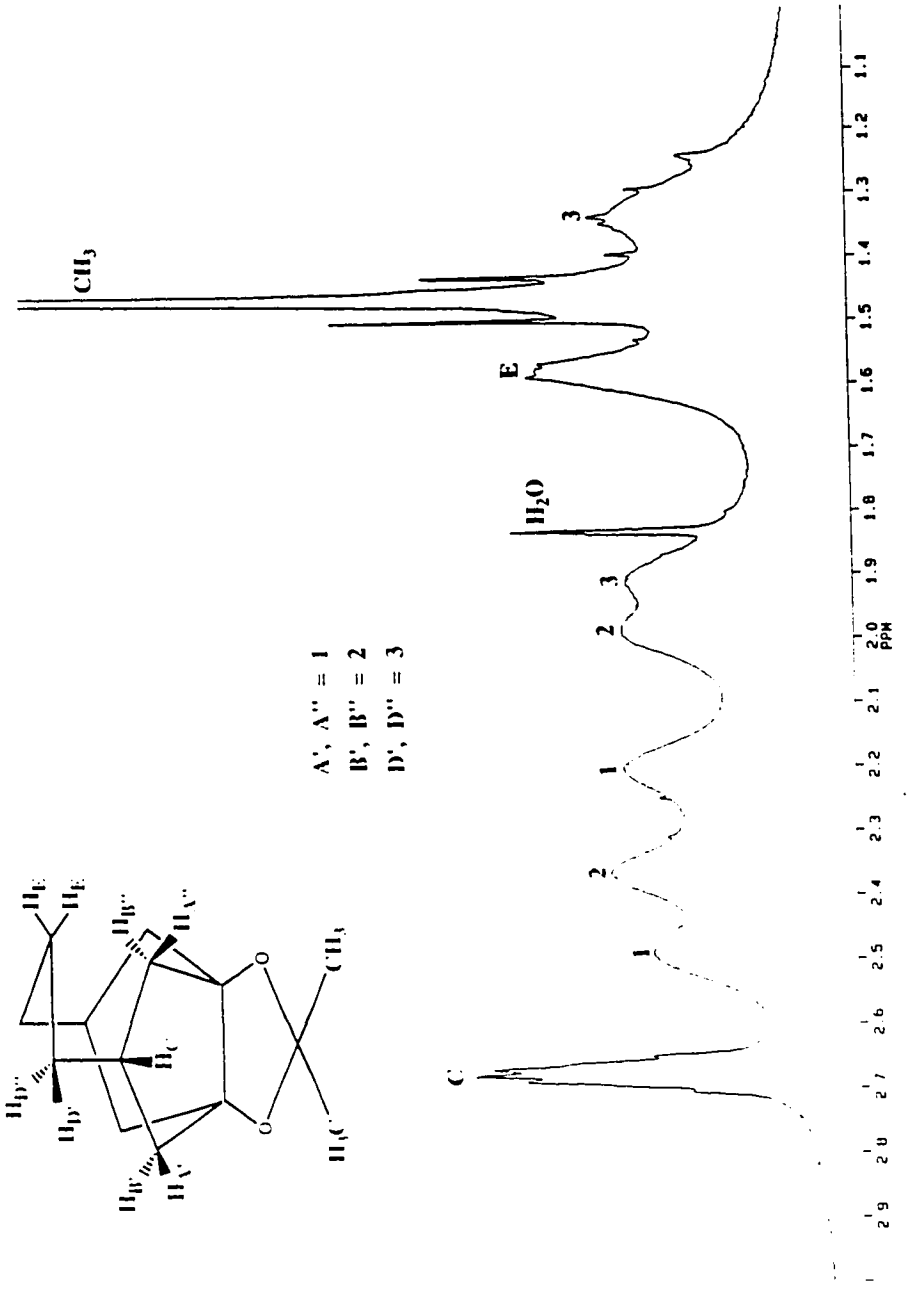


Figure IIIE.26 ^{1}H NMR (500 MHz, $CDCl_3$, 231 K) of Acetonide 79.

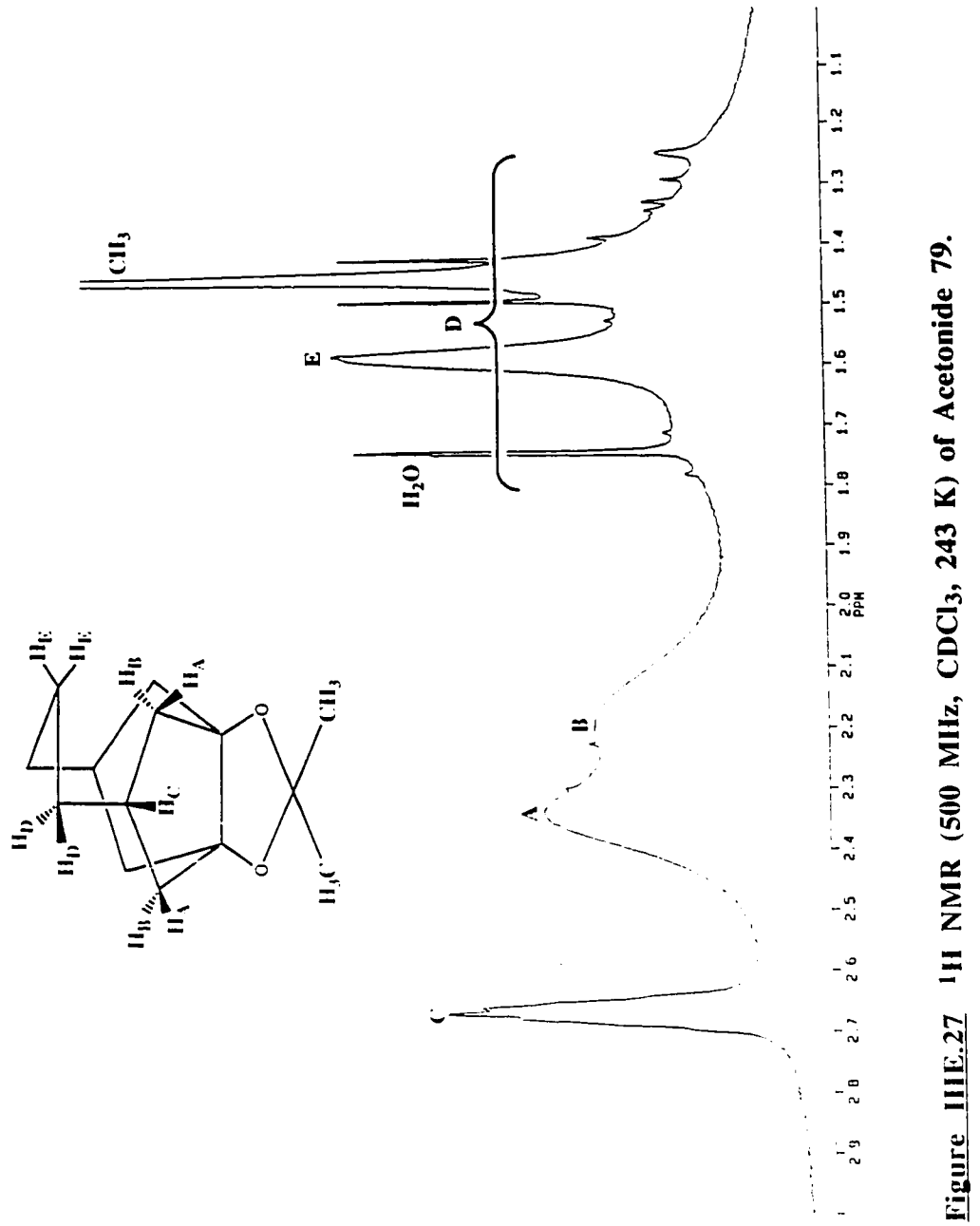


Figure IIIE.27 ^{1}H NMR (500 MHz, $CDCl_3$, 243 K) of Acetonide 79.

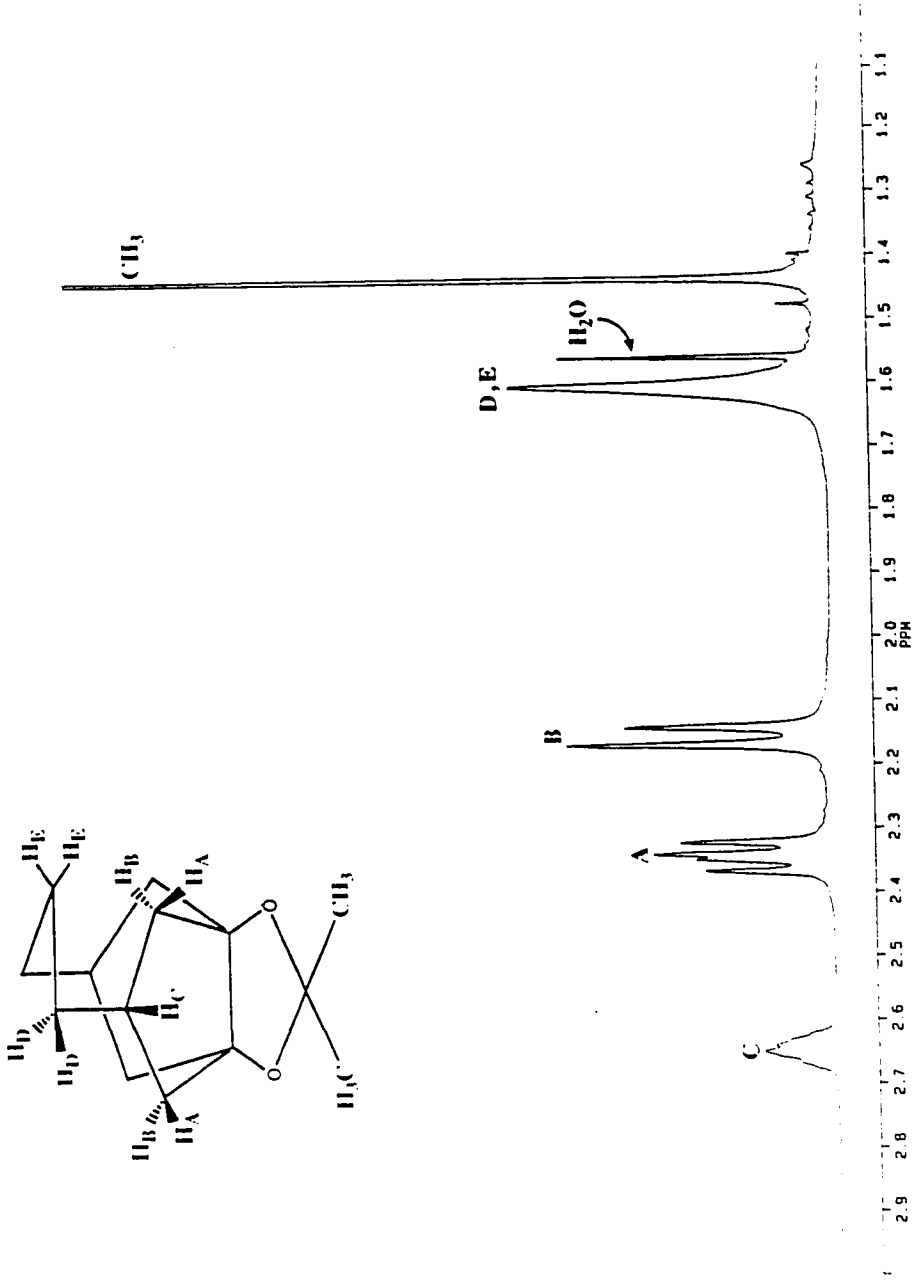


Figure IIIE.28 ^1H NMR (500 MHz, $CDCl_3$, 298 K) of Acetonide 79.

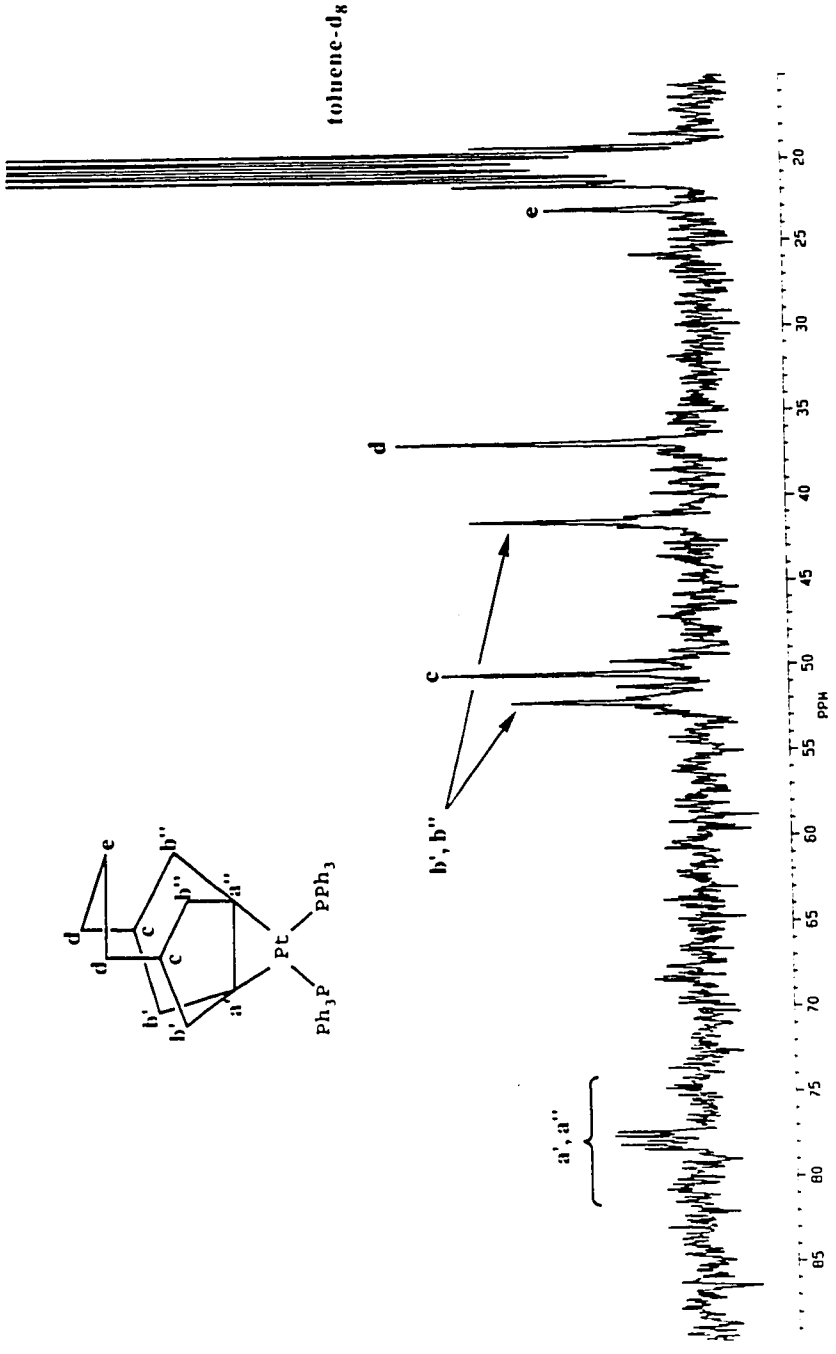


Figure IIIE.29 ^{13}C NMR (50 MHz, Toluene-d_8, 229 K) of the $(Ph_3P)_2Pt$ Complex (106a) of the n=3 Olefin (1a).

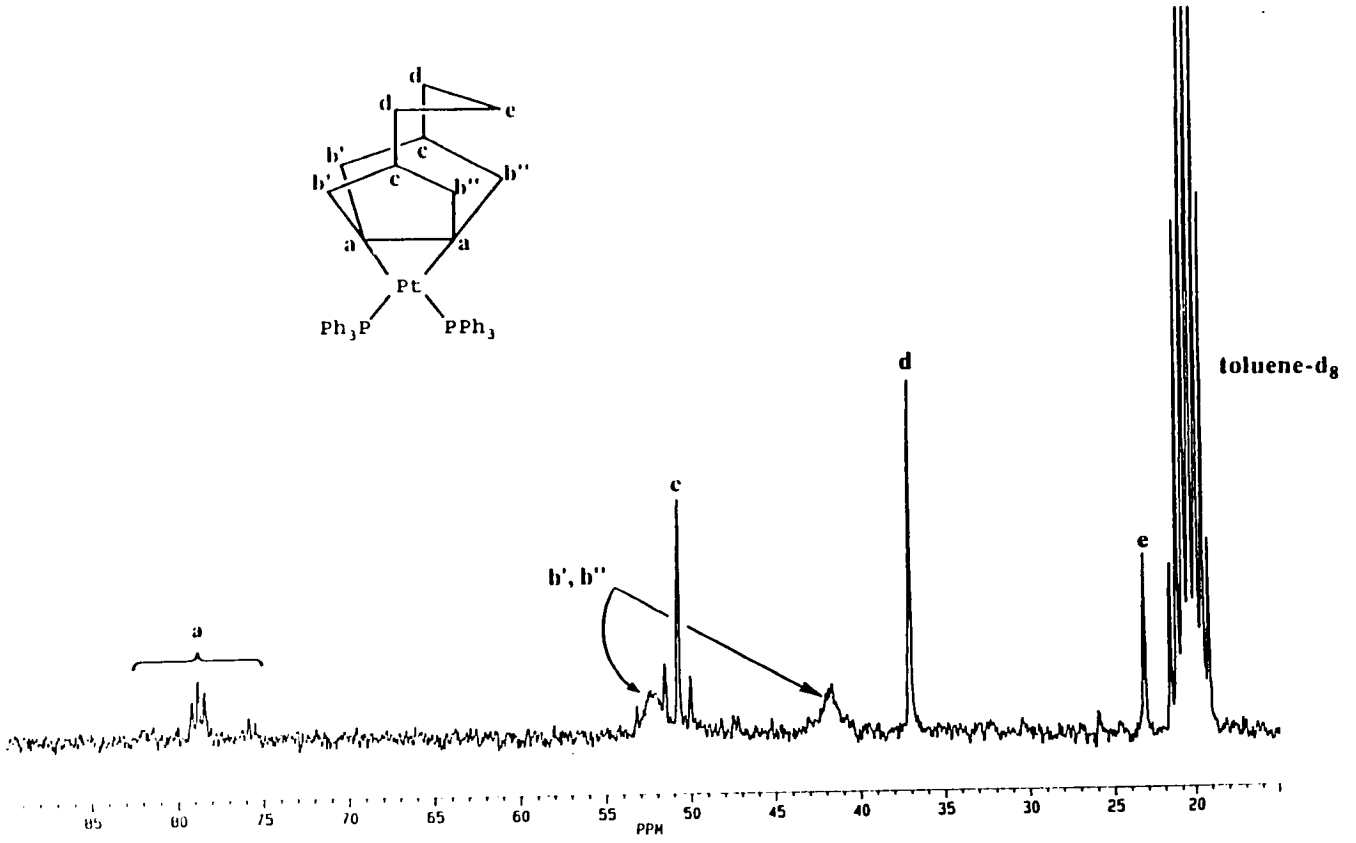


Figure IIIE.30 ^{13}C NMR (50 MHz, Toluene-d_8, 298 K) of the $(Ph_3P)_2Pt$ Complex (106a) of the n=3 Olefin (1a).

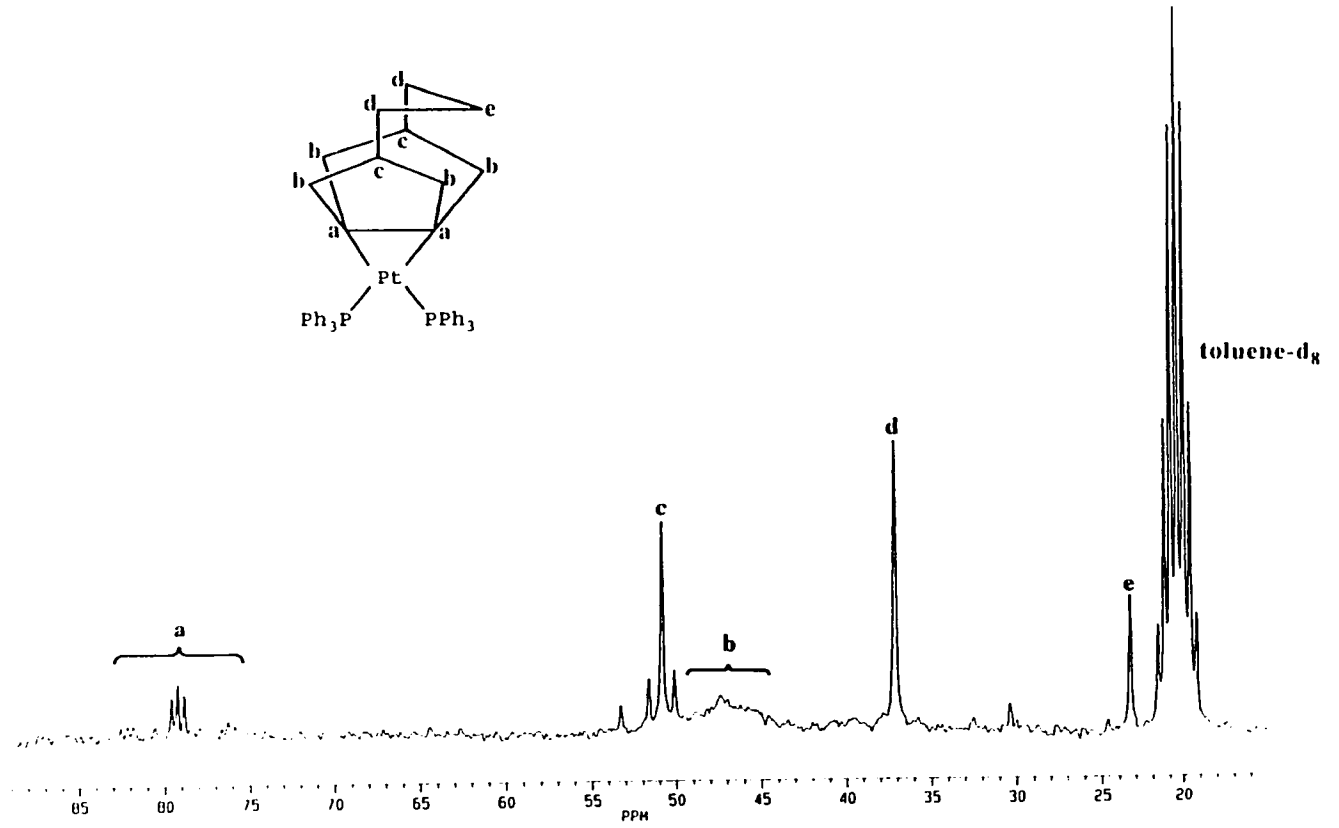
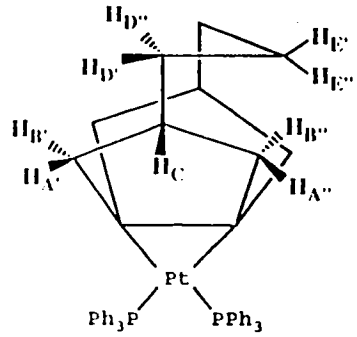


Figure IIIE.31 ^{13}C NMR (50 MHz, Toluene-d_8, 338 K) of the $(Ph_3P)_2Pt$ Complex (106a) of the n=3 Olefin (1a).



A',A'' = 1
B',B'' = 2
D',D'' = 4
E',E'' = 3

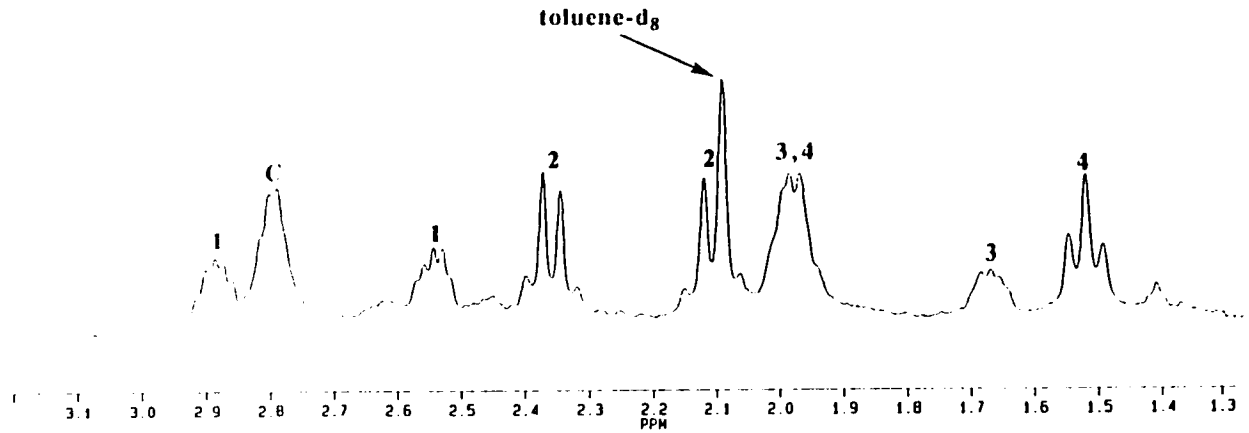
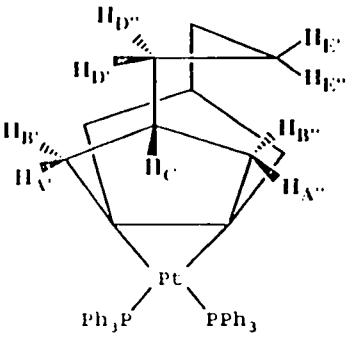


Figure IIIE.32 ^1H NMR (500 MHz, Toluene-d_8, 239 K) of the $(Ph_3P)_2Pt$ Complex (106a) of the n=3 Olefin (1a).



A',A'' = 1
B',B'' = 2
D',D'' = 4
E',E'' = 3

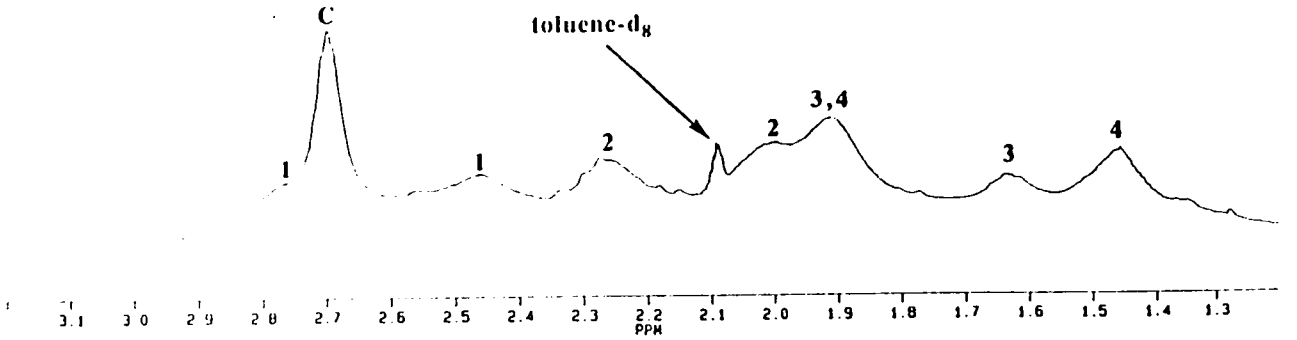
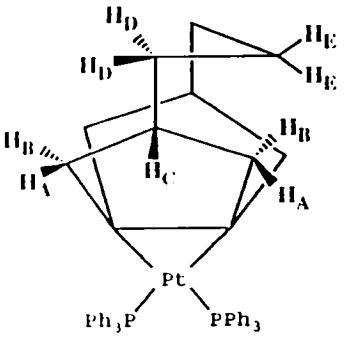


Figure IIIE.33 ^1H NMR (500 MHz, Toluene-d_8, 298 K) of the $(Ph_3P)_2Pt$ Complex (106a) of the n=3 Olefin (1a).



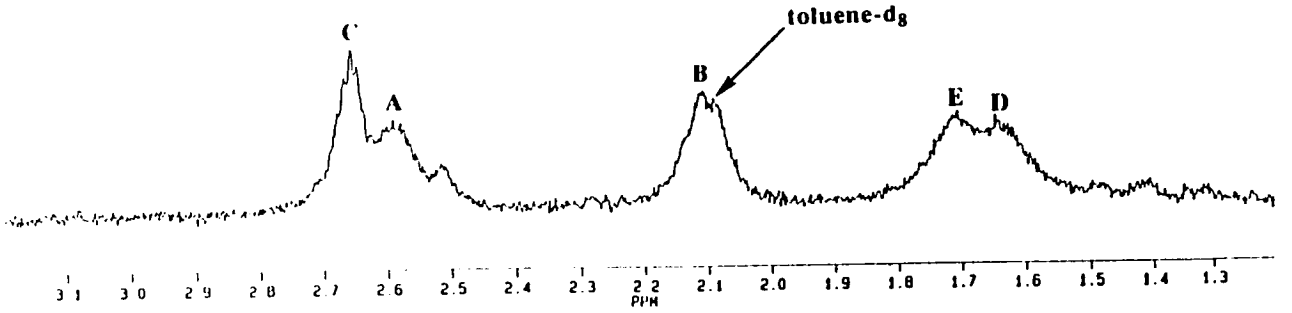


Figure IIIE.34 **^{1}H NMR (500 MHz, Toluene-d_8, 332 K) of the $(Ph_3P)_2Pt$ Complex (106a) of the n=3 Olefin (1a).**

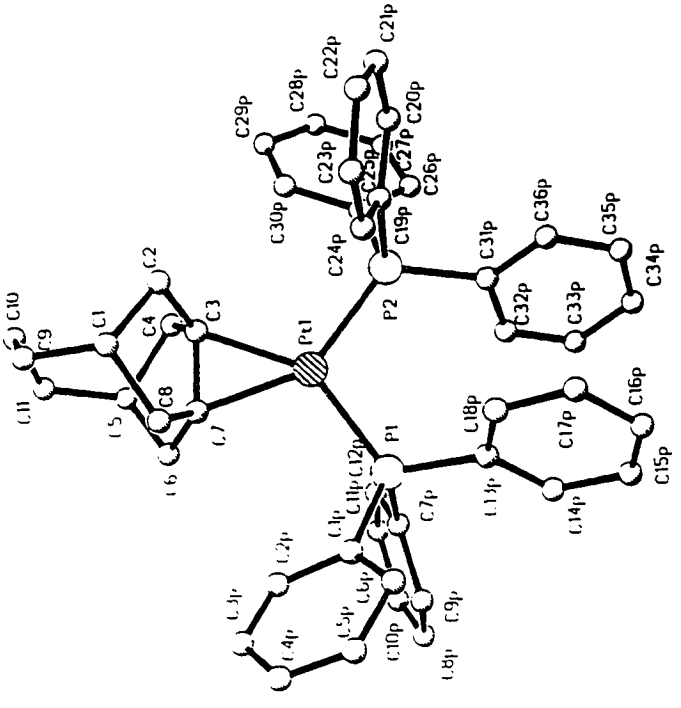


Figure IIIE.35 X-Ray Structure of the $(Ph_3P)_2Pt$ Complex (106a) of the n=3 Olefin (1a).

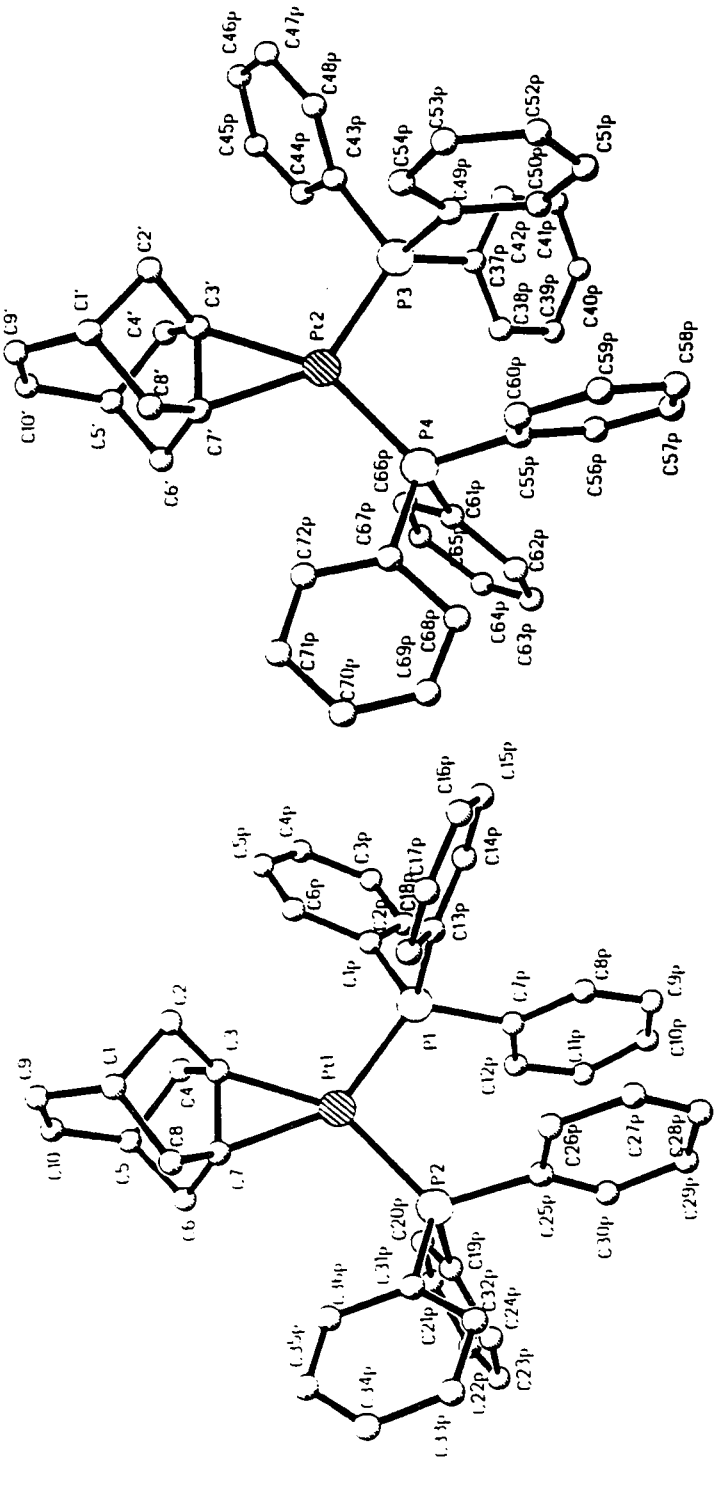


Figure IIIE.36 X-Ray Structure of the $(Ph_3P)_2Pt$ Complex (106b) of the n=2 Olefin (1b).

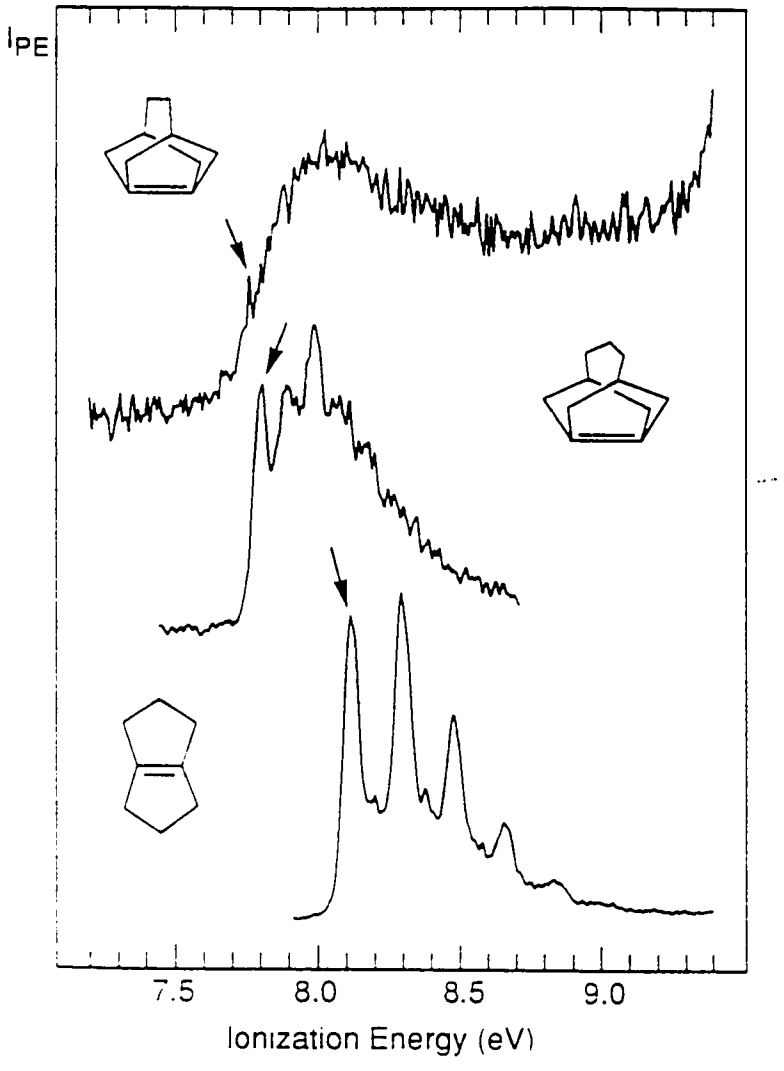


Figure IIIE.37 Photoelectron Spectra of the n=2 Olefin (1b), the n=3 Olefin (1a), and Unbridged Olefin (2).

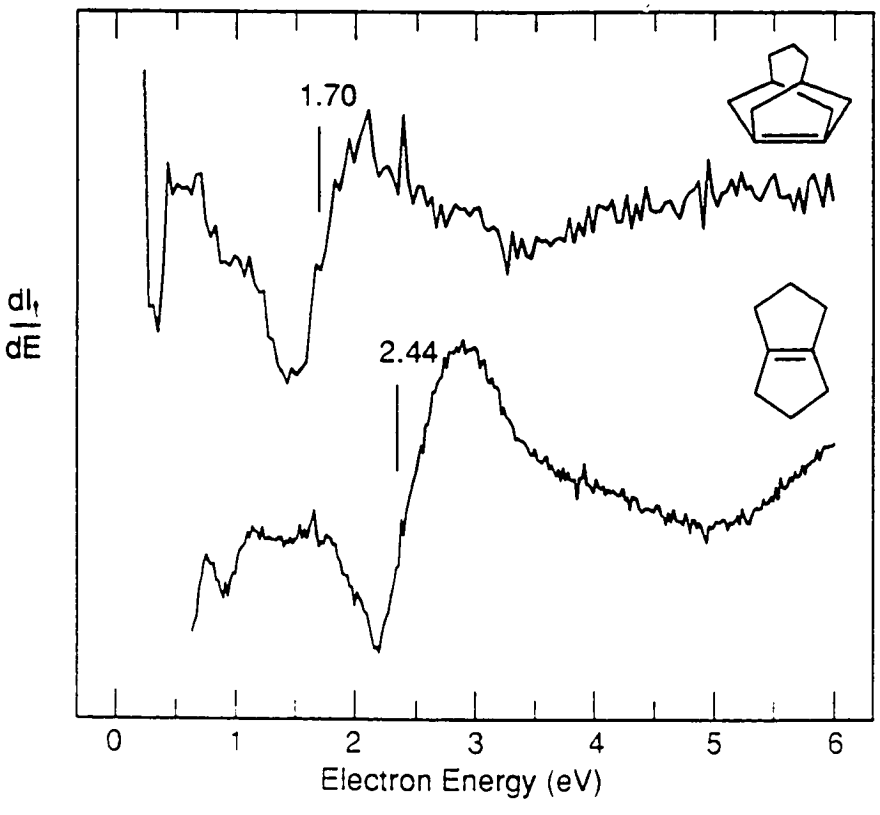


Figure IIIE.38 Electron Transmission Spectra of the n=3 Olefin (1a) and the Unbridged Olefin (2).

IV. Experimental

A. General Methods

Reagents and Solvents

Dry deoxygenated diethyl ether and tetrahydrofuran (THF) was distilled from sodium/benzophenone ketyl. Hexane and pentane used in flash chromatographic separations was simply distilled. All flash chromatography was carried out using Silica Gel 60, 40-63 μm (230-400 mesh). All thin layer chromatography (TLC) was carried out using glass supported Silica Gel 60 plates (0.25 mm thick). Other reagents and solvents were used as obtained, unless otherwise stated.

Instrumentation

NMR experiments were done on Bruker 200, 300, and 500 MHz instruments. The ^{1}H NMR spectra were recorded on chloroform-d_1 solutions with chemical shifts reported in ppm downfield from internal standard tetramethylsilane, unless otherwise stated. ^{13}C NMR were recorded on chloroform-d_1 solutions with chemical shifts reported in ppm relative to chloroform-d_1 as the internal standard, unless otherwise stated. ^{31}P NMR were recorded in C_6D_6 solutions with chemical shifts reported in ppm relative to 85% H_3PO_4, unless otherwise stated. FAB high resolution mass spectra were obtained on a VG Analytical 70-SEQ with a 11-250J data system using a xenon gun. Other high resolution mass spectra were carried out on a VG Analytical 70-SEQ with a 11-250J data system or on a Kratos Analytical, medium resolution GCMS with a Mach 3 data system. Low resolution mass spectra were carried out on a Kratos Analytical GC/MS, a Hewlett-Packard 5985 GC/MS, or on a Hewlett-Packard 5971A GC/MS. The infrared absorption spectra

were obtained using a Perkin Elmer 1600 series FTIR and were recorded in solution cells, versus a solvent reference cell, unless otherwise stated. The ultraviolet/visible absorption spectra were obtained using a Hewlett-Packard 8452A diode array UV/VIS spectrophotometer. Gas chromatographic analyses were carried out on a Hewlett-Packard 5790A series gas chromatograph, equipped with a 30m x 0.32mm ID FSOT SE-54, 0.25 micron capillary column, and coupled to a Hewlett-Packard 3390A integrator.

B. Experimental Procedures

Tetramethyl 9,10-benzobicyclo[3.3.2]dec-9(10)-en-3,7-dione-2,4,6,8-tetracarboxylate (63):[43]

A solution of 25.6 g phthalic dicarboxaldehyde and 67.4 g dimethyl 1,3-acetonedicarboxylate in 400 ml methanol was cooled to 0° and 1.0 ml piperidine added. The clear yellow solution was stirred at 0° for 1 h, warmed to room temperature, and stirred overnight. The mixture was cooled to 0°, and the white precipitate was vacuum filtered and then washed with cold methanol. The resulting white solid after air drying overnight weighed 31.2 g. The filtrate was boiled until about 300 ml of the solution remained. The filtrate was then cooled to 0° and another 1.0 ml piperidine added. The mixture was subjected to the same reaction conditions and work-up as was the first crop. Combining both crops gave 68.8 g (81%) tetramethylester **63**, pure by TLC (R_f = 0.43, ethyl acetate:hexane, 1:1), mp 160.0-165.0°. (lit. mp 169-173°).[43] ^{1}H NMR ($CDCl_3$, 500 MHz, relaxation delay = 1.0 s, complex due to mixture of stereoisomers); the spectrum is a series of sharp signals in the following ranges: δ 3.35-4.0 (12 H), 4.55-4.65 (2 H), 7.0-7.3 (4 H), 13.2-13.45 (2 H, exchangeable with D_2O). ^{13}C NMR ($CDCl_3$, 50 MHz): δ

39.51 (CH), 41.03 (CH), 41.54 (CH), 51.85 (CH_3), 52.01 (CH_3), 52.07 (CH_3), 52.28 (CH_3), 52.58 (CH_3), 52.67 (CH_3), 55.60 (CH), 55.80 (CH), 56.04 (CH), 99.97 (C), 100.61 (C), 100.80 (C), 127.55 (CH), 128.11 (CH), 128.15 (CH), 128.60 (CH), 128.81 (CH), 137.96 (C), 138.11 (C), 140.70 (C), 169.18 (C), 169.61 (C), 169.81 (C), 169.90 (C), 170.50 (C), 170.76 (C), 172.84 (C), 172.89 (C), 173.18 (C). IR ($CHCl_3$, cm^{-1}): 3200-2670 (broad,weak), 3026, 2955, 1738, 1653, 1618, 1439, 1261, 1226. MS (EI): 446 (M^+, 9.3), 414 (24.8), 382 (12.4), 273 (70.5), 241 (65.6), 213 (60.5), 173 (86.0), 105 (64.7), 68 (100).

9,10-Benzobicyclo[3.3.2]dec-9(10)-en-3,7-dione (8):[43]

A mixture of 67.5 g (151.3 mmol) tetraester **63**, 450 ml glacial acetic acid, and 125 ml concentrated hydrochloric acid was stirred under reflux at 120° for 15 h. The solution was cooled and solvent removed at reduced pressure on a rotary evaporator. The slightly yellow solid residue was broken up into a powder, placed in a vacuum filtration apparatus, and washed with cold acetone. After air drying overnight, the diketone **8**, 32 g (99%), was isolated as a white powder, 100% pure by GC (retention time = 8.96 min. at 185° on a capillary column), pure by TLC (R_f = 0.05, ethyl acetate:hexane, 1:1). The crude diketone can be purified by vacuum sublimation (190°, 1 torr) to give white crystals, mp 196.0-198.0°. (lit. mp 196-199°).[43] [Note: The ^1H and ^{13}C NMR spectra of diketone **8** show the presence of two major conformers, one of which (the boat-boat form) predominates after work-up under mild conditions. The other conformer (the chair-chair form) is shown to predominate after vacuum sublimation as described above. Furthermore, the ^1H NMR spectra of both conformers vary significantly depending on the NMR solvent used.] ^1H

NMR (500 MHz): (boat-boat, DMSO-d_6) δ 1.50 (d, J = 13.0 Hz, 4 H), 1.86 (dd, J = 13.0 Hz, J = 5.7 Hz, 4 H), 3.18 (t, J = 5.7 Hz, 2 H), 7.10 (m, one half of a symmetric AA'BB' pattern, 2 H), 7.14 (m, one half of a symmetric AA'BB' pattern, 2 H); (boat-boat, $CDCl_3$) δ 1.87 (d, J = 12.2 Hz, 4 H), 1.97 (dd, J = 12.2 Hz, J = 5.8 Hz, 4 H), 3.29 (t, J = 5.8 Hz, 2 H), 7.15 (m, one half of a symmetric AA'BB' pattern, 2 H), 7.18 (m, one half of a symmetric AA'BB' pattern, 2 H); (chair-chair, DMSO-d_6) δ 2.66 (dd, J = 15.2 Hz, J = 4.7 Hz, 4 H), 2.71 (dd, J = 15.2 Hz, J = 3.6 Hz, 4 H), 3.37 (tt, J = 4.7 Hz, J = 3.6 Hz, 2 H, note: overlapping triplet of triplets appears as a pentet because J values are similar in magnitude), 7.31 (m, one half of a symmetric AA'BB' pattern, 2 H), 7.39 (m, one half of a symmetric AA'BB' pattern, 2 H); (chair-chair, $CDCl_3$) δ 2.75 (dd, J = 15.2 Hz, J = 3.6 Hz, 4 H), 2.89 (dd, J = 15.2 Hz, J = 4.4 Hz, 4 H), 3.36 (tt, J = 4.4 Hz, J = 3.6 Hz, 2 H, [Note: Overlapping triplet of triplets appears as a pentet because J values are similar in magnitude], 7.32 (s, 4 H). ^{13}C NMR: (boat-boat, DMSO-d_6, 75 MHz): δ 38.43 (CH), 39.17 (CH_2), 97.18 (C), 126.59 (CH), 128.30 (CH), 145.22 (C); (boat-boat, $CDCl_3$, 75 MHz): not available due to solubility problems; (chair-chair, DMSO-d_6, 75 MHz): δ 36.85 (CH), 48.77 (CH_2), 127.77 (CH), 128.55 (CH), 143.51 (C), 209.20 (C); (chair-chair, $CDCl_3$, 75 MHz): δ 37.80 (CH), 48.99 (CH_2), 128.28 (CH), 128.65 (CH), 142.86 (C), 208.81 (C). IR (boat-boat, $CHCl_3$, cm^{-1}): 3025, 1708; (chair-chair, $CHCl_3$, cm^{-1}): 3025, 1702. GCMS (EI): 214 (M^+, 56.4), 186 (19.2), 172 (16.2), 157 (40.3), 144 (45.5), 129 (100), 115 (52.0).

9,10-Benzotricyclo[3.3.2.$0^{3,7}$]dec-9(10)-en-3,7-diol (9):[44]

Into a 2 liter 3-neck round bottom flask, equipped with a condenser and mechanical stirrer, was added 8.0 g (37.4 mmol) diketone **8**, 60 ml of methanol, 300 ml of water, and

400 ml of concentrated hydrochloric acid. With vigorous stirring, a zinc amalgam [prepared by slowly stirring 92.0 g (1.407×10^3 mmol) of zinc powder into a solution of 9.2 g (33.9 mmol) of mercuric chloride in 800 ml 5% aqueous hydrochloric acid, followed by vacuum filtration and washing with water] was slowly added. The heterogeneous mixture was slowly warmed up to and maintained at 80° for 20 min. Occasional frothing was alleviated by addition of small amounts of methanol to the reaction mixture. The contents of the flask were cooled to about 60°, vacuum filtered; and the amalgam collected was rinsed with hot methanol. [Note: Keeping the temperature above 60° prevents the product diol **9** from precipitating out of solution, thereby making separation from the amalgam much easier]. The filtrate was cooled, saturated with sodium chloride, and extracted with 3 - 300 ml portions of methylene chloride. The combined organic extracts were washed with 200 ml of saturated aqueous sodium bicarbonate and dried over magnesium sulfate. Solvent removal gave 7.92 g (98.1%) diol **9** as a white solid, 100% pure by GC (retention time = 7.97 min. at 175° on a capillary column), pure by TLC (R_f = 0.13, ethyl acetate:hexane, 1:1), mp 182.0-182.5°.[44] ^{1}NMR ($CDCl_3$, 500 MHz): δ 2.06 (d, J = 11.2 Hz, 4 H), 2.23 (dd, J = 11.2 Hz, J = 6.2 Hz, 4 H), 2.65 (s, 2 H, exchangeable with D_2O), 3.14 (t, J = 6.2 Hz, 2 H), 7.07-7.16 (m, symmetric AA'BB' pattern, 4 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 41.68 (CH), 49.28 (CH_2), 83.41 (C), 126.47 (CH), 129.38 (CH), 143.94 (C). IR ($CHCl_3$, cm^{-1}): 3577, 3401 (broad), 3025, 2943, 1096. MS (EI): 216 (M^+, 81.6), 198 (14.7), 158 (86.6), 141 (40.8), 129 (100), 115 (58.5).

9,10-Benzotricyclo[3.3.2.0^{3,7}]dec-9(10)-en-3,7-diol Acetonide (64):[7]

A mixture of 4.3 g (0.02 mmol) diol **9** and 134 ml acetone in a 250 ml round bottom flask was heated until all of the diol was dissolved. Approximately 10 drops of concentrated hydrochloric acid was added, and the solution was stirred under reflux for 24 h. After cooling the solution, the solvent was removed under reduced pressure. The resulting solid residue was dissolved in a mixture of 150 ml methylene chloride and 150 ml hexane. This made the following extraction easier by causing the organic phase to be the top layer and the aqueous phase to be the bottom layer. The solution was extracted with saturated aqueous sodium bicarbonate, saturated aqueous sodium chloride, and dried over magnesium sulfate. Solvent removal under reduced pressure on a rotary evaporator gave 5.05 g (99.1%) of solid acetonide **64**, 100% pure by GC (retention time = 7.36 min. at 175° on a capillary column). [Note: Occasionally, a small amount of unreacted diol **9** was present (< 10% by GC, retention time = 7.86 min. at 175° on a capillary column) in the product mixture. Submitting this product mixture to the above reaction conditions did not remove the residual diol. In one instance, reacting 10.0 g diol **9** gave 12.4 g of a product mixture that was 9.1% unreacted diol by GC]. If necessary, purification of acetonide **64** (R_f = 0.63, ethyl acetate:hexane, 1:1) was carried out by flash chromatography. Passing 3.0 g of the product mixture through 150 g silica, using ethyl acetate:hexane (1:1) as eluent, and collecting 250 ml fractions gave 2.41 g acetonide **64** (fractions 3-8, 99% pure by GC, pure by TLC, 84% isolated yield based on original 12.4 g product mixture). The acetonide was then recrystallized from diethyl ether to give 2.27 g clear crystalline acetonide **64** (79% isolated yield based on original 12.4 g product mixture), 100% pure by GC, pure by TLC, mp = 147-148.5° (not previously reported). ^{1}NMR ($CDCl_3$, 500

MHz): δ 1.55 (s, 6 H), 2.03 (d, J = 11.6 Hz, 4 H), 2.47 (dd, J = 11.6 Hz, J = 6.1 Hz, 4 H), 3.45 (t, J = 6.1 Hz, 2 H), 7.07-7.18 (m, symmetric AA'BB' pattern, 4 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 29.85 (CH_3), 48.12 (CH), 49.25 (CH_2), 98.51 (C), 119.02 (C), 126.47 (CH), 129.39 (CH), 143.97 (C). IR ($CHCl_3$, cm^{-1}): 3025, 2967, 2944, 2865, 1239, 1097. MS (EI): 241 (M^+ - CH_3, 100), 181 (70.6), 141 (23.1), 128 (24.4), 115 (19.8).

Bicyclo[3.3.0]octane-3,7-dicarboxylate-1,5-diol Acetonide (38):[7,38]

Into a 500 ml round bottom flask was added 4.0 g (15.6 mmol) acetonide **64** as a powder, 65 mg (0.49 mmol) ruthenium (IV) oxide hydrate, 50.0 g (233.8 mmol) sodium meta-periodate, 66 ml carbon tetrachloride, 66 ml acetonitrile, 100 ml water, and a 2 inch magnetic stirring bar. The flask was sealed with a septum that was held in place by a wire and the heterogeneous mixture vigorously stirred for 3-5 days. The carbon dioxide gas produced in the reaction was frequently bled off during the first 24 hours of the reaction and less frequently during the remaining reaction time. [Note: The evolution of carbon dioxide gas was used to monitor the progress of the reaction. The reaction was found to be complete when the evolution of carbon dioxide ceased.] The resulting cream colored product mixture was added to a 2 liter separatory funnel, and just enough water was added (approximately 700 ml) to dissolve the sodium iodate precipitate. The organic layer was separated and saved. The aqueous phase was saturated with sodium chloride (approximately 200 g) and extracted with 2 - 700 ml portions of diethyl ether. The carbon tetrachloride/acetonitrile and diethyl ether phases were combined and all but 150 ml of solvent was removed at reduced pressure on a rotary evaporator. The resulting dark

solution was filtered under vacuum through celite in a scintered glass funnel of medium porosity. The evaporation flask was rinsed with diethyl ether and the rinse solvent also poured through the celite bed. This process was repeated two more times. The filtrate was dried over magnesium sulfate, gravity filtered, and solvent removed at reduced pressure on a rotary evaporator until a significant amount of solid precipitated out of solution. The remaining dark ether phase was carefully removed from the solid, first by decanting and then via disposable pipette. Two more crops of product were collected from the dark ether phase after repeating the concentration and separation procedure just described. The crops were combined to give 2.25 g (53.3%) diacid **38** as a solid white powder, pure by TLC (R_f = 0.14, ethyl acetate:hexane, 1:1). The product diacid can be recrystallized from either diethyl ether or acetonitrile to give colorless crystals, mp 204-205° (not previously reported). ^{1}H NMR (DMSO-d_6, 500 MHz): δ 1.35 (s, 6 H), 1.91 (dd, J = 14.0 Hz, J = 9.1 Hz, 4 H), 2.12 (dd, J = 14.0 Hz, J = 7.3 Hz, 4 H), 3.12 (tt, J = 9.1 Hz, J = 7.3 Hz, 2 H, [Note: Overlapping triplet of triplets appears as a pentet because J values are similar in magnitude], 3.30 (broad s, exchangeable with D_2O). ^{13}C NMR (DMSO-d_6, 50 MHz): δ 28.70 (CH_3), 41.10 (CH_2), 44.63 (CH), 99.48 (C), 111.80 (C), 175.38 (C). IR (KBr, cm^{-1}): 3650-2355 (broad), 1734, 1705, 1447, 1417, 1283, 1223, 1128, 858. MS (EI): 255 (M^+ - CH_3, 77.9), 195 (6.6), 177 (35.2), 149 (100), 105 (36.5).

Dimethyl bicyclo[3.3.0]octane-3,7-dicarboxylate-1,5-diol Acetonide (88):

The distillation apparatus used in this reaction had flame polished joints and came from a kit designed specifically for safe generation of diazomethane. A mixture of 16 ml ethanol, 5.5 ml water, and 3.28 g (0.059 mol) potassium hydroxide was stirred in a 100 ml

distilling flask fitted with a dropping funnel, Claisen head, and condenser. The condenser was connected via a vacuum adapter to a 250 ml round bottom flask which contained a stirred solution of 6.3 g (0.023 mol) diacid **38** in 30 ml dry tetrahydrofuran (THF). The flask containing the diacid was kept at 0° throughout the reaction. The flask containing the stirring alkali solution was heated to 60°, and a solution of 14.6 g (0.068 mol) N-methyl-N-nitroso-p-toluenesulfonamide in 100 ml diethyl ether was added slowly. The rate of addition was approximately equal to the rate of distillation. After a yellow color had persisted in the receiving flask for an hour, a solution of saturated aqueous ammonium chloride was slowly added until the yellow color disappeared. The two phases were separated and the aqueous phase extracted with methylene chloride. The organic phases were washed separately with saturated aqueous sodium chloride, combined, and dried over magnesium sulfate. Solvent removal under reduced pressure on a rotary evaporator gave 6.7 g (96%) diester **88** as an oil, 100% pure by GC (retention time = 7.68 min. on a capillary column using the following temperature program: initial temp. = 100° for 0.0 min., rate = 20°/min., final temp. = 200° for 12.5 min.) and TLC (R_f = 0.48, ethyl acetate:hexane, 1:1). Crystals of the diester **88** were obtained from a saturated solution of **88** in diethyl ether:pentane (1:6), mp 63.5-64.5°. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.44 (s, 6 H), 1.99 (dd, J = 14.2 Hz, J = 10.9 Hz, 4 H), 2.31 (dd, J = 14.2 Hz, J = 7.4 Hz, 4 H), 3.33 (tt, J = 10.9 Hz, J = 7.4 Hz, 2 H), 3.68 (s, 6 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 28.80 (CH_3), 41.34 (CH_2), 45.47 (CH), 51.79 (CH_3), 100.13 (C), 112.29 (C), 174.67 (C). IR ($CHCl_3$, cm^{-1}): 3021, 2992, 2954, 2855, 1730, 1437, 1372, 1283, 1228, 1201, 1175, 1124. MS (EI): 283 (M^+ - CH_3, 74.9), 267 (7.6), 223 (14.8), 191 (53.3), 163 (100), 103 (36.5). Exact mass (EI): calcd. for $C_{14}H_{19}O_6$ (M^+ - CH_3), 283.1180; found, 283.1196.

9,10-Bis(trimethylsiloxy)tricyclo[3.3.2.0^{3,7}]dec-9(10)-en-3,7-diol Acetonide (89):

A 250 ml 3-neck morton flask was fitted with a mechanical stirrer, glass stirrer shaft, glass stirrer blade, condenser, addition funnel, and filled with an atmosphere of argon. To the flask was added 85 ml dry toluene (previously distilled from calcium hydride under argon) and 3.0 g (0.13 mol) sodium (freshly sliced and weighed in dry toluene). The solvent was refluxed for 10 min. before the stirrer was turned on and operated at high speed until the sodium was fully dispersed into small beads. [Note: Stirring unmelted sodium can jam and break the glass stirring blade. Waiting approximately 10 min. before stirring allows enough time for the sodium to melt completely.] The stirrer speed was reduced and a solution of 8.3 g (0.03 mol) diester **88** and 15.4 ml (0.12 mol) trimethylsilylchloride (previously distilled from calcium hydride under argon) in 35 ml dry toluene was added over a period of 1 h. The system was kept at reflux and flushed under argon during and after the addition. After stirring at reflux for 5 h, the reaction mixture was cooled and the dark sediment allowed to settle for about 1 h. The liquid phase was then carefully decanted and poured through a vacuum filtration apparatus, set up to allow the filtration of pyrophoric materials, without exposing them to the air. The pyrophoric sediment remaining in the flask was rinsed with 100 ml anhydrous diethyl ether, allowed to settle, and the liquid phase was poured through the filtration apparatus. This procedure was carried out two more times. Solvent removal at reduced pressure on a rotary evaporator gave 9.4 g of a dark oil which was 80% pure product **89** by GC (retention time = 8.18 min. on a capillary column using the following temperature program: initial temp. = 100° for 0.0 min., rate = 20°/min., final temp. = 200° for 12.5

min.). The desired product **89** (R_f = 0.65, ethyl acetate:hexane, 1:1; R_f = 0.51, ethyl acetate:hexane, 1:4) was purified by flash chromatography on 300 g silica using ethyl acetate:hexane (1:4) as the eluent. The desired product eluted when 300-600 ml of solvent had passed through the column and was isolated as 7.1 g (66.7 %) of a pure white solid, mp 86.5-89°. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 0.16 (s, 18 H), 1.47 (s, 6 H), 2.01 (d, J = 11.4 Hz, 4 H), 2.24 (dd, J = 11.4 Hz, J = 6.2 Hz, 4 H), 2.77 (t, J = 6.2 Hz, 2 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 0.68 (CH_3), 29.82 (CH_3), 45.38 (CH), 48.07 (CH_2), 98.36 (C), 119.10 (C), 139.86 (C). IR ($CHCl_3$, cm^{-1}): 3018, 2955, 1655, 1456, 1375, 1350, 1250, 1206, 1100, 864, 846. MS (EI): 382 (M^+, 6.8), 367 (0.7), 307 (2.2), 219 (2.8), 167 (3.5), 147 (20.8), 133 (3.9), 131 (3.0), 75 (11.8), 74 (9.1), 73 (100).

Tricyclo[3.3.2.0^{3,7}]decan-3,7,10-triol-9-one Acetonide (90):

Into a 2 liter round bottom flask was dissolved 3.44 g (9.01 mmol) **89** in 1.2 liter deoxygenated methanol. The solution was refluxed under nitrogen for 4 days. After the solution was cooled, solvent removal gave 1.8 g (84%) ketoalcohol **90** as a white crystalline solid, mp 125.0-128.0°, 96% pure by GC (retention time = 5.77 min. at 165° on a capillary column), pure by TLC (R_f = 0.27, ethyl acetate:hexane, 1:1). ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.49 (s, 3 H), 1.51 (s, 3 H), 1.90 (dd, J = 13.9 Hz, J = 2.1 Hz, 1 H), 2.08 (d, J = 12.5 Hz, 1 H), 2.22-2.42 (m, 6 H), 2.67 (t, J = 6.5 Hz, 1 H), 3.20 (m, 1 H), 3.87 (d, J = 1.3 Hz, 1 H, exchangeable with D_2O), 4.15 (d, J = 1.3 Hz, 1 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 30.07 (CH_3), 30.13 (CH_3), 41.90 (CH_2), 43.59 (CH), 44.71 (CH_2), 45.64 (CH_2), 46.77 (CH_2), 50.49 (CH), 80.61 (CH), 96.78 (C), 97.30 (C), 120.03 (C), 215.87 (C). IR ($CHCl_3$, cm^{-1}): 3472, 3022, 3000, 2978, 2867, 1693, 1460,

1375, 1240, 1215, 1185, 1046. MS (EI): 223 (M^+ - CH_3, 100), 193 (5.5), 117 (10.5), 107 (13.0), 95 (16.9), 79 (21.6). Exact mass (EI): calcd. for $C_{12}H_{15}O_4$ (M^+ - CH_3), 223.0969; found, 223.0932.

10-Ethanoyloxytricyclo[3.3.2.$0^{3,7}$]decane-3,7-diol-9-one Acetonide (91):

To a stirred solution of 1.8 g (7.56 mmol) ketoalcohol **90** and 9.24 g (75.6 mmol) 4-dimethylaminopyridine in 250 ml dry methylene chloride (previously distilled from calcium hydride and stored over molecular seives) at 0° was slowly added 2.7 ml (37.8 mmol) acetyl chloride. The solution was warmed to room temperature and stirred for 2 h. After adding 300 ml of hexane, the solution was washed with 3 - 300 ml portions of 5% aqueous hydrochloric acid, 200 ml saturated aqueous sodium bicarbonate, 200 ml saturated aqueous sodium chloride and dried over magnesium sulfate. Solvent removal at reduced pressure on a rotary evaporator gave 2.22 g of a solid, which GC analysis showed to be 91% pure ketoacetate **91** (retention time = 12.98 min. at 165° on a capillary column). Recrystallization of the crude product from chloroform:pentane (1:1) gave 1.73 g (81.7%) of the product ketoacetate **91** as a white solid, 99% pure by GC, pure by TLC (R_f = 0.44, ethyl acetate:hexane, 1:1), mp 155.0-157.0°. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.50 (s, 3 H), 1.50 (s, 3 H), 2.06 (dd, J = 13.3 Hz, J = 2.3 Hz, 1 H), 2.15 (s, 3 H), 2.15 (dd, J = 12.5 Hz, J = 1.0 Hz, 1 H), 2.26-2.44 (6 H), 2.59 (t, J = 6.4 Hz, 1 H), 3.11 (t, J = 5.7 Hz, 1 H), 5.33 (s, 1 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 20.66 (CH_3), 30.02 (CH_3), 30.08 (CH_3), 42.00 (CH), 42.12 (CH_2), 45.13 (CH_2), 46.02 (CH_2), 46.10 (CH_2), 51.44 (CH), 80.84 (CH), 96.90 (C), 97.16 (C), 120.11 (C), 169.73 (C), 207.93 (C). IR ($CHCl_3$, cm^{-1}): 3030-2860, 1740, 1711, 1443, 1368, 1237, 1200, 1041. MS (EI): 265

(M^+ - CH_3, 33.5), 163 (2.7), 133 (2.3), 117 (3.6), 105 (5.3), 79 (7.5), 67 (9.2), 55 (10.5), 43 (100). Exact mass (EI): calcd. for $C_{14}H_{17}O_5$ (M^+ - CH_3), 265.1074; found, 265.1073.

Tricyclo[3.3.2.$0^{3,7}$]decan-3,7-diol-9-one Acetonide (92):

To a stirred solution of 1.6 g (5.7 mmol) ketoacetate **91** in 20 ml dry THF and 10 ml methanol under nitrogen was added a solution of samarium diiodide[66] (19.2 mmol) in THF. The dark solution was stirred at room temperature for 1 h, poured into 340 ml saturated aqueous potassium carbonate, extracted with 4 - 300 ml portions of diethyl ether, and dried over magnesium sulfate. Solvent removal under reduced pressure on a rotary evaporator gave 1.3 g of a solid, which GC analysis showed to be 88% product ketone **92** (retention time = 5.07 min. at 165° on a capillary column). Purification of the desired product ketone **92** (R_f = 0.33, ethyl acetate:hexane, 1:2) was carried out by flash chromatography on silica using ethyl acetate:hexane (1:2) as the eluent, which afforded 1.15 g (91%) of **92** in fractions collected when 300-550 ml of solvent had passed through the column. The ketone could be recrystallized from diethyl ether:pentane (1:4), which gave clear crystals, mp 97.0-98.0°. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.50 (s, 3 H), 1.51 (s, 3 H), 2.02 (d, J = 12.4 Hz, 2 H), 2.17 (d, J = 13.6 Hz, 2 H), 2.32 (ddd, J = 13.6 Hz, J = 6.5 Hz, J = 1.5 Hz, 2 H), 2.39 (ddd, J = 12.4 Hz, J = 5.8 Hz, J = 1.5 Hz, 2 H), 2.51-2.60 (m, 1 H), 2.54 (s, 2 H), 3.03 (t, J = 6.5 Hz, 1 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 29.84 (CH_3), 29.93 (CH_3), 35.13 (CH), 44.46 (CH_2), 48.06 (CH_2), 48.67 (CH_2), 53.46 (CH), 97.82 (C), 119.56 (C), 215.04 (C). IR ($CHCl_3$, cm^{-1}): 3026, 2964, 2877, 1687, 1457, 1376, 1326, 1210, 1069. MS (EI): 207 (M^+ - CH_3, 100), 165 (1.9),

147 (1.2), 119 (3.8), 105 (8.2), 95 (10.2). Exact mass (EI): calcd. for $C_{12}H_{15}O_3$ (M^+ - CH_3), 207.1021; found, 207.1036.

9-Ethoxycarbonyltricyclo[3.3.3.0^{3,7}]undecane-3,7-diol-10-one Acetonide (93a) and 10-Ethoxycarbonyltricyclo[3.3.3.0^{3,7}]undecane-3,7-diol-9-one Acetonide (93b):[47]

To a round bottom flask, sealed with a septum and containing 1.15 g (5.18 mmol) ketone **92** under nitrogen was added 26.3 ml of 1.0 M (26.3 mmol) triethyloxonium tetrafluoroborate in methylene chloride.[67] After stirring for 5 min., 2.2 ml (20.9 mmol) ethyl diazoacetate was slowly added over a period of 15 min. Throughout the addition and for 30 min. thereafter a needle was passed through the septum to allow escape of the nitrogen produced by the reaction. The needle was removed and the mixture stirred for 7 h with occasional bleeding of nitrogen. The reaction was quenched by slowly adding 175 ml of saturated aqueous sodium bicarbonate and vigorously stirring the two-phase mixture for 30 min. The aqueous layer was separated from the organic layer and extracted with 2 - 100 ml portions of methylene chloride. The organic layers were combined and dried over magnesium sulfate. Solvent removal at reduced pressure on a rotary evaporator gave 2.8 g of a dark yellow oil. GC analysis showed that the product mixture contained approximately equal amounts of the two regioisomeric β-ketoesters **93a** and **93b** (retention times = 8.62 and 8.87 min. on a capillary column using the following temperature program: initial temp. = 100° for 0.0 min., rate = 20°/min., final temp. = 250° for 12.5 min.). A purified sample of the β-ketoesters (both having R_f = 0.30, ethyl acetate:hexane, 1:3) was obtained as follows. A 245 mg sample of the crude product mixture was

submitted to a flash chromatographic separation using 25 g silica and ethyl acetate:hexane (1:3) as the eluent. Fractions of 20 ml were collected and fractions 14-18 were found by GC to be comprised of 87% product β-ketoesters (approximately 1:1) and 13% unreacted ketone **92**. This mixture was concentrated and recrystallized twice from diethyl ether:pentane (1:1) to give 63.2 mg (45.3%) of a white solid mixture of β-ketoesters **93a** and **93b** (approximately 3:2), 100% pure by GC and pure by TLC. An attempt to separate β-ketoesters **93a** and **93b** from each other using preparative GC at 230° was unsuccessful and accompanied by 50% conversion to the corresponding ketones **95a** and **95b**.

Because the ring expansion reaction and subsequent purification steps produce mixtures, containing nearly equal amounts of the regioisomeric β-ketoesters, (**93a**) and (**93b**), the spectroscopic data was obtained on these mixtures. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.2-1.3 (q, 6 H), 1.4-1.5 (m, 12 H), 1.95 (t, 1 H), 2.1 (m, 1 H), 2.2-2.9 (20 H), 3.08 (t, 1 H), 3.17 (t, 1 H), 3.64 (s, 1 H), 4.1-4.2 (5 H, overlap of t and m). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 13.90 (CH_3), 13.93 (CH_3), 29.67 (CH_3), 29.73 (CH_3), 29.93 (CH_3), 35.42 (CH), 36.57 (CH), 37.23 (CH_2), 39.32 (CH), 43.47 (CH_2), 43.99 (CH_2), 45.41 (CH_2), 46.39 (CH_2), 48.24 (CH_2), 48.38 (CH_2), 48.59 (CH_2), 49.05 (CH_2), 49.78 (CH_2), 50.29 (CH), 52.77 (CH), 61.04 (CH_2), 61.08 (CH_2), 64.11 (CH), 99.18 (C), 99.26 (C), 100.28 (C), 100.30 (C), 117.49 (C), 117.98 (C), 169.70 (C), 169.84 (C), 209.03 (C), 213.25 (C). [Note: Only thirty three of the expected thirty four carbon resonances in this mixture of β-ketoesters were observed. It appears that two of the expected four resonances corresponding to the acetonide methyl carbons overlap.] IR ($CHCl_3$, cm^{-1}): 3026, 2988, 1740, 1693, 1229. One isomer: MS (EI): 293 (M^+ - CH_3, 100), 263 (3.4), 187 (21.5), 145 (10.5), 95 (10.0), 67 (11.0), 43 (21.9); (CI): 309 (MH^+, base peak), 263, 233, 59. Exact mass (EI): calcd. for $C_{16}H_{21}O_5$ (M^+ - CH_3), 293.1387;

found, 293.1400. Other isomer: MS (EI): 293 (M^+ - CH_3, 100), 263 (4.5), 187 (12.4), 159 (20.2), 131 (29.5), 117 (21.1), 104 (26.2), 79 (18.9), 67 (18.7), 43 (20.2); (CI): 309 (MH^+, base peak), 263, 233, 59. Exact mass (EI): calcd. for $C_{16}H_{21}O_5$ (M^+ - CH_3), 293.1387; found, 293.1388.

9-Carboxytricyclo[3.3.3.$0^{3,7}$]undecane-3,7-diol-10-one Acetonide (94a) and 10-Carboxytricyclo[3.3.3.$0^{3,7}$]undecane-3,7-diol-9-one Acetonide (94b):

Into a flask was placed 374 mg (1.214 mmol) of a mixture (approximately 1:1) of pure β-ketoesters **93a** and **93b** and 100 ml of 5% aqueous sodium hydroxide. After stirring at room temperature for 15 h, the mixture was cooled to 0° and carefully adjusted to pH = 3 using hydrochloric acid. [Note: If there is any unreacted ketone **92** present in the reaction mixture, care should be taken at this point in the synthesis to remove it. This can be carried out easily by extraction of the alkaline phase with chloroform, before acidification.] The acidified solution was extracted with 3 - 100 ml portions of chloroform and the combined organic layers dried over magnesium sulfate. Solvent removal gave 334 mg (approximately 98%) of a white solid residue. TLC (ethyl acetate:hexane, 1:1) showed predominately the regioisomeric β-ketoacids **94a** and **94b** (both with $R_f = 0.15$) and a very small amount of regioisomeric ketones **95a** and **95b** (both with $R_f = 0.43$). GC analysis of the product mixture showed the presence of 100% pure ketones **95a** and **95b** (retention times = 7.28 min. and 7.59 min. respectively at 165° on a capillary column) in approximately equal amounts, presumably formed by decarboxylation of β-ketoacids **94a** and **94b** within the heated injection port.

Spectra taken of the product mixture were consistent with the two major components having the structures, **94a** and **94b**, assigned to them. The ^1H NMR ($CDCl_3$, 500 MHz) spectrum had the same appearance as a ^1H NMR spectrum of an equimolar mixture of β-ketoesters **93a** and **93b**, except that the triplet at δ 4.16 and the quartet at δ 1.24 in the ethyl esters were absent. Instead, there was also a very broad signal at δ 10.5 which disappeared upon addition of D_2O. IR ($CHCl_3$, cm^{-1}): 3600-2400 (broad), 3026, 2980, 2950, 1752, 1722, 1693, 1223.

Tricyclo[3.3.3.$0^{3,7}$]undecan-3,7-diol-10-one Acetonide (95a) and Tricyclo[3.3.3.$0^{3,7}$]undecan-3,7-diol-9-one Acetonide (95b):

A 334 mg mixture consisting predominantly of regioisomeric β-ketoacids **94a** and **94b** (approximately 1.193 mmol total) and a small amount of regioisomeric ketones **95a** and **95b** was stirred in 450 ml p-dioxane under reflux for 8 h. Solvent removal gave 580 mg of a solid residue. GC analysis of the crude product mixture showed a 6:7 mixture of **95b** and **95a** (retention times = 7.59 min. and 7.28 min. respectively at 165° on a capillary column). Purification by flash chromatography (both ketones have R_f = 0.28 in ethyl acetate:hexane, 1:2) on 100 g silica using ethyl acetate:hexane (1:2) as the eluent gave 176.4 mg (63% total) of a 2:3 mixture of **95b** and **95a**, 100% pure by GC and TLC, in fractions collected after 200-300 ml of solvent had been eluted. Also isolated in fractions collected after 150-200 ml and 300-350 ml of solvent had eluted was 54.7 mg of a 1:2 mixture of **95b** and **95a**, 95% pure by GC, pure by TLC.

The more symmetric ketone, **95a**, has a greater solubility in chloroform than does the less symmetric isomer, **95b**. This fact allowed a sample of **95b** to be isolated as a white solid, 100% pure by GC and by TLC, from a mixture of ketones **95a** and **95b** by performing five successive precipitations from chloroform. The less symmetric ketone, **95b**, was then recrystallized from diethyl ether:pentane (1:4) and collected as a colorless crystalline solid, mp 106.5-108.5°. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.46 (s, 3 H), 1.47 (s, 3 H), 1.82 (m, 2 H), 1.98 (d, J = 14.5 Hz, 2 H), 2.37 (ddd, J = 13.9 Hz, J = 7.9 Hz, J = 1.9 Hz, 2 H), 2.53-2.65 (6 H), 2.79 (m, 1 H), 2.93 (t, J = 7.9 Hz, 1 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 29.77 (CH_3), 29.94 (CH_3), 34.68 (CH_2), 35.94 (CH_2), 36.57 (CH), 46.70 (CH_2), 47.05 (CH_2), 52.74 (CH), 99.68 (C), 117.74 (C), 218.82 (C). IR ($CHCl_3$, cm^{-1}): 3025, 2988, 2938, 1687, 1456, 1369, 1231, 1112, 1012. MS (EI): 221 (M^+ - CH_3, 100), 179 (3.1), 161 (13.8), 133 (18.1), 117 (40.8), 105 (16.4), 91 (26.3), 79 (18.2), 67 (11.0), 55 (16.5), 43 (7.7). Exact mass (EI): calcd. for $C_{13}H_{17}O_3$ (M^+ - CH_3), 221.1176; found, 221.1148.

The ^{1}H NMR spectrum of ketone **95a** was obtained by subtracting the resonances of ketone **95b** from the resonances found in a ^{1}H NMR spectrum of an equimolar mixture of ketones **95a** and **95b**. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.44 (s, 6 H), 2.28 (d, J = 13.1 Hz, 4 H), 2.47 (dd, J = 13.1 Hz, J = 7.6 Hz, 4 H), 2.59 (d, J = 5.4 Hz, 4 H), 2.72-2.79 (m, 2 H). Similarly, the ^{13}C NMR spectrum of ketone **95a** was obtained by subtracting the eleven resonances of ketone **95b** from the eighteen resonances found in a ^{13}C NMR spectrum of an equimolar mixture of ketones **95a** and **95b**. ^{13}C NMR ($CDCl_3$, 125 MHz): δ 29.65 (CH_3), 36.21 (CH), 47.44 (CH_2), 50.47 (CH_2), 100.47 (C), 117.10 (C), 213.66 (C). The carbonyl stretching frequency of ketone **95a** is undoubtedly the same as that for ketone **95b**, 1687 cm^{-1} in $CHCl_3$, since an IR spectrum of an equimolar

mixture of ketones **95a** and **95b**, taken in $CHCl_3$, looked identical to the IR spectrum of a pure sample of ketone **95b**. Having a pure sample of ketone **95b** also provided us with a means of knowing, unequivocally, which isomer in the mixture corresponded to which GCMS analysis. MS (EI): 221 (M^+ - CH_3, 100), 179 (3.9), 161 (18.6), 133 (11.6), 119 (28.2), 109 (10.4), 91 (28.0), 79 (25.1), 67 (9.6), 55 (5.4), 43 (12.1). Exact mass (EI): calcd. for $C_{13}H_{17}O_3$ (M^+ - CH_3), 221.1176; found, 221.1159.

Tricyclo[3.3.3.$0^{3,7}$]undecane-3,7-diol Acetonide (79):

A 498 mg (2.11 mmol) mixture of the regioisomeric ketoacetonides **95a** and **95b**, 1.0 ml (20.6 mmol) of hydrazine monohydrate, 650 mg (16.3 mmol) sodium hydroxide, and 100 ml of diethylene glycol were placed in a 250 ml round bottom flask, fitted with a condenser. The mixture was stirred under nitrogen at 185° for 24 h. An aliquot was worked up by adding water, extracting three times with diethyl ether, washing the combined ether extracts twice with water, and drying the ether phase over magnesium sulfate. GC analysis showed > 80% acetonide **79** (retention time = 6.11 min. at 150° on a capillary column), < 20% unreacted hydrazone(s), and the absence of any unreacted ketoacetonides **95a** and **95b**. Another 2.0 g (50 mmol) of sodium hydroxide was added and the reaction mixture heated for another 7 h. GC analysis of another aliquot showed the absence of any hydrazone(s). The reaction mixture was cooled and worked up as described above. Diethyl ether was used to rinse a significant amount of acetonide that had sublimed on the inside wall of the condenser. Solvent removal at reduced pressure on a rotary evaporator gave 363 mg (77.5%) solid white acetonide **79**, 100% pure by GC and

pure by TLC (R_f = 0.69, ethyl acetate:hexane, 1:1). Clear crystals of acetonide **79**, mp 74.5-76.5°, were obtained by recrystallization from diethyl ether:pentane (1:4), or via sublimation at 85° (1 atm). ^{1}H NMR ($CDCl_3$, 500 MHz, 298 K): δ 1.43 (s, 6 H), 1.60 (broad s, 6 H), 2.15 (d, J = 13.4 Hz, 4 H), 2.34 (dd, J = 13.4 Hz, J = 9.2 Hz, 4 H), 2.61-2.69 (broad m, 2 H); ($CDCl_3$, 500 MHz, 208 K): δ 1.31 (t, J = 15.0 Hz, 2 H), 1.47 (s, 6 H), 1.45-1.65 (m, 2 H), 1.91 (m, 2 H), 1.99 (d, J = 13.0 Hz, 2 H), 2.19 (dd, J = 13.3 Hz, J = 9.0 Hz, 2 H), 2.38 (d, J = 13.3 Hz, 2 H), 2.50 (dd, J = 13.0 Hz, J = 9.5 Hz, 2 H), 2.69 (m, 2 H). ^{13}C NMR (toluene-d_8, 50 MHz, 298 K): δ 21.91 (CH_2), 30.08 (CH_3), 35.28 (CH_2), 37.61 (CH), 48.06 (CH_2), 101.23 (C), 116.68 (C); (toluene-d_8, 50 MHz, 215 K): δ 21.59 (CH_2), 29.87 (CH_3), 34.88 (CH_2), 37.27 (CH), 43.55 (CH_2), 51.96 (CH_2), 100.42 (C), 101.74 (C), 116.51 (C). IR ($CHCl_3$, cm^{-1}): 3036, 2927, 2865, 1456, 1370, 1106, 1013. MS (EI): 207 (M^+ - CH_3, 100), 165 (5.2), 147 (23.6), 119 (36.8), 105 (32.0), 91 (75.2), 79 (50.6), 67 (82.0), 55 (26.0). Exact mass (EI): calcd. for $C_{13}H_{19}O_2$ (M^+ - CH_3), 207.1384; found, 207.1376.

Tricyclo[3.3.3.0^{3,7}]undecane-3,7-diol (3a):

A mixture of 56.8 mg (0.26 mmol) acetonide **79** and 40 ml of 20% aqueous acetic acid was stirred at 85° for 48 h in a 100 ml round bottom flask, fitted with a condenser. The solution was cooled and solvent removed at reduced pressure on a rotary evaporator. The resulting solid residue was dissolved in 50 ml chloroform, washed with 25 ml saturated aqueous sodium bicarbonate, washed with 25 ml saturated aqueous sodium chloride, and then dried over magnesium sulfate. Solvent removal at reduced pressure on a rotary evaporator gave 37.5 mg (80.5%) solid white diol **3a**, 100% pure by GC (retention

time = 4.80 min. at 150° on a capillary column) and by TLC (R_f = 0.17, ethyl acetate:hexane, 1:1). Clear crystals of diol **3a**, mp 214-217° (d), were obtained by recrystallization from diethyl ether:pentane (1:1). ^1H NMR ($CDCl_3$, 500 MHz): δ 1.53-1.65 (m, 6 H), 2.06 (dd, J = 13.5 Hz, J = 9.2 Hz, 4 H), 2.17 (s, 2 H, exchangeable with D_2O), 2.19 (d, J = 13.5 Hz, 4 H), 2.29-2.37 (m, 2 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 21.44 (CH_2), 30.97 (CH), 34.06 (CH_2), 47.95 (CH_2), 85.78 (C). IR ($CHCl_3$, cm^{-1}): 3572 (sharp), 3600-3150 (broad), 3019, 2923, 2853, 1462, 1222, 1206, 1108, 966. MS (EI): 182 (M^+, 81.8), 164 (4.5), 149 (28.8), 139 (31.0), 121 (57.5), 111 (72.2), 95 (100). Exact mass (EI): calcd. for $C_{11}H_{18}O_2$, 182.1307; found, 182.1302.

Tricyclo[3.3.3.$0^{3,7}$]undecane-3,7-dimesylate (96):

To a stirred solution of 158.7 mg (0.872 mmol) diol **3a** in 60 ml dry THF under nitrogen at 0° was added 1.9 ml (2.66 mmol) of a 1.4 M solution of methyllithium in diethyl ether. After 20 min, 0.155 ml (2.0 mmol) methanesulfonylchloride was added dropwise. After 3 h, the reaction was quenched with 100 ml of water, extracted with 3 - 100 ml portions of methylene chloride, and the combined organic phases dried over magnesium sulfate. Solvent removal at reduced pressure on a rotary evaporator gave 268.3 mg of a solid product mixture. Separation by flash chromatography on 40 g silica using ethyl acetate:hexane (4:3) as the eluent gave 161 mg (54.6%) dimesylate **96** (R_f = 0.43, ethyl acetate:hexane, 4:3) in fractions collected when 30-55 ml of solvent had passed through the column and 64 mg monomesylate **110** (R_f = 0.22, ethyl acetate:hexane, 4:3) in fractions collected when 65-135 ml of solvent had passed through the column. The monomesylate could be converted to the dimesylate by the above procedure in 47% yield,

for an overall yield of dimesylate of 67.9%. Recrystallization of dimesylate **96** from chloroform:pentane (1:10) gave clear crystals, mp 140-142° (d). ^{1}H NMR ($CDCl_3$, 500 MHz, 298 K): δ 1.54-1.67 (6 H), 2.45 (d, J = 13.5 Hz, 4 H), 2.55-2.63 (m, 2 H), 2.79 (dd, J = 13.5 Hz, J = 9.9 Hz, 4 H), 3.07 (s, 6 H); ($CDCl_3$, 500 MHz, 193 K): δ 1.37 (broad, 2 H), 1.57 (s, 2 H), 1.90 (broad, 2 H), 2.36 (broad, 2H), 2.66 (s, 2 H), 2.77 (broad, 6 H), 3.191 (s, 3 H), 3.196 (s, 3 H). ^{13}C NMR ($CDCl_3$, 50 MHz, 298 K): δ 21.07 (CH_2), 32.37 (CH), 33.08 (CH_2), 41.05 (CH_3), 45.29 (CH_2), 101.11 (C); ($CDCl_3$, 125 MHz, 193 K): δ 20.31 (CH_2), 31.47 (CH), 32.18 (CH_2), 40.42 (CH_3), 40.60 (CH_3), 40.95 (CH_2, broad), 47.89 (CH_2, broad), 100.74 (C). IR (CH_2Cl_2, cm^{-1}): 3054, 2929, 2854, 1356, 1181, 955. MS (EI): 338 (M^+, 0.2), 259 (29.2), 173 (28.9), 163 (34.9), 121 (38.5), 105 (98.3), 93 (34.9), 77 (66.5), 68 (100). Exact mass (EI): calcd. for $C_{13}H_{22}O_6S_2$, 338.0856; found, 338.0851.

Tricyclo[3.3.3.0^{3,7}]undec-3(7)-ene (1a):

Generation of olefin **1a** using sodium amalgam: Inside a nitrogen filled glovebox, 0.4% sodium amalgam [prepared in the glovebox by adding 80 mg sodium (3.478 mmol) to 20 g mercury (99.701 mmol)] was added to a 100 round bottom flask containing 150 mg dimesylate **96** (0.444 mmol). The flask was sealed with a septum and removed from the glovebox. After adding 50 ml dry deoxygenated diethyl ether to the flask, the black heterogeneous mixture was stirred for 20 h. The stirring was stopped to allow sediment to settle. The ether phase was canula transfered into a 100 ml 2-neck flask after first passing it through a fritted funnel containing 2.5 g celite, all under argon. The amalgam residue was rinsed using 20 ml dry deoxygenated diethyl ether and the rinse added to the first ether

phase after passing it through the celite bed. Analysis by GC showed the olefin (**1a**) to be >98% pure. A light grey, oily film was left after removing solvent under reduced pressure on the vacuum line. ^{1}H NMR (toluene-d_8, 500 MHz, 298 K): δ 1.1-2.8 (very broad with a sharp peak at 2.56 ppm); (toluene-d_8, 500 MHz, 213 K): δ 1.20 (dd, J = 14.4 Hz, J = 12.2 Hz, 2 H), 1.34-1.45 (m, 1 H), 1.47-1.55 (m, 1 H), 1.67 (d, J = 13.45 Hz, 2 H), 1.70-1.78 (m, 2 H), 2.00 (d, J = 13.50 Hz, 2 H), 2.58 (broad d, J = 13.50 Hz, 2 H), 2.60 (broad s, 2 H), 2.81 (broad d, J = 13.45 Hz, 2 H); (toluene-d_8, 500 MHz, 386 K): δ 1.45 (broad s, 6 H), 1.79 (d, J = 12.7, 4 H), 2.54 (s, 2 H), 2.57 (d, J = 12.7 Hz, 4 H). ^{13}C NMR (toluene-d_8, 50 MHz, 298 K): δ 24.39 (CH_2), 35.19 (CH_2, broad), 36.80 (CH_2), 42.91 (CH_2, broad), 53.06 (CH), 155.50-158.50 (C, broad); (toluene-d_8, 50 MHz, 240 K): δ 24.22 (CH_2), 35.07 (CH_2), 36.55 (CH_2), 42.75 (CH_2), 52.84 (CH), 156.39 (C), 157.37 (C); (toluene-d_8, 50 MHz, 371 K): δ 24.64 (CH_2), 37.23 (CH_2), 39.35 (CH_2, broad), 53.44 (CH), 157.28 (C). IR (Pentane, cm^{-1}): 3000-2842, 1464, 1449. UV (Pentane): λ_{max} = 217±4 nm (ε = 10^4). MS (EI): 148 (M^+, 23.8), 133 (25.9), 119 (29.5), 105 (100), 91 (91.0), 79 (59.8), 77 (40.4), 65 (16.6), 53 (14.2). Exact mass (EI): calcd. for $C_{11}H_{16}$, 148.1251; found, 148.1259.

Generation of olefin **1a** using sodium naphthalide: A 0.31 M solution of sodium naphthalide in THF was prepared by adding 87 mg (3.78 mmol) sodium to a solution of 480 mg (3.75 mmol) naphthalene in 12 ml dry THF. The flask was sealed with a septum and the mixture stirred overnight under argon in which time the color had changed from clear to purple.

To a stirring solution of 56.3 mg (0.167 mmol) dimesylate **96** in 12 ml dry THF under argon at 0° was added 2.0 ml of the 0.31 M sodium naphthalide solution. After an

hour, the dark blue solution was warmed to room temperature. In the following work-up, not only were deoxygenated solvents used but the separatory funnel and gravity filtration apparatuses were blanketed with argon while being used. The solution was quenched with 40 ml of saturated aqueous ammonium chloride and then extracted with 3 - 25 ml portions of methylene chloride. The combined organic phases were washed once with 25 ml water and then dried over magnesium sulfate. After gravity filtration, partial concentration was carried out by passing a stream of argon over the surface of the solution. The resulting solution was stored under argon in a septum sealed flask. GC analysis showed the presence of 27% product olefin **1a** (retention time = 2.32 min. at 150° on a capillary column) and 73% naphthalene (retention time = 2.20 min.). The olefin **1a** in this mixture was trapped with DPIBF as the corresponding Diels-Alder adduct, (**97**) (see page 163).

In a different reaction where 28 mg of dimesylate **96** was reacted, pentane was used instead of chloroform during work-up. GC analysis showed the product solution to consist of a 1:4 mixture of olefin **1a** and naphthalene, respectively. Separation of the olefin (**1a**) (R_f = 0.60, pentane) from naphthalene (R_f = 0.39, pentane) was carried out by flash chromatography on 12 g silica using deoxygenated pentane as the eluent, which afforded olefin **1a** in fractions collected when 14-21 ml of solvent had passed through the column. [Note: The silica packed column was thoroughly flushed with argon before adding deoxygenated pentane. Furthermore, the top of the column was blanketed with argon while the concentrated olefin **1a**/naphthalene/pentane solution was carefully loaded onto the column.]

Trapping of Tricyclo[3.3.3.$0^{3,7}$]undec-3(7)-ene (1a) with Diphenylisobenzofuran to Give the Diels-Alder Adduct (97):

The n=3 olefin (**1a**)/naphthalene/methylene chloride solution, which contains approximately 0.167 mmol of olefin **1a** (see p.xxx), was diluted to 135 ml with deoxygenated methylene chloride. This solution was added to a nitrogen flushed 200 ml round bottom flask containing 45.1 mg (0.167 mmol) diphenylisobenzofuran (DPIBF). After stirring under nitrogen for 2 h, analysis of the reaction mixture by GC, TLC, and GCMS showed the presence of very little adduct **97** (retention time = 17.35 min. at 250° on a capillary column; R_f = 0.53, ethyl acetate:hexane, 1:12) and almost all of the olefin **1a** and DPIBF still present. The solution, after being concentrated to about 4 ml by passing nitrogen over the surface of the solution, was stirred overnight. GC analysis showed the absence of any olefin **1a** and the presence of adduct **97**. Solvent removal at reduced pressure on a rotary evaporator gave 127.6 mg of a solid product mixture. Isolation of 45.2 mg (64.8%) of the desired Diels-Alder adduct **97**, 100% pure by GC and by TLC, was carried out by flash chromatography on silica using ethyl acetate:hexane (1:40) as the eluent followed by preparative thick-layer chromatography using ethyl acetate:hexane (1:12) as the eluent. The adduct **97** was recrystallized from ethanol to give colorless crystals, mp 202-203°. ^{1}H NMR ($CDCl_3$, 500 MHz, RT): δ 1.45-2.15 (very broad with partial resolution at 1.60, 1.70, 1.77, 1.86, and 2.01 ppm, 14 H), 2.35 (m, 1 H), 2.47 (m, 1 H), 6.96 (m, one half of a symmetric AA'BB' pattern, 2 H), 7.07 (m, one half of a symmetric AA'BB' pattern, 2H), 7.34 (t, J = 7.3 Hz, 1 H), 7.43 (t, J = 7.3 Hz, 2 H), 7.58 (broad d, J = 7.3 Hz, 2 H). ^{13}C NMR ($CDCl_3$, 50 MHz, RT): δ 22.14 (CH_2), 34.93 (CH_2), 36.49 (CH_2), 40.53 (CH), 43.30 (CH), 72.92 (C, broad), 95.02 (C), 121.56 (CH), 126.01 (CH), 126.06 (CH), 127.02 (CH), 128.16 (CH), 138.97 (C),

147.46 (C); ($CDCl_3$, 50 MHz, 224 K): δ 21.82 (CH_2), 34.54 (CH_2), 36.00 (CH_2), 38.05 (CH_2), 40.01 (CH), 41.19 (CH_2), 42.83 (CH), 47.04 (CH_2), 50.89 (CH_2), 71.19 (C), 73.56 (C), 94.67 (C), 94.96 (C), 121.35 (CH), 121.46 (CH), 124.74 (CH), 126.02 (CH), 126.38 (CH), 126.95 (CH), 127.70 (CH), 128.63 (CH), 138.35 (C), 146.39 (C), 146.88 (C); ($CDCl_3$, 50 MHz, 343 K): δ 22.25 (CH_2), 35.10 (CH_2), 36.66 (CH_2), 40.76 (CH), 43.00 (CH_2), 43.51 (CH), 46.40 (CH_2), 73.00 (C), 95.19 (C), 121.67 (CH), 126.09 (CH), 126.21 (CH), 127.08 (CH), 128.20 (CH), 139.23 (C), 147.78 (C). IR (CH_2Cl_2, cm^{-1}): 3049, 2972, 2849, 1598, 1496, 1462, 1299, 1265, 1010. MS (FAB): 419 (MH^+, 7.0), 270 (100). Exact mass (FAB): calcd. for $C_{31}H_{31}O$ (MH^+), 419.2373; found, 419.2384.

6,7-Epoxytricyclo[3.3.3.$0^{3,7}$]undecan-3-ol (104):

Flash chromatography on 85 g of silica, using ethyl acetate:hexane, (1:2) as the eluent, on of a mixture of oxygen addition products, obtained by allowing olefin **1a** to react with atmospheric oxygen, resulted in several fractions, some of which contained pure samples of the compound which has been assigned the structure **103**. These fractions were combined and, after further exposure to atmospheric oxygen, became contaminated with a new mixture of compounds. One of GC analysis showed a major component (35%) with retention time = 6.21 min. at 150° on a capillary column. Flash chromatography of a 104 mg sample of the mixture through 8 g silica, using ethyl acetate:pentane (1:2) as the eluent, gave 31 mg of this component (R_f = 0.27, ethyl acetate:pentane, 1:2), collected in fractions when 120-180 ml of solvent had passed through the column. This compound was identified as 6,7-epoxytricyclo[3.3.3.$0^{3,7}$]undecan-3-ol (**104**) on the basis of its

spectral data. ^{1}H NMR (C_6D_6, 500 MHz): δ 0.69-0.76 (m, 1 H), 0.98-1.06 (m, 1 H), 1.12-1.19 (2 H), 1.17 (d, J = 10.4 Hz, 1 H), 1.19-1.26 (m, 1 H), 1.46 (dd, J = 14.4 Hz, J = 7.1 Hz, 1 H), 1.56 (s, exchangeable with D_2O, 1 H), 1.54-1.63 (m, 1 H), 1.82 (d, J = 14.4 Hz, 1 H), 1.85 (dd, J = 13.8 Hz, J = 6.8 Hz, 1 H), 1.97-2.04 (m, 1 H), 2.03 (d, J = 13.8 Hz, 1 H), 2.11 (dd, J = 7.1 Hz, J = 6.2 Hz, 1 H), 2.10 (dd, J = 10.4 Hz, J = 5.2 Hz, 1 H), 2.87 (s, 1 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 20.95 (CH_2), 31.38 (CH_2), 31.89 (CH), 32.01 (CH_2), 35.30 (CH_2), 36.75 (CH), 38.85 (CH_2), 41.56 (CH_2), 70.58 (CH), 73.36 (C), 80.56 (C). IR ($CHCl_3$, cm^{-1}): 3566 (sharp), 3625-3260 (broad), 3013, 2931, 2849, 1443, 1314, 1096, 908. MS (EI): 180 (M^+, 5.8), 162 (2.6), 137 (42.5), 123 (65.4), 111 (71.5), 95 (100), 84 (97.7), 67 (32.4), 55 (54.9). Exact mass (EI): calcd. for $C_{11}H_{16}O_2$, 180.1150; found, 180.1145.

Bicyclo[3.3.3]undecane-3,7-dione (4a):

Flash chromatography, using silica and ethyl acetate:hexane (1:2), of a mixture of oxygen addition products, obtained by allowing olefin **1a** to react with atmospheric oxygen, resulted in a number of fractions which contained diketone **4a** (R_f = 0.16, ethyl acetate:hexane, 1:2) These fractions were combined and the resulting mixture was shown by GC analysis to consist of diketone **4a** (80% by GC, retention time = 9.38 min. at 150° on a capillary column) and epoxyalcohol **104** (10%) and several other compounds (10%). Attempts to purify diketone **4a** by recrystallization were unsuccessful. ^{1}H NMR (C_6D_6, 500 MHz): δ 1.25-1.32 (m, 2 H), 1.32-1.38 (m, 4 H), 1.87-1.92 (m, 4 H), 2.16 (dd, J = 12.4 Hz, J = 5.5 Hz, 4 H), 2.30 (dd, J = 12.4 Hz, J = 5.3 Hz, 4 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 22.03 (CH_2), 29.74 (CH_2), 30.83 (CH), 46.52 (CH_2), 213.74 (C). IR

($CHCl_3$, cm^{-1}): 3025, 2928, 2861, 1685, 1447, 1227. MS (EI): 180 (M^+, 0.7), 152 (3.1), 136 (19.9), 122 (31.9), 109 (22.8), 95 (100), 81 (68.4), 67 (44.2), 55 (61.1). Exact mass (EI): calcd. for $C_{11}H_{16}O_2$, 180.1150; found, 180.1151.

Reduction of Diketone 4a to Diol 3a:

A 49.7 mg mixture consisting of diketone **4a** (80% by GC) was subjected to the same reduction conditions used to transform diketone **8** to diol **9**.[8] The product mixture (28.2 mg) was found to consist primarily of one compound (71% by GC). This compound was identified as diol **3a** after comparing its GC retention time, TLC R_f value, and ^1H NMR spectrum with those of an authentic sample of diol **3a**.

Tricyclo[3.3.2.$0^{3,7}$]decane-3,7-diol Acetonide (107):

Into a 250 ml round bottom flask fitted with a condenser was added 647 mg (2.914 mmol) ketone **92**, 1.42 ml (29.19 mmol) of hydrazine monohydrate, 1.04 g (25.98 mmol) sodium hydroxide, and 140 ml diethylene glycol. The mixture was stirred under nitrogen at 185° for 30 h. An aliquot was worked up by adding water, extracting three times with diethyl ether, washing the combined ether extracts twice with water, and drying the ether phase over magnesium sulfate. GC (retention time = 3.28 min. at 165° on a capillary column) and GCMS analysis showed acetonide **107** to be the major product and showed the absence of any unreacted ketone **92** or hydrazone. The reaction mixture was cooled to room temperature and worked up as described above. Diethyl ether was used to rinse a

significant amount of acetonide that had sublimed on the inside wall of the condenser. Solvent removal at reduced pressure on a rotary evaporator gave 629 mg of a solid which GC analysis showed to be 97% acetonide **107**. Attempts to recrystallize the acetonide **107** from varying solvent mixtures using diethyl ether, pentane, chloroform, methanol, and ethanol were unsuccessful. Purification of acetonide **107** (R_f = 0.30, diethyl ether:hexane, 1:10) was carried out by flash chromatography on 45 g of silica using diethyl ether:hexane (1:10) as the eluent, which yielded 538 mg (88.7%) of solid white acetonide **107**, 100% pure by GC and pure by TLC, in fractions collected when 160-260 ml of solvent had passed through the column, mp 45.5-46.5°. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.47 (s, 6 H), 1.70 (m, 4 H), 1.88 (d, J = 11.7 Hz, 4 H), 2.16 (dd, J = 11.7 Hz, J = 6.1 Hz, 4 H), 2.39 (m, 2 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 29.67 (CH_2), 30.10 (CH_3), 35.50 (CH), 47.66 (CH_2), 98.46 (C), 118.01 (C). IR ($CHCl_3$, cm^{-1}): 3018, 2943, 2861, 1454, 1372, 1199, 1052. MS (EI): 193 (M^+ - CH_3, 100), 151 (13.5), 133 (14.6), 109 (15.5), 93 (31.8), 79 (30.3), 67 (28.9), 55 (22.9), 43 (63.2). Exact mass (EI): calcd. for $C_{12}H_{17}O_2$ (M^+ - CH_3), 193.1227; found, 193.1220.

Tricyclo[3.3.2.0^{3,7}]decane-3,7-diol (3b):

A mixture of 49.0 mg (0.236 mmol) acetonide **107** and 40 ml of 20% aqueous acetic acid was stirred at 85° for 48 h in a 100 ml round bottom flask, fitted with a condenser. The solution was cooled and the solvent was removed at reduced pressure on a rotary evaporator. The resulting solid residue was dissolved in 20 ml chloroform and washed with 20 ml saturated aqueous sodium bicarbonate. The aqueous phase was extracted with 2 - 20 ml portions of chloroform, and the combined organic phases dried

over magnesium sulfate. Solvent removal at reduced pressure on a rotary evaporator gave 32.9 mg of solid white diol **3b** (83.1%), which was 100% pure by GC (retention time = 3.16 min. at 165° on a capillary column) and pure by TLC (R_f = 0.06, diethyl ether:pentane, 1:1). The diol was recrystallized from diethyl ether, mp > 260° (sublimation begins around 220° at 1 atm). ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.68 (m, 4 H), 1.85-1.95 (8 H), 2.10 (m, 2 H), 2.26 (s, 2 H, exchangeable with D_2O). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 29.15 (CH_2), 29.41 (CH), 48.04 (CH_2), 83.21 (C). IR ($CHCl_3$, cm^{-1}): 3578, 3402 (broad), 3015, 2936, 2861, 1451, 1322, 1114. MS (EI): 168 (M^+, 100), 166 (40.8), 150 (9.8), 138 (30.1), 123 (14.5), 111 (60.6), 109 (63.4), 108 (58.8), 95 (62.0), 81 (61.8), 67 (20.5), 55 (17.8). Exact mass (EI): calcd. for $C_{10}H_{16}O_2$, 168.1149; found, 168.1144.

Tricyclo[3.3.2.0^{3,7}]decane-3,7-dimesylate (108):

To a stirred solution of 37.2 mg (0.221 mmol) diol **3b** in 14 ml dry THF under argon at 0° was added 0.5 ml (0.70 mmol) of a 1.4 M solution of methyllithium in diethyl ether. After 20 min, 0.056 ml (0.724 mmol) methanesulfonyl chloride was added dropwise. After 3 h, most of the solvent was removed at reduced pressure on a rotary evaporator. To the remaining mixture was added 25 ml water and this aqueous phase extracted with 3 - 25 ml portions of chloroform. The combined organic phases were dried over magnesium sulfate. Solvent removal at reduced pressure on a rotary evaporator gave 59.1 mg of a white solid. Separation by flash chromatography on 7 g silica using ethyl acetate:hexane, (4:3) as the eluent gave 37 mg (51.7%) dimesylate **108** (R_f = 0.43, ethyl acetate:hexane, 4:3) in fractions collected when 35-45 ml of solvent had passed through the

column and 17 mg monomesylate (R_f = 0.18, ethyl acetate:hexane, 4:3) in fractions collected when 50-100 ml of solvent had passed through the column. Recrystallization of dimesylate **108** from chloroform:pentane (1:4) gave clear crystals, mp 134-135°. ^{1}H NMR ($CDCl_3$, 500 MHz): δ 1.71 (m, 4 H), 2.22 (d, J = 11.8 Hz, 4 H), 2.37 (m, 2 H), 2.60 (dd, J = 11.8 Hz, J = 6.7 Hz, 4 H), 3.09 (s, 6 H). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 28.23 (CH_2), 30.39 (CH), 40.70 (CH_3), 45.70 (CH_2), 96.90 (C). IR ($CHCl_3$, cm^{-1}): 3025, 2937, 2865, 1343, 1168, 1036, 931, 846. MS (EI): 245 (17.6), 149 (100), 121 (24.0), 109 (33.4), 107 (54.1), 91 (23.3), 79 (32.0). Exact mass (FAB): calcd. for $C_{12}H_{21}O_6S_2$, 325.0778; found, 325.0775.

Preparation of the Bis(triphenylphosphine) platinum Complex (105) of Ethylene:[56]

Dichloro-bis-triphenylphosphine platinum (1.02 g, 1.3 mol), was stirred in methylene chloride (7 ml) and ethanol (7 ml) at 0°C. Ethylene was bubbled through the slurry for 20 min. before $NaBH_4$ (0.25g, 0.66 mol) was added slowly over a period of 20 min. During this time some more ethanol (10-15 ml) was added. Ethylene was bubbled through the reaction mixture for 30 more min. and then ethanol (30 ml) was added. The precipitate was suction filtered, washed with water, ethanol, and pentane and then air dried to give (0.87g, 91% yield) of complex (**105**), which then was stored under nitrogen. ^{1}H NMR (C_6D_6, 200 MHz): δ 7.51 (m, 12 H), 6.94 (m, 18 H), 2.63 (t, J_{Pt-H} = 60.6 Hz, 4 H). ^{13}C NMR (C_6D_6, 75 MHz): δ 39.2 (t of m, J_{Pt-C} = 194 Hz), 128.6 (s), 129.8 (s), 134.6 (m), 139.2 (m). ^{31}P NMR (C_6D_6, 81 MHz): δ 34.1 (t of m, J_{Pt-Pt} = 3740 Hz). ^{195}Pt NMR (C_6D_6, 42.8 MHz): δ -555[61] (t , J_{Pt-P} = 3738 Hz).

Preparation of the Bis(triphenylphosphine)platinum Complex (106b) of the n=2 Olefin (1b):

A flask containing dimesylate **108** (201 mg, 0.62 mol), Na/Hg (100 mg Na in 22 g Hg) and $(PPh_3)_2PtC_2H_4$ (520 mg, 0.70 mol) was attached to a vacuum line and evacuated. Dry ether (50 ml) was distilled in and then the flask was filled with argon and the reaction mixture was stirred overnight. Filtration through celite (under an argon atmosphere) gave a clear yellow solution. The celite bed was washed with dry ether (2 x 10 ml). The ether solutions were combined and the solvent removed under vacuum to afford a yellowish powder, which was washed with pentane (2 x 5 ml) and ethanol (4 ml) and then recrystallized from THF/ethanol to afford crystals of the desired complex (**106b**) (220 mg, 42% yield). ^1H NMR (C_6D_6, 300 MHz): δ 7.59 (s, 12 H), 6.95 (m, 18 H), 2.97 (t, J_{Pt-H} = 39 Hz, 2 H), 2.47 (t, J_{Pt-H} = 69 Hz, 4 H), 1.86-1.82 (8 H). ^{13}C NMR (C_6D_6, 50 MHz): δ 138.0 (m, C), 134.3 (m, CH) 129.1(s, CH), 128.0 (s, CH), 74.9 (t of m, J_{Pt-C} = 343 Hz, C), 53.1 (t, J_{Pt-C} = 105 Hz, CH), 48.4 (t, J_{Pt-C} = 24 Hz, CH_2), 31.6 (s, CH_2). ^{31}P NMR (C_6D_6, 81 MHz): δ 31.1 (t of m, J_{P-Pt} = 3115 Hz). ^{195}Pt NMR (C_6D_6, 42.8 MHz): δ -514[61] (t , J_{P-Pt} = 3115 Hz). The FAB spectrum showed that the parent ion at (M+H)/e = 855 (exact mass calculated for $C_{46}H_{45}P_2Pt$ 855.2646, found 855.2649), with peaks at 853 and 854 for the two other abundant isotopes of Pt.

Preparation of the Bis(triphenylphosphine)platinum Complex (106a) of the n=3 Olefin (1a):

A round bottom flask containing dimesylate **96** (212 mg, 0.63 mol) and Na/Hg (prepared by adding 100 mg Na to 22 g Hg under inert atmosphere) was attached to a

vacuum line and evacuated. Dry ether (40 ml) was distilled in, the flask was filled with argon, and the reaction mixture was stirred overnight. The reaction mixture was concentrated to about half its volume by blowing argon through it and then it was filtered through celite (under argon atmosphere) into a solution of $(PPh_3)_2PtC_2H_4$ (420 mg, 0.56 mol) in dry THF (30 ml). Removal of the solvent under vacuum afforded a yellowish powder which was recrystallized from THF/ethanol (1:3) to give yellowish crystals of the desired complex (**106a**) (235 mg, 43% yield based on the $(Ph_3P)_2Pt$ complex (**105**) of ethylene), mp (sealed tube) 145-148° (d), which were pure by NMR. MS (FAB): (M^+) = 867 (calc. 867.2646, found 867.2630). Peaks at 866 and 868 for the other abundant isotopes of Pt were also observed. ^1H NMR (toluene-d_8, 500 MHz, 245 K): δ 7.54 (s, 12 H), 6.96 (m, 18 H), 2.88 (t of m, 2 H, J_{Pt-H} = 80.6 Hz), 2.80 (d, 2 H, J = 5.8 Hz), 2.54 (t of m, 2 H, J_{Pt-H} = 80.6 Hz), 2.36 (dd, 2 H, J_{Pt-H} = 20.1Hz, J_{H-H} = 13.7 Hz), 2.10 (dd, 2 H, J_{Pt-H} = 20.1Hz, J_{H-H} = 14.0 Hz) 1.98 (d, 3 H, J = 8.2 Hz), 1.67 (m, 1 H) 1.52 (t, 2 H, J = 13.2 Hz). ^{13}C NMR (toluene-d_8, 50 MHz, 338 K): δ 138.3 (m, C), 134.2 (m, CH) 129.0 (CH), 128.0 (CH), 78.8 (t of m, J_{Pt-C} = 296 Hz, C), 52.2 (broad s, CH_2), 50.7 (t, J_{Pt-C} = 76 Hz, CH), 41.5 (broad s, CH_2), 36.9 (CH_2), 23.1 (CH_2). ^{31}P NMR (C_6D_6, 81 MHz): δ 32.2 (t of m, J_{P-Pt} = 3328 Hz). ^{195}Pt NMR (toluene-d_8, 42.8 MHz): δ -5016[1] (t , J_{P-Pt} = 3332 Hz).

X-Ray structures of the Bis(triphenylphosphine)platinum Complex (106b) of the n=2 Olefin (1b) and the Bis(triphenylphosphine)platinum Complex (106a) of the n=3 Olefin (1a):

Both complexes are basically stable in air, but were examined in mineral oil, and suitable crystals were placed in capillaries. Both crystals were clear colorless rhombs and

were examined at room temperature. The dimensions of the crystals were 0.25 x 0.35 x 0.35 mm. and 0.2 x 0.25 x 0.3 mm., respectively. Both crystals were found to be triclinic (space groups P1 and P1, respectively). The unit cell dimensions for the first crystal were: a = 11.656 (2) Å, b = 16.548 (3) Å, c = 21.353 (4) Å, α = 68.37 (2)°, β = 79.33 (2)°, γ = 86.70 (2)° and for the second: a = 11.715(2) Å, b = 12.015(2) Å, c = 14.878(3) Å, α = 97.76 (2)°, β = 109.36 (2)°, γ = 96.90 (2)°. A total of 8009 and 4621 reflections were observed for the two crystals, respectively, using a Siemens R3m/V diffractometer with MoKα radiation (λ = 0.71073 Å). Data reduction was performed using the MOLen system of programs and all subsequent solutions and refinements were carried out using the PC version of Siemens SHELX. In both cases the LAUE merging R factor for equivalents was quite good, and densities agreed with the space groups found.

The location of heavy atoms and determination of space group statistics was easily carried out. The first crystal gave two molecules per unit cell in P1 and this result was examined carefully, but no higher space group was possible for the observed intensities. The refinement for the first compound converged to R = 4.77%, Rw = 6.44% and GOF 1.20, and for the second to R = 3.2%, Rw = 4.02% and GOF 0.80.

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Vita

Joseph Michael Smith was born in Oswego, New York on March 9, 1961 to Joseph R. and Mary I. Smith. Following graduation from Oswego High School in 1979, he attended the State University of New York at Oswego where he received his Bachelor of Science degree in chemistry in 1984. He entered the graduate program in organic chemistry at the University of Washington in Seattle, Washington in 1986 and received the degree of Doctor of Philosophy on January 11, 1993.