STUDIES INVOLVING THE BINDING OF ISODICYCLOPENTADIENE AND C_2-SYMMETRIC ANSA-TYPE CYCLOPENTADIENYL LIGANDS TO GROUP IV METALS

A Thesis

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By

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* * * * *

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ABSTRACT

The synthesis of new C_2-symmetric ansa-type cyclopentadienyl ligand derived from thujone was initiated. Two independent synthetic strategies were developed leading to the advanced intermediates **27** and **32**.

Preliminary investigations illustrated the principal possibility of synthesizing binaphtol-like ligand **33**. The synthetic strategy adopted is based on the electrocyclization of triene **55**, followed by oxidative aromatization and benzylic oxidation. Key intermidiate **54** was efficiently prepared. Its further dehydration in order to approach **55** was evaluated. The procedure for optical purification of (+)-nopinone, which served as starting material, was developed.[40]

Metal comlexation chemistry of isodicyclopentadiene was thoroughly investigated. It was shown that silyl inversion methodology can be used to generate synthetically useful titanocene trichloride complex **63** as well as to prepare μ-oxo complexes **65** and **68** thereby allowing the direct comparison of ligand distortion, ligand orientation and metal environment effects.

Dedicated to my husband, Sergey

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LIST OF ABBREVIATIONS

α	alpha
β	beta
γ	gamma
n-Bu	*normal*-butyl
t-Bu	*tert*-butyl
^{0}C	dergees Celsius
calcd	calculated
d	day(s); doublet (spectral)
DMF	N,N-dimethylformamide
Et	ethyl
g	gram(s)
h	hours
Hz	hertz
IR	infrared
J	coupling constant (NMR)
m	milli-; multiplet (NMR)
m-CPBA	meta-chloroperbenzoic acid
M	moles per liter
MHz	megahertz
min	minute(s)

mol	mole(s)
mp	melting point
MS	mass spectrometry
m/z	mass to charge ratio
obsd	observed
ppm	part per million (NMR)
q	quartet (NMR)
s	singlet (NMR)
t	triplet (NMR)
THF	tetrahydrofuran
TMS	trimethylsilane

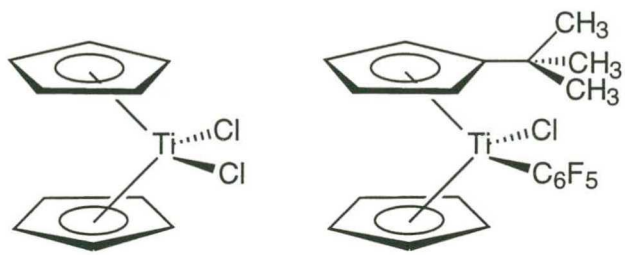
CHAPTER 1

INTRODUCTION

1.1. Historical Perspective on the Use of Optically Active Titanocene Complexes in Asymmetric Hydrogenation.

The use of chiral catalysts to effect the asymmetric hydrogenation of prochiral olefinic substrates with high optical yields represents one of the most impressive achievements to date in catalytic selectivity, rivaling the corresponding stereoselectivity of enzymic catalysts.[1,2] Notably high optical yields, approaching 100% enantiomeric excess, have been achieved in the hydrogenation of enamides to the corresponding amino acid derivatives with cationic rhodium or ruthenium catalysts containing chiral phosphine (especially bis(tertiary)-phosphines) ligands.[3] Unfortunately, the scope of the Rh or Ru-catalyzed reaction is not very wide. Highly enantioselective hydrogenation is observed only in cases where *several criteria* are met, among them the presence of a carbonyl group to allow the substrate to chelate, the presence of a small or very flexible group *trans* to the carbonyl group and the presence of an electron-withdrawing group *gem* to the carbonyl group.[5]

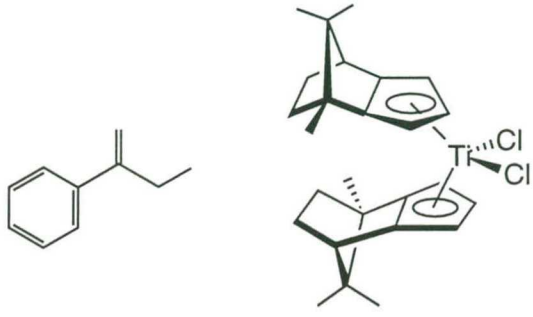
Titanocene dichloride (**1**),[6] on the other hand, uses only the π-bond of the olefin substrate as its "handle" to enable the reaction to take place. With the cyclopentadienyl moiety present, chirality can be introduced by substituents on the ring as well as by generating a chiral metal atom as in **2**.



1 **2**

Figure 1.1: Structures of Complexes **1** and **2**.

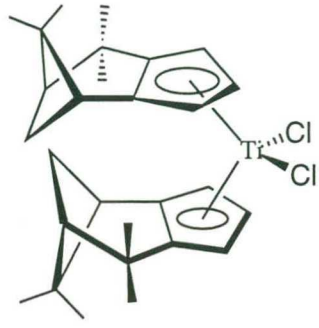
Chiral titanocene-catalyzed hydrogenation of unfunctionalized olefins was first reported by Kagan in 1979. He showed that α-ethylstyrene (**3**) was hydrogenated with low to moderate enantioselectivity using titanium complexes with menthyl or neomenthylcyclopentadienyl ligands.[7] In 1986, Halterman and Vollhardt reported concurrently with the Paquette research group the use of **4** for the asymmetric reduction of **3**.[4,8]



3 4

Figure 1.2: Structures of α-Ethylstyrene (**3**) and Complex **4**.

Much earlier, complex **2** was prepared.[9] In 1992, Sivik reported on the synthesis of **5** and showed that the reduction of **3** in the presence of **5** afforded product in 69% ee.[10]



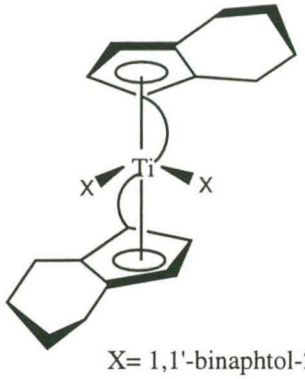
5

Figure 1.3: Structure of Complex **5**.

1.2. Ansa Ligands in Metallocene Complexes.

Since the first results on enantioselective hydrogenation of olefins with titanocene complexes were reported, several groups initiated the search for other complexes of Group IV transition metals that would give higher levels of asymmetric induction. It was suggested[11] that in order to be used as stereospecific catalysts for olefin hydrogenation, compounds of this type have to retain their configutational stability even upon exchange of both equatorial ligands, which invariably occurs in catalytic reaction sequences. Titanocene derivatives with configurational stability vis-á-vis exchange of equatorial ligands and with high stereorigidity could be obtained by introduction of ring substituents into a metallocene framework in which both cyclopentadienyl rings are covalently connected by a $(CH_2)n$ bridge. A key breakthrough was the

development by Brintzinger and coworkers of the chiral titanium metallocene shown in Figure 1.4.[12-14]



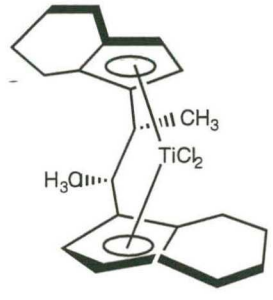
X= 1,1'-binaphtol-2,2'-diolate

6

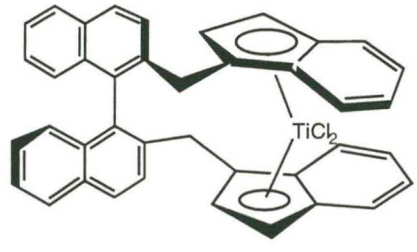
Figure 1.4: Structure of Complex **6**.

Buchwald employed **6** for asymmetric hydrogenation of trisubstituted olefins. The reaction proceeded in good chemical and excellent optical yields.[15] Still, it is worse mentioning that the synthesis of **6** itself was extremely inefficient. An optical resolution required to obtain enantiomerically pure material, was complicated by the presence of a meso diastereomer and the overall yield in the preparation of pure **6** was low.

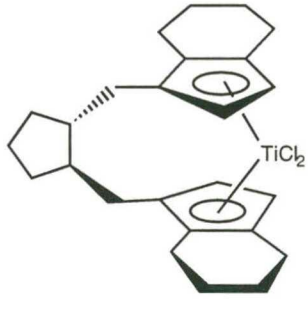
In order to overcome problems with optical resolution, the introduction of asymmetry on the bridging carbons of a tethered bis(cyclopentadienide) ligand has been used to promote the diastereoselective complexation of the Cp rings. This strategy has been applied in the preparation of **7**, **8**, and **9** (Figure 1.5).[16-18]



(*R,R*)-**7**



(*R*)-**8**



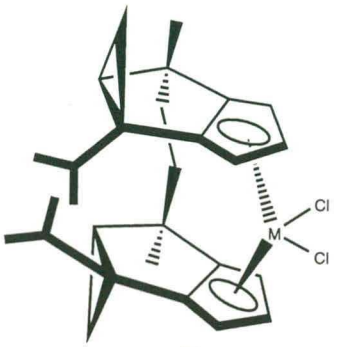
(*S,S*)-**9**

Figure 1.5: Structures of the Complexes **7-9**.

1.3. Definition of the Thesis Project.

As was shown above, chiral ansa-metallocene derivatives of Group IV transition metals are of considerable current interest as catalysts for asymmetric hydrogenation of unfunctionalized olefins. So far, however, only complexes with bridged bis-indenyl or bis(tetrahydroindenyl)ligand frameworks have been reported. Since the stereoselectivities of these catalysts must have their origin in steric interactions between the substituted olefin and the chiral ligand framework, it would be desirable to extend the range of the available chiral ansa-metallocene catalysts to types with other, e.g sterically more demanding, substituents.

Therefore, the goal of the present research was to develop synthetic entries to the new C_2-symmetric ansa-type titanocenes. In keeping with our interest in developing optically active cyclopentadienyl ligands from readily available chiral pool starting materials, the first complex to be approached was **10**. Chapter 2 will address the advances made toward it.



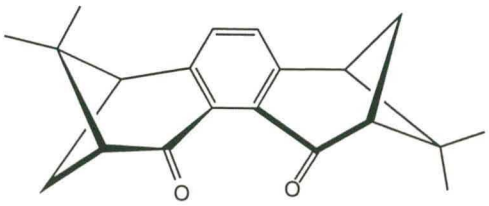
E

M = Ti, Zr

10

Figure 1.6: Target Complex **10**.

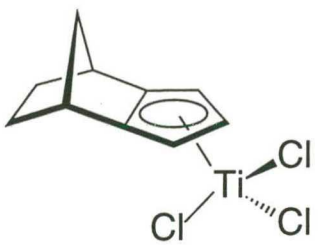
Along somewhat different lines, the purpose of my research was also to look into the possible synthesis of **11**, a potential binaphthol-like ligand.



11

Figure 1.7: Target Diketone **11**.

In addition, it was desired to study the metal complexation chemistry of (trimethylsilyl)isodicyclopentadiene in order to analyze the conditions for preparation of the titanium trichloride complex **12**. Chapter 4 will discuss this topic.



12

Figure 1.8: Structure of Complex **12**.

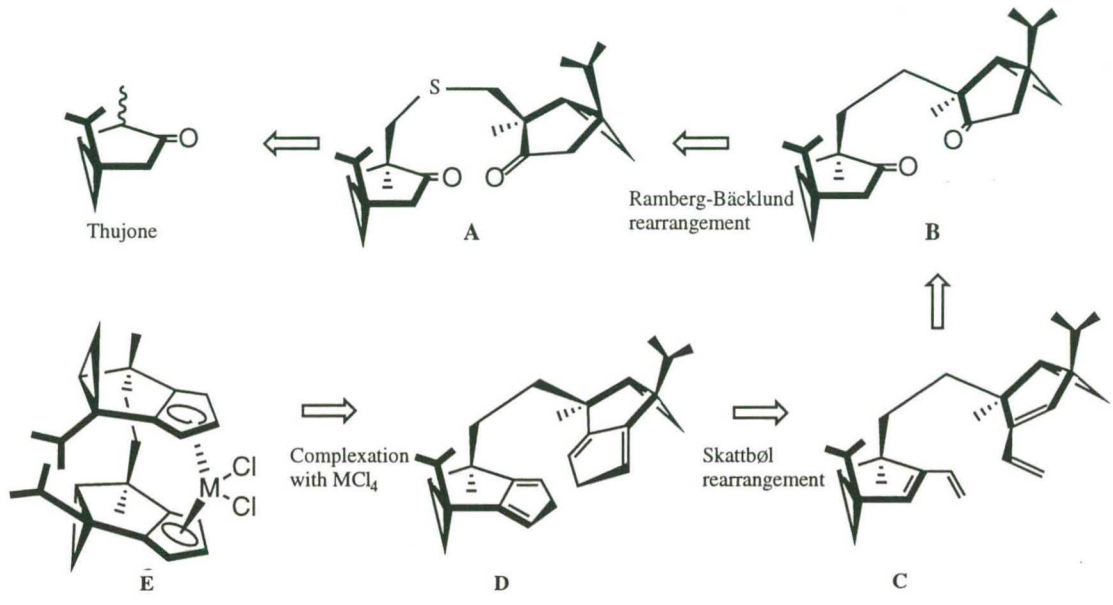
CHAPTER 2

SYNTHETIC STRATEGY TOWARD A C_2-SYMMETRIC ANSA-TYPE CYCLOPENTADIENYL LIGAND DERIVED FROM THUJONE

2.1. Retrosynthetic Analysis.

Our disconnective approach, as summarized by the retrosynthetic analysis depicted in Scheme 2.1, utilizes the readily available chiral natural product thujone as starting material. This compound, having adequate functionality for later annulation of a cyclopentadienyl ring, features a bicyclic framework crucial for facial differentiation upon coordination to a metal in the final step.

The Ramberg-Bäcklund rearrangement appeared to constitute a strategy of choice for the introduction of an ethylene bridge (subtarget **B**) early in the scheme. Once tetraene **C** had been crafted by conventional means, twofold addition of dibromocarbene would be accomplished at the less sterically congested vinyl groups, and Skattebøl rearrangement would give rise to the crucial hydrocarbon **D**. Upon reaction of its dianion with MCl_4 (M= Ti, Zr), the coiled metallocene **E** should result.

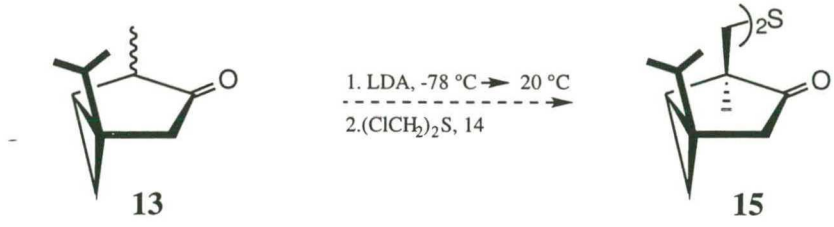


Scheme 2.1: Retrosynthetic Analysis of Target Complex **E**.

Our first synthetic challenge was therefore the subtarget **A**, a key intermediate for Ramberg-Bäcklund rearrangement. The next two sections explore this topic.

2.2. Attempted Alkylation of Thujone with Bis(chloromethyl)sulfide.

Alkylation of thujone (**13**) with bis(chloromethyl)sulfide (**14**) as electrophile would give the desired compound **15** if the reaction would prove to be thermodynamically controlled.



13 **15**

Scheme 2.2: Proposed synthesis of **15**.

Unfortunately, the simple deprotonation of **13** followed by addition of chlorotrimethylsilane gave a mixture of silyl enol ethers **16** and **17**, with **17** predominating in most cases.

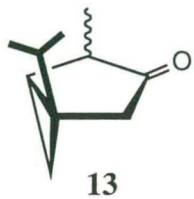
13 16 17

Scheme 2.3: Selectivity in the Deprotonation of **13**.

Base	**16:17** ratio, %
LDA, -78 °C	0:100
LDA, -78 °→25 °C	0:100
KH, -10 °→25 °C	40:60
t-BuOK, 0 °C	25:75

Table 2.1: Selectivity in the Deprotonation of **13**.

These results (Table 2.1) clearly demonstrated that the preference the deprotonation of **13** operates under kinetic control. We also independently investigated the reactivity of **14** as an electrophile and found it to be completely unresponsive to substitution.



13

1. LDA, -78 °C → 20 °C
2.$(ClCH_2)_2S$, A

start. mat.

Scheme 2.4: Alkylation of **13** in the Presence of Different Additives.

In order to generate a more reactive species in situ, various additives have been tried.[19-21] However no changes in the outcome were detected (Table 2.2).

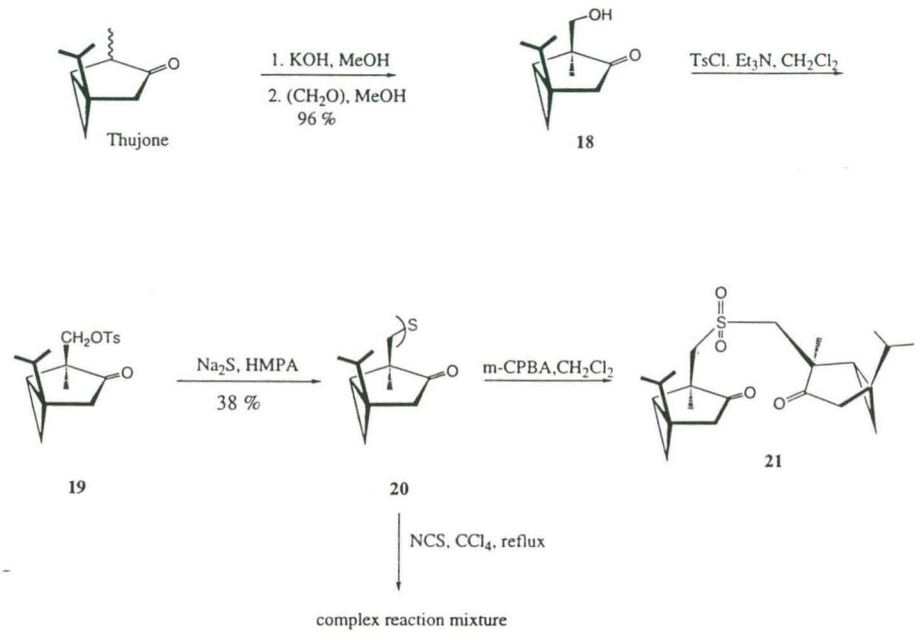
A	Results of Alkylation
HMPA	no rxn
$ZnBr_2$	no rxn
NaI	no rxn

Table 2.2: Use of Additives in the Alkylation of **13**.

Taking the above findings into consideration, we decided to approach **15** differently. This is the subject of the next section.

2.3. Alternative Synthesis of a Key Intermediate for the Ramberg-Bäcklund Rearrangement.

Aldol condensation between thujone and formaldehyde was recognized to deliver compound **18**, where exclusive formation of the thermodynamic product was explained by the slow equilibria through which this reaction proceeded.[22] Conversion of **18** to its tosylate **19** followed by nucleophilic substitution with Na_2S in HMPA afforded **20** in 38% yield.[23] Oxidation of the resulting sulfide with *m*-CPBA gave sulfone **21,** though all further attempts to obtain the α-chlorosulfone failed and resulted in the formation of complex reaction mixtures.



Scheme 2.5: Synthesis of Sulfone **21**.

We reasoned that the presence of the unprotected carbonyl group in **20** could be a source of complications. Therefore, attempts were undertaken to protect it. Several conditions have been tried (Table 2.3), but surprisingly all resulted in unchanged starting material.

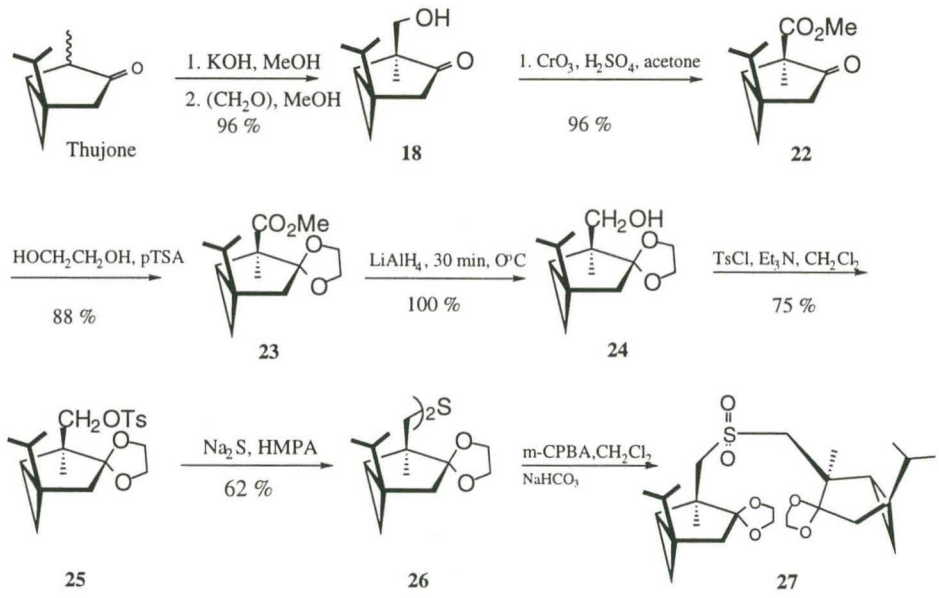
Conditions	Results
$(HOCH_2)_2$, *p*-TSA, benzene, reflux	no rxn
$(HOCH_2)_2$, $HC(OMe)_3$	no rxn
$(TBSOCH_2)_2$, TBSOTf, -78 °C	no rxn
$(HOCH_2)C(CH_3)_3$, *p*-TSA, benzene, reflux	no rxn

Table 2.3: Attempted Ketalization of **20**.

Ketone groups on five-membered rings have been known to give difficulty in acetal protections due to the ring strain assocciated with $sp^2 \rightarrow sp^3$ hybridization.[24] In our particular case, we also considered the significant steric hindrance in **20** and reasoned that protection of the carbonyl moiety should take place before the two thujone fragments are coupled.

With that in mind, we attempted the direct ketalization of 4β-(hydroxymethyl)thujone (**18**). The standard conditions of a catalytic amount of *p*-TSA in refluxing benzene did not give the desired product however. To overcome this problem, keto ester **22** was prepared according to a recent protocol and then protected to give **23**.[22] It is worth mentioning that the protection of **22** was found at first to be troublesome, but after several experiments the right set of conditions was found. Refluxing of a 1 M solution of **22** in benzene with 11 equivalents of ethylene glycol in the presence of 7 mol % of *p*-TSA for 72 h afforded **23** in 88% yield. Reduction of **23** with $LiAlH_4$ gave alcohol **24** in

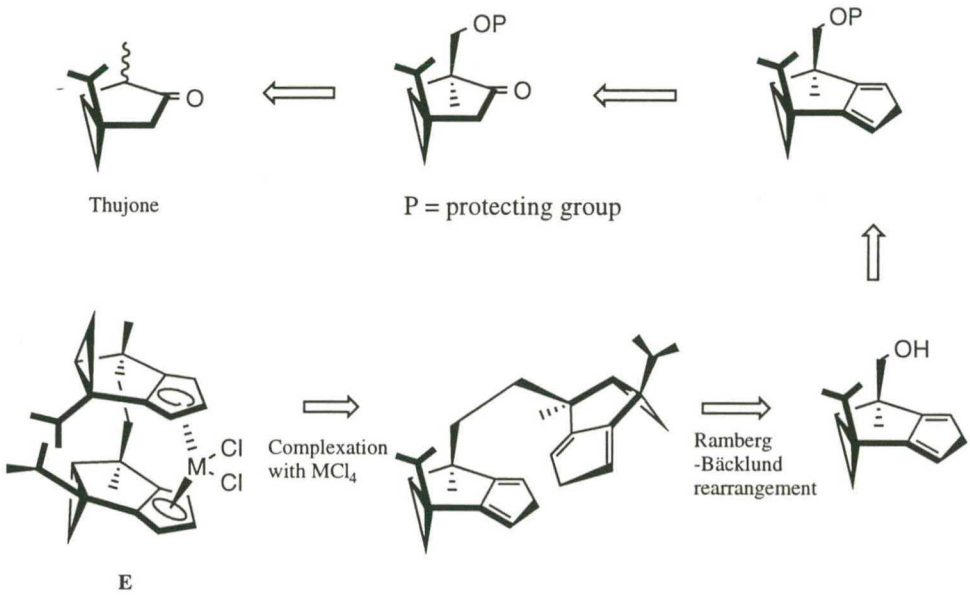
quantitative yield. The latter was converted to tosylate **25** as shown in Scheme 2.6. With **25** in hand, nucleophilic substitution with Na_2S in HMPA was performed in a manner analogous to that used in the case of unprotected thujone (see Scheme 2.4) and finally furnished **26**, as previously desired. The oxidation of **26** with *m*-CPBA under buffered conditions ($NaHCO_3$) gave **27**, a key intermediate for SO_2 extrusion under Ramberg-Bäcklund rearrangement conditions.



Scheme 2.6: Synthesis of Key Intermediate **27** for the Ramberg-Bäcklund Rearangement.

2.4. Annulation of Cyclopentadienyl Ring onto the Thujone Framework.

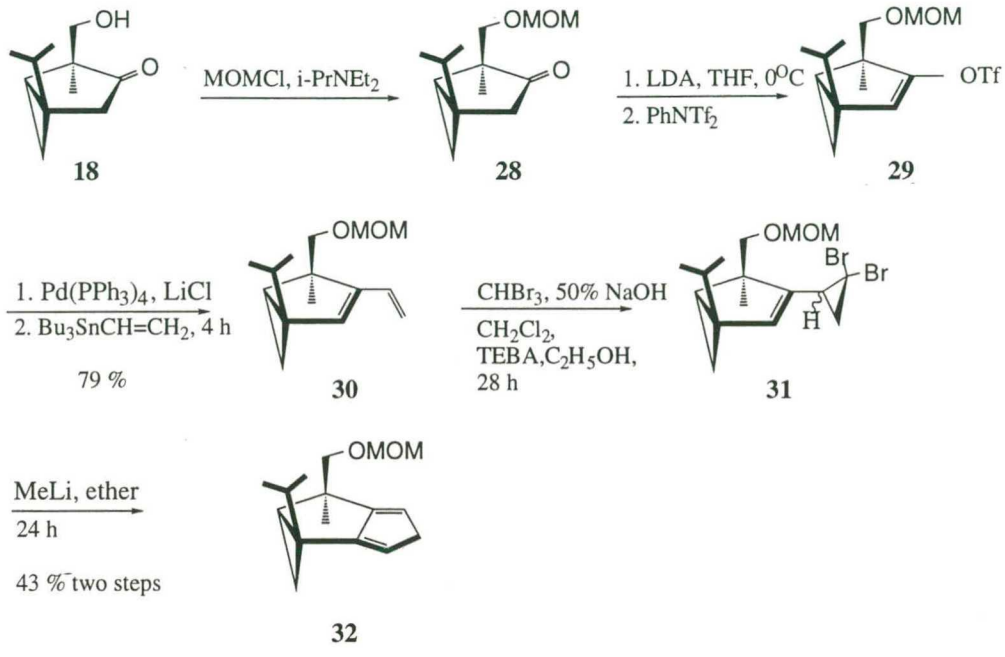
At the same time, we pursued an alternative synthesis of target complex **E**. In contrast to the previous approach, we wanted to annulate the cyclopentadienyl ring early in the synthesis (Scheme 2.7).



Scheme 2.7: Alternative Synthetic Strategy Toward Target Complex **E.**

We considered the methoxymethyl ether as a suitable protecting group for this synthetic strategy, reasoning that it should be compatible with the reaction conditions applied during the following steps.

4β-(Hydroxymethyl)thujone (**18**) was synthesized as described earlier[22] and protected with chloromethyl methyl ether to give **28** in 89% yield. Triflate **29** was formed by deprotonation of **28** with LDA and trapping of its enolate with N-phenyltrifluoromethanesulfonamide. Palladium (0)-promoted vilylation of **28** led to diene **30** in 79% yield. The treatment of it with bromoform and 50% sodium hydroxide solution under phase transfer conditions led to dibromide **31**. Subsequent exposure of **31** to methyllithium furnished cyclopentadiene **32** in 43% yield (Scheme2.8).[25-27]



Scheme 2.8: Synthesis of Key Intermediate **32** for the Alternative Synthetic Approach.

2.5. Attempted removal of methoxymethyl protecting group.

As summarized in Scheme 2.8, cyclopentadiene **32** was promptly synthesized in good overall yield. With it in hand we were ready to initiate the coupling of two thujone fragments with annulated cyclopentadienyl rings following removal of the protecting group. Unfortunately, the cyclopentadiene moiety obtained in **32** showed extremely low stability toward conditions applied

for the deprotection of hydroxyl groups and underwent full and rapid decompositon in all cases (Table 2.4).

CONDITIONS	RESULTS
HCl-H_2O-THF/1:2:1	decomp.
p-TsOH, H_2O,THF	decomp.
$TiCl_4$ in CH_2CL_2	decomp.
$LiBF_4$ in acetonitrile	decomp.
CF_3COOH	decomp.

Table 2.4: Attempted Deprotection of **32**.

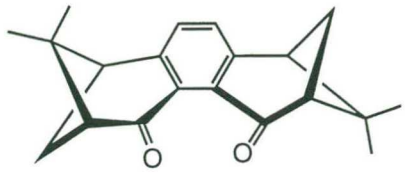
Taking the above results into consideration, we believe for future synthetic efforts that the choice of protecting group should be reevaluated. We can suggest the use of SEM-protecting group.[28-29] We anticipate that it should be stable toward all of the required steps for the synthesis of **32**, as MOM-protecting group is and at the same time will not require the use of harsh acidic conditions for its removal. Its deprotection could be performed cleanly by use of fluoride anion as was shown before in numerous different cases.[30-32]

CHAPTER 3

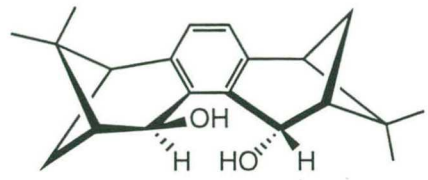
PRELIMINARY INVESTIGATIONS INTO AN ALTERNATE SYNTHESIS OF A VERDI LIGAND

3.1 Introduction

In addition to our early investigations discussed in Chapter 2, we looked into various possibilities for synthesizing of **11** (Figure 1.7). This compound, we believe, can be of significant interest due to it C_2-symmetry and rigidity that holds the two oxygens close proximity. The reduction of its carbonyl groups to hydroxyls would give the conformationally rigid system **33** (Figure 3.1) with great potential for enantioselective synthesis.[32-34]



11



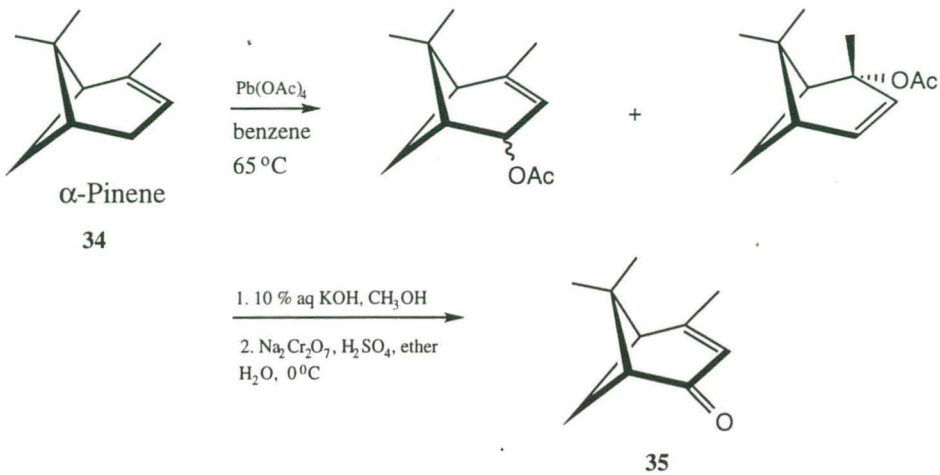
33

Figure 3.1: Target Molecules **11** and **33**.

3.2. Consideration of Metal-Induced Oxidative Coupling of Verbenone Enolate for Construction of Aromatic Ring.

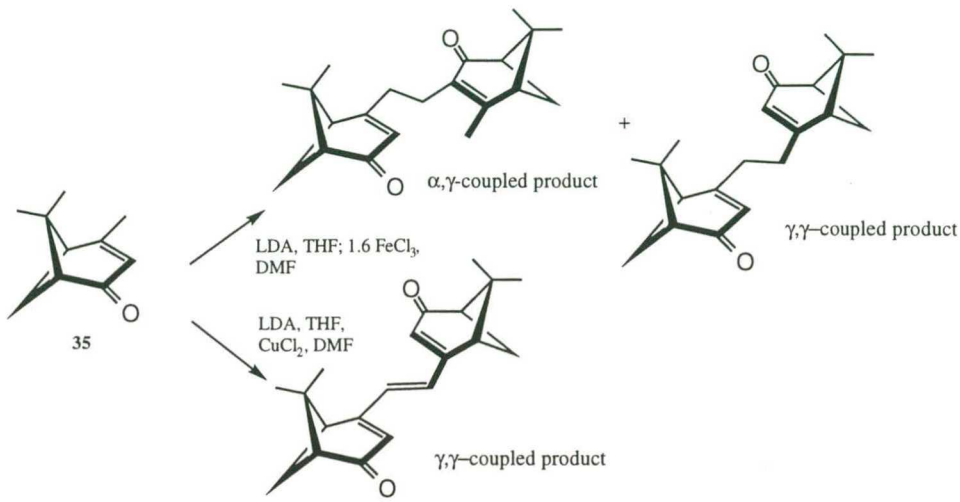
We initially looked at **11** as a VERDI (VER -verbenone, Di- dimer) ligand and entertained the idea of a possible approach to it via metal-induced oxidative coupling of the verbenone enolates.

The synthesis of the (*1R*)-(+)-verbenone **35** was accomplished starting form α-pinene (**34**), according to the procedure developed previously by Stanton (Scheme 3.1).[31]



Scheme 3.1: Synthesis of the (1*R*)-(+)-Verbenone.[31]

Earlier, the regioselectivity of the oxidative coupling of the enolate anion of **35** had been examined with $CuCl_2$ and $FeCl_3$ as catalysts. In the presence of Fe(III), the coupling gave α,γ-product, placing this reaction out of consideration for the synthesis of **11**. With Cu(II), selective formation of the γ,γ-product was observed, though the yields obtained were low for adopting this process to our synthetic sequence.[35]



Scheme 3.2: Metal-Induced Oxidative Coupling of the Verbenone Enolate.[35]

We briefly attempted to improve the yield of the oxidative coupling of **35**. It was shown that $Cu(OTf)_2$ can be a better catalyst due to the presence of a good leaving group. Also, *i*-PrCN was claimed to be a better solvent for these type of reactions since the solubility of copper salt therein is higher.[36] However, in the case of verbenone as substrate, no significant changes in the outcome were seen and we discontinued the exploration of this route.

We suggested that (*1R,5S*)-(+)-nopinone (**41**) might be a possible precursor to **33** and recognized before that the starting material had to be of sufficient optical purity (higher than 98% ee) in order to afford eventually

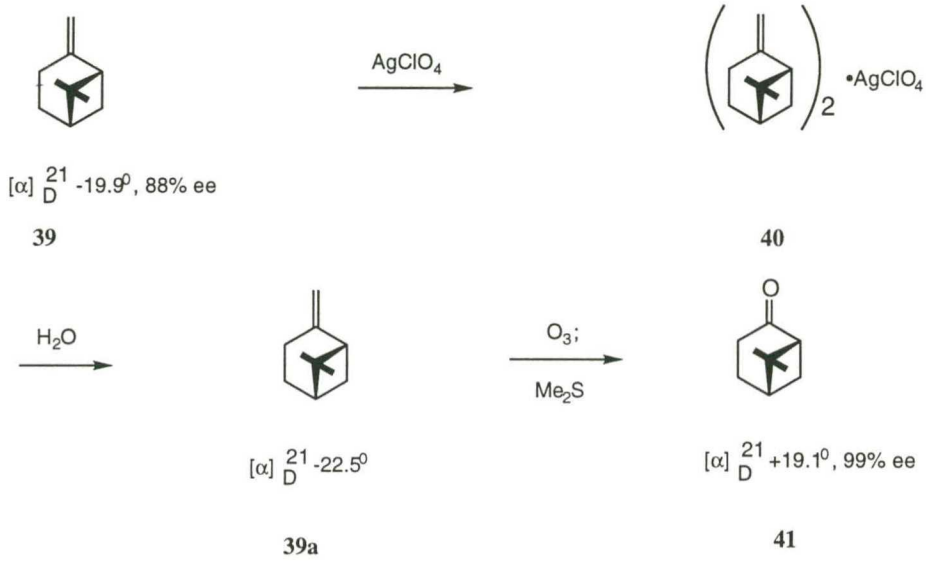
optically pure complexes. Therefore the commercially available nopinone (84% ee) had to be purified prior to its involvment in the synthesis. Next to be addressed is the development of a procedure for upgrading the optical purity of (+)-nopinone.

3.3. Development of a Procedure for Upgrading the Optical Purity of Nopinone.

(*1R,5S*)-(+)-Nopinone has often been used as a cheap, chiral starting material for the synthesis of a wide range of optically active compounds and for mechanistic investigations. Previously, Boger proceeded to develop a means for optical purification based upon sodium borohydride reduction to (-)-*cis*-nopinol, repetitive crystallization of this alcohol from hexane, and oxidation with pyridinium dichromate. The overall yield was 30%.[37]

We considered enzymatic resolution of (-)-*cis*-nopinol.[39] The ozonolysis of commercially available β-pinene afforded (*1R,5S*)-(+)-nopinone (88% ee) in 98% yield. Its reduction with DIBAL-H proceeded smoothly and gave (-)-*cis*-nopinol. Then enzymatic resolution with lipase PS-30 was attempted. However, after 14 days no changes were seen. Possibly due to the large steric hindrance about the hydroxyl group, attack by vinyl acetate was not possible.

We then turned our attention to the preparation of optically pure β-pinene prior to ozonolysis, reasoning that during the ozonolysis step no stereogenic centers are involved and enantiomeric purity can not be affected. We took advantage of the simple technique described earlier by Comyns and Lucas[38] and prepared optically pure β-pinene (99% ee) according to Scheme 3.3.

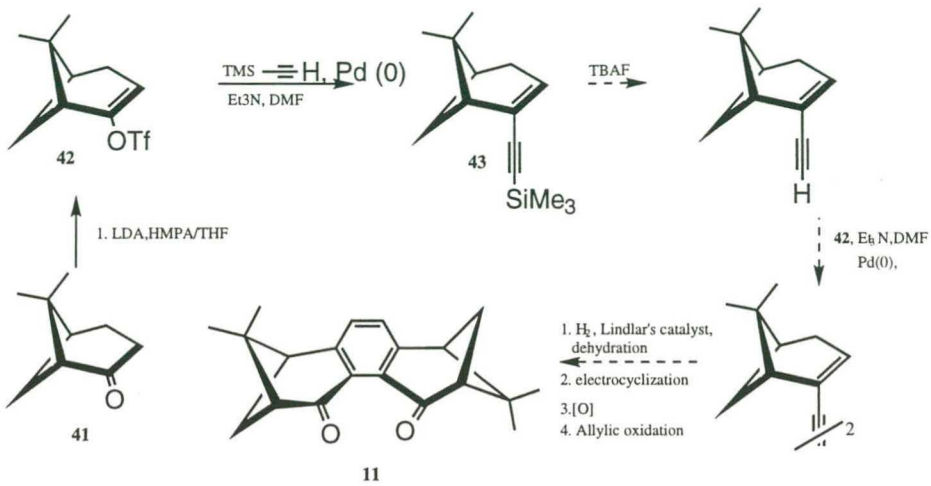


Scheme 3.3: Preparation of (*1R,5S*)-(+)-Nopinone (**41**) of High Enantiomeric Purity.[40]

Upon mixing somewhat less than one mole of silver perchlorate with two moles of inferior quality β-pinene (**39**), the complex **40** formed. Evidentely, the rate of complex formation was more rapid when two like enantiomers were involved than when a racemate was produced. It was then necessary only to remove the uncomplexd β-pinene and to dissolved the remaining salt in water in order to free the higher quality hydrocarbon. The subsequent ozonolysys of **39a** afforded nopinone of 99% ee in excellent chemical yield (96%).[40]

3.4. Consideration of Alternative Approaches to Introduction of the Aromatic Ring.

With (+)-nopinone (**41**) of high enantiomeric purity in hand, we considered the following alternative routes to **11**.



Scheme 3.4: Alternative Synthetic Approach to **11**.

We reasoned that an acetylenic link had to be introduced between two nopinone fragments and reduced cis-selectively in the presence of the Lindlar's catalysts. This protocol would conveniently set the triene system for electrocyclization with formation of aromatic ring upon oxidation. Our initial approach evolved from the previously reported preparation of the triene system of vitamin D_3[41-43] and was based on the palladium-catalysed coupling reaction of enol triflate **42** with trimethylsilylacetylene (**48**), removal of the trimethylsilyl group, and repetitive coupling with the second molecule of the enol triflate **42** as summarized in Scheme 3.4.

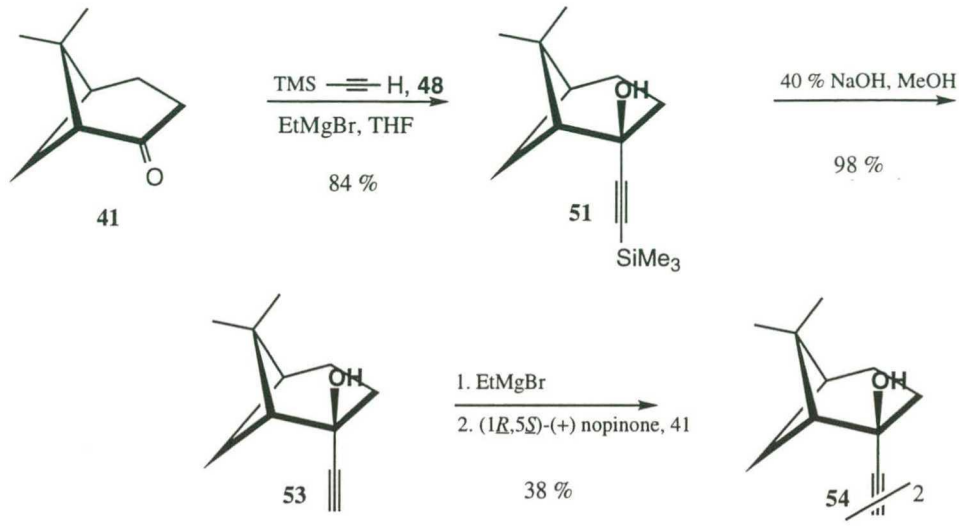
Deprotonation of **41** with LDA at -78 °C followed by the addition of N-phenyltrifluoromethanesulfonimide, however did not give the desired enol triflate. Several different bases were tried in order to elucidate proper conditions for the deprotonation of **41**. Finally, the use of LDA at room temperature in the presence of 1 eq of HMPA, followed by trapping of the enolate formed with triflating agent gave the enol triflate **42** in 89% yield. With **42** in hand, Pd-catalyzed coupling with trimethylsilylacetylene was attempted. The original reaction was performed in DMF in the presence of tertiary amine base (Et_3N) and $PdCl_2(PPh_3)_2$ as a sourse of Pd(0). Unfortunately, only trace amounts of **43** were formed. At the same time, extensive homocoupling involving trimethylsilylacetylenes was observed according to GC-MS spectrometry. Several different conditions have been applied, as summarized in Table 3.1. However, efficient formation of the desired product was not observed.

Set of reagents	Result of the reaction
$PdCl_2(PPh_3)_2$, Et_3N, DMF	trace amounts of **43**
$Pd(PPh_3)_4$, Et_3N, DMF	only dimer of **48**
$PdCl_2(PPh_3)_2$, CuI, Et_3N, DMF	trace amounts of **43**

Table 3.1: Results of the Attempted Pd-catalysed Coupling of **42** with Trimethylsilylacetylene.

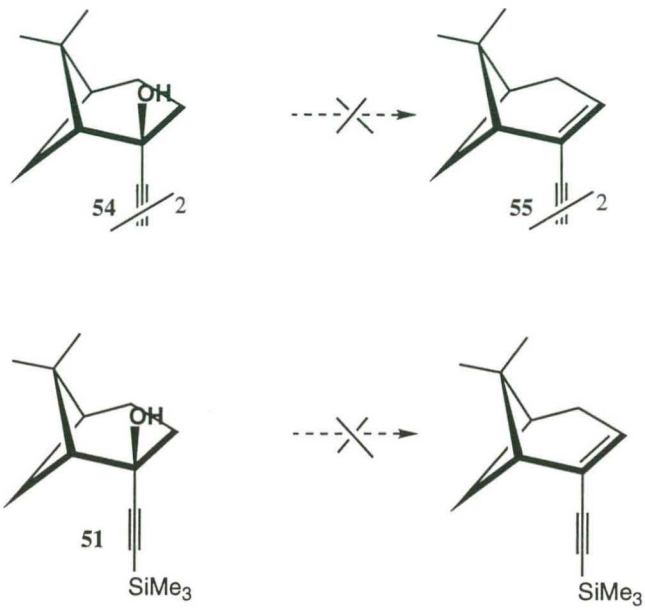
The competitive dimerization of trimethylsilylacetylene must be a faster process than the desired Pd-catalyzed coupling of **42,** probably due to the low activity of enol triflate toward the oxidative addition to Pd(0). This route was therefore abandoned.

We next considered the addition of organometallic compounds derived from **48** to the carbonyl moiety of (+)-nopinone. The lithium reagent, prepared by deprotonation of **48** with *n*-BuLi at -78 °C, was added to (+)-nopinone and gave the desired product **51** in 65% yield when 11 eq of lithium reagent were used. Use of the Grignard reagent prepared from **48** by deprotonation of trimethylsilylacetylene with EtMgBr afforded **51** in 84% yield, when only 2.5 eq of alkylating agent were used. We adopted the latter reaction for our synthesis (Scheme3.5). Removal of the trimethylsilyl group proceeded smoothly in 40% methanolic sodium hydroxide solution and gave **53** in almost quantitative yield (98%). The Grignard reagent was then prepared from **53**. Its addition to (+)-nopinone (**41**) in THF afforded the desired dimer **54** in 33% yield. A slight improvement in yield (38%) was seen when the reaction was performed in ether.



Scheme 3.5: Synthesis of the Dimer **54**.

However, the ensuing dehydration was found to be troublesome and did not result in the formation of **55** under a variety of conditions. Instead, complex mixtures of UV-active products were formed, and attempts to isolate these compounds failed.

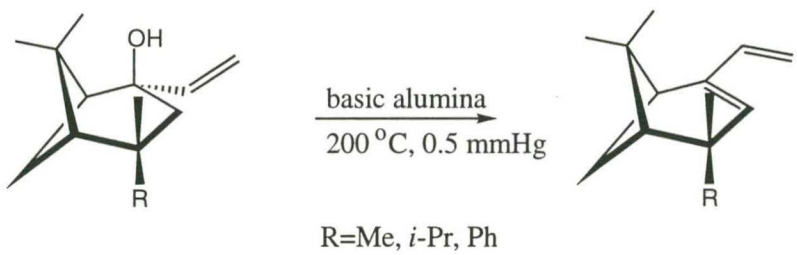


Scheme 3.6: Attempted Dehydration of Alcohols **54** and **51**.

We also attempted the dehydration of **51** prior to its addition to (+)-nopinone. Interestingly, no changes were observed when the Martin sulfurane dehydrating agent was applied. It was suggested that the hydroxy group must be too hindered for the reagent to approach and form a better leaving group for elimination to occur. The same set of conditions found in Table 3.5 was applied to **51**; only decomposition occured again.

Despite the above results, we are still confident that the problem with dehydration can be overcome. It was shown previously[44] that the dehydration

of tertiary alcohols in this bicyclic system is possible on activated basic alumina at 200 °C and , for example, gave diene in reasonable yields, as shown in Scheme 3.7.



Scheme 3.7: Dehydration of Allylic Alcohol by Stanton.[44]

Unfortunately, this protocol can be applied only to large scale preparations and could not be performed at this point of our investigation. With larger supplies of **54**, the dehydration is expected to proceed smoothly under these conditions and afford **55**.

CHAPTER 4

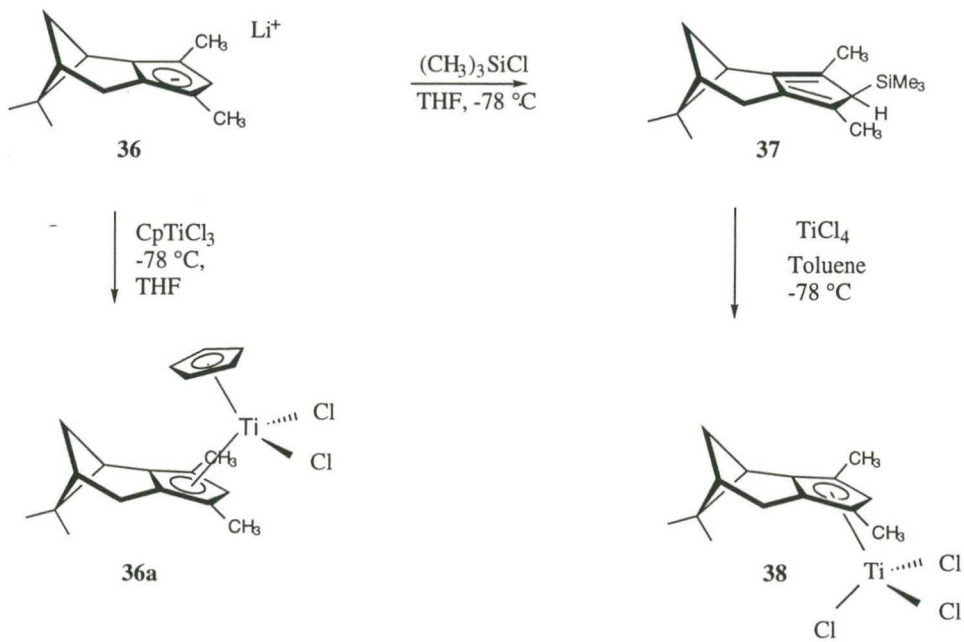
COMPLEXATION CHEMISTRY OF ISODICYCLOPENTADIENE

4.1. Introduction.

In a ligand where the cyclopentadienyl ring is annulated onto a non-C_2-symmetric bicyclic system, the two π-faces of the cyclopentadiene can be differentiated by the structural features on either side of the rigid bicyclic framework. The degree of differentiation between the two faces is very important and crucial for stereocontrolled complexation to a metal nucleus. In most cases, complete selectivity is seen when the reaction is performed at low temperature, making preparation of optically pure complexes possible. The drawback of this strategy is that the other isomeric complex is not available by this methodology.

However, it has been demonstrated previously that the stereochemical preference of this class of ligand can be inverted by complexing the metal to the cyclopentadienyl silane rather than to its lithium salt. In some earlier studies by Sivik,[46] it was shown for example that the exposure of exo-silane **37** to $TiCl_4$ afforded trichloride **38** where inversion of stereochemistry relative to the

trimethylsilyl group transpired. On the other hand, direct reaction of the lithium salt **36** with $CpTiCl_3$ gave the exo complex **36a** as the major product (Scheme 4.1).

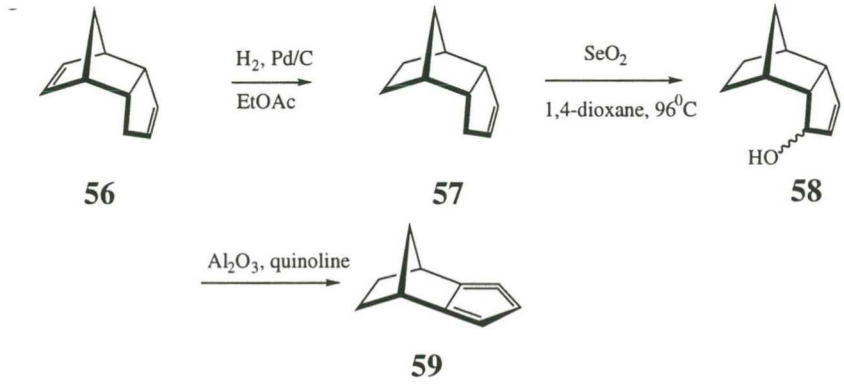


Scheme 4.1: Stereochemical Complexation Study on Cyclopentadiene **36**.[46]

In our continuing efforts to elucidate the conditions for controlled preparation of such complexes, we turned our attention to the complexation chemistry of isodicyclopentadiene. This is the topic of the next section.

4.2. Complexation of (Trimethylsilyl)isodicyclopentadiene with Titanium Tetrachloride.

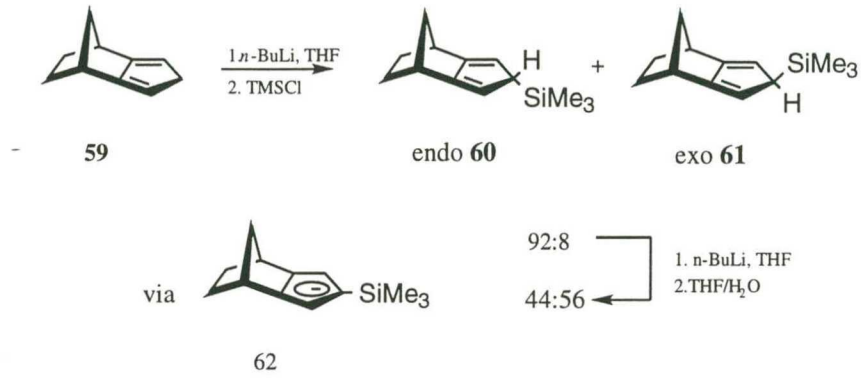
Selective catalytic hydrogenation of dicyclopentadiene **56** furnished **57**, which proved suitable for allylic oxidation. The resulting alcohol **58** was then dehydrated on basic alumina to provide the desired isodicyclopentadiene (**59**) (Sheme 4.2).



Sheme 4.2: Synthesis ot Isodicyclopentadiene **59**.[45]

Deprotonation of isodicyclopentadiene (**59**) at -78 °C and trapping of the resulting anion with dry chlorotrimethylsilane gave a mixture of **60** and **61** in a ratio of 92:8 (^{1}H NMR) favoring the endo isomer. In order to prepare

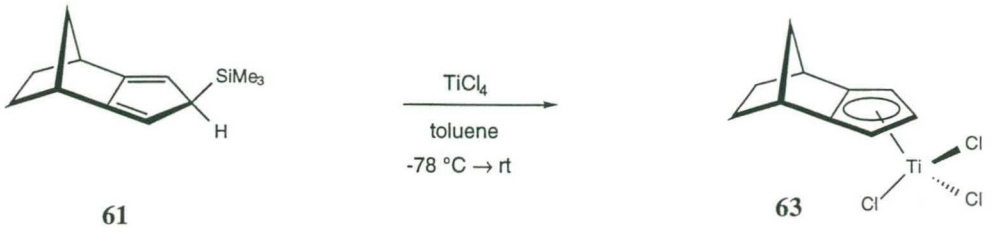
synthetically useful quantities of exo isomer **61**, however, the deprotonation could be repeated and the resulting anion **62** quenched at -78 °C with wet THF. Indeed, this methodology afforded isomeric silanes **60** and **61** in a 56:44 ratio. Further separation by MPLC furnished pure **61** (Scheme 4.3).



Scheme 4.3: Preparation of Exo and Endo Silanes of Isodicyclopentadiene.

It is worth mentioning that migration of the trimethylsilyl group can occur under purely thermal conditions. Therefore care must be practiced when preparing and handling exo silane **61**.

Once pure exo isomer **61** was in hand, its pivotal metal complexation chemistry could be studied. Reaction of silane **61** with $TiCl_4$ at -78 °C in dry toluene using a Schlenk line afforded **63** in modest yield (Scheme 4.4).



61 63

Scheme 4.4: Synthesis of endo Titanium Trichloride Complex **63**.

Consequently, stereochemical inversion had occurred as evidenced by X-ray crystallographical analysis (See Fig. 4.1).

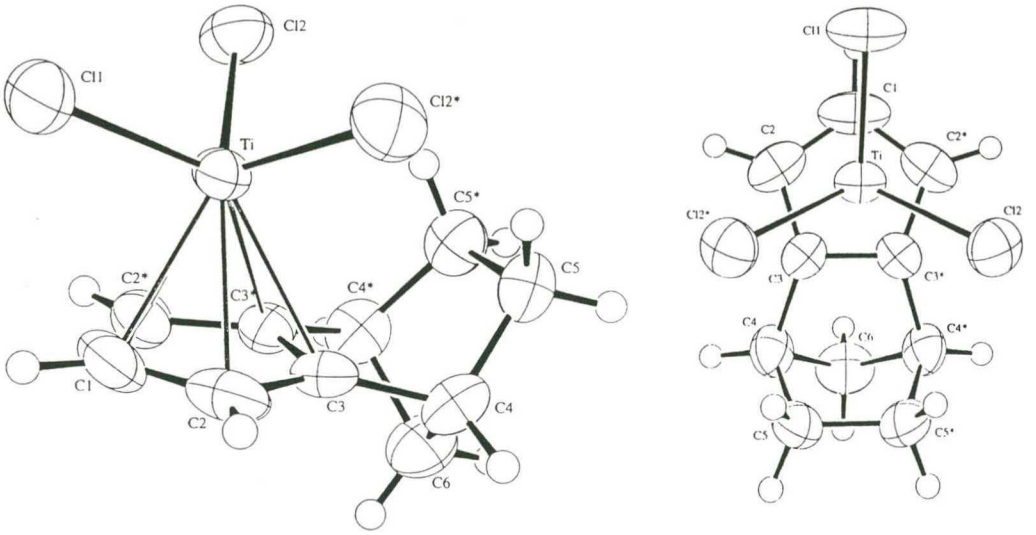


Figure 4.1: Two Views of Crystallographically Determined Molecular Structure of **63** as Drawn with 50 % Probability Ellipsoids.

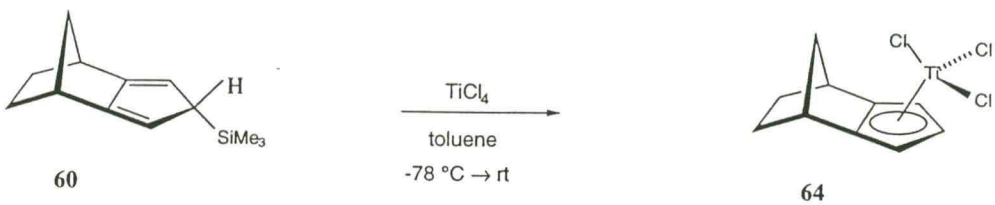
	63	64
Formula wt.	285.46	285.46
Space group	Pbcm	$Pca2_1$
Temp., °C	23 °C	23 °C
Cell constants		
a, Å	12.4368(8)[a]	12.4368(8)[b]
b, Å	9.062(1)[a]	9.062(1)[b]
c, Å	10.3153(9)[a]	10.3153(9)[b]
Cell Vol, $Å^3$	1163	1163
Formula units/unit cell	4	4
Density (calc), g/cm^3	1.63	1.63
Radiation, graph. monochrom.	MoKα ($\lambda(K\alpha_1)$=0.70930 Å)	MoKα ($\lambda(K\alpha_1)$=0.70930 Å)
Diffractometer/scan	Rigaku AFC5S	Rigaku AFC5S
Crystal size, mm	0.19*0.27*0.35	0.19*0.27*0.35
2θ limits	4°< 2θ< 55°	4°< 2θ< 55°
μ calc., cm^{-1}	13.82	13.82
Scan width	(1.40+0.35 tan θ) in w	(1.40+0.35 tan θ) in w
Scan speed	4°/min in w with max of 4 scans per reflection	4°/min in w with max of 4 scans per reflection
Transmission factors	0.680 to 0.738	0.680 to 0.738
Data collected	(+h,+k,+l), (-h,+k,+l), (+h,+k,-l)	(+h,+k,+l), (-h,+k,+l), (+h,+k,-l)
Unique data	2975	2975
Unique data, with $F^2>1\sigma(F^2)$	2436[a]	2436[b]
No. of parametrs varied	126	126
R(F)	0.026	0.026
$R_w(F)$	0.023	0.023

[a] Unit cell constants were obtained from a symmetry restricted least squares fit of the setting angles for 25 reflections in the 2θ range: 28 to 30°; absorption corrections: empirical psi scan.

[b] Unit cell constants were obtained from a symmetry restricted least squares fit of the setting angles for 25 reflections in the 2θ range: 26 to 30°; absorption corrections: analytical.

Table 4.1: X-ray Crystallographical Data for Complexes **63** and **64**.

Earlier work by Sivik demonstrated that the exo isomer **64** could be accessed from **60** in similar fashion (Scheme 4.6).[46]



60 **64**

Scheme 4.6: Synthesis of exo-Titanium Trichloride Complex **64** by Sivik.

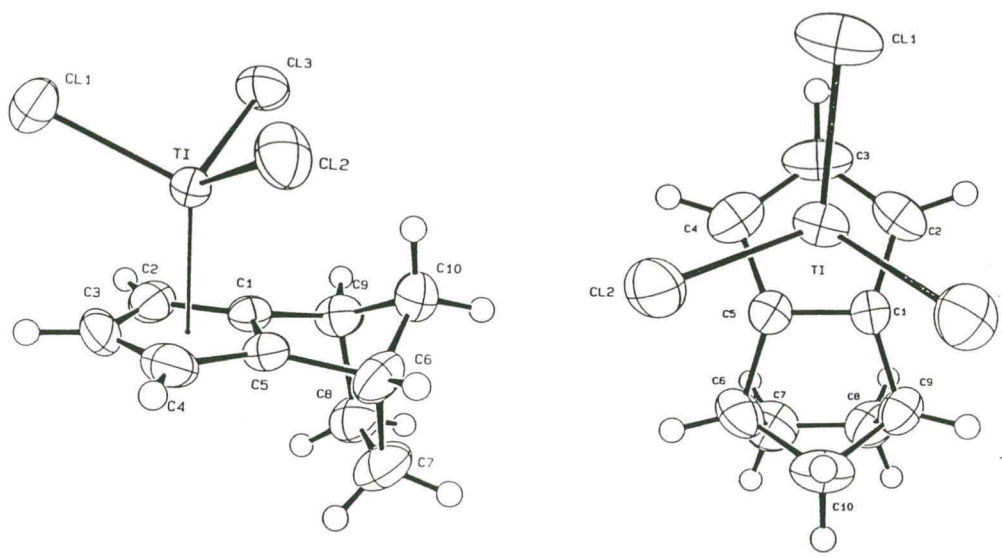
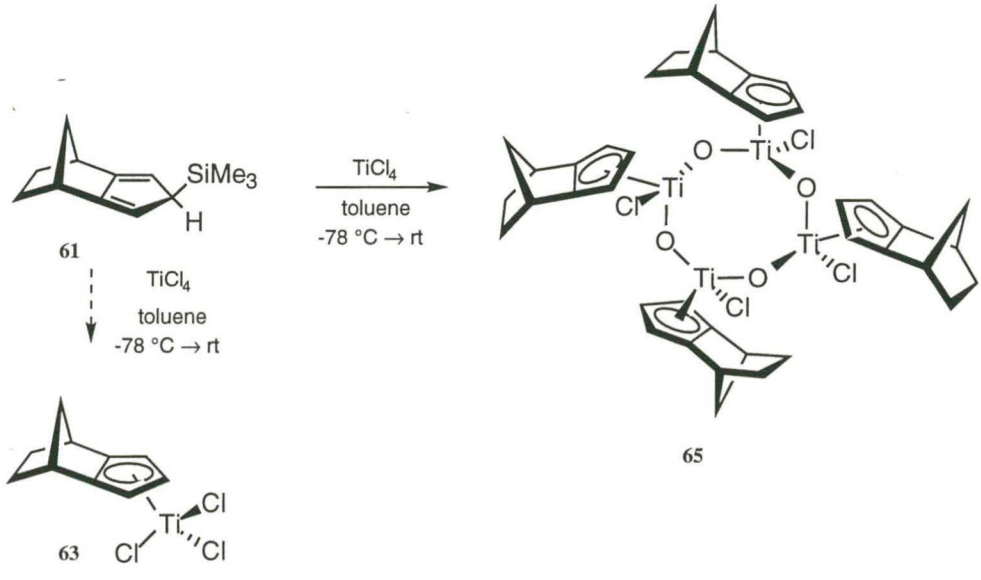


Figure 4.2: Two Views of Crystallographically Determined Molecular Structure of Complex **64** as Drawn with 50% Probability Ellipsoids.

Interestingly, Sivik also reported earlier on the synthesis of **63** (Scheme 4.7). However, high resolution mass spectrometry and X-ray crystallographical analysis later revealed that the compound formed was actually tetramer **65** (Table 4.2) where four TiCl(isodiCp) units are bonded together by μ-oxo bridges (See Fig. 4.3).



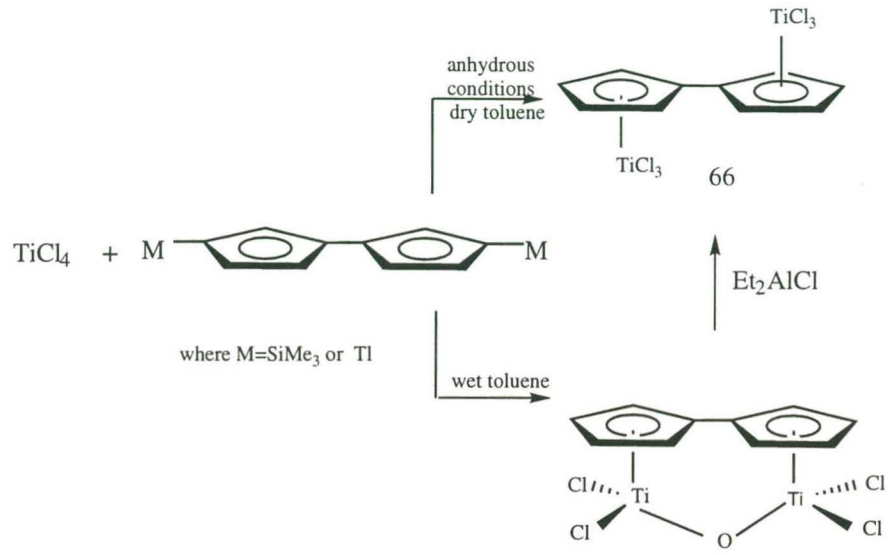
Scheme 4.7: Synthesis of μ-Oxo Titanium Complex **6**.

65	
Formula wt.	922.16
Space group	$P4_2/n$ (with origin at 1)
Temp., °C	23 °C
Cell constants[a]	
a, Å	16.331(1)
b, Å	
c, Å	7.498(1)
β, deg	90
Cell Vol, $Å^3$	1999.7(4)
Formula units/unit cell	8
Density (calc), g/cm^3	1.53
Crystal size, mm	0.19*0.31*0.35
Radiation, graphite monochromator	MoKα ($\lambda(K\alpha_1)$=0.70930 Å)
Diffractometer/scan	Rigaku AFC5S/ w-2θ
2θ limits	4°< 2θ <55°
μ calc., cm^{-1}	10.77
Scan width	(1.40 + 0.35 tan θ) in w
Scan speed	4°/min in w with maximum of 4 scans per reflection
Transmission factors	o.921 to 1.0
Data collected	±h, +k, +l
Unique data	2315
Unique data, with $F^2>2\sigma(F^2)$[b]	1907
No. of parameters varied	119
R(F)	0.073 (based on all data)
Rw(F)	0.045 (based on all data)
R (on F for $F^2>2\sigma(F^2)$)	0.026 (based on 1907 reflections)

[a]Unit cell constants were obtained from a symmetry restricted least squares fit of the setting angles for 25 reflections in the 2θ range: 24 to 30°.[b] Absorption corrections: empirical psi scan.

Table 4.2: X-ray Crystallographical Data for Complex **65**.

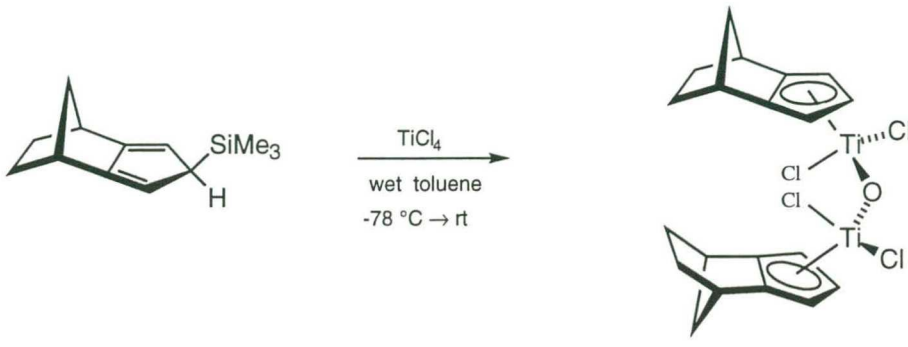
At first we speculated that complex **63** *was* initially formed but underwent the hydrolysis *inside of the crystalline structure* after isolation. A related μ-oxo dinuclear complex $[(TiCl_2)_2(\mu\text{-}O)(\mu\text{-}\eta^5\text{:}\eta^5C_{10}H_8)]$ was recently reported by Royo and Tiripiccio.[47] In their investigation, treatment of $TiCl_4$ in toluene with dithalliofulvalene or bis(trimethylsilyl)fulvalene under rigorous anhydrous conditions produced titanium complex **66**. But when the reaction to synthesize **66** was carried out under insufficiently dry conditions, hydrolysis was observed and μ-oxo complex **67** was produced (Scheme 4.8).



67

Scheme 4.8: Synthesis of Titanium Trichloride Complex **66** and μ-oxo Titanium Complex **67** Reported by Royo and Tiripiccio.[47]

In our investigation, we also observed the formation of μ-oxo dinuclear complex **68** when the experiment was performed under insufficiently anhydrous conditions.



61 **68**

Scheme 4.9: Synthesis of μ-Oxo Titanium Complex **68**.

The structure of **68** (see Fig.4.4) is similar to **65** and consists of two $TiCl_2$(isodiCp)units bonded together by a symmetrical μ-oxo bridge (Ti(1)-O(1)=1.803(3) Å and Ti(2)-O(1)=1.815(3) Å. The geometry about each Ti atom is approximately tetrahedral where the tetrahedron is defined by two chlorine atoms, an oxygen atom, and the ring centroid of the planar Cp ring.

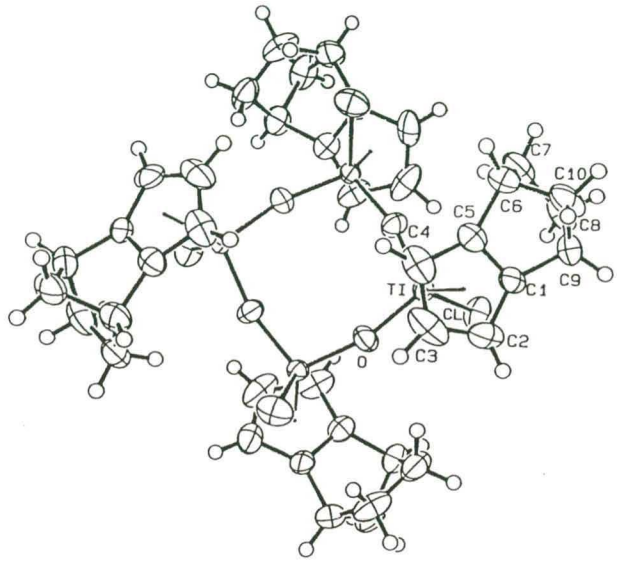


Figure 4.3: Crystallographically Determined Molecular Structure of **65** as Drawn with 50% Probability Ellipsoids.

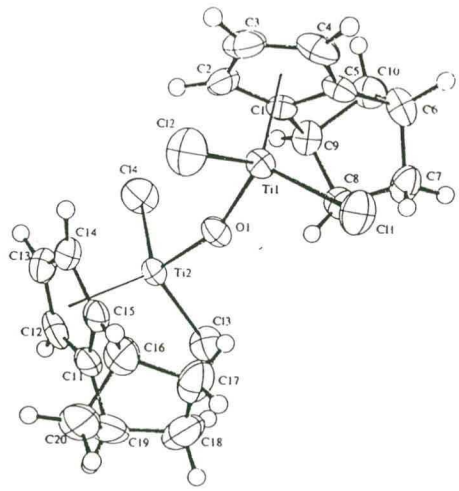


Figure 4.4: Crystallographically Determined Molecular Structure of **68** as Drawn with 50% Probability Ellipsoids.

	68
Formula wt.	516.01
Space group	$P2_1/a$
Temp., °C	23 °C
Cell constants[a]	
a, Å	12.972(2)
b, Å	10.062(1)
c, Å	16.555
β, deg	93.153(8)
Cell Vol, $Å^3$	2158
Formula units/unit cell	4
Density (calc), g/cm^3	1.59
Crystal size, mm	0.12*0.23*0.35
Radiation, graphite monochromator	MoKα ($\lambda(K\alpha_1)$=0.70930 Å)
Diffractometer/scan	Rigaku AFC5S/ w-2θ
2θ limits	4°< 2θ <55°
μ calc., cm^{-1}	12.43
Scan width -	(1.10 + 0.35 tan θ) in w
Scan speed	4°/min in w with maximum of 4 scans per reflection
Transmission factors	o.901 to 1.0
Data collected	+h, +k, +l
Unique data	5265
Unique data, with $F^2>1\sigma(F^2)$	3076
No. of parameters varied	244
R(F)	0.051
Rw(F)	0.040

[a]Unit cell constants were obtained from a symmetry restricted least-squares fit of the setting angles for 25 reflections in the 2θ range: 22 to 30°.[b]Absorption corrections: empirical.

Table 4.3: X-ray Crystallographical Data for Complex **68**.

The results discussed above have shown that the stereospecific inversion of cyclopentadienylsilanes can serve as an entry into the controlled preparation of organometallic complexes. It is apparent that synthetically useful titanocene trichloride complexes like **63** or **64** can be prepared when rigorous anhydrous conditions are imposed. At the same time, the silyl inversion methodology can be used as well to generate μ-oxo complexes **65** and **68** thereby allowing the direct comparision of ligand distortion, ligand orientation, and metal environment effects in the series of isodicyclopentadienyl complexes **63**, **64**, **65**, and **68** (Table 4.4). We believe that information obtained here can be conducive for future ligand design and modeling.

	63	**64**	**65**	**68**
Bond, Å				
Ti-Cl	2.236(1)	2.239(7)	2.276	2.250
Ti-O			1.802	1.803
Ti-CentCp[a]	2.031	2.013	2.066	2.051
Angle, deg				
CentCp-Ti-Cl	116.4	116.7	117.3	114.8
CentCp-Ti-O			116.2	115.1
Cl-Ti-O			103.02	107.7

[a]CentCp-centroid of cyclopentadienyl ring.

Table 4.4: Comparision of Selected Bonding Parametrs for **63**, **64**, **65** and **68**.

CHAPTER 5

EXPERIMENTAL

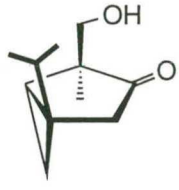
General Methods

All manipulations were performed under an inert atmosphere unless otherwise indicated. All solvents were reagent grade and pre-dried via standard conditions when deemed necessary. Dimethoxyethane, benzene, tetrahydrofuran (THF), and diethyl ether were distilled from sodium metal. Triethylamine (Et_3N), dichloromethane (CH_2Cl_2), and hexamethylphosphoric triamide (HMPA) were distilled from calcium hydride.

Melting points were measured using a Thomas-Hoover capillary melting point apparatus and all melting points are uncorrected. Infrared spectra were obtained using a Perkin-Elmer FT-IR spectrometer and are reported in reciprocal centimeters (cm^{-1}). Proton nuclear magnetic resonance spectra (^1H) were recorded at 300 MHz on a Bruker AC-300 spectrometer with chemical shifts (δ) reported in parts per million. Proton NMR splitting patterns are designated as follows: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad. Carbon nuclear magnetic resonance spectra (^{13}C) were recorded at 75 MHz using a Bruker AC-300 with chemical shifts recorded in parts per million. Optical rotations were recorded using a Perkin-Elmer Model

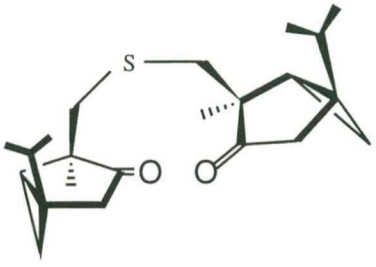
241 polarimeter fitted with a sodium lamp. Elemental analyses were performed by the Scandinavian Microanalytical Laboratory, Herlev, Denmark, or Atlantic Microlab, Inc., Norcross, Georgia, USA.

(1*S*,4*S*,5*S*)-4-(Hydroxymethyl)-1-isopropyl-4-methylbicyclo[3.1.0]hexan-3-one (18).[22]



Thujone (15 g, 0.1 mmol, [α] -15 °(neat), Aldrich (technical grade)) was dissolved in 150 mL of a 10 % solution of KOH in methanol. The resulting light yellow solution was cooled to -5 °C and formaldehyde (15 mL, as a 37 % solution in methanol by weight) was added dropwise during 30 min. The reaction mixture was stirred at -5 °C for 4 h, neutralized by the slow addition of 18 % HCl, diluted with water (100 mL), and extracted with chloroform (3 x 200 mL). The combined organic layers were dried over Na_2SO_4 and concentrated to give 11.2 g (90 %) of **18** as a light yellow oil suitable for further use without additional purification. Spectral and analytical data have been reported.[22]

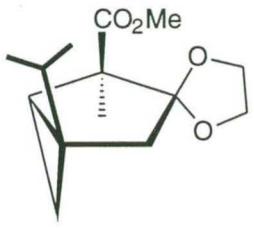
(1*S*,1'*S*,2*R*,2'*R*,5*S*,5'*S*)-2,2'-(Thiodimethylene)bis[5-isopropyl-2-methylbicyclo[3.1.0]hexan-3-one] (20).



A mechanically stirred slurry of 1.6 g (7.7 mmol) of freshly recrystallized (EtOH) sodium sulfide nonahydrate in 7 mL of HMPA was heated to 120 °C (20 mmHg). The aqueous distillate was collected and discarded. The slurry was cooled to room temperature, **19** (2.0 g, 5.9 mmol) was added at once, and the reaction mixture was stirred at 120 °C for 36 h. The brownish contents were cooled, treated with 25 mL of H_2O and extracted with ether (3 x 50 mL). The combined organic extracts were washed with water (50 mL) and brine (50 mL), dried over $MgSO_4$, and concentrated. The residue was purified by flash column chromatography on silica gel (elution with 5% ethyl acetate in hexanes) to give **20** as a white solid, mp 99.5-101 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.61 (s, 4 H), 2.59 (d, *J* = 18.4 Hz, 2 H), 2.17 (d, *J* = 18.6 Hz, 2 H), 1.52 (m, 2 H), 1.44 (m, 2 H), 1.06 (s, 6 H), 1.01 (d, *J* = 6.8 Hz, 6 H), 0.89 (d, *J* = 6.8 Hz, 6 H), 0.69 (m, 2 H), 0.0 (m, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 219.0, 52.9, 43.9, 42.1, 32.1, 28.9, 27.6, 20.1, 19.5, 19.1, 15.6; MS *m/z* [M^+] calcd 362.2280, obsd 362.2270.

Anal. Calcd for $C_{22}H_{34}O_2S$: C, 72.88; H, 9.46. Found: C, 72.97; H, 9.84.

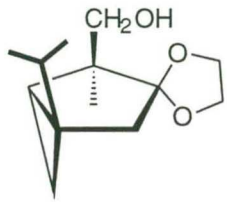
Methyl (1*S*,2*R*,5*S*)-5-Isopropyl-2-methylspiro[bicyclo[3.1.0]hexane-3,2'-[1,3]dioxolane]-2-carboxylate (23).



The mixture of **22**[22] (0.50 g, 2.4 mmol), ethylene glycol (3.5 mL, 70 mmol), p-TsOH (1 mg, 0.02 mmol) and benzene (25 mL) were placed in a flask equipped with a magnetic stirring bar and a Dean-Stark apparatus, and heated at reflux for 72 h under nitrogen. The reaction mixture was cooled and diluted with saturated sodium bicarbonate solution. The layers were separated and organic phase was washed with saturated sodium bicarbonate solution and brine, dried over $MgSO_4$, and concentrated. Purification of the residual oil by flash column chromatography (elution with 3% ethyl acetate in hexanes) gave an undetermined amount of starting material and 0.54 g (88%) of **23** as a more polar colorless oil; IR (neat, cm^{-1}) 2955, 2877, 1732, 1456, 1431, 1263, 1125, 1071, 1022, 987, 952; ^1H NMR (300 MHz, $CDCl_3$) δ 3.90-3.71 (m, 4 H), 3.70 (s, 3 H), 2.38 (dd, *J* = 13.0, 1.7 Hz, 1 H), 1.79 (d, *J* = 13.0 Hz, 1 H), 1.37 (m, 1 H), 1.19 (d, *J* = 3.8 Hz, 1 H), 1.16 (s, 3 H), 0.99 (d, *J* = 6.8 Hz, 3 H), 0.84 (d, *J* = 6.8 Hz, 3 H), 0.70 (dd, *J* = 5.1, 4.0 Hz, 1 H), 0.31 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 174.9, 116.4, 65.4, 64.5, 58.1, 51.6, 40.3, 32.9, 30.8, 30.3, 19.9, 19.4, 16.2, 12.3; MS *m/z* [M^+] calcd 254.1518, obsd 254.1507.

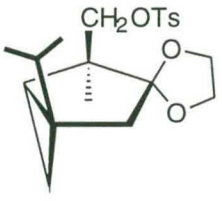
Anal. Calcd for $C_{14}H_{22}O_4$: C, 66.10; H, 8.72. Found: C, 66.19.; H, 8.82.

(1*S*,2*S*,5*S*)-5-Isopropyl-2-methylspiro[bicyclo[3.1.0]hexane-3,2'-[1,3]dioxolane]-2-methanol (24).



To a suspension of $LiAlH_4$ (64 mg, 1.8 mmol) in anhydrous ether (5 mL) at 0 °C was added a solution of **23** (300 mg, 1.2 mmol) in the same solvent (5 mL). The reaction mixture was stirred at room temperature for 1 h, quenched by the sequential addition of 0.06 mL of water, 0.06 mL of 10% potassium hydroxide solution, and 0.2 mL of water, filtered and extracted with ether (3x25 mL). The combined organic layers were dried over $MgSO_4$ and concentrated. The residual oil was purified by flash column chromatography to give **24** (267 mg, 100%) as a colorless oil; IR (neat, cm^{-1}) 3453, 2950, 2880, 1458, 1136, 1049; ^1H NMR (300 MHz, $CDCl_3$) δ 3.90-3.73 (m, 6 H), 3.34 (d, *J* = 11.5 Hz, 1 H), 2.87 (s, 1 H), 2.05 (dd, *J* = 13.4, 1.8 Hz, 1 H), 1.73 (d, *J* = 13.3 Hz, 1 H), 1.24 (m, 1 H), 0.99 (s, 3 H), 0.91 (d, *J* = 6.8 Hz, 3 H), 0.83 (d, *J* = 6.8 Hz, 3 H), 0.64 (dd, *J* = 8.3, 3.7 Hz, 1 H), 0.24 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 118.0, 70.0, 64.5, 64.1, 60.8, 49.0, 37.9, 32.9, 28.7, 19.8, 19.6, 14.9, 12.1; MS *m/z* [M^+] calcd 226.1569, obsd 226.1562.

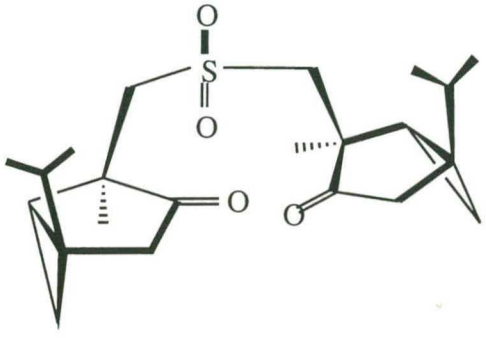
(1*S*,2*S*,5*S*)-5-Isopropyl-2-methylspiro[bicyclo[3.1.0]hexane-3,2'-[1.3]dioxolane]-2-methanol *p*-Toluenesulfonate (25).



Alcohol **24** (1.0 g, 4.4 mmol) was dissolved in 3 mL of pyridine. The resulting solution was cooled to -5 °C and freshly recrystallized (benzene-water,1:1)[24] tosyl chloride (1.0 g, 5.3 mmol)) was added in portions during 10 min. The reaction mixture was stirred at -5 °C for 1 h, and overnight at room temperature, diluted with water (50 mL), and extracted with ether (3x50 mL). The combined organic layers were washed with water (50 mL) and brine (50 mL), dried over Na_2SO_4 and concentrated. Purification of the residue by flash column chromatography on silica gel (elution with 7% of ethyl acetate in hexanes) gave **25** (1.2 g, 72%) as a colorless oil; ^1H NMR (300 MHz, $CDCl_3$) ppm 7.79 (d, J = 8.3 Hz, 2 H), 7.32 (d, J = 8.0 Hz, 2 H), 3.96-2.62 (m, 6 H), 2.43 (s, 3 H), 1.91 (d, J = 13.3 Hz, 1 H), 1.71 (d, J = 13.3 Hz, 1 H), 1.21 (m, 1 H), 1.11-1.07 (m, 1 H), 0.90 (s, 3 H), 0.77 (d, J = 6.8 Hz, 3 H), 0.75 (m, 4 H), 0.25 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 144.5, 133.0, 129.7, 128.0, 115.5, 75.7, 64.7, 64.4, 49.5, 39.0, 32.6, 29.1, 27.7, 21.6, 19.60, 19.56, 15.2, 12.1; MS *m/z* [M^+] calcd 379.1657, obsd 379.1665.

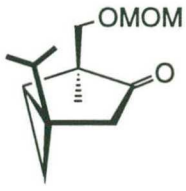
Anal. Calcd for $C_{20}H_{28}O_5S$: C, 63.30; H, 7.18. Found: C, 63.25; H, 7.18.

(1*S*,1''*S*,2*R*,2''*R*,5S,5''*S*)-2,2''-[Dimethylenesulfonyl]bis[5-isopropyl-2-methyl[bicyclo[3.1.0]]hexan-3-one (21).



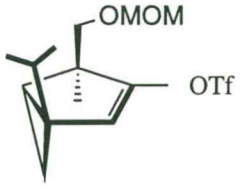
To a solution of **20** (10 mg, 0.03 mmol) in dry CH_2Cl_2 (1 mL) at 0 °C was added at once MCPBA (12 mg, 0.07 mmol). The reaction mixture was stirred at 0 °C for 1 h, at room temperature for 30 min., and quenched by the addition of sodium thiosulfite solution (2 mL). The layers were separeted, and aqueous phase was extracted with CH_2Cl_2 (3 x 25 mL). The combined organic layers were washed with sodium thiosulfite solution (25 mL), sodium bicarbonate (25 mL), and brine (25 mL), dried over $MgSO_4$ and concentrated. Purification of residue by flash column chromatography (elution with 5% ethyl acetate in hexanes) to give **21** (8 mg, 79%) as a white solid, mp 119-121 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 3.1 (dd, *J* = 24.2, 13.7 Hz, 4 H), 2.73 (dd, *J* = 9.1, 2.6 Hz, 2 H), 2.23 (d, *J* = 19.0 Hz, 2 H), 1.97 (dd, *J* = 8.4, 4.1 Hz, 2 H), 1.69-1.60 (m, 2 H), 1.2 (s, 6 H), 1.02 (d, *J* = 6.8 Hz, 6 H), 0.87 (d, *J* = 6.8 Hz, 6 H), 0.78 (m, 2 H), 0.05 (m, 2 H); ^{13}C NMR (75 MHZ, $CDCl_3$) ppm 218.0, 62.6, 49.9, 42.3, 31.6, 29.7, 28.6, 27.9, 20.3, 19.1, 15.4; MS *m/z* [M^+] calcd for $C_{22}H_{34}O_4S$ 394.2178, obsd 394.2182.

(1*S*,4*S*,5*S*)-1-Isopropyl-4-[(methoxymethoxy)methyl]-4-methylbicyclo[3.1.0]hexan-3-one (28).



To a cold (-5 °C), nitrogen-blanketed, magnetically stirred solution of **18** (3.0 g, 17 mmol) and diisopropylethylamine (43.6 mL, 252 mmol) in CH_2Cl_2 (100 mL) was slowly added chloromethyl methyl ether (3.66 mL, 48 mmol). The reaction mixture was allowed to warm to room temperature for 12 h and diluted with brine (100 mL). The layers were separated and the organic phase was washed in turn with water, 5% HCl, water, and brine prior to drying ($MgSO_4$). The residue obtained after concentration was purifed by silica gel chromatography (elution with 8 % ethyl acetate in hexanes) to afford 3.0 g (89 %) of **28** as a colorless oil: IR (neat, cm^{-1}) 2954, 2872, 1736, 1465, 1384, 1365, 1149, 1112, 1048; ^1H NMR (300 MHz, C_6D_6) δ 4.31 (s, 2H), 3.39 (d, *J* = 8.9 Hz, 1 H), 3.19 (d, *J* = 8.9 Hz, 1 H), 3.07 (s, 3 H), 2.45 (dd, *J* = 18.2, 2.6 Hz, 1 H), 2.0 (d, *J* = 18.2 Hz, 1 H), 1.20-1.07 (m, 2 H), 0.99 (s, 3 H), 0.88 (d, *J* = 6.8 Hz, 3 H), 0.77 (d, *J* = 6.8 Hz, 3 H), 0.35 (m, 1 H); ^{13}C NMR (75 MHz, C_6D_6) ppm 217.4, 96.5, 74.0, 54.9, 52.6, 42.4, 33.2, 28.8, 27.8, 20.0, 19.5, 17.3, 15.5; MS *m/z* [M^+] calcd 226.1569, obsd 226.1605.

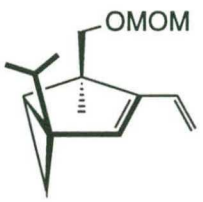
(1*S*,4*S*,5*S*)-1-Isopropyl-4-[(methoxymethoxy)methyl]-4-methylbicyclo[3.1.0]hex-2-en-3-yl Trifluoromethanesulfonate (29).



To a flame-dried one-necked round-bottom flask was added 3 mL of THF and freshly distilled diisopropylamine (0.37 mL, 2.65 mmol). The flask was cooled to -5 °C and n-butyllithium (1.63 mL, 2.6 mmol) was added via syringe. After 30 min, the resulting solution of lithium diisopropylamide was transferred via cannula to a cold solution of 0.50 g (2.2 mmol) of ketone **28** in 15 mL of THF. The mixture was stirred for 45 min before a solution of N-phenyltrifluoromethanesulfonimide (0.93 g, 2.6 mmol) in 7 mL of THF was added via cannula. The mixture was stirred at room temperature for 6 h prior to concentration. The resulting oily residue was placed atop a column of silica gel and eluted with 5 % ethyl acetate in hexanes to give **29** as a colorless oil (0.69 g, 87 %): IR (neat, cm^{-1}) 2954, 2931, 2884, 1637, 1437, 1419, 1219, 1143, 1043, 896, 855, 602; ^1H NMR (300 MHz, $CDCl_3$) δ 5.84 (s, 1 H), 4.63 (s, 2 H), 3.46 (dd, *J* = 16.2, 9.3 Hz, 2 H), 3.36 (s, 3 H), 1.49-1.40 (m, 1 H), 1.32 (m, 1 H), 1.14 (s, 3 H), 0.99 (d, *J* = 6.8 Hz, 3 H), 0.925 (d, *J* = 6.8 Hz, 3 H), 0.72 (dd, *J* = 7.8, 4.8 Hz, 1 H), 0.35 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 149.07, 120.69, 116.3, 96.6, 73.5, 55.2, 48.9, 34.6, 30.8, 25.0, 20.5, 20.4, 18.7, 17.6; MS *m/z* [M^+-OCH_3] calcd 327.0878, obsd 327.0854,

Anal. Calcd for $C_{14}H_{21}F_3O_5S$: C, 46.91; H, 5.91. Found: C, 46.83 H, 5.81.

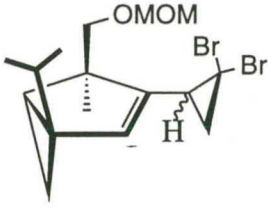
(1*R*,4*R*,5*S*)-1-Isopropyl-4-[(methoxymethoxy)methyl]-4-methyl-3-vinylbicyclo[3.1.0]hex-2-ene (30).



In a 50 mL three-necked round-bottom flask fitted with a gas inlet, condenser, and septa was placed LiCl (0.24 g, 5.6 mmol), which was flame-dried in vacuo for 10 min. THF was added, followed by a solution of triflate **29** (0.50 g, 1.4 mmol) in 7 mL of THF via cannula. Tetrakistriphenylphosphinepalladium(0) (80 mg, 0.07 mmol) was added at once and flask was quickly evacuated and inert atmosphere reestablished. Tributylvinylstannane (0.44 g, 1.4 mmol) was introduced via syringe at room temperature and the flask was placed in a heating mantle. The light yellow solution dissipated as the reaction mixture began to reflux and turned dark-brown after 4 h. The reaction mixture was cooled to room temperature and water was added (15 mL). After extraction with ether (3 x 50 mL), the combined organic layers were washed with water (50 mL) and brine (50 mL) and dried over $MgSO_4$ prior to concentration. The residual oil so obtained was purified by column chromatography on silica gel (elution with pentane, followed by 3% ethyl acetate in hexanes) to give 260 mg (79%) of diene **30** as a colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.13 (m, 1 H), 5.98 (s, 1 H), 5.23 (dd, *J* = 17.9, 1.5 Hz, 1 H), 4.92 (dd, *J* = 11.3, 1.5 Hz, 1 H), 4.64 (s, 2 H), 3.61 (d, *J* = 9.2 Hz, 1 H), 3.41 (d, *J* = 9.2 Hz, 1 H), 3.36 (s, 3 H), 1.50-1.39 (m, 2 H), 1.19 (s, 3 H), 0.99 (d, *J* = 6.9 Hz, 3 H), 0.91 (d, *J* = 6.8 Hz, 3 H), 0.65 (dd, *J* = 8.0, 3.8 Hz, 1 H), 0.17 (t, *J* = 4.0 Hz, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 142.8, 135.0, 131.9, 113.2, 96.7, 75.5, 55.1, 39.1, 30.6, 20.9, 20.7, 19.3, 19.1; MS *m/z* [M^+] calcd 236.1776, obsd 236.1763.

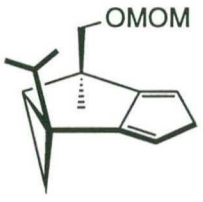
Anal. Calcd for $C_{15}H_{24}O_2$: C, 76.21; H, 13.54. Found: C, 75.73; H, 13.84.

(1*R*,4*S*,5*S*)-3-(2,2-Dibromocyclopropyl)-1-isopropyl-4-[(methoxymethoxy)methyl]-4-methylbicyclo[3.1.0]hex-2-ene (31).



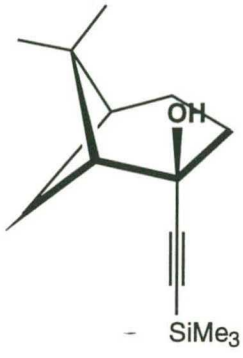
Diene **30** (2.1 g, 8.9 mmol), bromoform (3.37 g, 13.4 mmol), benzyltriethylammonium chloride (45 mg,), ethanol (0.04 mL) and CH_2Cl_2 (1 mL) were combined at room temperature in a 25 mL three-necked round-bottomed flask fitted with a mechanical stirrer, gas inlet, and additional funnel. The mixture was vigorously stirred at 0 °C while a 50% sodium hydroxide solution (4.5 mL) was added dropwise over 10 min, afterwhat the reaction mixture turned brown. The stirring was continued at room temperature for 24 h, before being poured into 25 mL of water. The layers were seperated, and aqueous layer was extracted with CH_2Cl_2 (3x25 mL). The combined organic layers were dried over $MgSO_4$ and concentrated to leave a brown oil which was taken up in an equal amount of ether and passed through a short plug of silca gel (eluting with ether). Concentration gave 3.0 g of a mixture of diastereomers of **8** as an orange oil. The proton and carbon NMR results were too complex to characterize, however the absence of the vinyl protons and the presence of broad singlets at 5.53 and 5.47 in ^1H NMR (in $CDCl_3$) indicated the cyclopropyl dibromide was isolated.

(1a*S*,5*R*,5a*S*)-1a,3,5,5a-Tetrahydro-1a-isopropyl-5-[(methoxymethoxy)methyl]-5-methyl-1H-cyclopropa[a]pentalene (32).



The above oil (3.0 g, 7.4 mmol) was placed in a flame-dried flask and dissolved in a 250 mL of anhydrous ether. The yellowish solution was cooled to 0 °C and methyl lithium (21.4 mL, 1.4 M in ether, 30 mmol) was added via syringe. The mixture was stirred at 0 °C for 1 h and then at room tempereture for 24 h before the yellow mixture was added to 300 mL of ice-water via cannula. The layers were separated and the aqueous layer was extracted with ether (3x100mL).. The combined organic phase was dried over $MgSO_4$, filtered, and concentrated to give a light yellow oil of **3 2** as a mixture of dienes (0.95 g, 43% from **3 0**): ^1H NMR (300 MHz, $CDCl_3$) δ 5.79 (m, 1 H), 5.75 (m, 1 H), 4.63 (s, 2 H), 3.39 (s, 2 H), 3.34 (s, 3 H), 3.16 (s, 2 H),1.74 (dd, *J* = 8.3, 4.3 Hz, 1 H), 1.54 (m, 1 H), 1.22 (s, 3 H), 1.11 (d, *J* = 6.8 Hz, 3 H), 1.00 (d, *J* = 6.8 Hz, 3 H), 0.90 (m, 1 H), 0.47 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 159.1, 155.6, 121.5, 117.5, 96.7, 76.1, 55.1, 46.4, 43.0, 37.4, 35.1, 31.4, 21.1, 20.2, 20.1, 19.9.

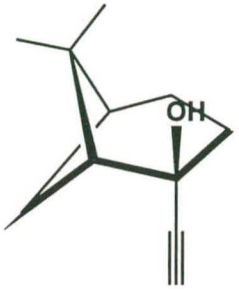
(1*R*,2*R*,5*S*)-6,6-Dimethyl-2-[(trimethylsilyl)ethynyl]bicyclo[3.1.1]-heptan-2-ol (51).



The Grignard reagent was prepared from a suspension of ethyl bromide (5.5 g, 0.05 mol) and magnesium turnings (1.2 g, 0.05 mol) in dry THF (25 mL) according to precedent [35]. To the resulting gray solution was transferred a precooled (0 °C) solution of trimethylsilylacetylene (6.1 g, 0.06 mol) in dry THF (25 mL). The slurry was stirred for 1.5 h and added to a cold (-10 °C) solution of ketone **41** [40] (3.5 g, 0.025 mol) in dry THF (10 mL) via cannula. The reaction mixture was stirred at 0 °C for 30 min and then at room temperature for 2 h, quenched by slow addition of saturated ammonia chloride solution, extracted with ether (3x100 mL), dried over $MgSO_4$, and concentrated. Purification of the residue by flash column chromatography on silica gel (elution with 15% of ethyl acetate in hexanes) gave **51** (5.2 g, 88%) as a white solid, mp 77 °C, $[\alpha]_{20}^{D}$ +7.5° (*c* 0.1, $CHCl_3$); IR (neat, cm^{-1}) 3598, 3001, 2983, 2871, 1710, 1607, 1463, 1362, 1282, 1234, 1112; ^1H NMR (300 MHz, $CDCl_3$) δ 2.47-2.27 (m, 2 H), 2.15-1.8 (series of m, 6 H), 1.29 (d, *J* = 10.5 Hz, 1 H), 1.22 (s, 3 H), 1.05 (s, 3 H), 0.14 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 127.8, 112.4, 84.4, 73.6, 53.1, 40.4, 38.1, 32.9, 28.7, 27.5, 24.3, 23.1, 0.0; MS *m/z* [M^+] calcd 236.1596, obsd 236.1596.

Anal. Calcd for $C_{14}H_{24}OSi$: C, 71.12; H, 10.23. Found: C, 70.88; H, 10.08.

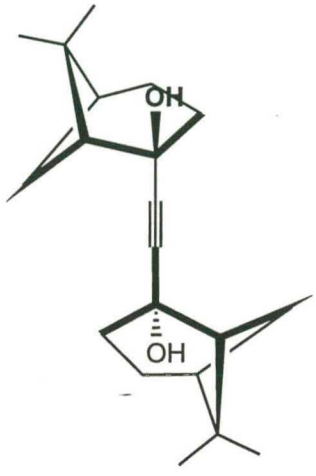
(1*R*,2*R*,5*S*)-2-Ethynyl-6,6-dimethylbicyclo[3.1.1]-heptan-2-ol (53).



In a 5 mL round-bottomed flask was placed **5 1** (0.2 g, 0.85 mmol) and dissolved in 40% sodium hydroxide solution in methanol (10 mL). The reaction mixture was stirred for 2 h, diluted with water (20 mL) and extracted with ether (3x50 mL). The organic phase was washed with water (2x50 mL) and brine (50 mL), and dried over $MgSO_4$ prior to concentration. The resulting white solid was purified by flash column chromatography on silica gel (elution with 5% of ethyl acetate in hexanes) to afford **5 3** (0.14 g, 98%) as a white fluffy solid, mp 47 °C; $[\alpha]_{20}^{D}$ -3.9° (*c* 1.3, $CHCl_3$); IR (neat, cm^{-1}) 3462, 3309, 3274, 2918, 2869, 1727, 1461, 1368, 1324, 1281, 1235, 1078; ^1H NMR (300 MHz, $CDCl_3$) δ 2.50-2.28 (m, 3 H), 2.18-1.79 (series of m, 6 H), 1.29 (d, *J* = 10.6 Hz, 1 H), 1.23 (s, 3 H), 1.06 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 90.1, 73.2, 68.8, 53.0, 40.4, 38.0, 32.7, 28.6, 27.5, 24.2, 23.0; MS *m/z* [M^+] calcd 164.1202, obsd 164.1212.

Anal. Calcd for $C_{11}H_{16}O$: C, 80.43; H, 9.83. Found: C, 80.56; H, 9.86.

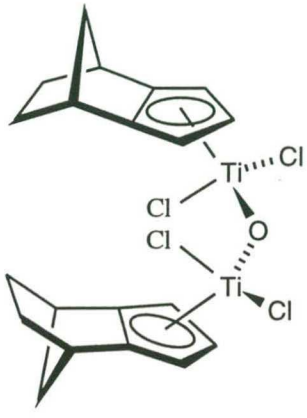
(1*R*,1'*S*,2*R*,2'*S*,5*S*,5'*R*)-2,2'-Ethynylenebis[6,6-dimethyl-bicyclo[3.1.1]-heptan-2-ol] (54).



The Grignard reagent was prepared from a suspension of ethyl bromide (1.1 g, 0.012 mol) and magnesium turnings (0.23 g, 0.01 mol) in dry THF (5 mL). To the resulting gray solution was transferred a precooled (0 °C) solution of **5 3** (130 mg, 0.8 mmol) in dry THF (1 mL). The slurry was stirred for 1.5 h and formation of white precipitate was observed. To this suspension was added a cold (-10 °C) solution of ketone **4 1**[40] (0.1g, 0.75 mmol) via syringe. The reaction mixture was stirred at 0 °C for 30 min and then at room temperature for 2 h, quenched by a slow addition of saturated ammonium chloride solution, extracted with ether (3 x 25 mL), dried over $MgSO_4$ and concentrated. The purification of the residue by flash column chromatography on silica gel (elution with 15% of ethyl acetate in hexanes) gave **5 4** (100 mg, 44%) as a white solid, mp 179 °C; $[\alpha]_{20}^{D}$ +7.1° (*c* 1, $CHCl_3$); IR (neat, cm^{-1}) 3593, 3008, 2920, 2870, 1711, 1602, 1461, 1367, 1318, 1282, 1236, 1116; ^1H NMR (300 MHz, $CDCl_3$) δ 2.41-2.24 (m, 4 H), 2.15-1.76 (series of m, 12 H), 1.23 (d, *J* = 7.5 Hz, 2 H), 1.22 (s, 6 H), 1.05 (s, 6 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 73.3, 53.4, 40.5, 38.0, 33.1, 28.8, 27.5, 24.3, 23.0, 15.2; MS *m/z* [M^+] calcd 302.2246, obsd 302.2231.

Anal. Calcd for $C_{20}H_{30}O_2$: C, 79.41; H, 10.0. Found: C, 79.23; H, 9.93.

Bis-(*endo*-Isodicyclopentadienyldichlorotitanium)-μ-oxo (68).

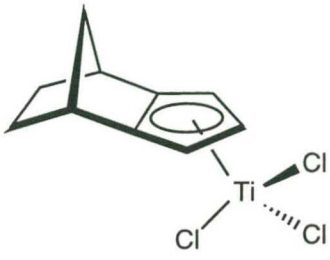


To titanium tetrachloride (0.93 g, 4.9 mmol) in toluene (30 mL) at -78 °C was added a solution of **61**[45] (1.0 g, 4.9 mmol) in 15 mL of toluene via cannula. The reaction mixture was stirred at -78 °C for 1 h and at room temperature for 12 h, filtered through a Celite® pad, and concentrated in vacuo to leave a brown residue, which was redissolved in toluene (1 mL) and allowed to stand under nitrogen for 48 h at -5 °C. The red crystalls that formed were collected to afford **68** (650 mg, 48%); mp 128 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.86 (t, J = 2.8 Hz, 2 H), 6.47 (d, J = 2.9 Hz, 4 H), 3.51 (br s, 4 H), 2.25 (br d, J = 7.1 Hz, 4 H), 2.03 (br d, J = 8.0 Hz, 4 H), 1.89 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 157.3, 122.2, 115.5, 57.7, 42.8, 27.5; MS *m/z* [M^+] calcd 515.9325, obsd 515.9334.

Anal. Calcd for $C_{20}H_{22}Cl_4OTi_2$: C, 46.70; H, 4.31. Found: C, 46.81.; H, 4.33.

X-Ray Crystallographic Analysis of 68. A red single crystal of **68** was mounted on a pin and transferred to the goniometer. The space group was determined to be $P2_1/a$. A summary of data collection is given in Table 4.3. The final values of the positional parameters are given in Tables 5-9 in Appendix C.

***endo*-Isodicyclopentadienyltrichlorotitanium (63).**



To titanium tetrachloride (186 mg, 1.4 M in toluene, 1.0 mmol) in toluene (storred over molecular sieves for 24 h, prior to being distilled from CaH_2) (7 mL) at -78 °C was added a solution of **61**[45] (200 mg, 1.0 mmol) in the same solvent (10 mL) via cannula. The reaction mixture was stirred at -78 °C for 1 h and at room temperature for 10 h. The flask was then fitted with a Schlenk apparatus for filtering under inert atmosphere. The red solution resulting after filtration was concentrated in vacuo to leave a brownish residue, which was redissolved in toluene (1 mL) and allowed to stand under nitrogen for 24 h at -5 °C. The red crystalls of that formed were collected to afford **63** (108 mg, 38%); ^{1}H NMR (300 MHz, $CDCl_3$) ppm 6.88 (t, J = 2.8 Hz, 1 H), 6.46 (br d, J = 2.9 Hz, 2 H), 3.48 (br s, 2 H), 2.25 (br d, J = 7.2 Hz, 2 H), 2.01 (br d, J = 7.9 Hz, 2 H), 1.89 (m, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 158.0, 122.7, 116.2, 57.9, 43.0, 27.8; MS *m/z* [M^+] calcd 283.9406, obsd 283.9400.

X-Ray Crystallographic Analysis of 63. A red single crystal of **63** was mounted on a pin and transferred to the goniometer. The space proup was determined to be Pbcm. A summary of data collection is given in Table 4.1. The final values of the positional parameters are given in Tables 10-14 in Appendix B.

REFERENCES

1. Halpern, J. *J . Am. Chem. Soc.* **1980**, *102,* 838.
2. Halpern, J. in *Catalysis of Organic Reactions.*Marcel Deeker, Inc, New York, 1984.
3. Noyori, R. *et al Tetrahedron*, **1984**, *40*, 1245; Noyori, R. *et al J. Am. Chem. Soc.* **1980**, *102,* 7932.
4. Paquette, L. A.; McKinneye, J. A.; McLaughlin, M. L. *Tetrahedron Lett*, **1986**, *27*, 5599.
5. Noyori, R. *Asymmetric Catalysis in Organic Synthesis.* John Wiley & Sons, Inc, 1994.
6. Wilkinson, G.; Birmingham, G. M. *J. Am. Chem. Soc.* **1954**, *76,* 4281.
7. Cesarotti, E.; Kagan, H. B. *Angew. Chem. Int. Ed. Engl.* **1979**, *18*, 779.
8. Halterman, R. L.; Vollhard, K. P. C. *Tetrahedron Lett.* **1986**, *27*, 1461.
9. Moise, C.; Lablanc, J. C.; Tirouflet, J. *J. Amer. Chem. Soc.* **1975**, *97*, 6272.
10. Sivik, M. R. Ph.D. Dissertation, Ohio State University, 1992.
11. Brintzinger, H. H. in *Transition Metals and Organometallics as Catalysts for Olefin Polymerization.* Springler-Verlag: Berlin, 1988.
12. Brintzinger, H. H. *et al J.Organomet. Chem.* **1982**, *232*, 233.

13. Brintzinger, H. H. *et al J.Organomet. Chem.* **1989**, *369,* 343.

14. Brintzinger, H. H. *et al J.Organomet. Chem.* **1989**, *378*, 153.

15. Buchwald, S.L.; Broene, R.D. *J. Amer. Chem. Soc.* **1993**, *115*, 12569.

16. Collins, S.; Hong, Y., Taylor, N.J. *Organometallics* **1990**, *9*, 2695

17. Sutton, S. C.; Nantz, M. H.*Organometallics* **1993**, *12,* 2248.

18. Halterman, R. L.; Colletti, S. L.; Burk, M. J. *Organometallics*, **1991**, *10*, 2998.

19. Fleming, I.; Golghill, J.; Paterson, I. *Tetrahedron Lett.* **1979**, *34*, 3209.

20. Tardella, P. A. *Tetrahedron Lett.* **1969**, *23*, 1117.

21. Morita, Y.; Suzuki, M. *J. Org. Chem.* **1989**, *54,* 1785.

22. Brieskorn, C. H.; Schwack, W. *Chem. Ber.* **1981**, *114*, 1993

23. Paquette, L. A. *et al. J. Amer. Chem. Soc.* **1971**, 4508.

24. Evans, D. A.; Grimm, K. G. *J. Amer. Chem. Soc.* **1977**, *99,* 5009.

25. Paquette, L. A.; Gugelchuk, M.; McLaughlin, M. L. *J. Org. Chem.* **1987**, *52,* 4732.

26. Coates, R. M.; Fretz, E. R.; Last, L. A. *J. Org. Chem.* **1982**, *47,* 3211.

27. Paquette, L. A.; Gugelchuk, M.; McLaughlin, M. L. *J. Org. Chem.* **1987**, *52,* 4732.

28. Weiss, M. J.; Poletto, J. F.; Floyd, M. B. *J. Org. Chem.* **1979**, *44*, 1438.

29. Grieco, P. A. *et al J. Org. Chem.* **1977**, *42*, 3772.

30. Polla, E.; Orlovic, M.; Laszlo, P. *Synthesis*, **1979**, 655.

31. Sivik, M. R.; Stanton, K. J.; Paquette, L. A. *Org. Synth.* **1993**, *72*, 57.

32. Noyori, R.; Tomino, I.; Yamada, M. *J. Amer. Chem. Soc.* **1984**, *106,* 6609

33. Sakai, K.; Suemune, H.; Ogawa, T. *Tetrahedron: Asymmetry* **1991**, *2*, 389.

34. Terfort, A.; Brunner, H. *Tetrahedron: Asymmetry* **1995**, *6,* 919.

35. Paquette, L. A.; Bzowej, E. I.; Branon, B. M.; Stanton, K. J. *J. Org. Chem.* **1995**, *60*, 7277.

36. Kobayashi, Y.; Morikawa, T.; Taguchi, T. *Chem. Pharm. Bull.* **1980**, *28(1)*, 262; Morikawa, T.; Kobayashi, Y. *Tetrahedron Lett.* **1978**, *38,* 3555.

37. Boger, D.L.; Mullican, M. D. *J. Org. Chem.* **1985**, *50*, 1904.

38. Comyns, A. E.; Lucas, H. J. *J. Amer. Chem. Soc.* **1957**, *79*, 4341.

39. Ogasawara, K.; Iida, H.; Yamada, O. *Synthesis*, **1993**, 592.

40. Kozmina, N. S.; Paquette, L. A. *Synth. Comm.* **1996**, *26* (2), 2027-2030.

41. Liu, R. S. H.; Thiel, J. R. *Tetrahedron Lett.* **1994**, *35,* 7177.

42. Nicolaou, K. C.; Hong, Y.-P.; Torisawa, Y. *J. Amer. Chem. Soc.* **1991**, *113,* 9878.

43. Okamura, W. H.; Norman, A. W.; Lee, A.S. *J. Org. Chem.* **1992**, *57*, 3 846.

44. Stanton, K. J. Master Thesis, 1993, Ohio State University.

45. Paquette, L. A.; Charumilind, P. *J. Amer. Chem. Soc.* **1982**, *104,* 3749.

46. Sivik, M. R. Ph. D. Dissertation, Ohio State University, 1992.

47. Tiripicchio A.; Royo, P. *Organometallics*, **1992**, *11*, 3301.

APPENDIX A: ^{1}H NMR Spectra.

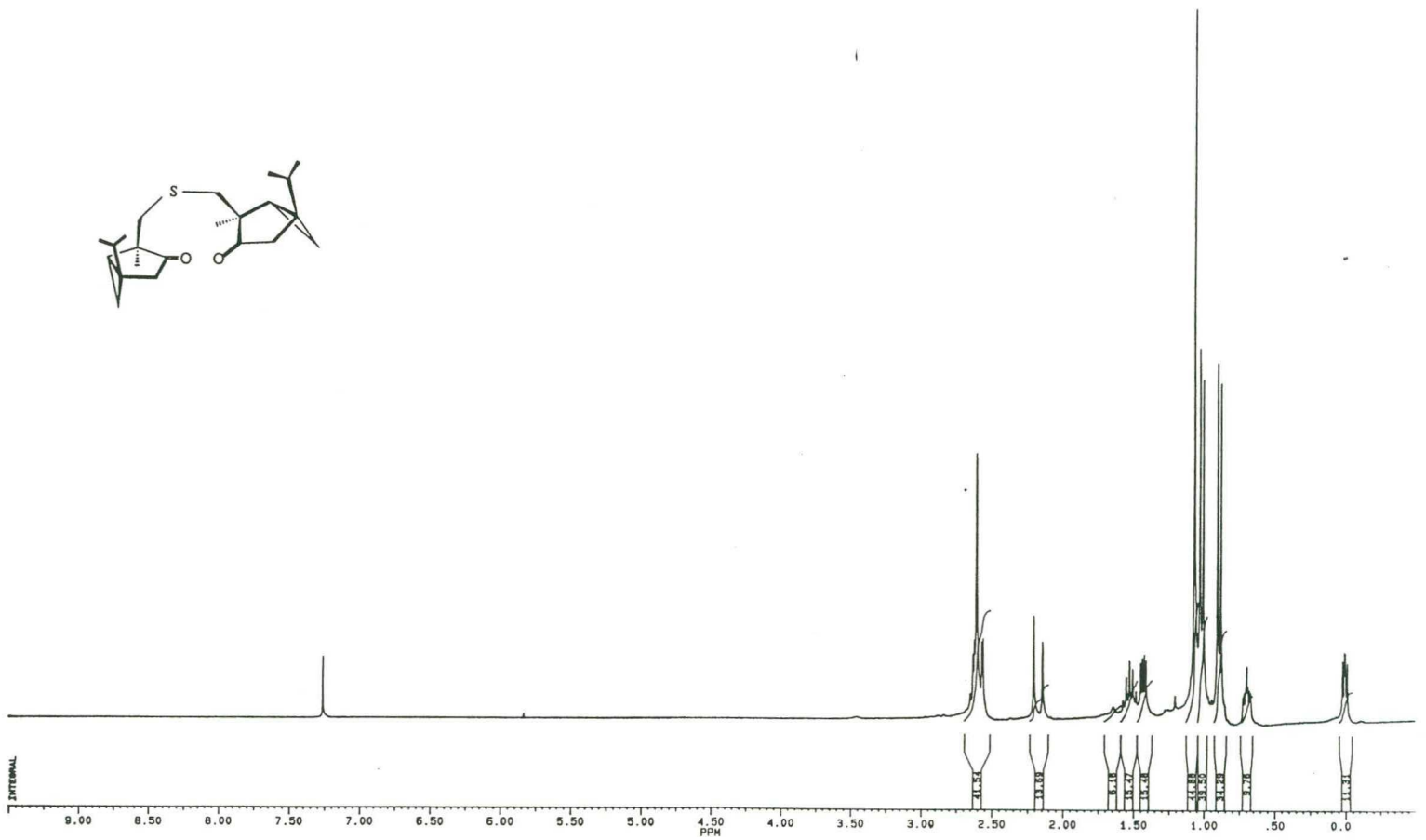


Figure A.1: ^{1}H NMR Spectrum of Compound 20.

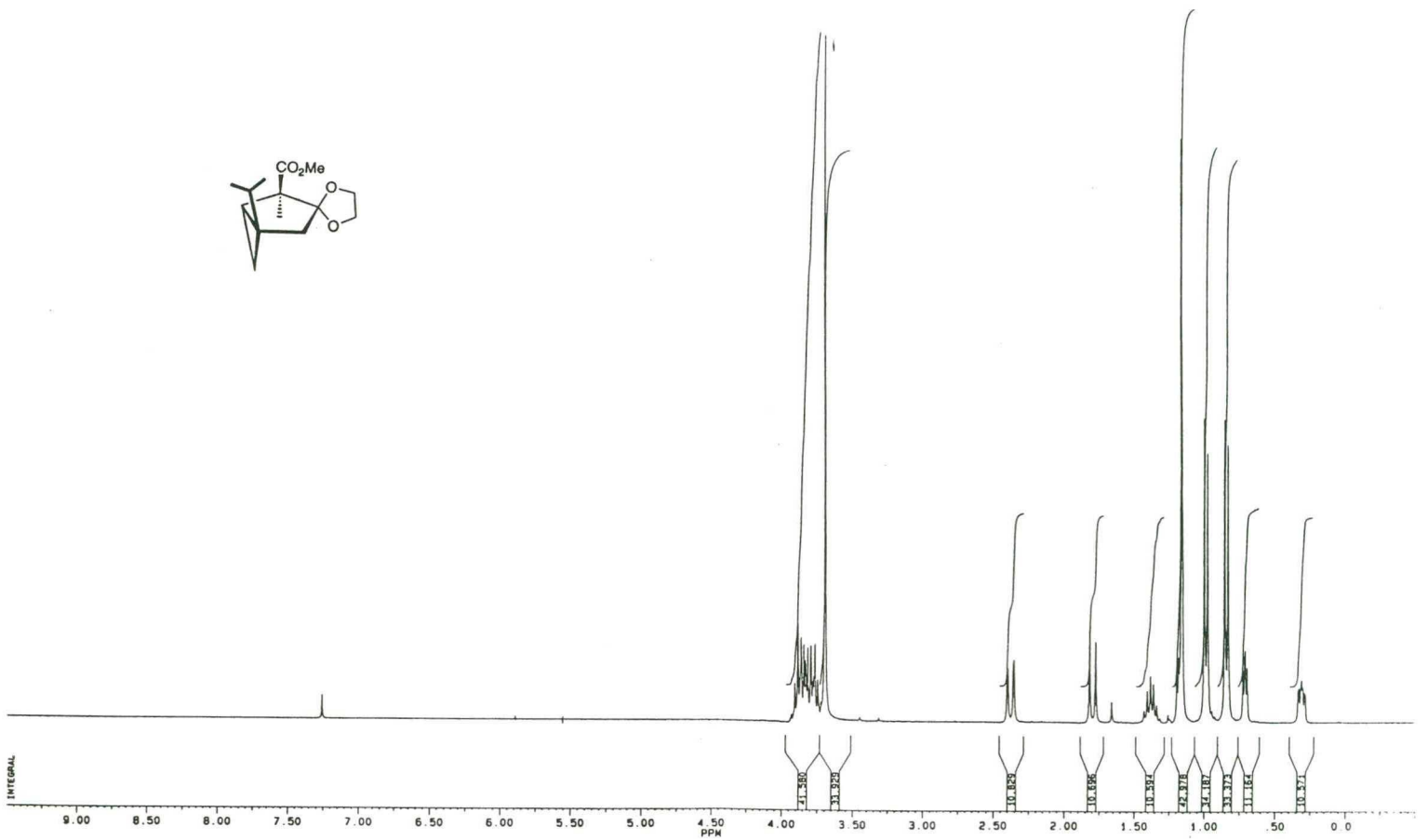


Figure A.2: ^{1}H NMR Spectrum of Compound 23

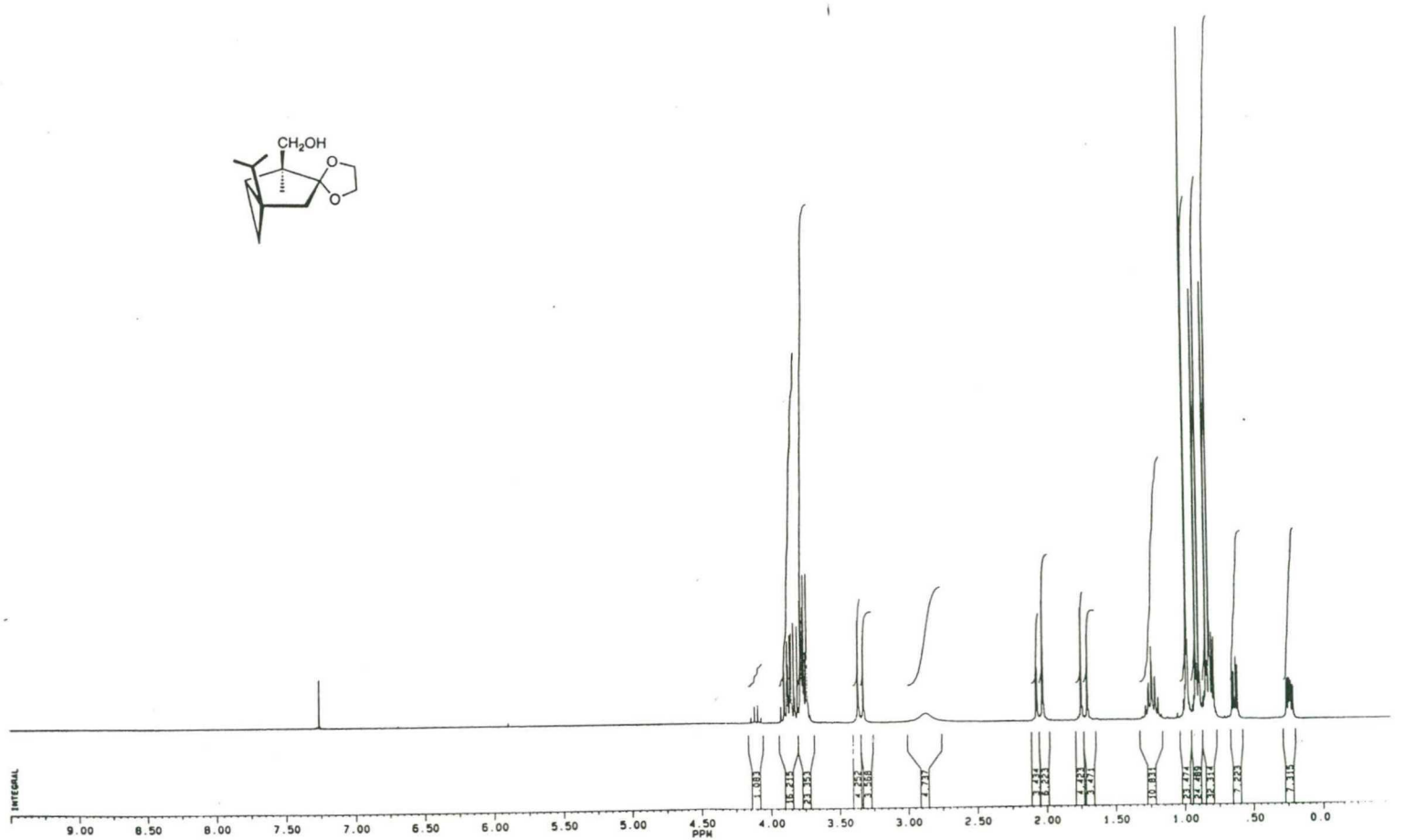


Figure A.3: ^{1}H NMR Spectrum of Compound 24.

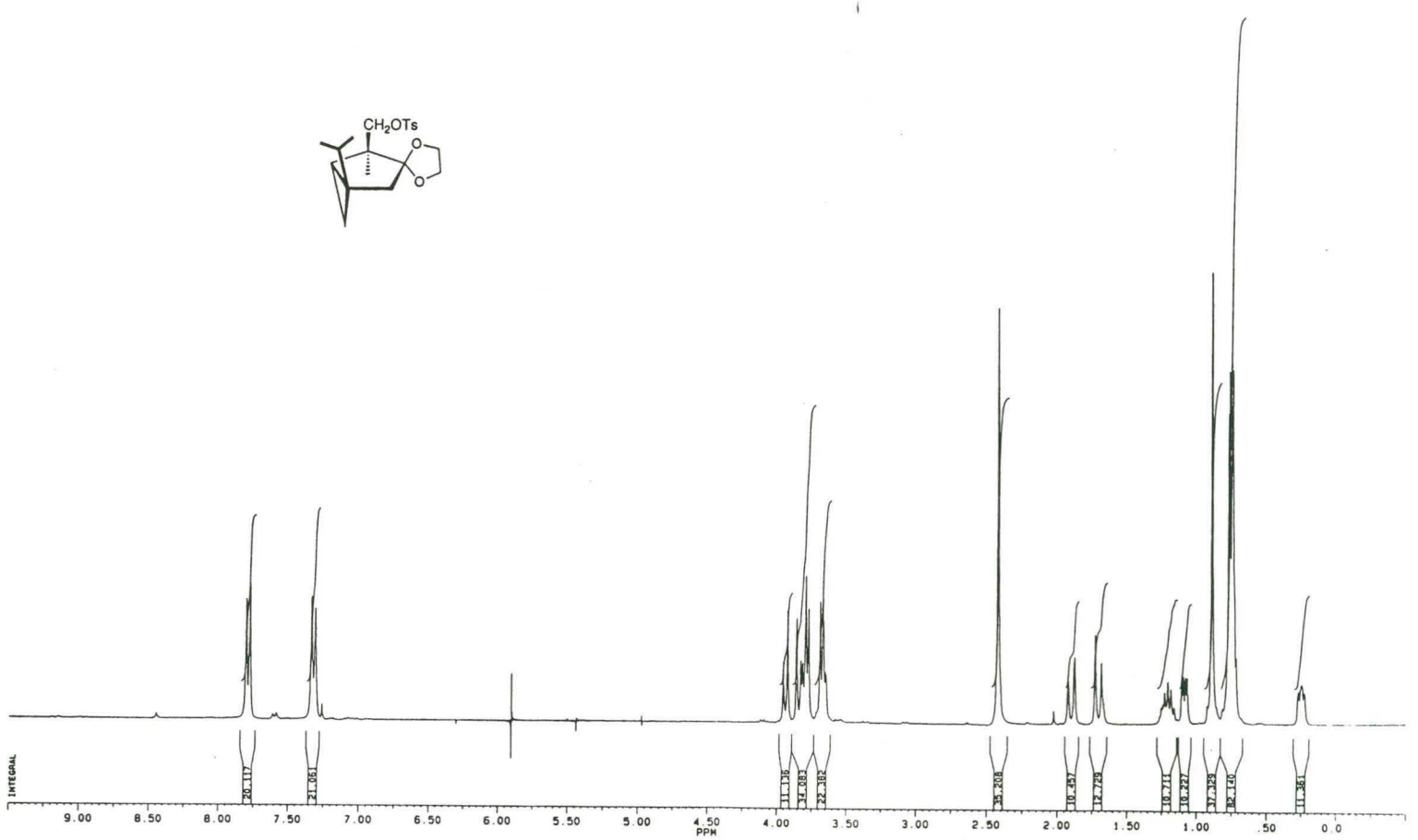


Figure A.4: ^{1}H NMR Spectrum of Compound 25.

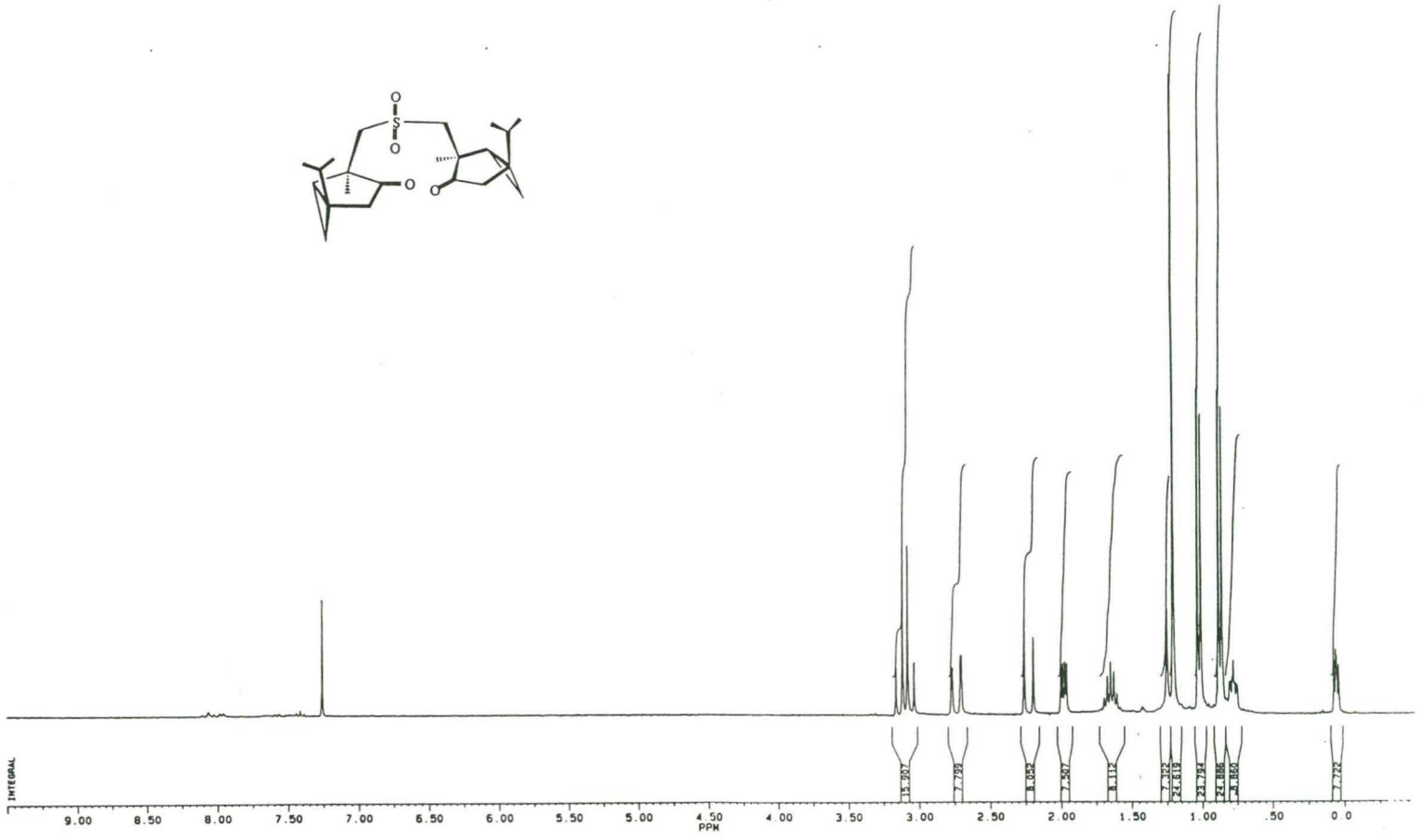


Figure A.5: ^{1}H NMR Spectrum of Compound 21.

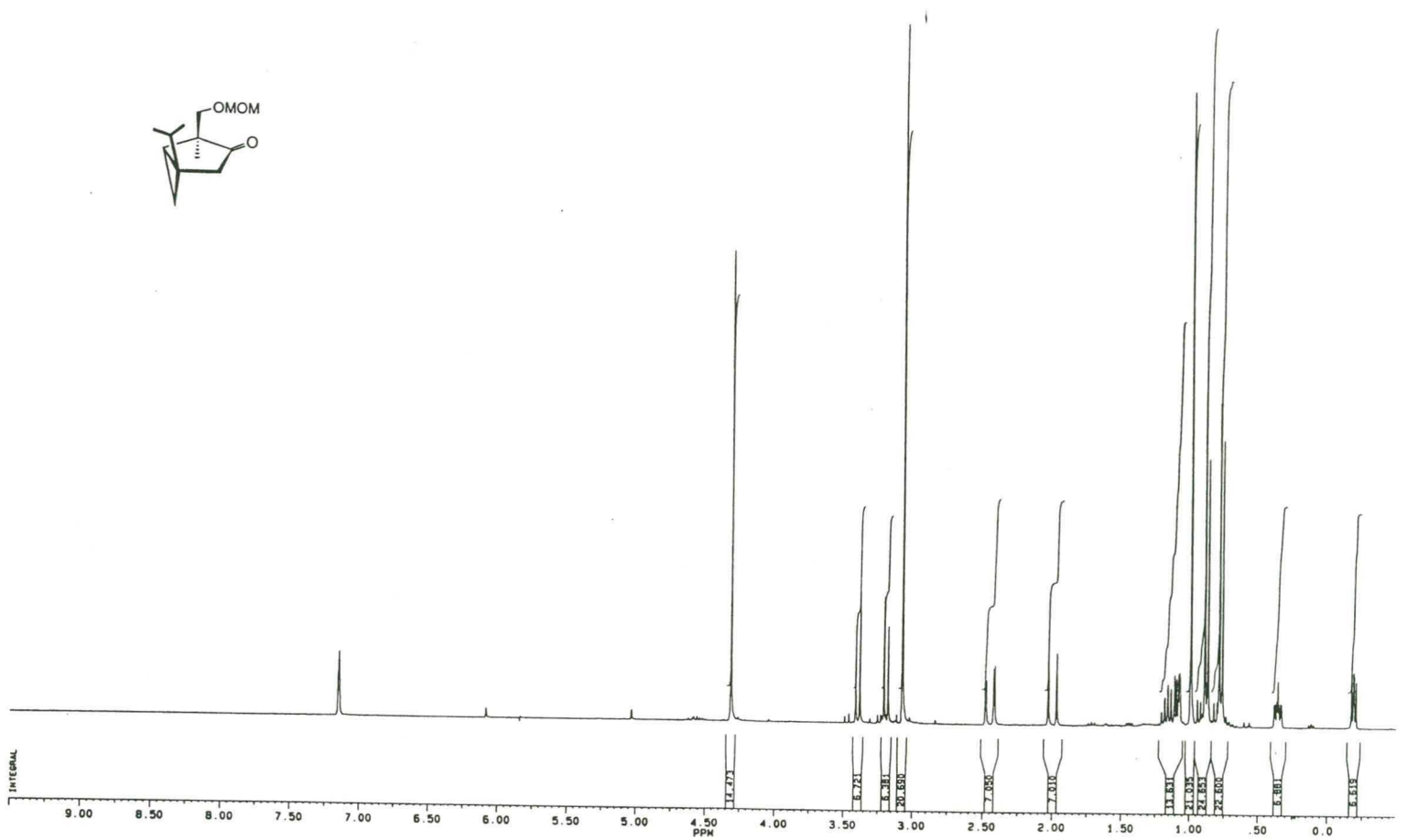


Figure A.6: ^{1}H NMR Spectrum of Compound 28.

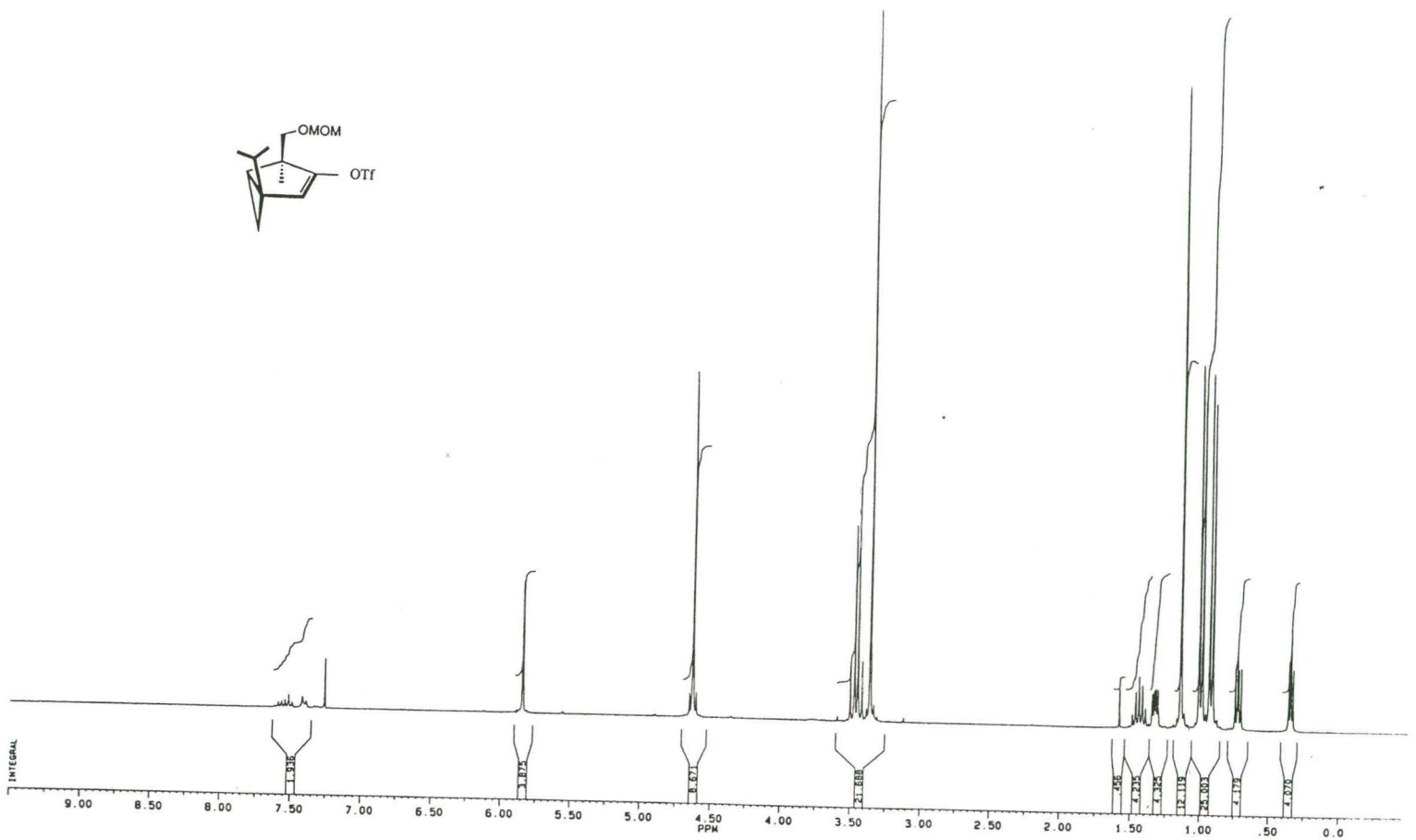


Figure A.7: ^{1}H NMR Spectrum of Compound 29.

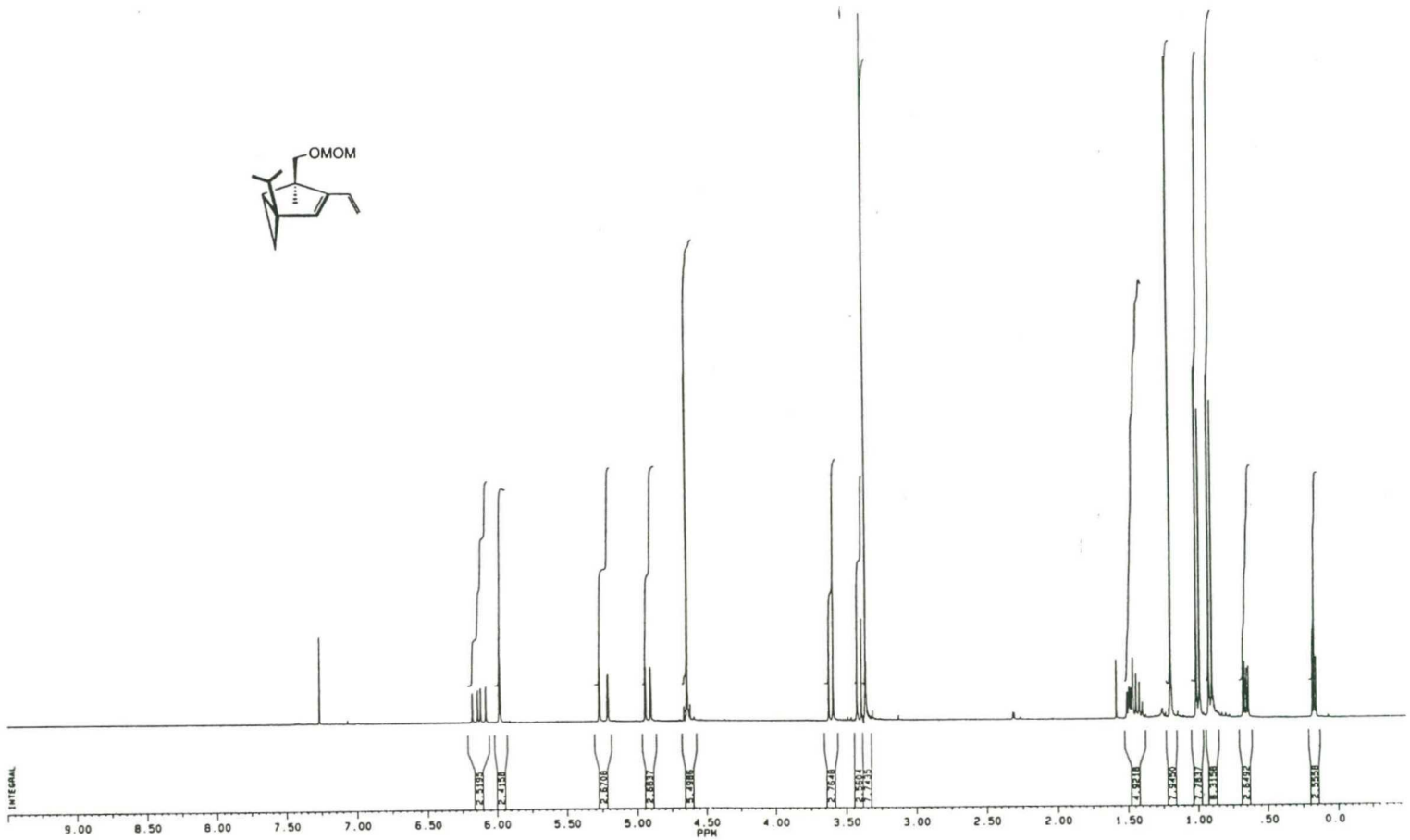


Figure A.8: ^{1}H NMR Spectrum of Compound 30.

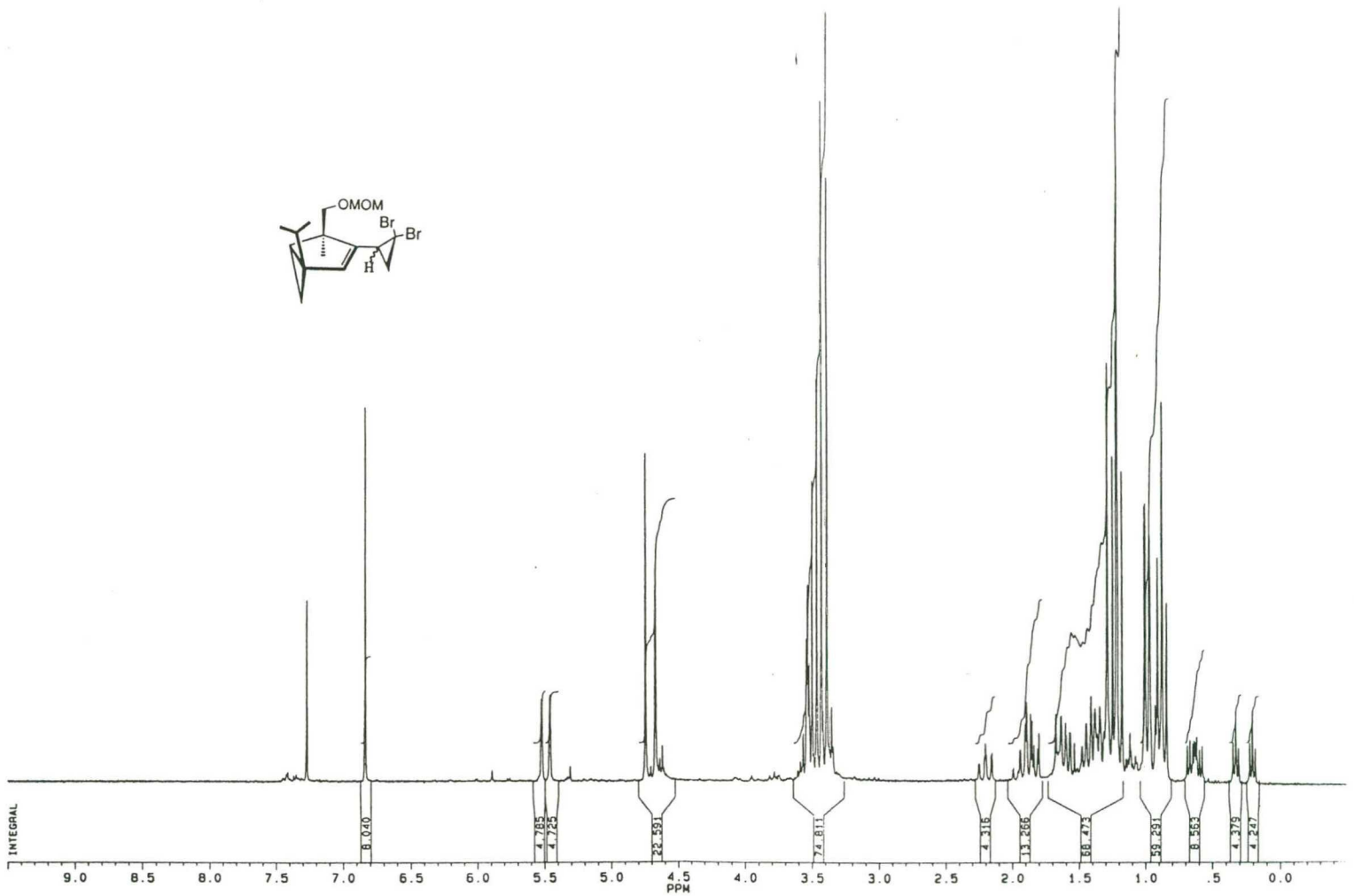


Figure A.9: ^{1}H NMR Spectrum of Compound 31.

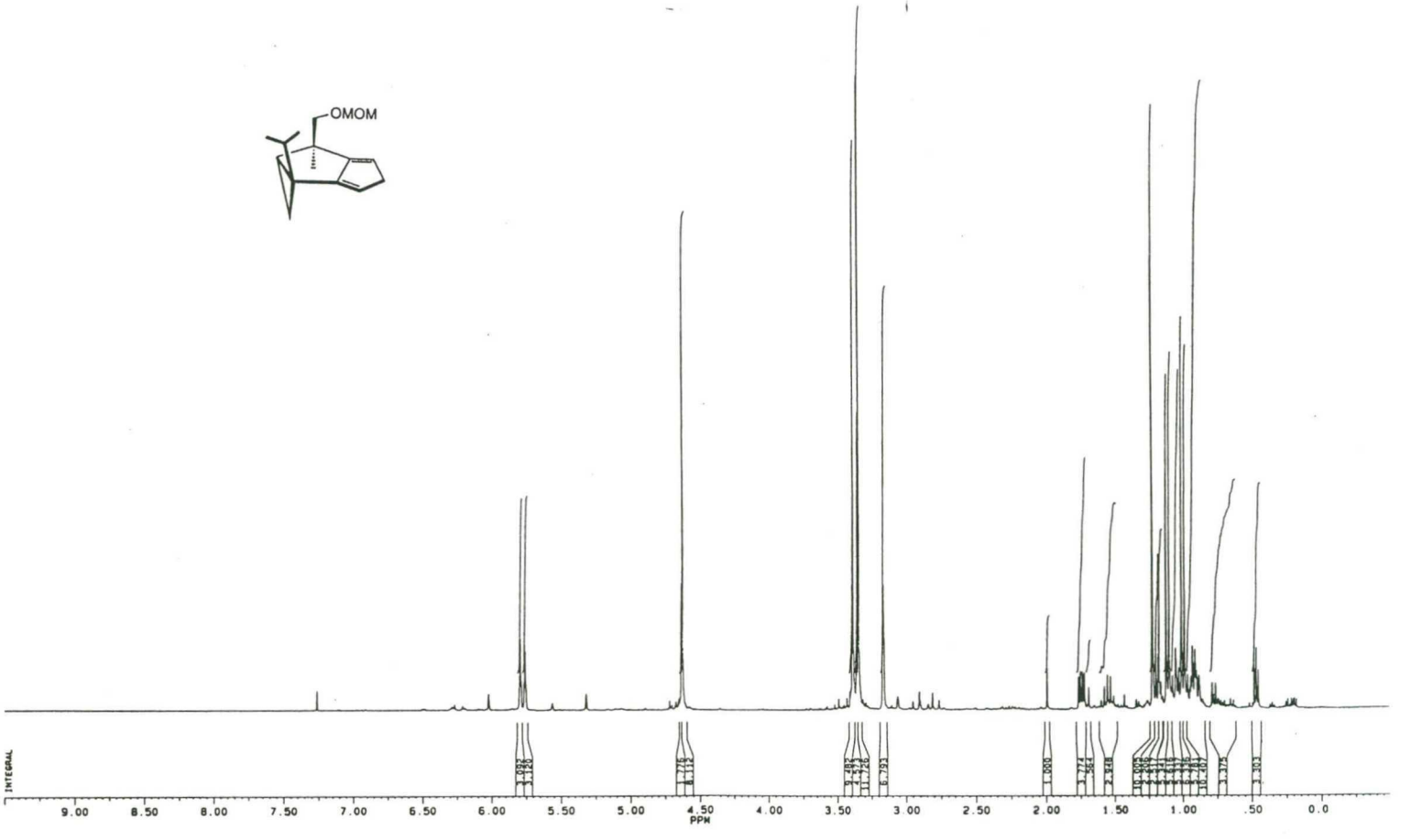


Figure A.10: ^{1}H NMR Spectrum of Compound 32.

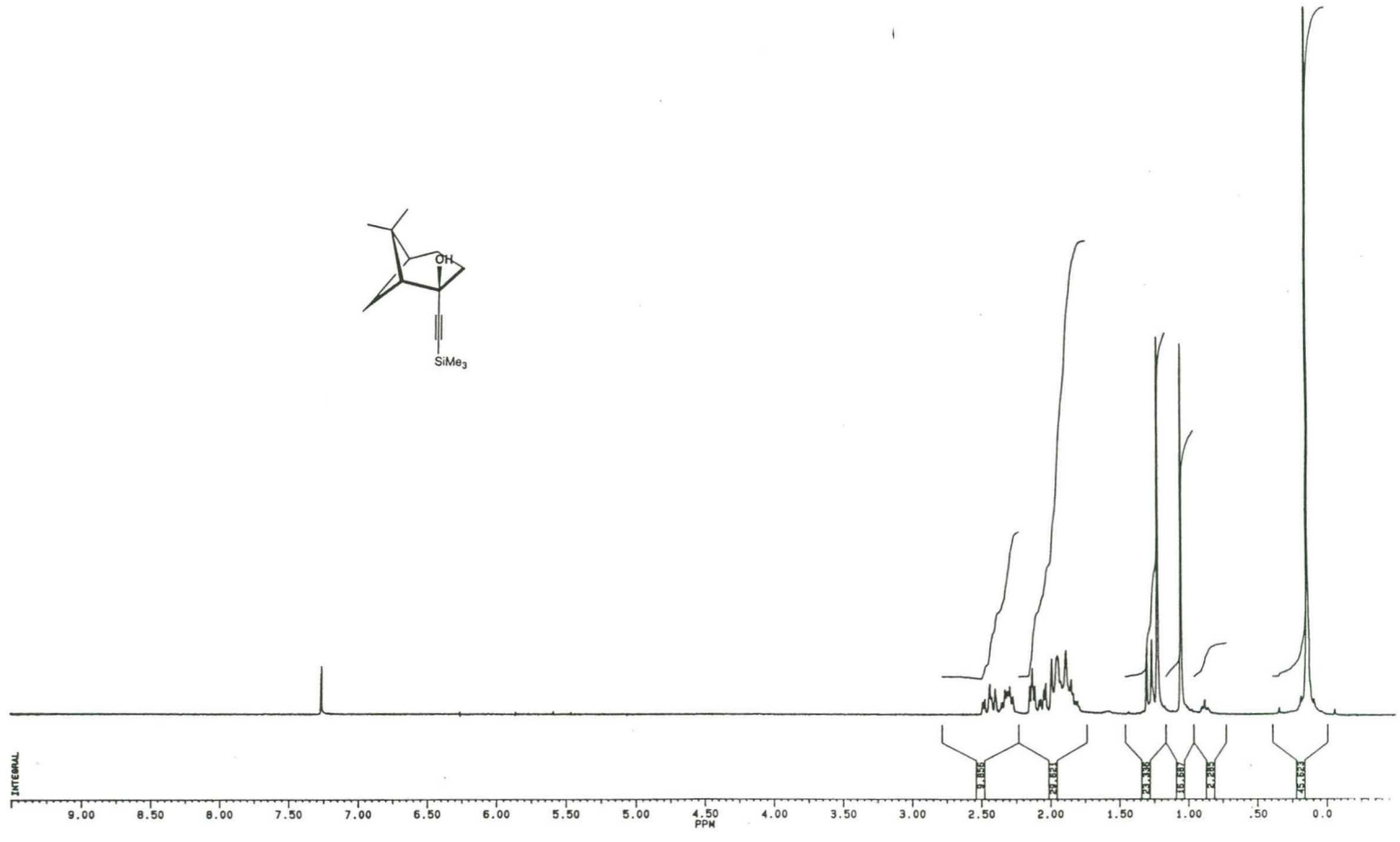


Figure A.11: ^{1}H NMR Spectrum of Compound 51.

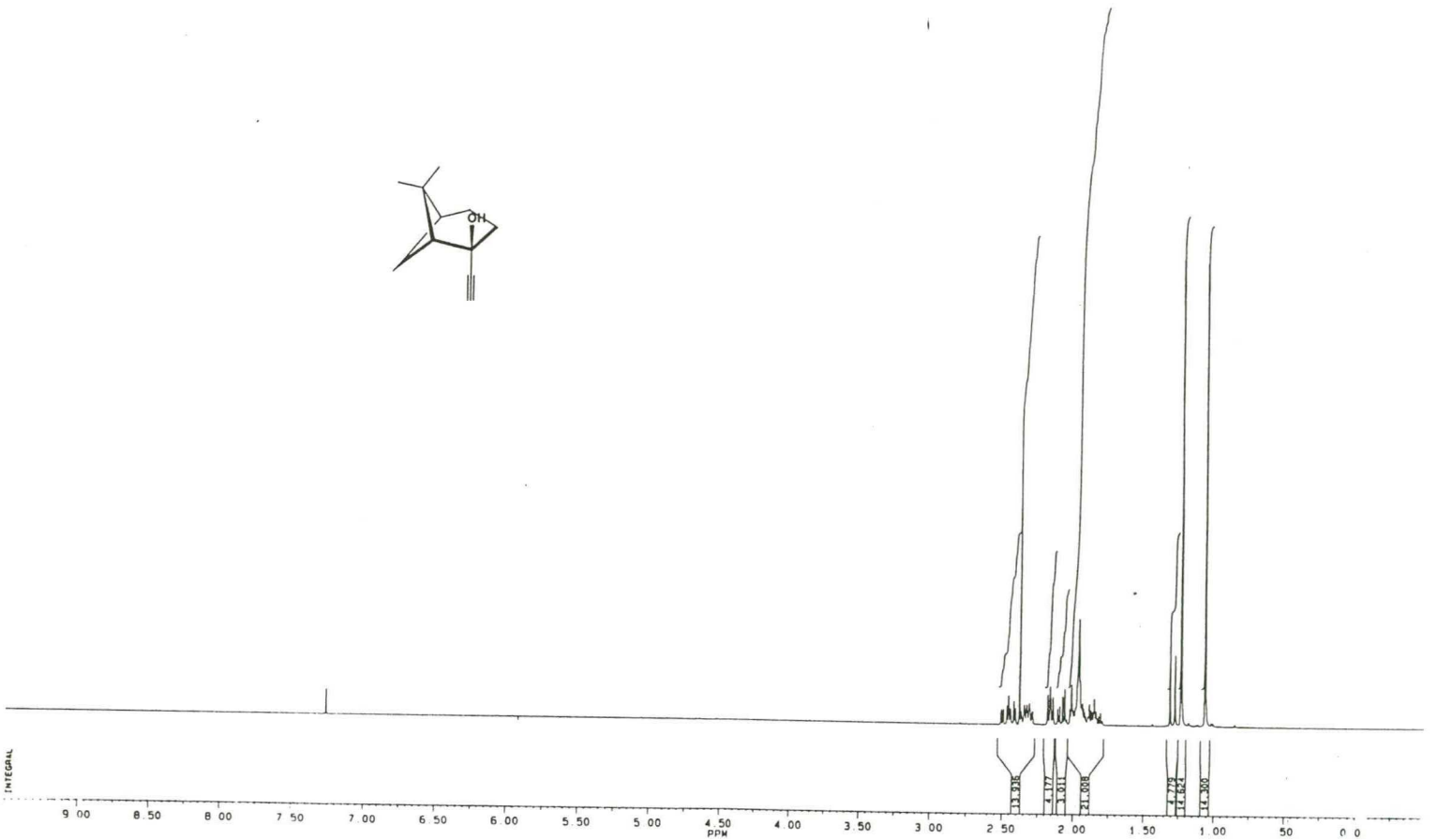


Figure A.12: ^{1}H NMR Spectrum of Compound 53

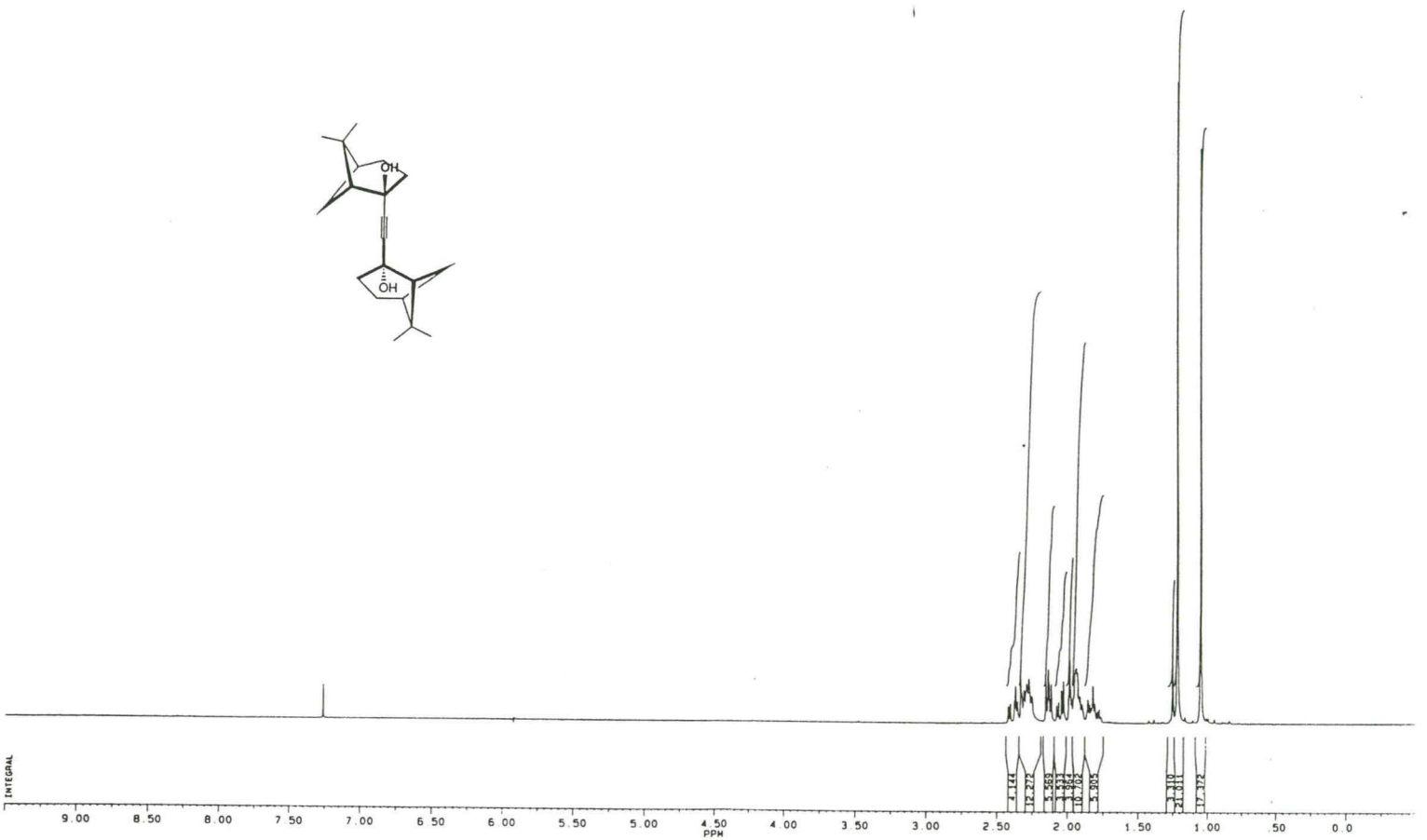


Figure A.13: ^{1}H NMR Spectrum of Compound 54.

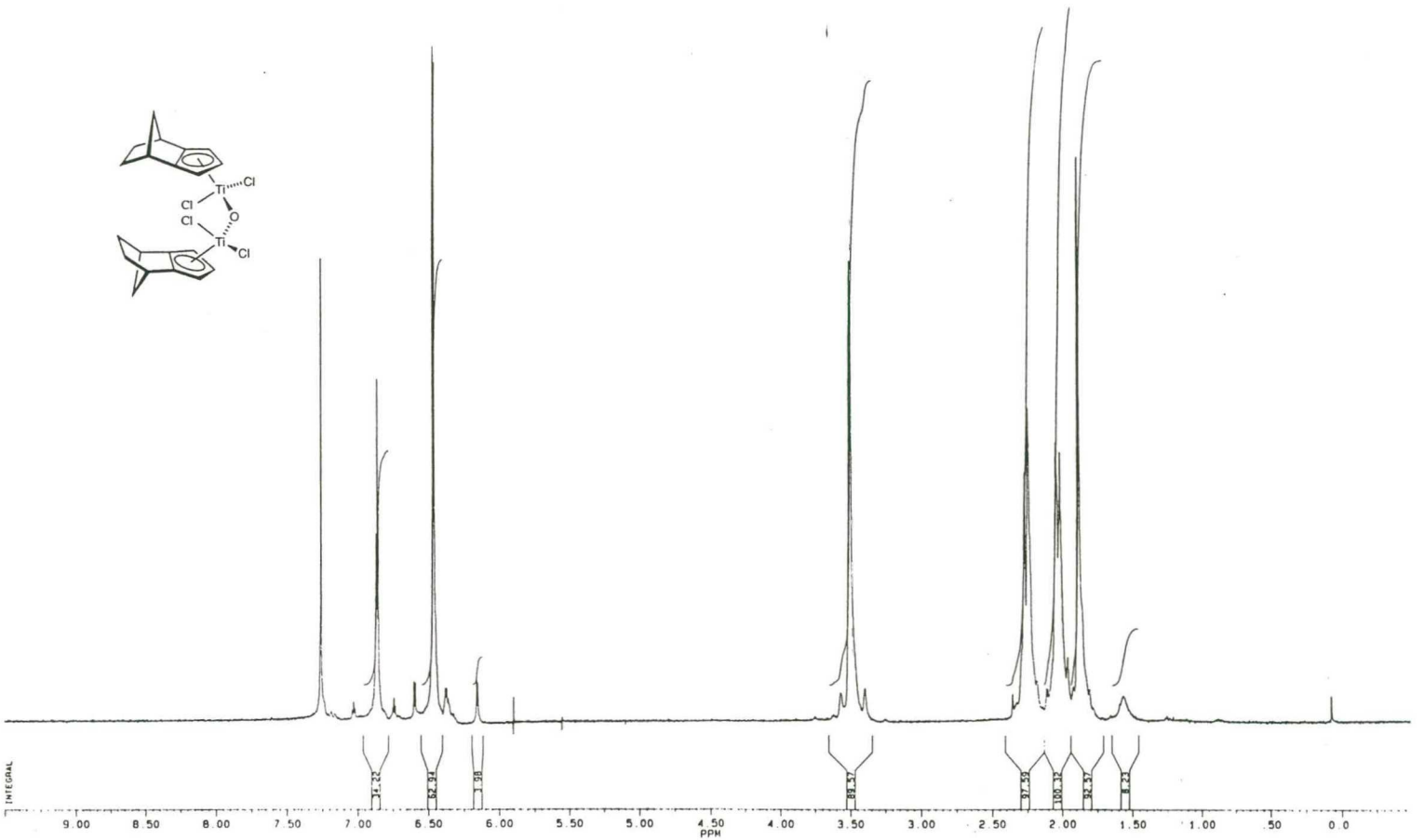


Figure A.14: ^{1}H NMR Spectrum of Compound 68.

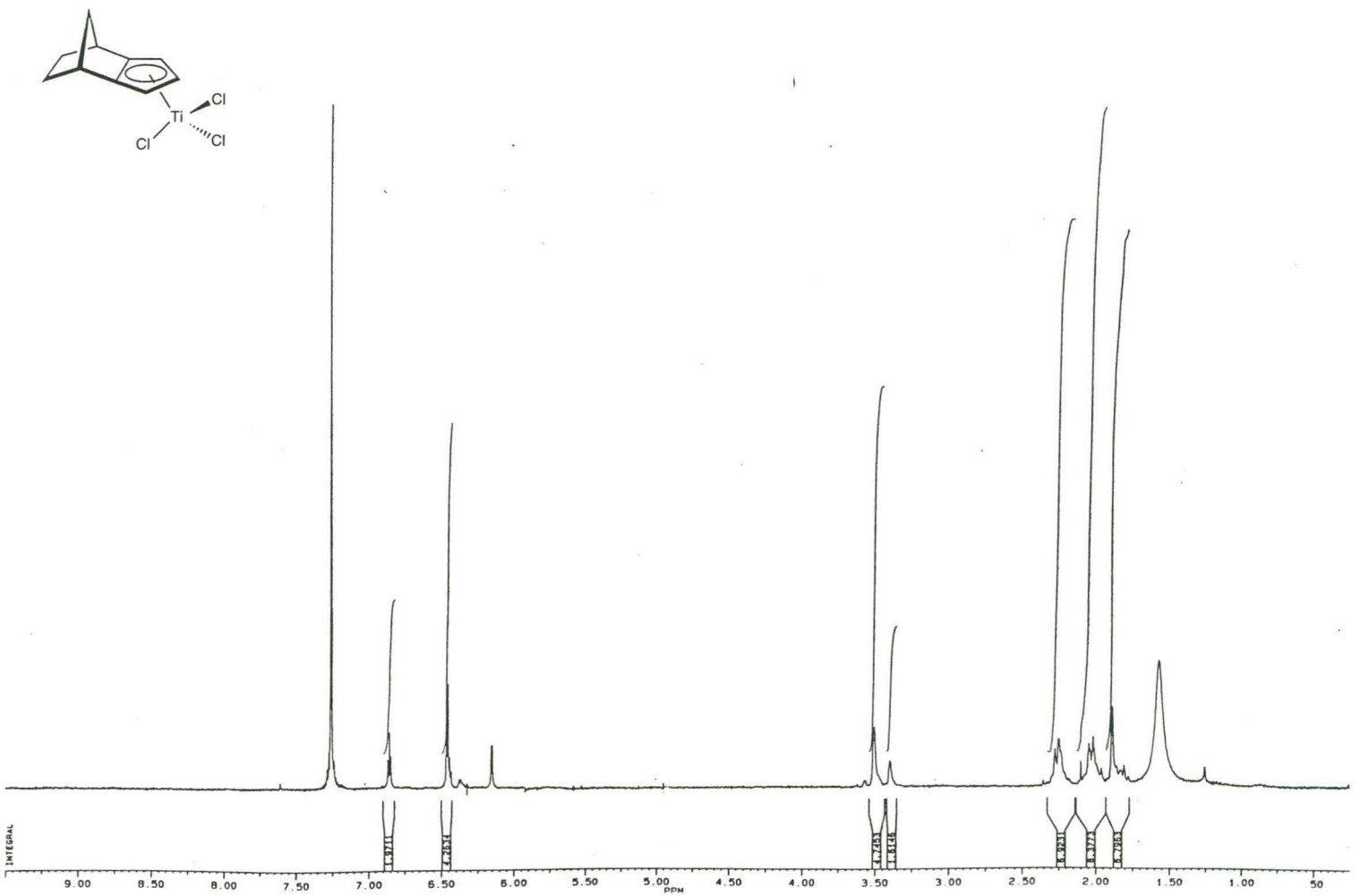


Figure A.15: ^{1}H NMR Spectrum of Compound 63.

APPENDIX B: X-Ray Crystallographic Data for 63.

atom	atom	distance	atom	atom	distance
Ti	Cl(1)	2.236(1)	C(2)	C(3)	1.401(3)
Ti	Cl(2)	2.2288(7)	C(3)	C(3′)	1.411(5)
Ti	C(1)	2.272(4)	C(3)	C(4)	1.508(3)
Ti	C(2)	2.329(2)	C(4)	C(5)	1.536(3)
Ti	C(3)	2.424(2)	C(4)	C(6)	1.554(3)
C(1)	C(2)	1.403(4)	C(5)	C(5′)	1.540(5)
Ti	R.C.	2.031			

Table 5: Bond Lengths for Complex 63.

atom	atom	atom	angle	atom	atom	atom	angle
Cl(1)	Ti	Cl(2)	100.77(3)	C(3′)	C(3)	C(4)	106.6(1)
Cl(2)	Ti	Cl(2′)	105.08(4)	C(3)	C(4)	C(5)	110.8(2)
C(2)	C(1)	C(2′)	109.2(3)	C(3)	C(4)	C(6)	97.5(2)
C(1)	C(2)	C(3)	107.2(3)	C(5)	C(4)	C(6)	99.9(2)
C(2)	C(3)	C(3′)	108.2(2)	C(4)	C(5)	C(5′)	103.8(1)
C(2)	C(3)	C(4)	143.7(2)	C(4)	C(6)	C(4′)	94.0(3)

Table 6: Bond Angles for Complex 63.

atom	x	y	z	B(eq), $Å^2$
Ti	0.11770(7)	0.02711(5)	0.2500	3.18(1)
Cl(1)	-0.1183(1)	0.07537(8)	0.2500	5.69(3)
Cl(2)	0.19922(8)	0.11900(5)	0.07846(7)	4.76(2)
C(1)	0.0314(4)	-0.1457(3)	0.2500	5.4(1)
C(2)	0.1197(3)	-0.1374(2)	0.3609(3)	4.55(7)
C(3)	0.2646(3)	-0.1263(2)	0.3184(2)	3.30(5)
C(4)	0.4223(3)	-0.1355(2)	0.3602(3)	4.15(6)
C(5)	0.5077(3)	-0.0323(2)	0.3247(2)	4.25(6)
C(6)	0.4748(4)	-0.2121(3)	0.2500	5.1(1)

Table 7: Positional Parameters and B(eq) values for Complex 63.

atom	x	y	z	B, $Å^2$
H(1)	-0.0751	-0.1557	0.2500	6.5
H(2)	0.0863	-0.1392	0.4512	5.4
H(3)	0.4378	-0.1624	0.4486	5.0
H(4)	0.4586	0.0324	0.3585	5.1
H(5)	0.6079	-0.0355	0.3585	5.1
H(6)	0.5809	-0.2237	0.2500	6.2
H(7)	0.4246	-0.2824	0.2500	6.2

Table 8: Calculated Positional Parameters for the Hydrogen Atoms of Complex 63.

atom	U11	U22	U33	U12	U13	U23
Ti	0.0372(3)	0.0287(3)	0.0550(4)	-0.0007(3)	0.0000	0.0000
Cl(1)	0.0383(6)	0.0530(6)	0.125(1)	0.0040(5)	0.0000	0.0000
Cl(2)	0.0661(4)	0.0523(4)	0.0623(4)	0.0030(4)	0.0021(4)	0.0169(3)
C(1)	0.045(3)	0.032(2)	0.128(4)	-0.009(2)	0.0000	0.0000
C(2)	0.063(2)	0.033(1)	0.077(2)	-0.003(1)	0.021(2)	0.011(1)
C(3)	0.050(1)	0.028(1)	0.047(1)	0.003(1)	0.006(1)	0.007(1)
C(4)	0.058(2)	0.056(2)	0.044(2)	0.011(1)	-0.005(1)	0.010(1)
C(5)	0.042(1)	0.064(2)	0.055(2)	0.004(1)	-0.008(1)	-0.001(2)
C(6)	0.056(3)	0.051(3)	0.088(3)	0.022(2)	0.0000	0.0000

Table 9: Anisotropic Displacement Parameters for Complex 63.

APPENDIX C: X-Ray Crystallographic Data for 68.

atom	atom	atom	angle	atom	atom	atom	angle
Cl(1)	Ti(1)	Cl(2)	99.59(5)	C(1)	C(9)	C(10)	97.6(3)
Cl(1)	Ti(1)	O(1)	107.7(1)	C(8)	C(9)	C(10)	99.0(3)
Cl(2)	Ti(1)	O(1)	100.9(1)	C(6)	C(10)	C(9)	94.9(3)
Cl(3)	Ti(2)	Cl(4)	99.65(5)	C(12)	C(11)	C(15)	108.6(4)
Cl(3)	Ti(2)	O(1)	106.3(1)	C(12)	C(11)	C(19)	143.9(5)
Cl(4)	Ti(2)	O(1)	102.2(1)	C(15)	C(11)	C(19)	106.2(4)
Ti(1)	O(1)	Ti(2)	159.5(2)	C(11)	C(12)	C(13)	106.9(4)
C(2)	C(1)	C(5)	108.9(4)	C(12)	C(13)	C(14)	109.5(4)
C(2)	C(1)	C(9)	143.4(4)	C(13)	C(14)	C(15)	106.6(4)
C(5)	C(1)	C(9)	106.9(4)	C(11)	C(15)	C(14)	108.3(4)
C(1)	C(2)	C(3)	106.1(4)	C(11)	C(15)	C(16)	107.5(4)
C(2)	C(3)	C(4)	109.6(4)	C(14)	C(15)	C(16)	142.9(4)
C(3)	C(4)	C(5)	106.8(4)	C(15)	C(16)	C(17)	109.1(4)
C(1)	C(5)	C(4)	108.6(4)	C(15)	C(16)	C(20)	97.4(4)
C(1)	C(5)	C(6)	106.9(4)	C(17)	C(16)	C(20)	100.2(4)
C(4)	C(5)	C(6)	143.3(4)	C(16)	C(17)	C(18)	104.1(5)
C(5)	C(6)	C(7)	110.3(4)	C(17)	C(18)	C(19)	104.1(4)
C(5)	C(6)	C(10)	98.0(3)	C(11)	C(19)	C(18)	111.0(4)
C(7)	C(6)	C(10)	99.1(4)	C(11)	C(19)	C(20)	97.3(4)
C(6)	C(7)	C(8)	103.6(4)	C(18)	C(19)	C(20)	99.0(5)
C(7)	C(8)	C(9)	104.4(4)	C(16)	C(20)	C(19)	94.6(4)
C(1)	C(9)	C(8)	109.8(3)				

Angles are in degrees. Estimated standard deviations in the least significant figure are given in parentheses.

Table 10: Bond Angles for Complex 68.

atom	atom	distance	atom	atom	distance
Ti(1)	Cl(1)	2.250(1)	C(3)	C(4)	1.407(7)
Ti(1)	Cl(2)	2.254(1)	C(4)	C(5)	1.404(6)
Ti(1)	O(1)	1.803(3)	C(5)	C(6)	1.515(6)
Ti(1)	C(1)	2.417(4)	C(6)	C(7)	1.536(7)
Ti(1)	C(2)	2.322(4)	C(6)	C(10)	1.548(6)
Ti(1)	C(3)	2.292(5)	C(7)	C(8)	1.540(6)
Ti(1)	C(4)	2.383(5)	C(8)	C(9)	1.544(6)
Ti(1)	C(5)	2.458(4)	C(9)	C(10)	1.553(6)
Ti(2)	Cl(3)	2.243(1)	C(11)	C(12)	1.400(6)
Ti(2)	Cl(4)	2.268(1)	C(11)	C(15)	1.411(6)
Ti(2)	O(1)	1.815(3)	C(11)	C(19)	1.515(6)
Ti(2)	C(11)	2.430(4)	C(12)	C(13)	1.405(7)
Ti(2)	C(12)	2.359(4)	C(13)	C(14)	1.410(6)
Ti(2)	C(13)	2.287(5)	C(14)	C(15)	1.405(6)
Ti(2)	C(14)	2.330(4)	C(15)	C(16)	1.501(6)
Ti(2)	C(15)	2.418(4)	C(16)	C(17)	1.543(6)
C(1)	C(2)	1.408(6)	C(16)	C(20)	1.547(7)
C(1)	C(5)	1.406(6)	C(17)	C(18)	1.530(8)
C(1)	C(9)	1.509(6)	C(18)	C(19)	1.538(8)
C(2)	C(3)	1.418(6)	C(19)	C(20)	1.559(7)

Ti(1) — R.C.(1) 2.051

Ti(2) - R.C.(2) 2.041

Distances are in angstroms. Estimated standard deviations in the least significant figure are given in parentheses.

Table 11: Bond Lengths for Complex 68.

atom	x	y	z	B_{eq}, $Å^2$
Ti(1)	0.26551(6)	0.63808(8)	0.75810(4)	2.50(2)
Ti(2)	0.43035(5)	0.35542(8)	0.75501(4)	2.47(2)
Cl(1)	0.10209(9)	0.6155(1)	0.70715(7)	4.25(3)
Cl(2)	0.3335(1)	0.7487(1)	0.65531(7)	4.71(3)
Cl(3)	0.35476(9)	0.1605(1)	0.78053(7)	3.83(3)
Cl(4)	0.51006(10)	0.3952(1)	0.87801(7)	4.68(3)
O(1)	0.3283(2)	0.4790(3)	0.7506(2)	2.85(7)
C(1)	0.2890(3)	0.6211(4)	0.9036(2)	2.59(9)
C(2)	0.3704(3)	0.6930(5)	0.8714(3)	3.4(1)
C(3)	0.3256(4)	0.8106(5)	0.8379(3)	4.4(1)
C(4)	0.2186(4)	0.8100(4)	0.8480(3)	4.0(1)
C(5)	0.1967(4)	0.6925(4)	0.8894(2)	2.9(1)
C(6)	0.1156(3)	0.6243(5)	0.9372(3)	3.7(1)
C(7)	0.0888(3)	0.4877(5)	0.9004(3)	3.8(1)
C(8)	0.1903(4)	0.4089(4)	0.9125(3)	3.8(1)
C(9)	0.2651(3)	0.5061(5)	0.9580(2)	3.2(1)
C(10)	0.1868(4)	0.5788(5)	1.0101(3)	3.7(1)
C(11)	0.4813(4)	0.2624(5)	0.6277(3)	3.3(1)
C(12)	0.5635(4)	0.2535(5)	0.6858(3)	4.0(1)
C(13)	0.5911(3)	0.3842(5)	0.7076(3)	4.0(1)
C(14)	0.5259(3)	0.4744(5)	0.6643(3)	3.4(1)
C(15)	0.4582(3)	0.3979(4)	0.6141(3)	2.9(1)
C(16)	0.3837(4)	0.4058(5)	0.5416(3)	4.2(1)
C(17)	0.2797(4)	0.3446(7)	0.5631(3)	5.4(2)
C(18)	0.3033(5)	0.1964(7)	0.5740(3)	6.1(2)
C(19)	0.4199(5)	0.1860(5)	0.5625(3)	5.3(2)
C(20)	0.4287(4)	0.2898(6)	0.4933(3)	5.6(2)

$$B_{eq} = \frac{8}{3}\pi^2(U_{11}(aa^*)^2 + U_{22}(bb^*)^2 + U_{33}(cc^*)^2 + 2U_{12}aa^*bb^*\cos\gamma + 2U_{13}aa^*cc^*\cos\beta + 2U_{23}bb^*cc^*\cos\alpha)$$

Table 12: Positional Parameters and B(eq) values for Complex 68.

atom	x	y	z	B, Å^2
H(1)	0.4432	0.6672	0.8719	4.16
H(2)	0.3632	0.8814	0.8117	5.29
H(3)	0.1689	0.8787	0.8296	4.78
H(4)	0.0565	0.6794	0.9504	4.39
H(5)	0.3245	0.4654	0.9876	3.87
H(6)	0.0334	0.4451	0.9288	4.58
H(7)	0.0680	0.4957	0.8428	4.58
H(8)	0.1801	0.3288	0.9449	4.57
H(9)	0.2166	0.3836	0.8603	4.57
H(10)	0.2177	0.6533	1.0410	4.46
H(11)	0.1523	0.5192	1.0468	4.46
H(12)	0.5956	0.1715	0.7072	4.87
H(13)	0.6472	0.4089	0.7469	4.79
H(14)	0.5272	0.5714	0.6683	4.02
H(15)	0.3799	0.4918	0.5139	5.05
H(16)	0.4454	0.0966	0.5511	6.34
H(17)	0.2561	0.3830	0.6132	6.54
H(18)	0.2270	0.3586	0.5192	6.54
H(19)	0.2871	0.1667	0.6281	7.36
H(20)	0.2641	0.1437	0.5332	7.36
H(21)	0.3862	0.2672	0.4444	6.70
H(22)	0.5000	0.3051	0.4790	6.70

Table 13: Calculated Positional Parameters for the Hydrogen Atoms of Complex 68.

atom	U_{11}	U_{22}	U_{33}	U_{12}	U_{13}	U_{23}
Ti(1)	0.0356(4)	0.0294(4)	0.0301(4)	0.0042(4)	0.0036(3)	0.0032(4)
Ti(2)	0.0299(4)	0.0331(5)	0.0310(4)	0.0051(4)	0.0032(3)	-0.0003(4)
Cl(1)	0.0413(7)	0.0661(9)	0.0530(7)	0.0052(6)	-0.0068(6)	0.0122(7)
Cl(2)	0.0674(9)	0.0668(9)	0.0457(7)	-0.0054(7)	0.0125(6)	0.0203(7)
Cl(3)	0.0526(7)	0.0419(7)	0.0519(7)	-0.0013(6)	0.0090(6)	0.0122(6)
Cl(4)	0.0586(8)	0.0731(10)	0.0440(7)	0.0126(7)	-0.0154(6)	-0.0073(7)
O(1)	0.036(2)	0.038(2)	0.034(2)	0.011(1)	0.001(1)	-0.003(1)
C(1)	0.041(2)	0.031(2)	0.027(2)	0.000(2)	0.000(2)	-0.005(2)
C(2)	0.044(3)	0.042(3)	0.045(3)	-0.014(2)	0.004(2)	-0.012(2)
C(3)	0.084(4)	0.035(3)	0.050(3)	-0.022(3)	0.019(3)	-0.010(2)
C(4)	0.080(4)	0.028(3)	0.046(3)	0.012(3)	0.015(3)	0.000(2)
C(5)	0.053(3)	0.030(2)	0.030(2)	0.006(2)	0.009(2)	-0.005(2)
C(6)	0.044(3)	0.052(3)	0.044(3)	0.014(2)	0.014(2)	0.005(2)
C(7)	0.039(3)	0.063(3)	0.042(3)	-0.011(3)	0.008(2)	0.004(3)
C(8)	0.058(3)	0.036(3)	0.052(3)	-0.001(2)	0.019(3)	0.005(2)
C(9)	0.039(3)	0.049(3)	0.034(2)	0.002(2)	0.000(2)	0.010(2)
C(10)	0.063(3)	0.046(3)	0.034(3)	-0.004(3)	0.014(2)	0.001(2)
C(11)	0.045(3)	0.042(3)	0.042(3)	-0.003(2)	0.021(2)	-0.008(2)
C(12)	0.043(3)	0.054(3)	0.059(3)	0.020(3)	0.024(3)	0.003(3)
C(13)	0.030(3)	0.064(4)	0.058(3)	-0.003(3)	0.004(2)	-0.007(3)
C(14)	0.038(3)	0.042(3)	0.049(3)	-0.010(2)	0.015(2)	-0.001(2)
C(15)	0.037(2)	0.042(3)	0.034(2)	-0.003(2)	0.017(2)	0.001(2)
C(16)	0.059(3)	0.069(4)	0.033(3)	-0.009(3)	0.010(2)	0.003(3)
C(17)	0.049(3)	0.119(5)	0.039(3)	-0.021(4)	-0.004(2)	-0.011(3)
C(18)	0.081(4)	0.101(5)	0.051(3)	-0.050(4)	0.012(3)	-0.018(3)
C(19)	0.097(5)	0.057(4)	0.049(3)	-0.017(3)	0.026(3)	-0.020(3)
C(20)	0.086(4)	0.094(5)	0.035(3)	-0.027(4)	0.020(3)	-0.016(3)

The general temperature factor expression:

$$\exp(-2\pi^2(a^{*2}U_{11}h^2 + b^{*2}U_{22}k^2 + c^{*2}U_{33}l^2 + 2a^*b^*U_{12}hk + 2a^*c^*U_{13}hl + 2b^*c^*U_{23}kl))$$

Table 14: Anisotropic Displacement Parameters for Complex 68.