THE SYNTHESIS AND REACTIVITY OF
β-ARYL LIGNIN MODEL QUINONE METHIDES

A thesis submitted in partial fulfilment
of the requirements for the Degree

of

Doctor of Philosophy in Chemistry

at the

University of Waikato

by

RICHARD MICHAEL EDE

University of Waikato

1987

This thesis is dedicated to
my parents Trevor and Anne,
my sisters Jeanette and Alice,
and my wife Fiona

ABSTRACT

A range of 1,2-diarylpropane-1,3-diols and 2,3-dihydro-2-aryl-7-methoxy-benzofurans were synthesised as model compounds for the ß-5 (phenylcoumaran) structural unit found in wood lignin. The syntheses were performed following either established, or modifications of established procedures. Preliminary studies were carried out which showed the viability of a new general synthesis for ß-aryl lignin model compounds.

Phenylboronates of three of the 1,2-diarylpropane-1,3-diols were synthesised. The ^{1}H NMR coupling constants observed between the vicinal protons on the 6-membered ring confirmed the previously inferred erythro stereochemistry. Single crystal X-ray diffraction structures were obtained of 2,3-dihydro-2-(4-hydroxy-3-methoxyphenyl)-3-methyl-5-propyl-7-methoxybenzofuran and 1-(4-hydroxy-3-methoxyphenyl-2-(2,3-dimethoxyphenyl)-propane-1,3-diacetate.

Quinone methides (4-methylene-cyclohexa-2,5-dienones) derived from the ß-5 lignin model compounds were treated with anthranol (a reduced form of anthraquinone, AQ, found in soda-anthraquinone pulping liquors) to form a range of adducts. Anthrahydroquinone, the major catalytic species in the soda-AQ process, would not add to the quinone methides. The presence of erythro and threo isomers of the anthranol adducts was observed by ^{1}H and ^{13}C NMR, and in some cases a preparative chromatographic separation of the two

isomers was possible. The addition of anthranol to the quinone methides was shown to be reversible. The erythro adduct was found to be kinetically preferred, but over long reaction times, the threo isomer predominated. It was shown that for quinone methides possessing the ß-hydroxymethyl group, the retro-aldol elimination of formaldehyde to give stilbenes took precedence over adduct formation. Thus, stilbene formation was believed to be that which occurs for phenylcoumaran and ß-C-1 structures when reacted under soda-AQ pulping conditions, and the reactions of these structures would not contribute to delignification. Conversely, it was not expected that the phenylcoumaran and ß-C-1 structures would contribute to the loss of AQ from the process.

The stabilised quinone methides were characterised by ^{1}H and ^{13}C NMR. It was found that these and previously synthesised quinone methides derived from the ß-aryl ether lignin structure, existed in solution as a mixture of two isomers in a ratio of 2:1, SYN:ANTI. The preference for the formation of the SYN isomer was believed to be either product-controlled or from conformational equilibrium control in the transition-state leading to the quinone methide. It was found by a ^{1}H NMR method that the ANTI isomers of all the quinone methides studied reacted with amines approximately 40% faster than the SYN isomers. It was not possible to determine if this difference in reactivity would be exhibited by quinone methides reacted under pulping conditions.

ACKNOWLEDGEMENTS

First and foremost I must express my gratitude for the guidance and friendship of Dr John Ralph, previously of the Forest Research Institute, Rotorua, now Scientist-in-Charge, NMR Centre, University of Berkeley, California. He was responsible for the creation of an extremely interesting topic, he always showed unflagging enthusiasm even when I was barking up the wrong tree (puns intended), and he gave me as much access to the FRI Bruker AC200 NMR spectrometer as I wanted, as well as teaching me to run the instrument and sort out the 2D experiments. If Izaak Walton had written a book about him it would have been entitled "The Compleat Supervisor". I must also thank John and his wife Sally for the use of their home while they were overseas.

Thanks must also go to my two University of Waikato supervisors: Dr Lyndsay Main for his constant and extremely valuable input into the project and his assistance in liaising with the University, and Dr Alistair Wilkins for his initial efforts in developing a collaborative project between FRI and the University, which helped make this study a reality.

Dr Mervyn Uprichard was responsible for getting the project off the ground from the FRI end, and at times when it appeared the whole concept may have been in jeopardy, he and John pulled it through. Also, his kindness, and assistance and advice with editing will not be forgotten. Thanks also to Dr Terry Fullerton and Dr Ian Suckling (FRI) for many valuable discussions and for helpful editorial advice, Dr Larry Landucci (US Forest Products Laboratory, Madison, Wisconsin) and Dr Gösta Brunow (University of Helsinki) for some helpful comments in the early stages of the experimental work, Dr Brian Nicholson and Ralph Thomson (University of Waikato) for assistance with the crystal structures, and Dr C. Rickard (University of Auckland) for collection of the X-ray data. Dr P. Holland (Ruakura Soil and Plant Research Station) provided the high-resolution mass spectra.

Also thanks to Mr Nick Robinson (University of Waikato) for his gift of the ß-C-1 lignin model compound.

The other occupant of Room 462, Stage II, FRI, John Lloyd, deserves mention for his unfailing good humour, his archaic monstrosity of a fume-hood, and his in-depth analyses of the meaning of life, forthcoming on certain occasions at the Frestra Club.

Instrumentally I must thank Roger Meder for running NMR spectra, Dr Robert Franich and Hank Kroese for helping me run the mass spectrometer and Diane Steward for help with the G.C.

Thanks must go to the FRI Typing Section for three years of deciphering my handwriting, and especially to Adrienne Forbes for the excellent job she made of typing this thesis. Also thanks to the FRI Draughting Section for the publication diagrams.

Financially I acknowledge the assistance of the (now defunct) New Zealand Forest Service for providing the laboratory, the supervisor and the chemicals. I especially acknowledge Dr Colin Bassett, Chief Director of Research; Dr John Kininmonth, Regional Director of Research; and Dr John Butcher, Director, Wood Technology Division, for allowing this collaborative project to proceed. Thanks to the Pulp and Paper Research Organisation of New Zealand (PAPRO) and its Director, Professor Geoff Duffy; the Chemistry Department, University of Waikato; and the Royal Society of New Zealand (Young Scientists Fund Award) for assistance in attending the 1987 International Symposium on Wood and Pulping Chemistry in Paris.

I would also like to thank the people from FRI and Waikato University who made the life of a D.Phil. student that much more enjoyable, especially Dr David Coupland for sharing some atrocious golf, and the mighty FRESTRA Business House cricket team for letting me grace their side, even though I dropped catches, ran them out, bowled down leg-side, and drank Waikato.

Finally I thank my wife, Fiona, for her patience, understanding, concern (and shoulder massages) during the writing-up period.

TABLE OF CONTENTS

CHAPTER THREE

THE STEREOCHEMISTRY OF ß-5 LIGNIN MODEL COMPOUNDS

CHAPTER FOUR

REACTIONS OF ß-5 LIGNIN MODEL QUINONE METHIDES WITH ANTHRAHYDROQUINONE AND ANTHRANOL

CHAPTER FIVE

SYN AND ANTI LIGNIN MODEL QUINONE METHIDES: ASPECTS OF THEIR FORMATION, CHARACTERISATION AND DIFFERENTIAL REACTIVITY WITH AMINES

APPENDIX

LIST OF FIGURES

LIST OF TABLES

LIST OF REACTION SCHEMES

LIST OF ABBREVIATIONS

The following abbreviations have been used throughout this thesis.

Ac	acyl
OAc	acetate
AHQ	anthrahydroquinone
AQ	anthraquinone
Ar	aryl
Bz	benzyl
b.p.	boiling point
br	broad
DHP	dehydrogenation polymerisate
$CDCl_3$	deuterochloroform
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DEPT	distortionless enhancement by polarisation transfer
d	doublet
EI	electron impact
e	*erythro*
FT	fourier transform
FID	free induction decay
GC	gas chromatography
GC/MS	integrated gas chromatography/mass spectrometry
hr	hour
IR	infra-red
INEPT	insensitive nuclei enhancement by polarisation transfer
DMAP	4-dimethylaminopyridine
LAH	lithium aluminium hydride
T_2	longitudinal relaxation time
m/z	mass/charge ratio
MS	mass spectrometry
OMe	methoxyl
Me	methyl
m.p.	melting point

MWL	milled wood lignin
min.	minutes
NMR	nuclear magnetic resonance
ppm	parts per million
d_6-acetone	perdeuteroacetone
d_6-dmso	perdeuterodimethyl sulphoxide
pet. ether	petroleum ether
Ph	phenyl
plc	preparative layer chromatography
QM	quinone methide
q	quartet
s	singlet
sec.	second
S/N	signal-to-noise ratio
TBDMS	tertiary-butyldimethylsilyl
TMS	tetramethylsilane
T_1	spin-lattice relaxation time
tlc	thin layer chromatography
t	triplet or *threo*

CHAPTER 1

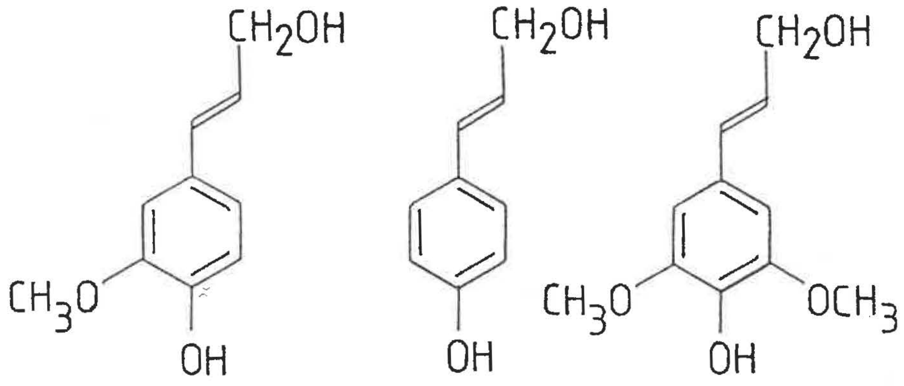
INTRODUCTION

1.1 LIGNIN

Reviews of the chemistry of wood in general and lignin in particular are many and varied, and rather than restate much of the information contained within them, the review below of lignin structure, formation, and reactivity, is selective rather than exhaustive. For more detailed information the reader is referred to the following: Harkin, 1967; Sarkanen, 1971; Adler, 1977; Sjostrom, 1981; Ralph, 1982; Ede, 1984; and Robinson, 1985.

Lignin is the term applied to the "encrusting material" (Payen, 1838) in which the cellulose fibres of a plant are imbedded. It is one of the world's most abundant natural products, comprising about 25% of the woody tissue in plants. The highest concentrations of lignin are found in the middle lamella of plant cells, but most of the lignin (about 70%) is located in the secondary cell wall.

Lignin has defied attempts to fully describe its structure for over 140 years, although modern techniques of isolation, purification, and characterisation, have improved the depth of understanding of lignin structure and reactivity. It is clear that lignin is an irregular cross-linked amorphous polymer of substituted phenylpropane units. The composition of lignin is species dependent, and there are three broad groupings of lignin types. Softwood lignins are almost entirely composed of coniferyl alcohol (guaiacyl) derivatives, combined with a small proportion of p-coumaryl alcohol units. It was thought that softwood lignin incorporated up to 5% sinapyl alcohol (syringyl) derivatives, but a recent study (Obst, 1986) has determined a very low maximum limit (<0.05%). Hardwood lignins consist of a co-polymer of coniferyl and sinapyl alcohols varying in composition from 4:1 to 1:2 guaiacyl-syringyl (Sjostrom, 1981). Grass lignins tend to incorporate p-coumaryl alcohol units. Little is known however, of the variations in composition which exist in the various morphological regions of the plant, although it is known, for example, (Sjostrom, 1981) that compression wood tends to contain more p-coumaryl alcohol structures than is average for the whole tree.



coniferyl alcohol (guaiacyl)

p-coumaryl alcohol (p-hydroxyphenyl)

sinapyl alcohol (syringyl)

Most of the information on lignin structure is obtained from degradative techniques applied to isolated lignin preparations. Two major approaches are used to obtain these "non-native" lignins:

- Cellulytic enzyme lignin (CEL) is isolated from extractive-free wood as insoluble material left after the hydrolytic removal of the polysaccharides.
- Extracted lignins from hydrolysis or extraction of the lignin can have structures extensively changed from native lignin. One such preparation however, milled wood lignin (MWL), is thought to be the isolated lignin preparation which most closely represents lignin as it occurs in nature. Even this preparation though, is thought to be of lower molecular weight than native lignin and can contain polysaccharides.

The degradation experiments on the lignin preparations give rise to a range of mono-, di-, and oligo-lignols, the structures of which provide information as to the arrangement and bonding of the phenylpropane units in the polymer. There is a vast body of results from these experiments which had led to the proposition of a range of structural schemes postulating the prominent structural features of the lignin polymer (e.g. Adler, 1977). A synopsis of the type and occurrence of common linkages in softwood lignin is shown in Table 1 and Figures 1 and 2.

Given the complexity of lignin structure and the difficulties pertaining to its characterisation, the body of knowledge about the formation of lignin is much less substantial. It is thought that the monomeric precursors are derived from glucose, which is

Table 1.1. Percentages of types of bonds connecting phenylpropane units in spruce (*Picea abies*) and birch (*Betula verrucosa*) MWL (Adler, 1977)

Bond type	Spruce (softwood)	Birch (Hardwood)		
		Guaiacyl	Syringyl	Total
A Arylglycerol-ß-aryl ether	48	22-28	34-39	60
B Glyceraldehyde-2-aryl ether	2			2
C Non-cyclic benzyl aryl ether	6-8			6-8
D Phenylcoumaran	9-12			6
E 2- or 6- condensed structures	2.5-3	1-1.5	0.5-1	1.5-2.5
F Biphenyl	9.5-11	4.5		4.5
G Diaryl ether	3.5-4	1	5.5	6.5
H 1,2-Diarylpropane	7			7
I ß-ß linked structures	2			2
	89.5-97			96.5-99.5

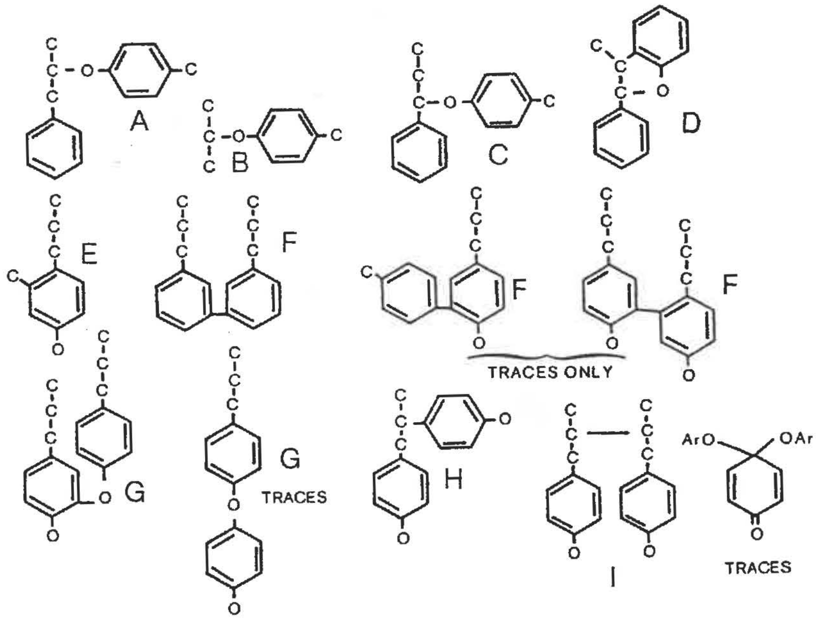


Figure 1.1 Predominant linkages between phenylpropane units (Adler, 1977)

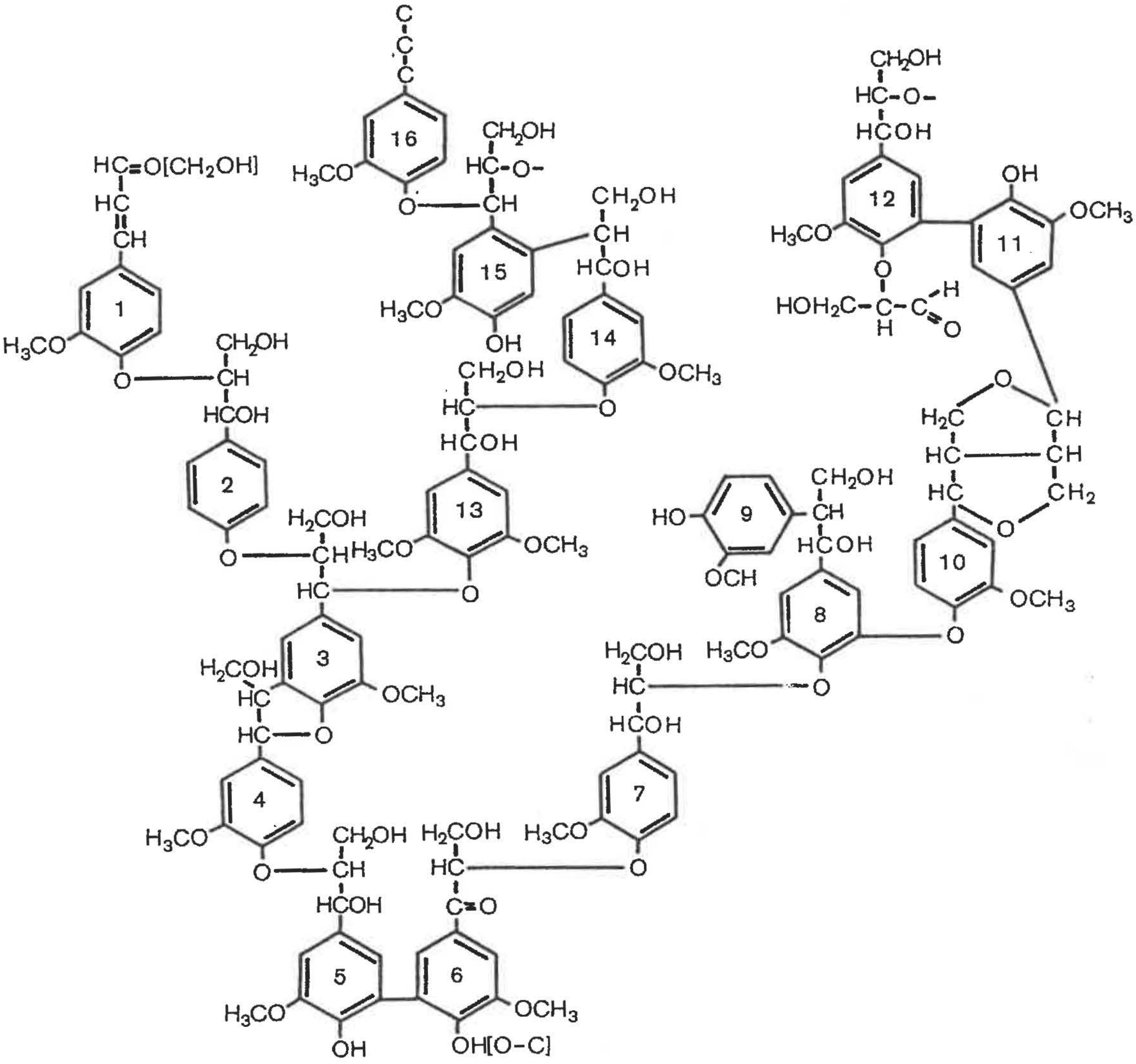


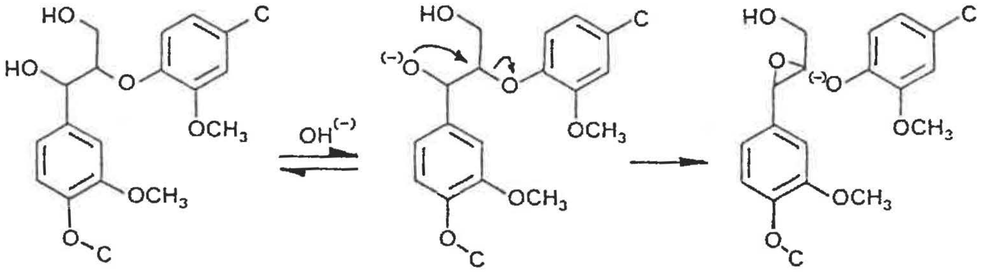
Figure 1.2 Prominent structures of softwood lignin comprising 16 phenylpropane units.

converted via shikimic acid to phenylalanine, from which the monomers are formed. The monomers are thought to exist in the cambial tissues as glucosides, and it has been shown that ^{14}C labelled coniferyl alcohol is incorporated by the plant into the lignin. The actual polymerisation is thought to be an enzyme-initiated dehydrogenative condensation of the allylic alcohol species. Transfer of $H^{\bullet}$ to the enzyme leads to the formation of a range of resonance stabilised phenoxy radicals which then appear to combine in an uncontrolled random fashion. Such condensations have been observed *in vitro* with the enzymatic dehydrogenation of coniferyl alcohol, and artificial lignin preparations, DHP lignin (Dehydrogenation polymerisate), have been isolated from these reactions with quite similar properties to MWL.

1.2 PULPING

Pulping is the process of removing the lignin from the wood or woody matter to leave the valuable cellulose fibres for conversion into a wide range of papers, cardboards, linerboards, fillers etc. The pulping industry is huge throughout the world, and a vast amount of research is devoted to the processes of removal of lignin from the wood in the most controlled and economically efficient manner. For the pulping industry by-and-large, lignin is seen as a nuisance; it has no major end use other than as a fuel to offset the energy requirements of a mill, it is often toxic (e.g. after chlorine bleaching), and has defied attempts at conversion to an economically viable source of useful chemicals for years.

Historically, lignin was removed from wood by reaction with caustic soda under elevated pressure and temperature (soda pulping). The phenolic nature of the lignin was such that fragments dissolved in the pulping liquor, and non-phenolic linkages could be cleaved by a variety of mechanisms (Miksche, 1980), the reaction contributing the most to delignification being the cleavage of the ß-aryl ether bond (Scheme 1).

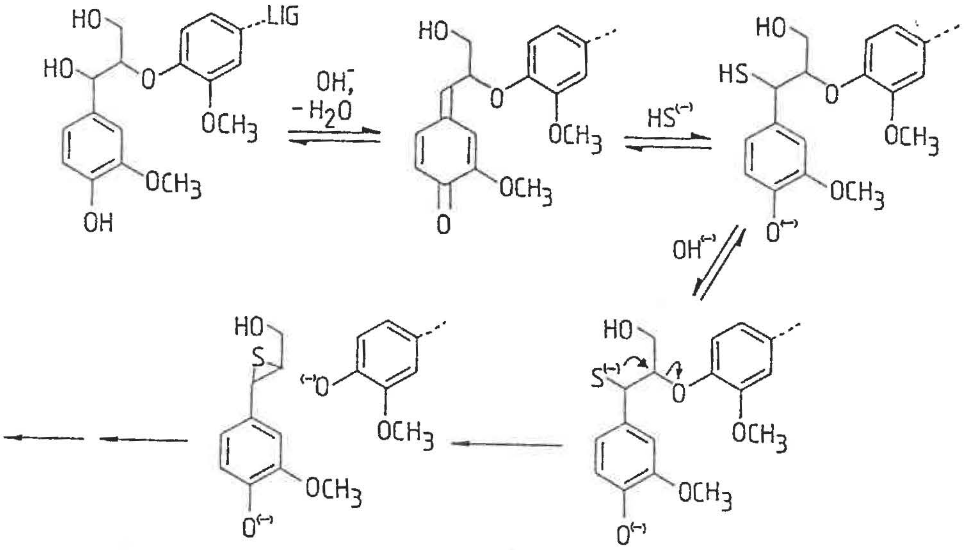


Scheme 1.1 ß-ether cleavage from etherified ß-ether moieties

A major breakthrough, and still the mainstay of the pulping industry, was the advent of the kraft process. The addition of Na_2S to a soda cook gave dramatically improved yields, pulp strengths, and pulp qualities compared to the soda process. The mechanism of kraft pulping is well understood: the HS^- (Scheme 2) species reacted through a different mechanism from the HO^- of the soda process, giving a large rate increase for the removal of lignin. This increase in rate meant that reaction times could be shortened. Hence the cellulose fibres were not exposed to high (1 mol l^{-1}) concentrations of NaOH for long periods, which caused degradation of the reactive end-groups of the polysaccharides, and consequently a lower pulp quality.

The complex, irregular, polymeric nature of lignin makes these studies on pulping mechanisms or indeed any lignin reaction difficult. As a result, lignin chemists often utilise low molecular weight monomeric or dimeric lignin model compounds which replicate, in part, a particular inter-unit linkage within the polymer. These compounds have the advantage of being much easier to manipulate and characterise than lignin, but conversely, results obtained do not necessarily reflect true lignin properties.

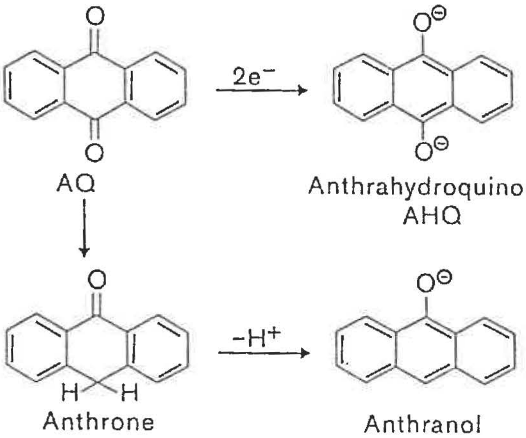
A whole range of chemical and semi-chemical pulping techniques have been developed and are applied world-wide to a limited extent which give rise to pulps of certain qualities for specific end-uses, but few have shown as much promise and attracted as much research interest as the soda-anthraquinone process discussed below.



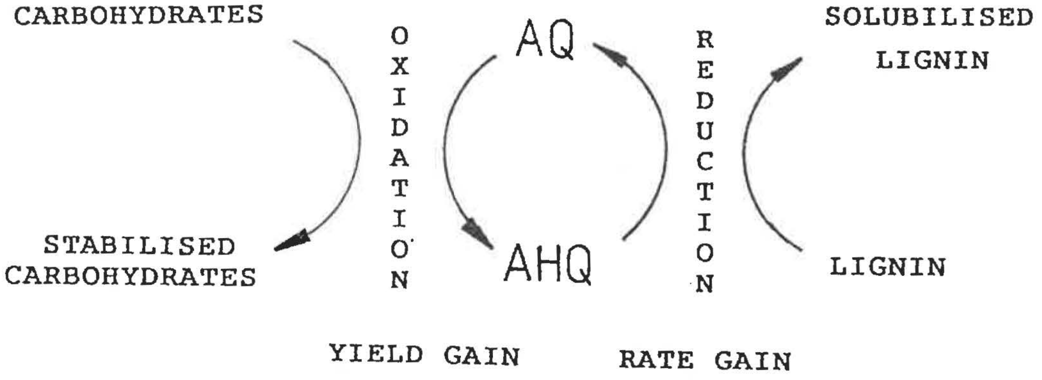
Scheme 1.2 ß-ether fragmentation from cleavage of ß-aryl ether quinone methides (kraft process).

1.3 AQ PULPING CHEMISTRY

In 1977, by a series of logical, yet fortunate steps, Holton (1977), noted the remarkable effect of anthraquinone on increasing the rate of alkaline delignification of wood. The soda-AQ process was seen to have great potential owing to the high activity of the catalyst (and hence the low loading required), the high yield of pulp obtained, and the minimal environmental effects compared to the frequently used kraft pulping process. There were major economic drawbacks however; anthraquinone was expensive, it was not fully recoverable from the pulping cooks and the resulting pulp was not as strong as a kraft pulp. These factors kept anthraquinone from replacing the sulphur-based catalysts which had been a mainstay of the pulping industry for over a century. Used in association with sulphur catalysts in the form of AQ/kraft and neutral sulphite/AQ (NS/AQ) pulping, AQ has become a very viable additive, but at the expense of its value as a more environmentally aesthetic process.



The potential benefits of the soda-AQ process have stimulated much research into the *modus operandi* of AQ in alkaline delignification, with a view to modifying the process to enhance its economic viability. Although no major breakthroughs have been established in modifying the performance of AQ, it is no coincidence that a resurgence in lignin chemistry, aided by modern instrumental techniques, had occurred in parallel with the discovery of the unusual catalytic effect of AQ.

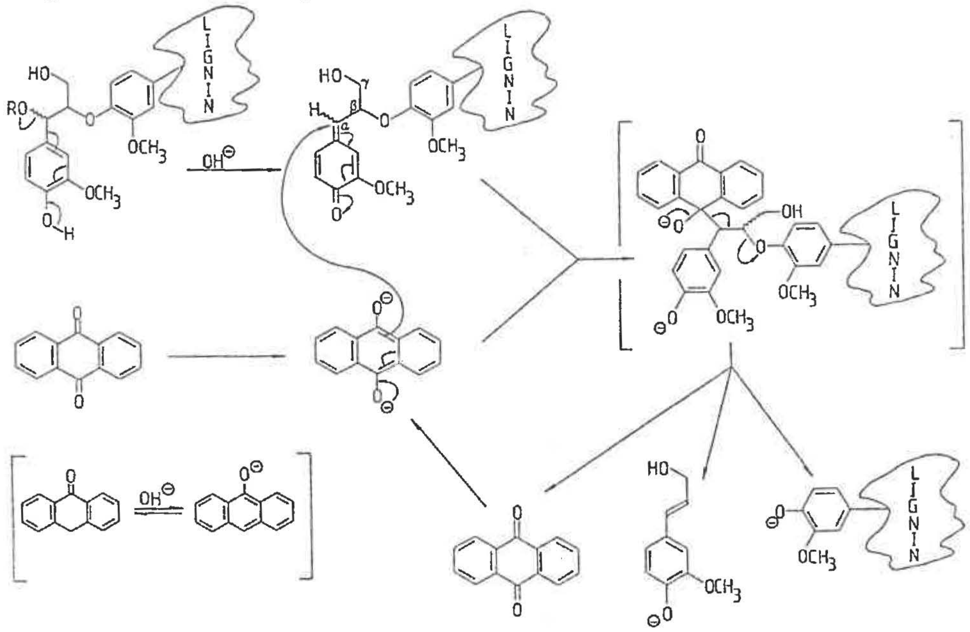


Scheme 1.3. Catalytic redox cycle of AQ in soda-AQ pulping (Fleming, 1978).

A commonly cited cyclic scheme (Fleming, 1978) has been put forward to describe the catalytic mechanism of lignin cleavage by AQ, but this uninformative scheme details none of the chemistry involved (Scheme 3). The effectiveness of AQ is known to be two-fold; it promotes the cleavage of ß-ether linkages in the lignin, thereby increasing the rate of delignification, and oxidises the reducing end groups of the carbohydrates, stabilising them with respect to the cellulose-destructive end-wise peeling reaction (Lowendahl, 1977, 1978). Most of the research on the AQ pulping mechanism has centred on its lignin cleavage reactions and two conflicting mechanisms have evolved that account for the enhanced cleavage of the ß-aryl ether linkage (accounting for up to 50% of the intermonomer lignin bonds) but neither is conclusive. Both mechanisms invoke the participation of quinone methides as the key lignin intermediates, and reduced forms of AQ as the active catalytic species, and both studies have utilised lignin model compounds as aids to elucidating the mechanisms. The adduct mechanism (Landucci, 1978) requires bond formation between a reduced AQ species, anthrahydroquinone, and the ß-ether quinone methide to give an intermediate adduct. This adduct subsequently undergoes a Grob fragmentation to cleave the lignin unit and regenerate AQ (Scheme 4). However, more than one reduced AQ species is known to be catalytic. Anthranol (the base-stable enol tautomer of anthrone) also adds to ß-ether QMs, and does so faster than AHQ. The adducts obtained however cannot undergo the same Grob fragmentation as the AQ adducts. AHQ and anthranol have been shown to cleave ß-ether linkages at similar rates (Poppius, 1985b), although the mechanism of anthrone adduct fragmentation is unclear. The adduct mechanism has some attractive features; it is analogous to the well established mechanism of HS^- accelerated cleavage of ß-ether linkages in the kraft process, and adducts between ^{13}C labelled anthrone and acetylated MWL have been observed *in situ* in the polymer (Landucci, 1978; Ralph, 1986a).

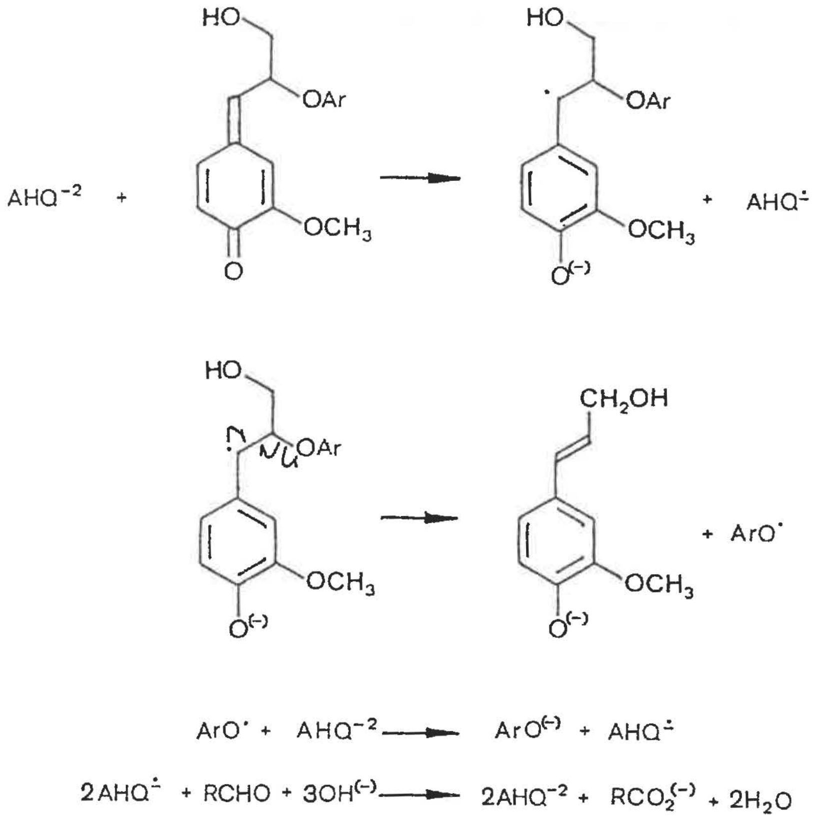
The single electron transfer (SET) mechanism (Dimmel, 1985a) involves transfer of an electron from AHQ^{2-} or $AHQ^{\dot{-}}$ to the quinone methide which then fragments (Scheme 5). The formation of $AHQ^{\dot{-}}$ (Hocking, 1980) has been observed during pulping and cyclic voltammetry (in organic solvents) has indicated the occurrence of SET leading to QM fragmentation (Dimmel, 1985b).

It is unlikely that either mechanism will ever be proved as adduct formation (or SET) is not thought to be the rate determining step in soda-AQ pulping. Attempts to prove the SET mechanism and disprove the adduct mechanism by a study of steric (Dimmel, 1986) effects on the reactions of QMs and reduced AQ species have been inconclusive at best, as it is well established that QM formation is the slow step in the process, masking any other effects from subsequent faster steps.



Scheme 1.4 Adduct mechanism accounting for the catalytic cleavage of ß-ether linkages Ralph 1986).

Even if one or other of these mechanisms is eventually proven, the "redox-cycle" is still incomplete. Some important questions still remain: for example, what happens to the rest of the AQ? Studies with ^{14}C labelled AQ show that up to 18% of the catalyst remains unrecovered in the pulp (Faix, 1980). A range of reduced AQ derivatives have been extracted from pulps and black liquors (Gourang, 1979), but it appears that most of the AQ (60%) remains irreversibly bound to the soluble lignin fragments in the black liquor, 20% is recovered as free AQ, and 15% recovered as extractable derivatives (Algar, 1979).



Scheme 1.5. SET mechanism accounting for the cleavage of ß-ether linkages (Dimmel, 1985a).

Also of interest is the role of AQ, not in promoting lignin cleavage reactions, but in preventing lignin condensation reactions. Recently, Fullerton (1986) has shown that under alkaline pulping conditions both AQ and HS$^-$ afford a decrease in the formation of alkali-stable carbon-carbon bonded products, which could contribute to relignification, and hence a slower pulping rate.

Another major area of interest, and one which has been largely unexplored, is the topic of this thesis. The reactions of the two next most abundant lignin inter-units, the phenylcoumaran and ß-C-1 linkages (accounting for up to 20% of the lignin polymer) with AQ and its derivatives have not yet been studied. The overall aim of this thesis is to fully characterise quinone methides of ß-C linked lignin model compounds and to determine if quinone methides of the ß-C linked lignin model compounds react with reduced forms of AQ either by forming adducts which then fragment, enhancing delignification; or if the reactions of these QMs with the AQ species contribute to the loss of AQ from the pulping cycle as alluded to previously (Landucci, 1984).

The first step in a study of this type is obtaining a range of suitable model compounds. Chapter 2 of this thesis evaluates a range of synthetic routes to lignin model compounds representing phenylcoumaran (ß-C-5), 1,2-diarylpropane-1,3-diol (ß-C-1) and pinoresinol (ß-ß) lignin sub-units, including a preliminary investigation into a new general synthesis of ß-C-5 and ß-C-1 lignin model compounds.

Chapter 3 details the characterisation of the stereochemistry of some of the compounds synthesised in Chapter 2, including the X-ray crystallographic structures of two ß-C-5 lignin model compounds.

The reactions of the quinone methides of the phenylcourmaran lignin model compounds with AHQ and anthranol is discussed in Chapter 4. The reactions of the ß-C-1 QMs with AHQ/anthranol was the subject of a MSc thesis carried out in conjunction with this study (Robinson, 1985).

Chapter 5 describes the full characteristion by NMR of the new ß-C-linked quinone methides and examines further aspects of the formation and reactivity of lignin model quinone methides in general.

CHAPTER 2

LIGNIN MODEL SYNTHESES

2.1 INTRODUCTION

Studies on the reactions of lignin in alkaline pulping processes have relied mainly on the use of low molecular weight model compounds replicating a partial lignin structural unit. These lignin model compounds can be manipulated and characterised more easily than native lignin and are of real value to the lignin chemist, especially if their syntheses are not too time consuming.

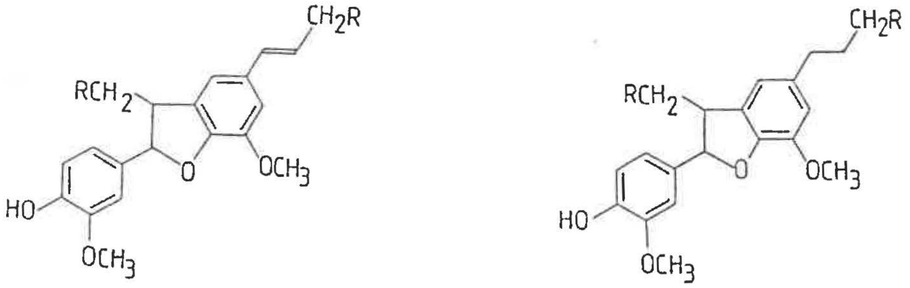
It should be noted however, that the structural diversity of lignin is such that no single compound could possibly serve as a universal lignin model, hence the extensive range of model compounds available for the different lignin sub-units. Also important is that the lignin model compound used in any study should be appropriate for that study. For example, there are many instances in the literature where studies have been carried out on model compounds not possessing the ß-CH_2OH group but it has been shown that this functionality plays a key role in many lignin reactions.

Footnote: For convenience, a series of fold-out sheets (at the rear of this thesis) are included with structures of the compound numbers referred to in each of Chapters 2 - 5.

There are many synthetic routes to the whole range of lignin model compounds, and it is the synthesis of ß-carbon linked model compounds that have been evaluated in this chapter.

2.1.1 Phenylcoumaran Syntheses

Until recently, the only commonly available model compounds replicating the phenylcoumaran linkage were dehydrodiisoeugenol 1 and dehydrodiconiferyl alcohol 5 (see Figure 1). Compound 1 was synthesised by the $FeCl_3$ initiated oxidative coupling of isoeugenol (Leopold, 1950), and 5 was formed from either an enzyme catalysed dehydrogenative coupling of coniferyl alcohol 4 (Freudenberg, 1952; Katayama, 1978), which lacked any synthetic control over the product yield and substitution, or through a multi-step organic synthesis (Nakatsubo, 1979), which was elegant but time-consuming. Compounds 1 and 5 have the added disadvantage of containing a non-representative vinylic side-chain which can pose complications in any reactivity studies, and compound 1 has a ß-CH_3 rather than the more representative ß-CH_2OH substituent found in native lignin structures. The vinylic side-chain in these models can easily be hydrogenated to give models 6 and 7.



1 R = H
5 R = OH

6 R = H
7 R = OH

Figure 2.1. Commonly available phenylcoumaran model compounds.

Recently, a synthetic route to a phenylcoumaran lignin model compound 24 (see Scheme 1) has been reported (Brunow, 1984). This method involved a $BF_3.Et_2O$ catalysed rearrangement of chalcone epoxide 15 as the key step, with subsequent $NaBH_4$ reduction giving rise to a 38% yield of a ß-5 lignin model 17, which can be deprotected and dehydrated to give the phenylcoumaran 24.

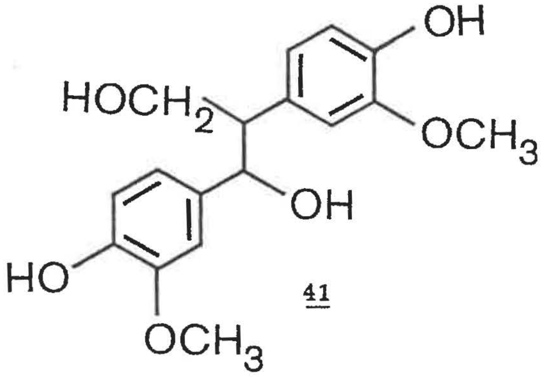
In the course of our studies, it was necessary to synthesise a model compound corresponding to a ß-5 model in which the 4'-OH group was protected to prevent an internal cyclisation to the phenylcoumaran. Compound 26 was obtained from a modification of the synthesis of 24 (Scheme 1).

2.1.2 Pinoresinol syntheses

At least four methods for the formation of d,l-pinoresinol 37 have been reported in the literature. Two (Freudenberg, 1953; Kratzl, 1963) require a catalysed coupling of monomeric precursors, while the previously discussed enzymatic condensation of coniferyl alcohol 4 (Katayama, 1978) affords d,l-pinoresinol as one of the products. A rational, high-yield synthesis (Fujimoto, 1982) has also been reported. This route has the advantage that pinoresinol derivatives can be prepared with different substituents on the 2 aromatic rings. The synthesis of pinoresinol by the method of Freudenberg (1953), including some attempted modifications, is discussed below.

2.1.3 ß-C-1 Syntheses

The most commonly available ß-C-1 model, 1,2-bis(4-hydroxy-3-methoxyphenyl)-propane-1,3-diol 41, has been synthesised by a range of methods (Brezny, 1977; Kristersson, 1980; Berndtsson, 1980; Brunow, 1981b; Nonni, 1982; Ahvonen, 1983; Chen, 1985). While 41 has been isolated in many instances as a lignin degradation product (e.g. Sarkanen, 1971), and is easily synthesised, it is unlikely to exist in native lignin as a dimer unattached to the lignin molecule. More representative structures would be etherified at the A4 or B4 positions as in e.g. 50. ß-C-1 model compounds with non-equivalent A and B rings have been synthesised in varying yields and degrees of difficulty (Nakatsubo, 1975; Brezny, 1977; Kristersson, 1980; Nonni, 1982; Ahvonen, 1983; Chen, 1985; Robinson, 1985; Ralph 1987a).



41

All the ß-C-1 models synthesised have possessed either the ß-CH_2OH substituent or a synthetic equivalent of this group. As yet there are no ß-C-1 model compounds available with other ß-substituents such as H or CH_3 groups. Although not representative of native lignin, models possessing such substitution are as valid as the commonly used ß-ether models 1-(4-hydroxy-3-

methoxyphenyl)-2-(2-methoxyphenoxy)-ethan-1-ol (guaiacylglycol-ß-guaiacyl ether), and 1-(4-hydroxy-3-methoxyphenyl)-2-(2-methoxyphenoxy)-propan-1-ol.

Preliminary investigations into the syntheses of a range of new ß-aryl model compounds which can possess a range of ß-substituents are discussed below.

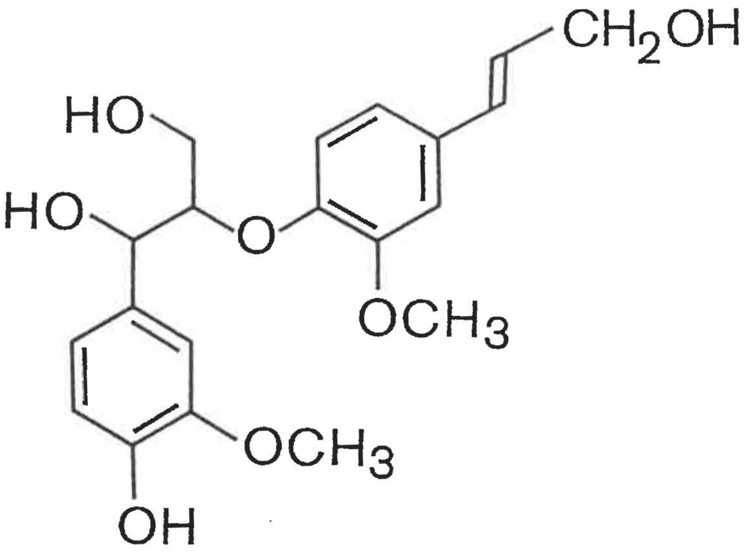
2.2 RESULTS AND DISCUSSION

2.2.1 Phenylcoumaran syntheses

The synthesis of dehydrodiisoeugenol 1, by the method of Leopold (1950) gave the required product in 50% yield. Hydrogenation with Pd/C catalyst in methanol gave 95% 6 (Aulin-Erdtman, 1942). Large (gram) quantities of these two compounds could be prepared easily and rapidly.

The synthesis of dehydrodiconiferyl alcohol by the enzymatic condensation method of Katayama (1978) required gram quantities of coniferyl alcohol 4. This compound is expensive to purchase and is sensitive to light, heat, and oxygen, and hence is best used soon after it is prepared. Coniferyl alcohol has been synthesised from a LAH reduction of ethyl ferulate obtained from the Claisen condensation of vanillin and monoethyl malonate (Freudenberg, 1952). However, as we had a supply of commercial ferulic acid 2 available, a simpler route was chosen involving the methylation of ferulic acid 2 with MeOH/acetyl chloride (Fieser, 1967) to give methyl ferulate 3, followed by LAH reduction to give 4.

The peroxidase/H_2O_2 dimerisation of coniferyl alcohol 4 has been reported to give three lignin model compounds in reasonable yields (Katayama, 1978): d,l-pinoresinol 37 (10%), dehydrodiconiferyl alcohol 5 (24%) and guaiacylglycerol-ß-coniferyl ether (20%). The success of the reaction appears to be tied to the activity of the enzyme. Katayama (1978) reported that using peroxidase of 58.8 unit/mg, the coniferyl alcohol was consumed within 3 hours. However, on carrying out a scaled-down preparation with 90 unit/mg peroxidase, it was 7 hours before the coniferyl alcohol was consumed, as monitored by tlc. ^1H NMR of the product showed that although small quantities of the required product were present, a degree of oligo- or polymerisation had occurred, as evidenced by the broadening of the signals. The mixture would have required multiple elution preparative chromatography to obtain any of the required products. This method of obtaining a phenylcoumaran model was not pursued further.

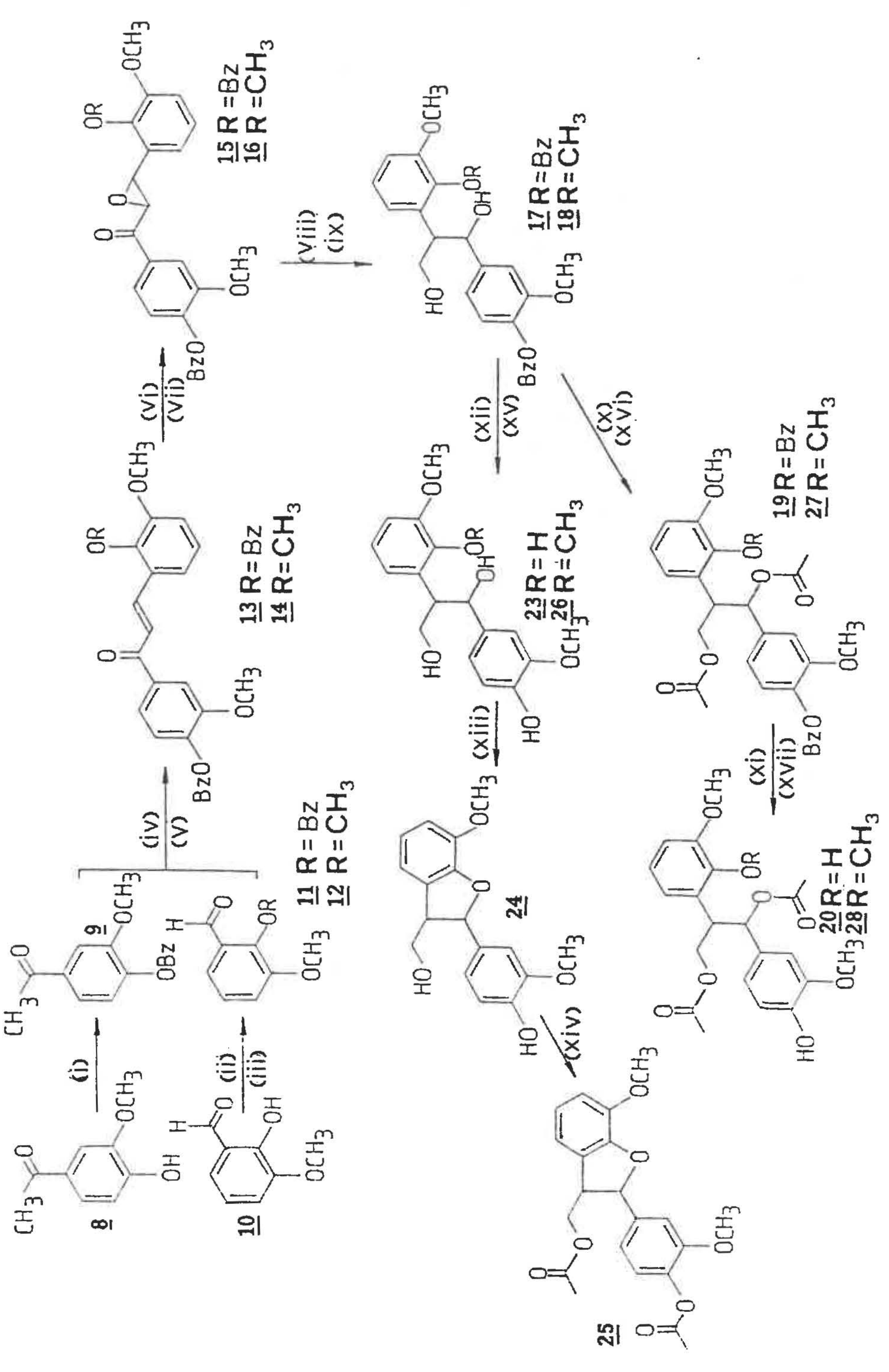


guaiacyl glycerol-ß-coniferyl ether

At the time this work was being carried out, Brunow and Lundquist (1984) published their synthesis of compound 24. This simple, yet versatile synthesis is a modification of a route to ß-C-1 model compounds (Kristersson, 1980) and with some modifications gave us a range of useful model compounds (Scheme 1).

The benzylation of acetovanillone 8 and o-vanillin 10 was carried out by a heterogeneous method, rather than the phase-transfer method of Brunow. The condensation of 9 and 11 to give the chalcone 13 proceeded in high yield. It was necessary to use equimolar quantities of 9 and 11, as chromatographic separation of the product from starting materials would have been difficult, owing to their similar tlc R_fs. The required phase-transfer catalyst for the oxidation of chalcone 13, tetrabutylammonium hydrogen sulphate, was obtained by reaction of tetrabutylammonium hydroxide with an equimolar quantity of sulphuric acid and the oxidation of chalcone 13 by the method of Brunow proceeded in high yield. Attempts to use other methods gave none of the required epoxide. The oxidation of chalcone 14 to the chalcone epoxide 16 was achieved in high yield with 1:1 5% aqueous NaOCl:pyridine (Marmor, 1963) rather than the method involving alkaline hydrogen peroxide in a phase transfer system (Brunow, 1984).

The $BF_3.Et_2O$ rearrangement of epoxides 15 and 16 required dry reagents and solvent, as any traces of water in the reaction resulted in very low yields of the rearranged product. Care had to be taken to neutralise the reaction mixture to pH 7 after the borohydride reduction (Brunow, 1985), as degradation of 17 and 18 occurred in acidic conditions.



(i) K_2CO_3/KI/$PhCH_2Cl$, $Me_2C=O$, 96%; (ii) 11: K_2CO_3/KI/$PhCH_2Cl$, $Me_2C=O$; (iii) 12: Me_2SO_4/NaOH/H_2O, 55%; (iv) 13: KOH, EtOH, 86%; (v) 14: KOH, EtOH, 76%; (vi) 15: H_2O_2/NaOH/Bu_4NHSO_4, 100%; (vii) 16: NaOCl/pyridine, 76%; (viii) 17: $BF_3.Et_2O$, Et_2O, 35%; (ix) 18: $BF_3.Et_2O$, Et_2O, 61%; (x) 19: Ac_2O/pyridine; (xi) 20: Pd/C/H_2, MeOH, 100%; (xii) 23: Pd/C/H_2, MeOH; (xiii) HCl, $CHCl_3$, 100%; (xiv) Ac_2O/pyridine, 94%; (xv) 26: Pd/C/H_2, MeOH, 95%; (xvi) 27: Ac_2O/pyridine, 94%; (xvii) 28: Pd/C/H_2, MeOH, 100%

Scheme 2.1. Synthetic route to β-5 model compounds

The best yield of 17 was 35% (cf 38% of Brunow). The main by-product crystallised after purification (yield not recorded) and was shown to be fluorohydrin 21 (see Figure 2). The formation of fluorohydrins in $BF_3.Et_2O$ rearrangements has been reported previously (House, 1956).

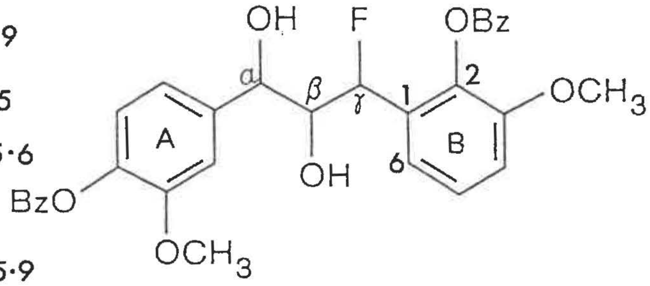
$^1H-^{19}F$/Hz

$^5J_{OH\alpha-F}$ = 0·9

$^4J_{OH\beta-F}$ = 1·5

$^3J_{\beta F}$ =25·6

$^2J_{\gamma F}$ = 45·9



$^{13}C-^{19}F$/Hz

$^3J_{\alpha F}$ = 4

$^2J_{\beta F}$ = 20

$^1J_{\gamma F}$ = 174

$^2J_{B1-F}$ = 22

$^3J_{B2-F}$ = 7

$^3J_{B6-F}$ = 9

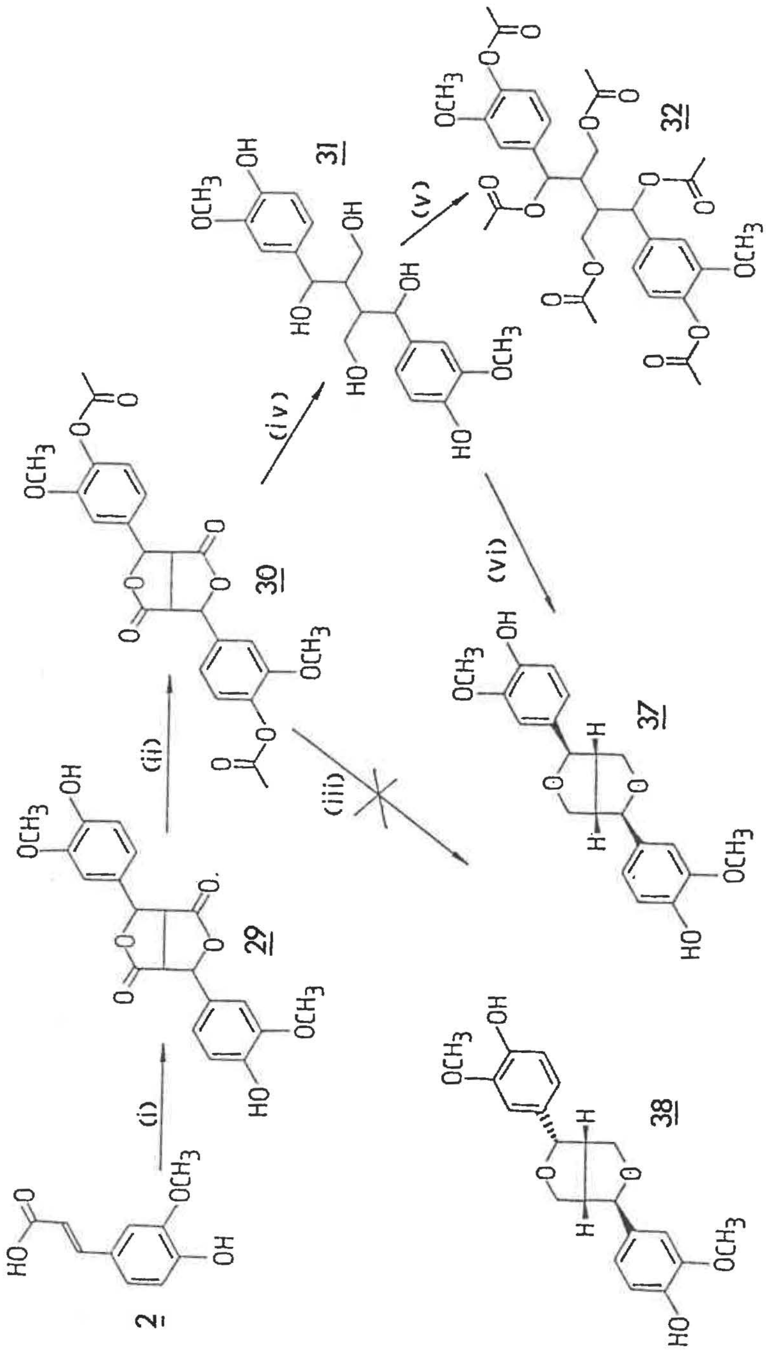
Figure 2.2 Fluorohydrin 21 isolated from synthesis of 17, with $^1H-^{19}F$ and $^{13}C-^{19}F$ NMR coupling constants.

Debenzylation of 17 in methanol afforded the non-cyclised precursor 23, rather than the phenylcoumaran 24 as reported by Brunow. Phenylcoumaran 24 was obtained by shaking a $CHCl_3$ solution of 23 with dilute aq. HCl. Acetylation of 17 and subsequent debenzylation gave compound 20.

The $BF_3.Et_2O$ rearrangement of chalcone epoxide 16 gave the required product 18 in 61% yield (after recrystallisation). No fluorohydrin was detected among the by-products. Debenzylation in the usual way gave the model compound 26 in good yield.

2.2.2 d,l-Pinoresinol Synthesis from Ferulic Acid

The key step in the method of Freudenberg (1953) was the $FeCl_3$- initiated radical dimerisation of ferulic acid 2 to give dehydrodiferulic acid 29 (Scheme 2). This step was low yield, but

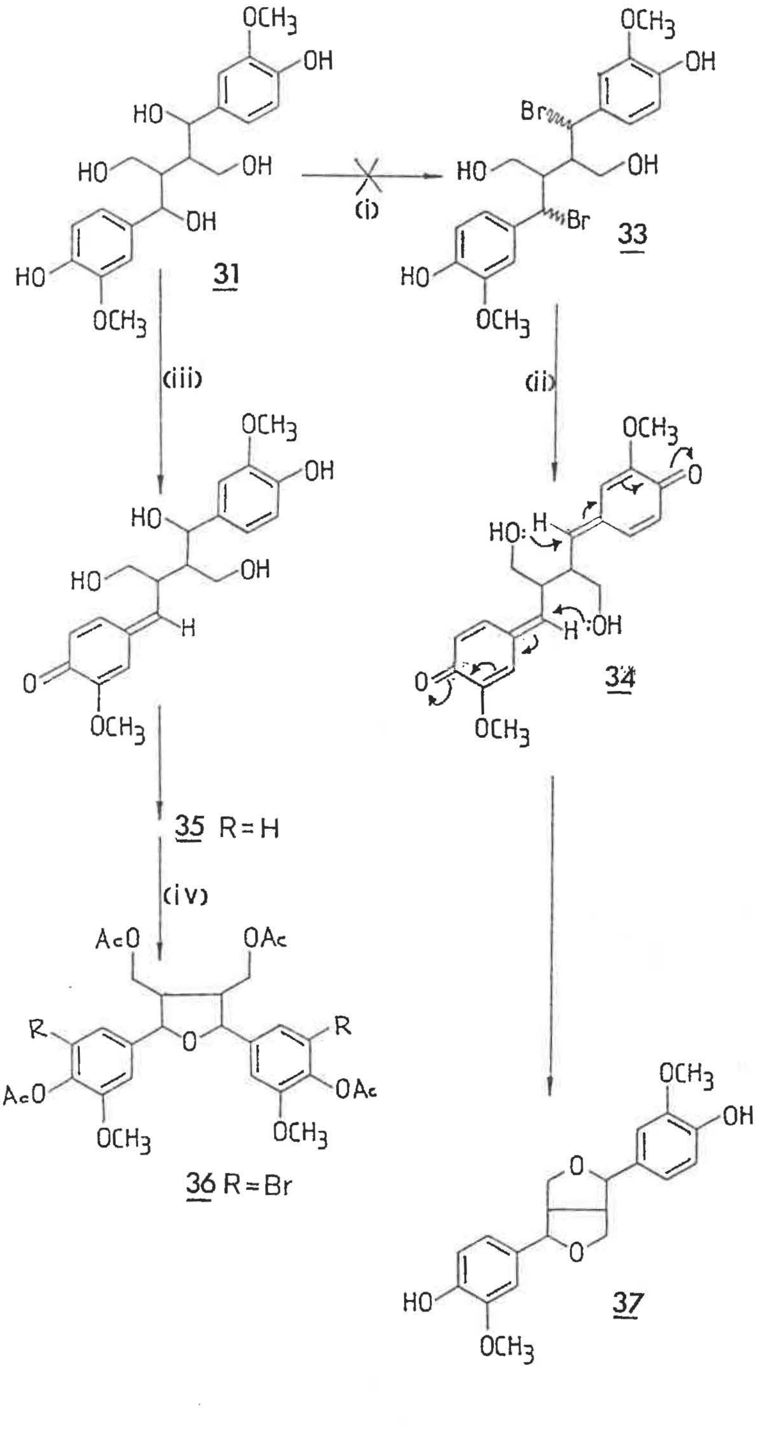


(i) $FeCl_3/O_2$, MeOH, 19%; (ii) Ac_2O/pyridine, 84%; (iii) BH_3.THF, THF or $BF_3.Et_2O/NaBH_4$; (iv) LAH, THF, 52%; (v) Ac_2O/pyridine, 88%; (vi) 0.5 mm Hg, 230-250 °C, 60% 37, 30% 38

Scheme 2.2. Synthesis of d,l-pinoresinol 37 the starting material was readily available. One problem with the synthesis was that the lactones in 29 must be reopened before the final product 37 was obtained, requiring three steps (acetylation, reduction and cyclisation) to accomplish a carbonyl reduction.

It had been reported (Pettit, 1961) that direct reduction of a lactone to a cyclic ether (without ring opening) was possible by reaction with $NaBH_4/BF_3.Et_2O$ (effectively "BH_3"). This method was tried on both the free phenolic and diacetylated lactones, 29 and 30, with both $NaBH_4/BF_3.Et_2O$ and BH_3.THF. The reaction between 30 and BH_3.THF appeared to proceed (as monitored by tlc) but it was not possible to isolate the required product from what was presumably an organoborane intermediate. This step was rejected as a possible simplification of the method.

The cyclisation of the hexol 31 was not trivial. Acid catalysed ring-closure results in observable yields of epipinoresinol 38 (Fujimoto, 1982). Some success had been obtained by reacting the dibenzyl tetrol with $BF_3.Et_2O$, but this reaction required that the phenols be protected, introducing another step into the reaction scheme (Fujimoto, 1982). Good yields for the cyclisation of 31 have been reported (Freudenberg, 1953) by molecular distillation, but this was counterbalanced by the low yield of 31 in the previous LAH reduction step. Assuming that the cyclisation proceeds via the p-diquinone methide 34, it was thought that reaction of the hexol with trimethylsilyl bromide (TMSBr) to form the benzyl bromide 33 (Ralph, 1983c), followed by quinone methide 34 formation (by reaction with aqueous $NaHCO_3$) and its subsequent cyclisation, may



(i) TMSBr, d_6-dmso; (ii) $NaHCO_3$; (iii) TMSBr, d_6-dmso;
(iv) (a) several days (b) Ac_2O/pyridine

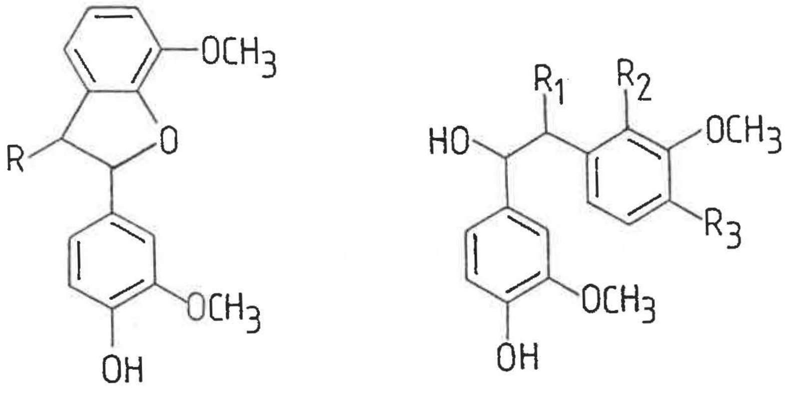
Scheme 2.3. Attempted formation of 37 via a quinone methide intermediate have proven to be a facile route to 37. Reaction of the hexol with TMSBr in dimethyl sulphoxide gave what appeared to be compound 35. This was likely to have resulted from quinone methide formation in half only of the hexol, with subsequent nucleophilic attack from the benzylic hydroxyl group. After a period of several days the compound was acetylated and it appeared that electrophilic aromatic substitution at C5 by free bromine in the reaction mixture had occurred at some stage to give 36 (see Scheme 3).

The cyclisation of 31 to give 37 was eventually accomplished by the previously reported method (Freudenberg, 1953). The distillation under vacuum of 0.5 mm Hg and a bath temperature of 230-250°C gave a mixture of 60% 37 and 30% 38. It is uncertain whether epipinoresinol, 38, is a true constituent of wood lignin, as it has been shown, for example (Harkin, 1967), that pinoresinol treated with acid (as in the lignin degradation experiments) gives epipinoresinol and it appears likely that the high yield of 38 was due to the high bath temperature required for the distillation of 31. It was not possible to carry out the distillation of 31 at the lower pressure (0.05 mmHg) and hence temperature (160-190°C) used by Freudenberg (1953).

2.2.3 Attempted ß-aryl Syntheses involving *Umpolung*

Two approaches were evaluated, both non-convergent, to the range of ß-C model compounds shown in Figure 3. The key step in both syntheses involved the acylation or alkylation of a 2-lithio-1,3-dithiane (Seebach, 1975).

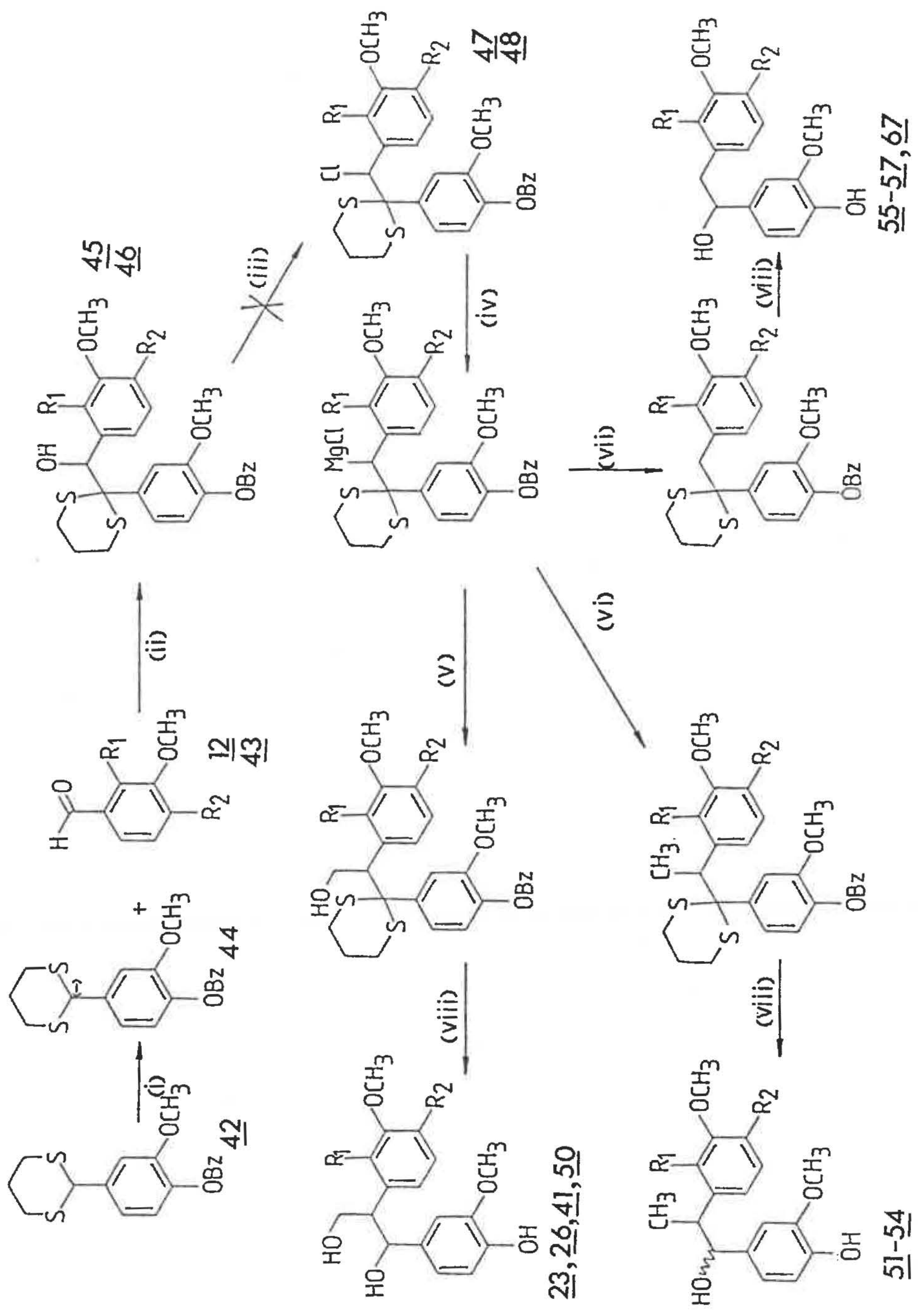
Abstraction of the benzylic proton from the dithiane 42 with n-BuLi in THF at -78°C gave a stabilised carbanion, and it was first envisaged that the addition of 2-(4-benzyloxy-3-methoxyphenyl)-2-lithio-1,3-dithiane 44 to a range of substituted benzaldehydes (Scheme 4) would provide useful precursor compounds to a range of ß-C-1 and ß-C-5 lignin models. In some preliminary attempts, the addition of 44 to 3,4-dimethoxybenzaldehyde 43 (veratraldehyde) and 2,3-dimethoxybenzaldehyde 12 proceeded smoothly and in high yield provided all reagents, solvents, and glassware were carefully dried. The protected ß-hydroxy ketones 45 and 46 crystallised from the unpurified product on trituration with ethanol.



	R
24	CH_2OH
69	H
70	CH_3

	R1	R2	R3
23	CH_2OH	OH	H
26	CH_2OH	OCH_3	H
41	CH_2OH	H	OH
50	CH_2OH	H	OCH_3
51	CH_3	OH	H
52	CH_3	OCH_3	H
53	CH_3	H	OH
54	CH_3	H	OCH_3
55	H	OH	H
56	H	OCH_3	H
57	H	H	OH
67	H	H	OCH_3

Figure 2.3. ß-C model compounds



n-BuLi, THF, -78°C; (ii) THF, -78°C; 45, 33%, 46, 64%; (iii) $SOCl_2$ or $SOCl_2/CHCl_3$ or $SOCl_2$/pyridine or CCl_4/PPh_3, Et_2O; (iv) Mg/Et_2O; (v) $CH_2=O$; (vi) MeI; (vii) H_2O; (viii) (a) HgO/$BF_3.Et_2O$, (b) Pd/C/H_2

Scheme 2.4. Attempted synthesis of β-C models involving addition of 44 to benzaldehyde derivatives

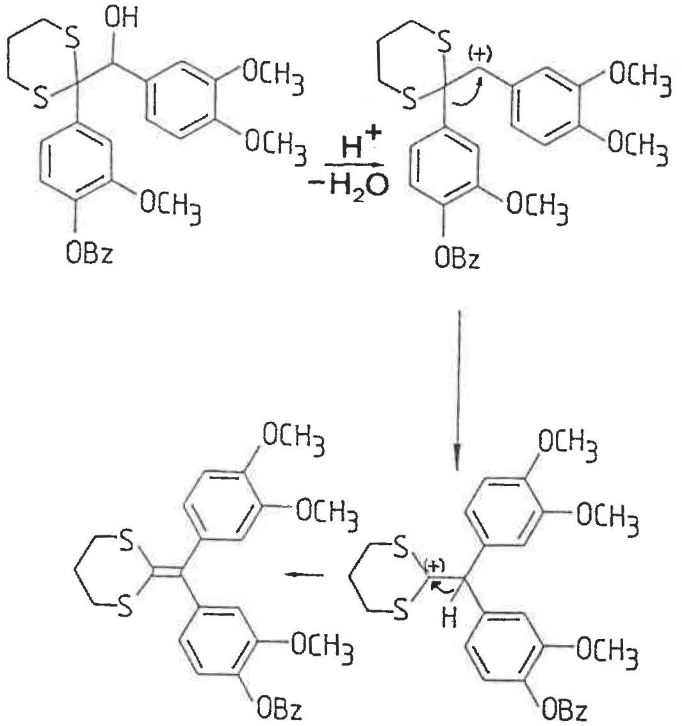
The next step in the synthesis, conversion of a benzyl alcohol to a benzyl halide, proved extremely difficult, and resulted in this method being discarded as a useful synthesis. A convenient reagent for displacement of alcohols by halides is thionyl chloride. However, reaction of 45 or 46 with neat $SOCl_2$, $SOCl_2$ in chloroform (Buehler, 1970), or $SOCl_2$/pyridine (Buehler, 1970) failed to give the required products 47 and 48. The reaction of 45 with neat $SOCl_2$ did result in halogenation, but at the expense of the loss of the dithiane protecting group, probably by reaction with the liberated HCl. Compound 49 was, however, unsuitable for further reaction as the carbonyl functionality would have created difficulties in the Grignard formation. The two other attempts with $SOCl_2$ ($SOCl_2/CHCl_3$ and $SOCl_2$/pyridine) in reaction with 45, resulted in the isolation of an unusual by-product 59, apparently resulting from aryl group migration. Compound 59 was identified by ^1H and ^{13}C NMR. A proposed mechanism for this reaction is shown in Scheme 5.

To overcome the problem of carbocation formation via acid catalysis, a milder halogenation method was evaluated, utilising PPh_3/CX_4, X = Cl or Br (Hooz, 1968). This method, involving several S_N2 displacements, supposedly gives non-acidic halogenation of alcohols by the following mechanism:

$$Ph_3P: + CX_4 \rightarrow Ph_3P^+{-}CX_3 + X^-$$

$$Ph_3P^+{-}CX_3 + R{-}OH \rightarrow Ph_3P^+{-}OR + HCX_3$$

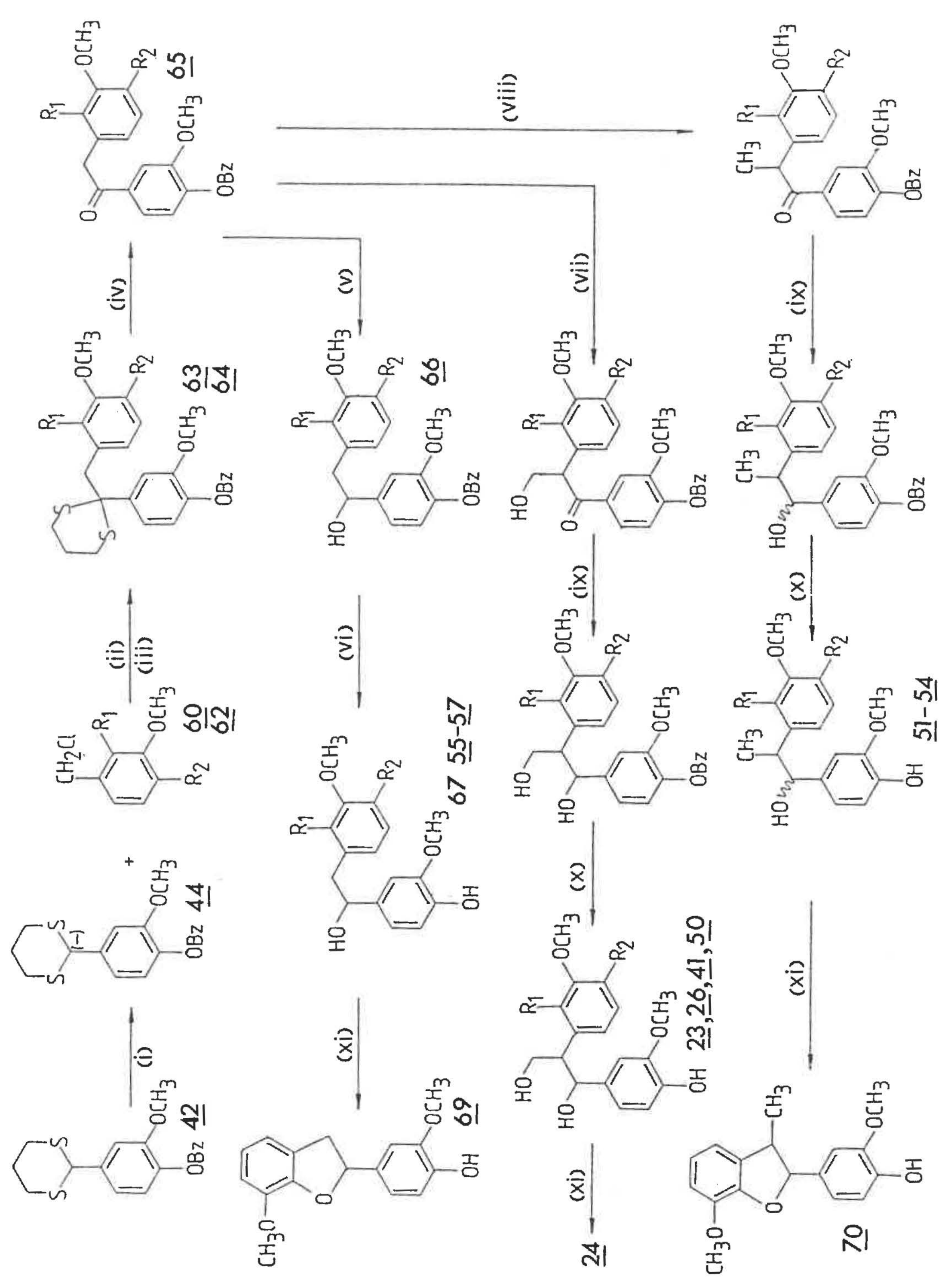
$$Ph_3P^+{-}O{-}R + X^- \rightarrow Ph_3P{=}O + R{-}X$$



Scheme 2.5. Mechanism for formation of 59

This method was limited to some extent by the solubility of the alcohol 45 in CCl_4, and also diethyl ether (for the reaction with CBr_4), but in all cases the only product obtained from the reaction was the rearranged compound 59. This route to the ß-C models was discarded.

An alternative route to the ß-C lignin model compounds appeared more promising. Addition of dithiane 44 to the substituted benzyl halides 60 and 62 (Scheme 6) gave up to 60% yields of the addition products 63 and 64. Deprotection of 63 by the method of Fujimoto (1982) gave the α-keto model 65, in quantitative yield. Reduction of 65 with $NaBH_4$ to give 66, followed by debenzylation gave a 90% yield of the ß-C-1 model 67. It was envisaged that similar



(i) n-BuLi, THF, -78°C; (ii) 63: THF, -78°C, 30%; (iii)64: THF, -78°C, 30%; (iv) HgO/$BF_3.Et_2O$, dioxane, 100%; (v) $NaBH_4$, EtOH, 100%; (vi) Pd/C/H_2, EtOH, 100%; (vii)CH_2=O, K_2CO_3, dmso; (viii) MeI, K_2CO_3, dmso; (ix) $NaBH_4$, EtOH; (x) Pd/C/H_2; (xi) HCl

Scheme 2.6. Route to ß-aryl lignin models involving additon of 44 to substituted benzyl chlorides.

reactions with suitably substituted precursors to give 55-57 would be equally successful. The phenylcoumaran model 70 would be obtained by reaction of 55 with dilute acid.

Aldolisation and alkylation of 68 proved to be difficult. Several methods were tried to accomplish the enol reactions, including $H_2C=O/K_2CO_3/EtOH$, $CH_3I/K_2CO_3/EtOH$, and $CH_3I/{}^tBuOK/{}^tBuOH$, but none of these methods gave the required product. Also attempted was the alkylation of the pyrollidine enamine with CH_3I in benzene (with and without catalysis by p-toluenesulphonic acid) under Dean-Stark reflux (Heyl, 1953).

It is likely however, that the alkylation would be accomplished by the method of Lundquist (1960). Subsequent to the completion of this work, it was found that the desoxybenzoin 1,2-bis(4-hydroxy-3-methoxyphenyl)-ethanone was alkylated by either formaldehyde or methyl iodide when reacted with K_2CO_3 in dimethylsulphoxide. It is envisaged that these methods, when applied to appropriately substituted ketones would give rise to the ß-C models 23, 26, 41, 50-54 and the phenylcoumarans 24 and 70.

2.3 EXPERIMENTAL

2.3.1 Spectroscopic Techniques

^1H NMR spectra for all compounds in this thesis were determined in $CDCl_3$, d_6-acetone, d_6-benzene, d_6-dimethyl sulphoxide or CCl_4 on a Varian T-60A CW, a JEOL FX90Q FT or a Bruker AC200 FT spectrometer, with Me_4Si as an internal reference. CW spectra were recorded with a sweep time of 250 seconds and a sweep width of 500 Hz. 90 MHz spectra were recorded with an 800 Hz spectral window and 8K data points resulting in J values accurate to 0.1 Hz. 200 MHz spectra were recorded with a 2500 Hz spectral window and 16K data points, resulting in J values accurate to 0.30 Hz (zero-filling to 32K data points resulted in J values accurate to 0.15 Hz). Commonly, Lorentzian-Gaussian resolution enhancement was applied to the 200 MHz spectra.

^{13}C NMR spectra were determined in $CDCl_3$, d_6-acetone, d_6-benzene or d_6-dimethyl sulphoxide on either a JEOL FX90Q FT spectrometer (operating at 22.5 MHz) or a Bruker AC200 FT spectrometer (operating at 50.1 MHz). 22.5 MHz spectra were obtained with broadband decoupling, while 50.1 MHz spectra were obtained with WATLZ-16 (Shaka, 1983) decoupling, to minimise dielectric heating and improve resolution and sensitivity. Assignment ambiguities were resolved where possible by either INEPT (Doddrell, 1980) pulse sequencing using $\tau = 1/4J$ and a delay $(\Delta) = 3/4J$ to give methylene resonance inversion and quaternary resonance suppression; or DEPT (Doddrell, 1982) pulse sequencing using $\theta = 135°$ to give methylene resonance inversion, or $\theta = 45°$ to give methine resonances only. Quaternary resonances were identified where necessary by the method of Bendall (1983).

For convenience, a tabulation of the assignments of a range of ^{13}C NMR shifts of lignin model compounds and precursors used in this thesis is included in the Appendix.

^{29}Si spectra were recorded on a Bruker AC200 FT spectrometer (operating at 39.8 MHz) using a broadband proton decoupled ^{29}Si DEPT (Doddrell, 1981, 1982) pulse sequence with 1/2J delays of 72 ms and a θ pulse of 17° (optimised). ^{29}Si-^{1}H coupling constants were determined from the ^{29}Si satellites in ^{1}H NMR spectra.

Mass spectra were obtained on a Hewlett-Packard HP 5985 spectrometer operating under EI ionisation with probe sample injection. Accelerating EMF was 70 eV and the inlet was heated from ambient temperature to 300°C at the rate of 28°C/min.

High resolution mass spectra were obtained on the Kratos instrument of the Ruakura Agricultural Research Centre.

2.3.2 Analytical Techniques

Tlc was carried out on silica gel coated glass or aluminium sheets. Plc was carried out on 1-mm silica gel coated glass plates. Flash column chromatography was carried out under the conditions optimised by Still (1978).

Unless otherwise stated, all compounds exhibited a single spot by analytical tlc (visualised by UV light or phosphomolybdic acid in ethanol).

Melting points (uncorrected) were obtained on a Reichert Thermopan hot-stage melting point apparatus.

2.3.3 General Synthetic Methods

Acetylations

The compound was dissolved in an excess of pyridine/acetic anhydride 1:1 and stirred overnight. The reaction mixture was then poured into H_2O, extracted with Et_2O or EtOAc, washed twice with 5% H_2SO_4, water, saturated $NaHCO_3$, and saturated NaCl. The organic layer was dried over anhydrous $MgSO_4$ and the solvent removed under reduced pressure.

$LiAlH_4$ Reductions

$LiAlH_4$ was added to anhydrous ether or THF. To this was added dropwise a solution of the compound to be reduced in anhydrous ether or THF. After reduction, the reaction was stopped by careful addition of THF/H_2O and the aluminium salts dispersed with saturated NH_4Cl for phenolics, or saturated potassium tartrate for non-phenolics. The mixture was extracted with Et_2O or EtOAc, washed with NH_4Cl or saturated sodium potassium tartrate, H_2O and saturated NaCl. The organic layer was dried over anhydrous $MgSO_4$ and the solvent removed under reduced pressure.

2.3.4 Synthetic Methods

Dehydrodiisoeugenol (1)

To a solution of isoeugenol (20 g, 0.12 mole) in ethanol (200 ml) and H_2O (80 ml) was added a freshly prepared solution of $FeCl_3.6H_2O$ (46.4 g, 0.17 mole) in H_2O (80 ml). The reaction mixture was stirred for a few minutes and seeded with a few crystals of 1. The reaction was left at 4°C for 24 hours during which time a pink solid precipitated. This was filtered and recrystallised from ethanol/H_2O (45%) to give 1 as off-white crystals (10 g, 50%).

^{1}H NMR (200 MHz, CDCl$_3$) δ: 1.40 (3H,d,J = 6.8 , Hγ), 1.88 (3H, dd, J = 6.0, 0.5, Hγ') 3.48 (1H, dq, J = 6.8, 8,8, Hβ), 3.88 (3H, s, OCH$_3$), 3.90 (3H, s, OCH$_3$), 5.11 (1H,d, J = 8.8, Hα), 5.67 (1H, s, ArOH), 6.11 (1H, dq, J = 16.2, 6.0, Hβ'), 6.37 (1H, dd, J = 16.2, 0.5, Hα'), 6.7-7.0 (5H, m. ArH).

^{13}C NMR (50 MHz, CDCl$_3$) δ:17.8 (Cγ), 18.3 (Cγ'), 45.6 (Cβ), 55.9 (OCH$_3$), 93.7 (Cα), 109.0 (A2), 109.4 (B2), 113.4 (B6), 114.2 (A5), 119.9 (A6), 123.4 (Cβ'), 131.0 (Cα'), 132.0 (A1), 132.1 (B1), 133.3 (B5), 144.1 (B3), 145.8 (A4), 146.6 (B4), 146.7 (A3).

Methyl ferulate (3)

Ferulic acid 2 (50 g, 0.257 mole) was dissolved in methanol (500 ml). To this was added acetyl chloride (25 ml, 0.32 mole) and the mixture stirred for 30 hours. The solvent was removed under reduced pressure to give 3 as a clear yellow oil (53.5 g, 100%).

^{1}H NMR (200 MHz, CDCl$_3$) δ: 3.38 (3H, s, OCH$_3$), 3.90 (3H, S, OCH$_3$), 5.99 (1H, br s, ArOH), 6.28, (1H, d, J = 16.0 H), 6.90 (1H, d, J_{56} = 8.1, H5), 7.01 (1H, d, J_{26} = 1.8, H2), 7.06 (1H, dd, J_{56} = 8.1, J_{26} = 1.8, H$_6$), 7.60 (1H, d, J = 16.0, Hα).

^{13}C NMR (50 MHz, CDCl$_3$) δ: 51.6 (OCH$_3$), 51.6 (COOCH$_3$), 109.5 (C2), 114.8 (C6), 115.2 (C5), 123.0 (Cβ), 127.0 (C1), 125.0 (Cα), 146.7 (C4), 148.1 (C3), 167.7 (Cγ).

Coniferyl alcohol (4)

Methyl ferulate 3 (8.76 g, 0.042 mole) in anhydrous THF (60 ml) was added dropwise to a stirred solution of LAH (3.19 g, 0.084 mole) in anhydrous THF (60 ml) in the usual way. The reaction was stopped and worked up in the normal manner to give coniferyl alcohol 4 as a clear colourless oil (7.2 g, 95%). This was compared with an authentic sample, and shown to be identical by co-tlc and ^{1}H NMR.

Attempted enzymatic synthesis of dehydrodiconiferyl alcohol (5)

Coniferyl alcohol 4 (6.75 g, 0.038 mole) was dissolved in acetone (27 ml) and gradually added to H_2O (675 ml) with stirring. Peroxidase (90 units/mg, 3.6 mg) in H_2O (27 ml) was added rapidly with vigorous stirring. The resulting milky yellow solution was stirred at room temperature until the coniferyl alcohol was consumed (monitored by tlc). After 7 hours the reaction mixture was extracted wth chloroform, the aqueous layer saturated with NaCl and extracted 4 times with $CHCl_3$. The combined fractions were dried over anhydrous $MgSO_4$ and the solvent removed under reduced pressure to give a yellow/brown oil (6.1 g). NMR analysis showed the mixture to be primarily a polymeric mixture and no attempt was made to purify the products.

Dehydrodihydrodiisoeugenol (6)

Dehydrodiisoeugenol 1 (1.0 g, 3.07 mmole) was dissolved in methanol (50 ml). To this was added 5% Pd/C (2.5 mg) and the mixture was stirred under H_2 for 30 minutes. Workup gave 6 as a clear, colourless oil (1.0 g, 99%). This was crystallised from pet. ether (100-120°C) to give 6 as white needles m.p. 89-91°C.

^{1}H NMR (200 MHz, $CDCl_3$) δ: 0.97 (3H, t, J = 7.4, Hγ'), 1.37 (3H, d, J = 6.8, Hγ), 1.65 (2H, m, Hβ'), 2.56 (2H, dd, J = 8.0, J = 7.4 Hα'), 3.45, (1H, dq, J = 9.8, J = 6.8, Hβ), 3.88 (6H, s, OCH_3), 5.08 (1H, d, J = 9.8, Hα), 5.64 (1H, S, ArOH), 6.50-7.00 (6H, m, ArH)

Acetovanillone Benzyl Ether (9)

Acetovanillone 8 (110 g, 0.602 mole) was dissolved in acetone (500 ml). To this solution was added powdered K_2CO_3 (84.72 g, 0.613 mole), potassium iodide (11.53 g, 0.07 mole) and benzyl chloride (77.61 g, 0.613 mole). The mixture was refluxed for 48 hours and the inorganic solids filtered off. The solvent was removed under reduced pressure to give a yellow solid (148 g, 96% yield), which was recrystallised from hot ethanol to give pale yellow crystals, m.p. 88°C.

^{1}H NMR (60MHz, $CDCl_3$) δ :2.50 (3H, s, CH_3), 3.90 (3H, S, OCH_3), 5.20 (2H, s, CH_2Ph), 6.80-7.60 (3H, m, Ar-H).

2-benzyloxy-3-methoxybenzaldehyde (11)

To a solution of 2-hydroxy-3-methoxybenzaldehyde 10 (30 g, 0.197 mole) in acetone (250 ml), was added benzyl chloride (25.33 g, 0.201 mole), powdered anhydrous K_2CO_3 (27.78 g, 0.201 mole) and KI (3.77 g, 0.0227 mole). The mixture was refluxed overnight and the inorganic material filtered off. The filtrate was evaporated under reduced pressure to give a dark oil (50 g).

A portion of this oil (10 g) was distilled under vacuum and the fraction distilling at 120-160°C was collected. This crystallised on standing to give a mass of white crystals. These were recrystallised from hot ethanol to give white needles.

^{1}<u>H NMR</u> (60 MHz, $CDCl_3$) δ: 3.80 (3H, s, OCH_3), 5.18 (2H, s, CH_2Ph), 7.00-7.20 (3H, m, Ar-H), 7.20-7.60 (5H, m, benzyl Ar-H).

<u>2,3-dimethoxybenzaldehyde (12)</u>

2-hydroxy-3-methoxybenzaldehyde <u>10</u> (10.0 g, 65.7 mmole) was dissolved in a solution of NaOH (2.76 g, 69 mmole) in water (26 ml). The solution was cooled to 10°C in an ice-bath. Dimethyl sulphate (8.3 g, 65.7 mmole) was added dropwise over 1 hour, while stirring vigorously. The solution was refluxed for 2 hours, then cooled. Water (100 ml) was added and the mixture extracted with chloroform, which was dried over $MgSO_4$ and the solvent removed under reduced pressure to give a dark oil (11.0 g). This oil was shown by ^{1}H NMR and tlc to contain equal quantities of the required product and starting material. The oil was re-reacted under identical conditions, and workup gave a brown oil (11.2 g). This oil was dissolved in diethyl ether, and washed with NaOH (8 x 4 ml, 1 $mol{-}l^{-1}$) to remove any remaining phenolics. The ether layer was dried over $MgSO_4$ and the solvent removed under reduced pressure to give a brown oil (8.7 g, 80% yield). Attempts to crystallise this oil failed, and it was vacuum distilled to give a clear, colourless oil (6.0 g, 55% yield) which crystallised on standing to give white crystals m.p. 46-48 °C (lit 54 °C, Dictionary of Organic Compounds, 1965).

^{1}H NMR (60 MHz, $CDCl_3$) δ: 3.88 (3H, s, OCH_3), 3.98 (3H, s, OCH_3), 6.80-7.50 (3H, m, Ar-H), 10.40 (1H, s, HC=0).

1-(4-benzyloxy-3-methoxyphenyl)-3-(2-benzyloxy-3-methoxyphenyl)-2-propen-1-one (13)

To a solution of 11 (3.52 g, 14.8 mmole) and 9 (3.79 g, 14.8 mmole) in ethanol (120 ml), was added a solution of KOH (30 g) in H_2O (30 ml) dropwise over 1 hour. The reaction was stirred overnight, with a yellow oil separating out. The ethanol was distilled off under reduced pressure to give a dark brown solution. This was neutralised with 2 mol/l HCl and the solution was extracted with chloroform. The organic layer was removed under reduced pressure to give a yellow oil (7 g, 100%). This was crystallised under cold ethanol and the crystals recrystallised from hot ethanol to give yellow plates (6 g, 86%), m.p. 83-87°C.

^{1}H NMR (60 MHz, $CDCl_3$) δ: 3.95 (3H, s, OCH_3), 4.00 (3H, s, OCH_3), 5.10 (2H, s, benzyl CH_2Ph), 5.30 (2H, s, benzyl CH_2Ph), 6.95 (1H, d, J=16 Hz, Hβ), 6.90-7.70 (16H, m, Ar-H), 8.10 (1H, d, J=16 Hz, Hγ).

^{13}C NMR (22.49 MHz, $CDCl_3$) δ : 55.4 (3,3' OCH_3), 70.2 (A4-benzyloxy CH_2), 74.9 (B2-benzyloxy CH_2), 110.8 (A2), 111.8 (B4), 113.7 (A5), 119.8 (B6), 122.5 (B5), 122.9 (A6), 123.9 (β), 126.9 (benzyl 3,5), 127.6 (benzyl 3',5'), 128.1 (benzyl 2,4,6), 128.2 (benzyl' 2,4,6), 129.1 (A1), 131.1 (B1), 136.0 (benzyl 1), 136.8 (benzyl 1), 138.8 (γ), 147.0 (B2), 149.7 (A3), 152.8 (A4), 153.1 (B3), 188.3 (α-C=0).

Mass Spectrum (probe, EI, 70eV) m/z : 480($M^{+\cdot}$, 0.4), 374(9), 373(31), 241(11), 176(9), 92(9), 91(100).

1-(4-benzyloxy-3-methoxyphenyl)-3-(2,3-dimethoxyphenyl)-2-propen-1-one (14)

Acetovanillone benzyl ether 9 (5.40 g, 21 mmole) and 2,3-dimethoxybenzaldehyde 12 (3.50 g, 21 mmole) were dissolved in ethanol (168 ml). A solution of KOH (42.4 g, 760 mmole) in water (42 ml) was added dropwise over 1 hour and the solution was stirred for a further 4.5 hours, during which a yellow oil separated from the reaction mixture. The reaction mixture was decanted off the oil, which was extracted into chloroform, dried over $MgSO_4$ and the solvent removed under reduced pressure to give a yellow oil (8.6 g, 100%). The oil was crystallised from hot ethanol to give yellow crystals (6.5 g, 76% yield), m.p. 94-95°C.

^{1}H NMR (60 MHz, $CDCl_3$) δ: 3.80 (6H, s, OCH_3), 3.90 (3H, s, OCH_3), 5.18 (2H, s, CH_2Ph), 6.70-7.80 (11H, m, Ar-H), 7.40 (1H, d, J=16 Hz, Hβ), 8.08 (1H, d, J=16 Hz, Hγ).

^{13}C NMR (22.5 MHz, $CDCl_3$) δ : 55.8, 55.9 (A3,B3-OCH_3), 61.6 (B2 -OCH_3), 70.7 (benzyl CH_2), 111.3 (A2), 112.2, (B4), 114.0 (A5), 119.6 (B6), 122.8, (A6) 123.2 (B5), 124.1 (Cβ), 127.2 (benzyl C3, C5), 128.0 (benzyl C4), 128.6 (benzyl C2, C6), 129.2 (A1), 131.6 (B1), 136.2 (benzyl 1), 138.7 (Cγ), 148.8 (B2), 149.6 (A3), 152.8 (A4), 153.1 (B3), 188.7 (α-C=O).

Mass spectrum (probe, EI, 70 eV) m/z: 404($M^{+\cdot}$, 12), 373(13), 254(19), 91(100).

Tetrabutylammonium hydrogen sulphate

To a solution of aqueous tetrabutylammonium hydroxide (2.5 ml, 40% w/v) was added H_2SO_4 (sp. gr. 1.84, 200 µl). The mixture was stirred for 1 hour and the water removed under reduced pressure to give colourless crystals, m.p. 168-171°C (cf. 169-171°C, Aldrich Catalogue).

1-(4-benzyloxy-3-methoxyphenyl)-3-(2-benzyloxy-3-methoxyphenyl)-2,3-epoxypropan-1-one (15)

Chalcone 13 (8.14 g, 16.9 mmole) was dissolved in CH_2Cl_2 (40 ml). To this was added a mixture of aqueous H_2O_2 (8 ml, 30% w/v, 68 mmole) and NaOH (25 ml, 3 mol/l). The mixture was cooled in an ice-bath and solid tetrabutylammonium hydrogen sulphate (0.6 g) was added over 1 hour with vigorous stirring. The reaction mixture was stirred for 2 hours at room temperature. The product was extracted into CH_2Cl_2 which was washed with 5% NH_4Cl solution. The organic layer was dried over $MgSO_4$ and the solvent removed under reduced pressure to give a yellow oil (8.7 g, 100%).

^{1}H NMR (60 MHz, $CDCl_3$) δ: 3.90 (3H, s, OCH_3), 3.95 (3H, s, OCH_3), 4.10 (1H, d, J=2 Hz, Hβ), 4.22 (1H, d, J=2 Hz, Hγ), 5.00 (2H, s, benzyl CH_2), 5.18 (2H, s, benzyl CH_2), 6.60-7.60 (16H, m, Ar-H).

^{13}C NMR (22.49 MHz, $CDCl_3$) δ: 55.5(β), 55.7, 55.9 (A3,B3 OCH_3), 59.8 (γ), 70.6 (A4-benzyloxy CH_2), 75.1 (B2-benzyloxy CH_2), 110.5 (A2), 112.0 (B4), 112.5 (A5), 117.0 (B6), 123.2 (A6), 124.4 (B5), 127.1 (benzyl 3,5), 128.1 (benzyl 2,4,6, benzyl'3,5), 128.5 (benzyl'2,6), 128.8 (A1), 130.0 (B1), 136.0 (benzyl 1), 136.8 (benzyl 1'), 146.5 (B2), 149.6 (A3), 152.4 (A4), 153.0 (B3), 191.4 (α-C=O).

Mass Spectrum (probe, EI, 70 eV) m/z: 496($M^{+\cdot}$, 0.4), 241(21), 92(9), 81(100).

1-(4-benzyloxy-3-methoxyphenyl)-3-(2,3-dimethoxyphenyl)-2,3-epoxypropan-1-one (16)

Chalcone 14 (20 g, 0.0495 mole) was dissolved in pyridine (160 ml). To this was added a solution of NaOCl (5.4% in water, 160 ml) and the mixture stirred for 3 hours. The yellow solution was poured into water (200 ml) in a separation funnel and extracted with ethyl acetate. The organic layer was washed several times with saturated aqueous NH_4Cl and dried over $MgSO_4$. The solvent was removed under reduced pressure to give a brown oil which crystallised on standing. The solid was recrystallised from hot ethanol to give 16 as white needles (15.8 g, 76% yield), m.p. 123-124°C.

^{1}H NMR (60 MHz, $CDCl_3$) δ: 3.79 (3H, s, OCH_3), 3.88 (3H, s, OCH_3), 3.94 (3H, s, OCH_3), 4.20 (1H, d, J=2 Hz, Hβ), 4.32 (1H, d, J=2 Hz, Hγ), 5.21 (2H, s, CH_2Ph), 6.70-7.70 (11H, m, Ar-H).

<u>^{13}C NMR</u> (22.5 MHz, $CDCl_3$) δ: 54.9, 55.3, 55.4 (A3, B2, B3 OCH_3), 59.5, 60.5 (Cß, Cγ), 70.2 (benzyl CH_2), 110.1 (A2), 111.8 (B4), 112.3 (A5), 116.5 (B6), 122.7 (A6), 124.0 (B5), 126.8 (benzyl C3, C5), 127.6 (benzyl C4), 128.1 (benzyl C2, C6), 128.4, 129.1 (A1, B1), 135.6 (benzyl C1), 147.6 (B2), 149.6 (A3), 152.0 (A4), 152.7 (B3), 191.0 (α-C=O).

<u>1-(4-benzyloxy-3-methoxyphenyl)-2-(2-benzyloxy-3-methoxyphenyl)-propane-1,3-diol (17)</u>

Et_2O (550 ml, freshly distilled over $LiAlH_4$) was added to chalcone epoxide <u>15</u> (8.7 g, 17.5 mmole, partially insoluble). To this was added $BF_3.Et_2O$ (22 ml, 175 mmole, freshly vacuum distilled over CaH_2). The mixture was refluxed for 2 hours and stopped by careful addition of water (vigorous reaction). The mixture was poured into a separation funnel and washed with water (150 ml). The ether layer was dried over $MgSO_4$ and removed under reduced pressure. The resulting deep red oil (9.1 g) was dissolved in dioxane (140 ml) and to this was added $NaBH_4$ (2 g) in NaOH (50 ml, 1 mol/l). The reaction mixture was stirred overnight and acidified to pH = 6.5 with 5% H_2SO_4. The product was extracted into Et_2O (2 x 150 ml) and washed with saturated $NaHCO_3$ (2x) and H_2O (2x). The ether layer was dried over $MgSO_4$ and the solvent removed under reduced pressure to give a clear yellow oil (8.8 g).

Multiple elution flash column chromatography (ethyl acetate : methylene chloride 5 : 2) of a portion (4 g) of this oil gave a fraction (1.5 g, 35%) containing the required product <u>17</u>, and a pure fraction (yield not recorded) containing pure fluorohydrin <u>21</u>. Both fractions crystallised on standing and were recrystallised from Et_2O/pet. ether to give 17 as white crystals m.p. 94-96°C and 21 as white plates m.p. 120-122°C.

^{1}H NMR (60 MHz, $CDCl_3$) δ:1.88 (1H, br s, γ-OH), 2.60 (1H, br s, α-OH), 3.62 (3H, s, OCH_3), 3.90 (3H, s, OCH_3), 3.30-4.00 (3H, m, Hβ Hγ's), 4.60 (1H, d, J=11 Hz, benzyl CH), 5.00 (1H, d, J=11 Hz, benzyl CH), 5.00 (1H, d, J=6 Hz, Hα), 5.10 (2H, s, benzyl CH_2), 6.60-7.30 (6H, m, Ar-H), 7.30-7.60 (10H, m, benzyl Ar-H).

^{13}C NMR (22.49 MHz, $CDCl_3$) δ: 47.7 (β), 55.5, 55.6 (A3,B3 OCH_3), 63.8 (γ), 70.9 (A4-benzyloxy CH_2), 74.4 (B2-benzyloxy CH_2), 74.9 (α), 110.2 (A2), 111.0 (B4), 113.4 (A5), 118.7 (B6), 120.7 (A6), 123.9 (B5), 127.1 (benzyl 3,5), 127.7 (benzyl' 3,5), 127.8 (benzyl 4,4'), 128.2 (benzyl 2,6), 128.3 (benzyl' 2,6), 133.0 (B1), 135.7 (A1), 137.1 (benzyl 1), 137.8 (benzyl 1'), 146.7 (B2), 147.4 (A3), 149.4 (A4), 152.8 (B3).

Mass Spectrum (probe, EI, 70 eV) m/z: 482 ($M^{+\cdot}-H_2O$, 0.05), 209(15), 208(16), 150(8), 137(11), 136(10), 121(12), 116(12), 92(16), 91(100).

1-(4-benzyloxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-propane-1,3-diol (18)

Crystalline chalcone epoxide 16 (15.0 g, 0.0357 mole) was added to diethyl ether (1200 ml, distilled over $LiAlH_4$). Freshly vacuum-distilled $BF_3.Et_2O$ (44.4 ml, 0.357 mole) was added and the chalcone epoxide dissolved to give a bright red solution. The reaction was refluxed for 40 minutes and stopped by the careful addition of water (300 ml). The mixture was transferred to a separation funnel and the ether layer was washed with water (300 ml), and dried over $MgSO_4$. The ether was evaporated under reduced pressure to give a bright red oil. The oil was dissolved in dioxane (300 ml) and to this was added dropwise a solution of $NaBH_4$ (4 g, 0.106 mole) in NaOH (100 ml, 0.1 mol/l). The reaction was stirred overnight and carefully neutralised to pH = 7 with 5% H_2SO_4. The mixture was extracted with diethyl ether, and the extract was dried over $MgSO_4$ and the solvent evaporated under reduced pressure to give a white solid (16 g). This was recrystallised from CH_2Cl_2/pet. ether to give white crystals (9.2 g, 61% yield), m.p. 122.5-123.5°C.

^{1}H NMR (60 MHz, $CDCl_3$) δ : 2.50 (2H, br s, OH), 3.55 (3H, s, OCH_3), 3.60 (3H, s, OCH_3), 3.78 (3H, s, OCH_3), 3.20-4.20 (3H, m, Hβ, Hγ's), 4.90 (1H, d, J=6 Hz, Hα), 5.05 (2H, s, CH_2Ph), 6.60-7.60 (11H, m, Ar-H).

^{13}C NMR (22.49 MHz, $CDCl_3$) δ: 47.8 (Cβ), 55.6, 55.7 (A3-OCH_3, B3-OCH_3), 60.5 (B2-OCH_3), 63.8 (Cγ), 71.0 (benzyl CH_2), 74.8 (Cα), 110.5 (A2), 111.0 (B4), 113.7 (A5), 118.8 (B6), 121.1 (A6), 123.7 (B5), 127.3 (benzyl C3, C5), 127.6 (benzyl C4), 128.4 (benzyl C2, C6), 132.7 (B1), 135.9 (A1), 137.1 (benzyl C1), 147.3 (B2), 147.7 (A3), 149.3 (A4), 152.6 (B3).

Mass Spectrum High resolution molecular ion not observed but $M^{+\cdot}-H_2O$ measured at m/z = 406.1795; calculated m/z for $C_{25}H_{26}O_5$ ($M^{+\cdot}-H_2O$) = 406.1780.

Compound 19

Compound 17 was acetylated in the usual way to give 19 as a clear, colourless oil.

^{1}H NMR (60 MHz, $CDCl_3$) δ:1.85 (6H, s, $OCOCH_3$), 3.70 (3H, s, OCH_3), 3.85 (3H, s, OCH_3), 3.60-4.00 (1H, m, Hβ), 4.00-4.40 (2H, m, Hγ's), 4.60 (1H, d, J=11 Hz, benzyl CH), 5.00 (1H, d, J=11 Hz, benzyl CH), 5.10 (2H, s, benzyl CH_2), 6.10 (1H, d, J=6 Hz, Hα), 6.60-7.30 (6H, m, Ar-H), 7.30-7.60 (10H, m, benzyl Ar-H).

1-(4-hydroxy-3-methoxyphenyl)-2-(2-hydroxy-3-methoxyphenyl)-propane-1,3-diacetate (20)

Compound 19 (25 mg, 0.042 mmole) was dissolved in MeOH (5 ml). To this was added a catalytic amount of 5% Pd/C and the reaction mixture was stirred for 3 hours under a balloon full of H_2. Debenzylation progress was monitored by tlc (ethyl acetate : pet. ether 1:1). The reaction mixture was filtered through celite and the solvent removed under reduced pressure to give 20 as a clear colourless oil (17 mg, 100%).

^{1}H NMR (60 MHz, $CDCl_3$)δ : 1.85 (3H, s, γ-$OCOCH_3$), 1.90 (3H, s, α-$OCOCH_3$), 3.30 (1H, m, Hβ), 3.80 (3H, s, OCH_3), 3.85 (3H, s, OCH_3), 4.00-4.40 (2H, m, Hγ's), 5.62 (1H, br s, Ar-OH), 5.80 (1H, s, Ar-OH), 6.15 (1H, d, J=8 Hz, Hα), 6.60-6.90 (6H, m, Ar-H).

1-(4-benzyloxy-3-methoxyphenyl)-3-fluoro-3-(2-benzyloxy-3-methoxyphenyl)-propane-1,2-diol (21).

Compound 21 was a white crystalline solid: m.p. 120-122°C; ^{1}H NMR (200 MHz, $CDCl_3$) δ: 2.09 (1H, dd, $J_{OH-\beta}$ = 5.4 Hz, J_{OH-F} = 0.9 Hz, β-OH), 2.24 (1H, dd, $J_{OH-\alpha}$ = 4.9 Hz, J_{OH-F} = 1.5 Hz, α-OH), 3.81 (3H, s, OCH_3), 3.89 (3H, s, OCH_3), 4.06 (1H, dddd, $J_{\beta F}$ = 25.6 Hz, $J_{\beta\alpha}$ = 6.8 Hz, $J_{\beta-OH}$ = 5.4 Hz, $J_{\beta\gamma}$ = 2.4 Hz, Hβ), 4.74 (1H, dd, $J_{\alpha\beta}$ = 6.8 Hz, $J_{\alpha-OH}$ = 4.9 Hz, Hα), 4.97 (1H, d, J = 10.9 Hz, B ring benzyl CH), 5.04 (1H, d, J = 10.9 Hz, B ring benzyl CH), 5.12 (2H, s, A ring benzyl CH_2), 5.98 (1H, dd, $J_{\gamma F}$ = 45.9 Hz, $J_{\gamma\beta}$ = 2.4 Hz, Hγ), 6.70-7.20 (6H, m, Ar-H), 7.30-7.50 (10H, m, benzyl Ar-H).

Mass Spectrum (probe, EI, 70 eV) m/z: 518($M^{+\cdot}$, 0.1), 256(5), 242(3), 238(3), 227(3), 165(3), 137(4), 92(8), 91(100), 65 (10).

Compound 22

Compound 21 was acetylated in the usual way to give 22 as a clear, colourless oil (98%).

^{1}H NMR (60 MHz, $CDCl_3$) δ : 1.60 (3H, s, α-$OCOCH_3$), 1.90 (3H, s, β-$OCOCH_3$), 3.75 (3H, s, OCH_3), 3.80 (3H, s, OCH_3), 5.08 (2H, s, benzyl CH_2), 5.15 (2H, s, benzyl CH_2), 5.40-6.40 (3H, m, Hα, Hβ, Hγ), 6.60-7.60 (16H, m, Ar-H).

^{13}C NMR (22.49 MHz, $CDCl_3$) δ: 20.1 (α-$OCO\underline{C}H_3$), 20.8 (β-$OCO\underline{C}H_3$), 55.7, 55.8 (A3,B3 OCH_3), 70.8 (A4-benzyloxy CH_2), 72.5 (d, $^3J_{\alpha F}$ = 7 Hz, α), 73.6 (d, $^2J_{\beta F}$ =18 Hz, β), 74.3

(2'-benzyloxy CH$_2$), 86.7 (d, ${}^1J_{\gamma F}$ = 178 Hz, γ), 111.3 (A2), 112.8 (B4), 113.4 (A5), 118.8 (d, ${}^3J_{6'F}$ = 9 Hz, B6), 120.3 (A6), 123.1 (B5), 127.2 (benzyl 3,5), 127.7 (benzyl 4), 128.4 (benzyl 2,6), 129.5 (A1), 129.6 (d, ${}^2J_{1'F}$ =20 Hz, B1), 136.9 (benzyl 1), 137.8 (benzyl 1'), 144.0 (d, ${}^3J_{2'F}$ =9 Hz, B2), 148.1 (A3), 149.2 (A4), 152.0 (B3), 168.7 (α-O$\underline{\text{C}}$OCH$_3$), 169.7 (β-O$\underline{\text{C}}$OCH$_3$).

Mass Spectrum (probe, EI, 70 eV), m/z: 602($M^{+\cdot}$, 0.3), 394(3), 343(4), 155(4), 153(3), 151(3), 72(7), 91(100), 43(7).

1-(4-hydroxy-3-methoxyphenyl)-2-(2-hydroxy-3-methoxyphenyl)-propane-1,3-diol (23).

Compound 17 (63 mg, 0.126 mmole) was dissolved in MeOH (5 ml). To this was added 5% Pd/C (2 mg), and the reaction was stirred under a balloon full of H$_2$ for 3.5 hours, with the extent of debenzylation being monitored by tlc (ethyl acetate : pet. ether 3:2). The reaction mixture was filtered through celite and the filtrate evaporated under reduced pressure to give a yellow oil (40 mg, 100%) which crystallised on standing to give white crystals of 23 which were almost insoluble in chloroform or acetone. The crystals of compound 23 slowly dehydrated to give an oil which was a mixture of 23 and 24.

^{1}H NMR (60 MHz, CDCl$_3$) δ: 2.20 (1H, br s, γ-OH) 2.60 (1H, br s, α-OH), 3.60 (1H, m, Hβ), 3.60-4.00 (2H, m, Hγ's), 3.70 (3H, s, OCH$_3$), 3.80 (3H, s, OCH$_3$), 5.05 (1H, d, J =6.5 Hz, Hα), 5.80 (2H, br s, Ar-OH), 6.60-7.00 (6H, m,Ar-H).

^{13}C NMR (22.49 MHz, $CDCl_3$/d_6-acetone/d_6-DMSO, side-chain carbons only) δ: 49.8 (β) 62.5 (γ), 71.7 (α).

2,3-dihydro-3-hydroxymethyl-2-(4-hydroxy-3-methoxyphenyl)-7-methoxybenzofuran (24)

The mixture of 23 and 24 described above was dissolved in $CHCl_3$ and 2 drops of HCl (1 mol/l) added. The mixture was vigorously shaken, dried over $MgSO_4$ and the solvent removed under reduced pressure to give a light yellow oil (38 mg, 100%).

^{1}H NMR (60 MHz, $CDCl_3$) δ: 2.10 (1H, br s, γ-OH), 3.60 (1H, m, Hβ), 3.80 (3H, s, OCH_3), 3.90 (3H, s, OCH_3), 3.80-4.00 (2H, m, Hγ's), 5.65 (1H, d, J =7 Hz, Hα), 5.85 (1H, br s, Ar-OH), 6.70-7.00 (6H, m, Ar-H).

^{13}C NMR (22.49 MHz, $CDCl_3$) δ : 53.7(β), 56.0 (A3,B3 OCH_3), 64.1 (γ), 87.9 (α), 108.9 (A2), 112.2 (B4), 114.4 (A5), 116.4 (B6), 119.4 (A6), 121.4 (B5), 127.9 (A1), 133.1 (B1), 144.6 (B2), 145.7 (A4), 146.7 (A3), 148.3 (B3).

Mass Spectrum (probe, EI, 70 eV) m/z: 302($M^{+\cdot}$, 60), 285(12), 284(67), 283(10), 272(56), 271(12), 270(20), 269(100), 253(24), 252(28), 243(22), 241(12), 239(14), 234(11), 225(13), 224(12), 223(11), 213(14), 211(20), 209(11), 197(25), 196(10), 183(16), 181(19), 169(22), 168(17), 153(15), 152(15), 151(15), 150(13), 141(15), 139(20), 137(36), 129(10), 128(24), 127(12), 115(18), 77(18).

Compound 25

Compound 24 (38 mg, 0.126 mmole) was acetylated in the usual way. Workup gave 25 as a clear, colourless oil (45 mg, 94%).

^{1}H NMR (200 MHz, $CDCl_3$) δ : 2.05 (3H, s, γ-$OCOCH_3$), 2.31 (3H, s, Ar-$OCOCH_3$), 3.80 (1H, m, Hβ), 3.81 (3H, s, OCH_3), 3.91 (3H, s, OCH_3), 4.30 (1H, dd, $J_{\gamma_1\gamma_2}$=11.1 Hz, $J_{\beta\gamma_1}$ =7.6 HZ, Hγ_1), 4.45 (1H,dd, $J_{\gamma_1\gamma_2}$= 11.1, $J_{\gamma_2\beta}$ = 5.5), 5.50 (1H, d, J =6.9 Hz, Hα), 6.70–7.10 (6H, m, Ar-H).

1-(4-hydroxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-propane-1,3-diol (26)

Compound 18 (94 mg, 0.22 mmole) was dissolved in MeOH (50 ml). To this was added 5% Pd/C (2 mg). The reaction flask was flushed with N_2 and the reaction was stirred under a balloon full of H_2 for 2 hours. The catalyst was removed by filtration through celite. The filtrate was evaporated under reduced pressure to give the required product as a light yellow oil (70 mg, 95% yield).

^{1}H NMR (60 MHz, $CDCl_3$) δ: 2.60 (2H, br s, OH), 3.62 (3H, s, OCH_3), 3.66 (3H, s, OCH_3), 3.80 (3H, s, OCH_3), 3.30–4.40 (3H, m, Hβ, Hγ's), 4.90 (1H, d, J=6 Hz, Hα), 6.60–7.00 (6H, m, Ar-H).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 48.2 (Cβ), 55.7, 57.8 (A3,B3-OCH_3), 60.7 (B2-OCH_3), 63.9 (Cγ), 75.1 (Cα), 109.4 (A2), 111.1 (B4), 114.2 (A5), 119.5 (A6), 121.0 (B6), 124.0 (B5'), 132.8 (A1), 134.3 (B1), 145.2 (A4), 146.5 (A3), 147.8 (B2), 152.8 (B3).

Mass Spectrum High resolution molecular ion not observed, but $M^{+\cdot}-H_2O$ measured at m/z = 316.1296; calculated m/z for $C_{18}H_{20}O_5$ ($M^{+\cdot}-H_2O$) = 316.1311.

1-(4-benzyloxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-propane-1,3-diacetate (27)

Compound 15 (100 mg, 0.236 mmole) was acetylated (Ac_2O/pyridine) to give a light yellow oil (113 mg, 94% yield). Multiple elution preparative tlc of this oil (EtOAc/pet. ether) gave the required product (94 mg, 74% yield).

^{1}H NMR (200 MHz, $CDCl_3$) δ : 1.80 (3H, s, γ-$OCOC\underline{H}_3$), 1.86 (3H, s, α-$OCOC\underline{H}_3$), 3.68 (3H, s, OCH_3), 3.80 (3H, s, OCH_3), 3.85 (3H, s, OCH_3), 4.05 (2H, m, $H\gamma_1$, β), 4.25 (1H, dd, $J_{\beta\gamma 2}$ = 5.8 Hz, $J_{\gamma 1\gamma 2}$ = 9.8 Hz, $H\gamma_2$), 5.60 (1H, s, Ar-OH), 6.05 (1H, d, $J_{\alpha,\beta}$ = 5.8 Hz, $H\alpha$), 6.70-7.05 (6H, m, Ar-H).

1-(4-hydroxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-propane-1,3-diacetate (28)

Compound 27 (20 mg, 0.039 mmole) was dissolved in MeOH (5 ml). To this was added a catalytic amount of 5% Pd/C and the reaction flask was flushed with N_2. The mixture was stirred under H_2 for 1 hour. The catalyst was filtered off through celite and the solvent removed under reduced pressure to give the required product as a light yellow oil (16 mg, 100% yield).

^{1}H NMR (200 MHz, $CDCl_3$) δ : 1.80 (3H, s, γ-$OCOC\underline{H}_3$), 1.86 (3H, s, α-$OCOC\underline{H}_3$), 3.68 (3H, s, OCH_3), 3.80 (3H, s, OCH_3, 3.85

(3H, s, OCH_3), 4.05 (2H, m $H_{\gamma1}$, ß), 4.25 (1H, dd, $J_{\beta\gamma2}$ = 5.8 Hz, $J_{\gamma1\gamma2}$ = 9.8 Hz, $H\gamma_2$), 5.60 (1H, s, Ar-OH), 6.05 (1H, d, $J_{\alpha\beta}$ = 5.8 Hz, Hα) 6.70-7.05 (6H, m, Ar-H).

<u>^{13}C NMR</u> (22.49 MHz, $CDCl_3$) δ : 20.7 ($\gamma\text{-OCO}\underline{\text{C}}\text{H}_3$), 21.0 ($\alpha\text{-OCO}\underline{\text{C}}\text{H}_3$), 42.1 (Cß), 55.6, 55.8 (A3-OCH_3, B3-OCH_3), 60.6 (B2-OCH_3), 64.7 (Cγ), 75.5 (Cα), 110.0 (B4), 111.2 (A2), 114.2 (A5), 120.3, 120.3 (A6, B6), 123.6 (B5), 130.6 (A1), 131.9 (B1), 145.6, 146.3, 147.8, (A3, A4, B2), 152.5 (B3), 169.8 ($\alpha\text{-O}\underline{\text{C}}\text{OCH}_3$), 170.7 ($\gamma\text{-O}\underline{\text{C}}\text{OCH}_3$).

<u>Dehydrodiferulic Acid (29)</u>

A solution of ferulic acid <u>2</u> (40 g, 0.2059 mole) in methanol (400 ml) was added dropwise to a solution of $FeCl_3.6H_2O$ (125 g, 0.45 mole) while bubbling a stream of oxygen through the reaction mixture. The reaction was left stirring (with O_2 supply) for 6 hours. Concentrated HCl (200 ml) was then added and the mixture heated to 50-60°C. A purple precipitate formed and the supernatant turned yellow. The precipitate was filtered off and crystallised from hot ethanol to give off-white crystals m.p. 205-210°C (7.5 g, 19% yield).

<u>IR</u> (nujol mull, KBr windows): $\nu_{C=0}$ 1780 cm^{-1}

<u>^{1}H NMR</u> (200 MHz, acetone-d_6) δ :3.87 (6H, s, OCH_3), 4.06 (2H, t, J = 0.94, Hß), 5.78 (2H, s, Ar-OH), 6.87 (2H, d, J = 8.0, H5), 6.91 (2H, dd, J = 8.0, 1.9, H6), 7.04 (2H, d, J = 1.9, H2).

^{13}C NMR (50 MHz, acetone-d_6) δ:49.1 (ß), 56.4 (OCH_3), 83.2 (Cα), 110.4 (C2), 116.1 (C5), 119.6 (C6), 130.9 (C1), 148.3, 148.8 (C3,C4), 176.0 (γ-C=O).

Mass Spectrum (Probe, EI, 70 eV), m/z: 386(M^+, 49), 206(10), 190(52), 177 (15), 153(11), 152(29), 151(100), 147(10), 137(18), 124(10).

Dehydrodiferulic acid diacetate (30)

Compound 29 (3.0 g, 7.77 mmole) was dissolved in a mixture of pyridine (20 ml) and acetic anhydride (20 ml), and stirred overnight. The mixture was poured into water in a separation funnel, extracted with ethyl acetate and washed with 5% H_2SO_4 (2 x 100 ml) and saturated aqueous $NaHCO_3$ (2 x 100 ml). The product crystallised out of the ethyl acetate in the separation funnel, so the mixture was filtered to recover the product, which was washed with water and dried to give pure white crystals m.p. 223-225°C (2.04 g, 84% yield). The ethyl acetate layer was dried and the solvent removed under reduced pressure to give a yellow solid (600 mg). This was crystallised to give more white solid (400 mg, total yield 94%).

^{1}H NMR (200 MHz, acetone-d_6): 2.16 (6H, s, OAc), 3.07 (2H, ddd, J = 7.1, 4.3, 3.9 Hß), 3.75 (6H, s, OCH_3), 3.85 (2H, dd, J = 9.2, 3.9, $H\gamma_1$), 4.21 (2H, dd, J = 9.2, 7.1, $H\gamma_2$), 4.72 (2H, d, J = 4.3, Hα), 6.90-7.10 (6H, m, ArH).

^{13}C NMR (50 MHz, acetone-d_6): 20.5 (Ar-$OCO\underline{C}H_3$), 48.9 (Cß), 56.5 (OCH_3), 82.4 (Cα), 111.0 (C2), 118.5 (C5), 124.2 (C6), 138.3 (C1), 141.4 (C4), 152.8 (C3), 169.0 ($\text{Ar-O}\underline{\text{C}}\text{OCH}_3$), 175.7 (γ-C=O).

$LiAlH_4$ Reduction of 30

The dilactone 30 (3.0 g, 6.356 mmole) dissolved in dry distilled THF (250 ml), was added dropwise to a solution of $LiAlH_4$ (1.7 g, 44.5 mmole) in dry THF (150 ml) and refluxed overnight under nitrogen. The reaction was stopped by the careful addition of water down the condenser and the reaction mixture poured into saturated aqueous NH_4Cl in a separation funnel. The organic layer was separated, dried with $MgSO_4$ and the solvent removed under reduced pressure to give a yellow oil. This was crystallised from acetone/ether to give pure white crystals of 31, m.p. very broad (1.3 g, 52%).

^{13}C NMR (50 MHz, d_6-dmso) δ : 44.9 (Cβ), 55.3 (OCH_3), 59.0 (Cγ), 71.5 (Cα), 110.1 (C2), 14.5 (C5), 118.5 (C6), 136.0 (C1), 144.7 (C4), 146.9 (C3).

Acetylation of 31

The hexol 31 (5 mg, 0.0133 mmole) was acetylated in the usual way. Workup gave 32 as a yellow oil (7 mg, 88%).

^1H NMR (200 MHz, acetone-d_6) δ: 1.98 (6H, s, γ-$OCOCH_3$), 2.11 (6H, s, α-$OCOCH_3$), 2.23 (6H, s, Ar-$OCOCH_3$), 2.60 (2H, ddd, $J_{\beta\alpha}$= 6.8, $J_{\beta\gamma_1}$ = 7.05, $J_{\beta\gamma_2}$= 5.0, Hβ), 3.78 (6H, s, OCH_3), 4.21 (2H, dd, $H_{\gamma_1\gamma 2}$ = 11.7, $J_{\gamma_1\beta}$ = 7.0, $H\gamma_1$), 4.26 (2H, dd, $J_{\gamma_1\gamma 2}$ = 11.7, $J_{\gamma 2\beta}$ = 5.0, $H\gamma_2$), 5.99 (2H, d, $J_{\beta\alpha}$= 6.8, Hα), 6.79

(2H, dd, J_{56} = 8.3, J_{26} = 2.0, H6), 6.94 (2H, d, H_{26} = 2.0, H2), 6.98 (2H, d, J_{56} = 8.1, H5).

^{13}C NMR (50 MHz, acetone-d_6) δ : 20.4 (γ-OCO$\underline{\mathrm{C}}\mathrm{H}_3$), 20.7 ($\alpha$-OCO$\underline{\mathrm{C}}\mathrm{H}_3$), 20.8 (Ar-OCO$\underline{\mathrm{C}}\mathrm{H}_3$), 41.9 (C$\beta$), 56.2 ($OCH_3$), 62.2 (C$\gamma$), 74.8 (C$\alpha$), 111.3 (C2), 119.0 (C5), 122.0 (C6), 138.9 (C1), 40.3 (C4), 152.1 (C3), 168.9 (Ar-O$\underline{\mathrm{C}}\mathrm{OCH}_3$), 170.0 ($\alpha$-O$\underline{\mathrm{C}}\mathrm{OCH}_3$), 171.0 ($\gamma$-O$\underline{\mathrm{C}}\mathrm{OCH}_3$).

Compound 35

Compound 31 (8 mg, 0.02 mmole) was dissolved in d_6-dmso (0.5 ml in a 5 mm NMR tube). TMSBr (30 μl, 0.2 mmole) was added and the tube shaken. A bright yellow colouration resulted which faded slowly. The ^{1}H NMR spectra showed no evidence of the bromide formation. The resolution of the spectrum was poor due to the viscosity of the solvent. The mixture was poured into H_2O and extracted with $CHCl_3$. The solvent was removed under reduced pressure to give a yellow oil (8 mg). This was tentatively identified as compound 35.

^{13}C NMR : (50 MHz, d_6-dmso)δ: 53.2 (Cβ), 56.3 (OCH_3), 59.9 (Cγ), 81.5 (Cα), 109.1 (C2), 109.5 (C5), 121.8 (C6), 135.2 (C1), 142.8 (C4), 148.4 (C3).

Compound 36

Acetylation of 35 in the usual way gave a compound believed to be 36.

^{1}H NMR (200 MHz, d_6-acetone) δ: 1.88 (6H, s, γ-OAc), 2.26 (6H, s, Ar-OAc), 2.56 (2H, m. Hß), 3.90 (6H, s, OCH_3), 4.25 (4H, dd, J = 5.0, 3.0, Hγ's), 5.08 (2H, d, J = 8.0, Hα), 7.17 (2H, d, J = 1.3, H2 or 6), 7.30 (2H, d, J = 1.3, H6 or 2).

^{13}C NMR (50 MHz, d_6-acetone) δ: 20.2 (γ-OAc), 20.6 (Ar-OAc), 51.4 (Cß), 56.8 (OCH_3), 66.1 (Cγ), 83.6 (Cα), 110.9 (C2), 117.5 (C5), 123.2 (C6), 143.1 (C4), 153.7 (C3), 168.1 (Ar-OAc), 170.9 (γ-OAc), missing or obscured, C1.

d,l-pinoresinol (37)

Hexol 31 was vacuum-distilled at 0.5 mm Hg and the fraction distilling at 230-250°C was collected. This was shown by ^{13}C NMR to be a 2:1 mixture of 37 and 38. The ^{1}H NMR spectrum was too complex to fully interpret as there were three different types of aliphatic ,ß and resonance present in the spectrum. The mixture was acetylated to give a mixture of 2:1 pinoresinol diacetate 39 and epipinoresinol diacetate 40.

Compound 39

^{13}C NMR (50 MHz, d_6-acetone) δ: 20.4 (Ar-OAc), 55.3 (Cß), 56.1 (OCH_3), 72.5 (Cγ), 86.1 (Cα), 111.0 (C2), 118.6 (C5), 123.4 (C6), 136.0 (C1), 141.7 (C4), 152.2 (C3), 168.9 (Ar-OAc).

Compound 40

^{13}C NMR (50 MHz, d_6-acetone, DEPT spectrum only) δ: 20.5 (A-Ar-OAc), 20.6 (B-Ar-OAc), 50.5 (Aß), 51.3 (Bß), 56.2 (OCH_3), 70.2 (Aγ), 71.6 (Bγ), 82.3 (Bα), 83.7 (Aα), 110.7 (A2), 111.3 (B2), 118.3 (A5), 119.0 (B5), 123.2 (B6), 123.4 (A6). B assignments are for epimeric carbons.

2-(4-benzyloxy-3-methoxyphenyl)-1,3-dithiane (42)

The synthesis was carried out following the method of Fujimoto (1982). To a stirred solution of 2-methoxy-4-benzyloxybenzaldehyde (20.0 g, 82.6 mmol) in dioxane (85 ml), was added $ZnCl_2$ (2.27 g, 16.9 mmol) and conc. HCl (2 ml). The mixture was cooled in an ice-bath. Propane-1,3-dithiol (8.7 ml, 87 mmol) was added and the solution stirred for 10 minutes. A white precipitate formed which was washed with EtOAc, saturated $NaHCO_3$ and H_2O, and dried to give a white mass of crystals (27.4 g, 100%). This was recrystallised from EtOAc to give white needles.

^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.95 (2H, m, $-CH_2-$), 2.80 (4H, m, $-SCH_2-$), 3.86 (3H, s, OCH_3), 5.11 (2H, s, CH_2Ph), 5.11 (1H, s, H), 6.70-7.16 (3H, m, Ar-H), 7.15-7.50 (5H, m, Ar-H).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 25.2 ($-CH_2-$), 32.3 ($-SCH_2-$), 51.3 (Cα), 56.1 (OCH_3), 71.0 (benzyl CH_2), 111.4 (C2), 113.8 (C5), 120.1 (C6), 127.4 (benzyl 3,5), 128.0 (benzyl 4), 128.7 (benzyl 2,6), 132.3 (C1), 137.1 (benzyl 1), 148.3 (C3), 149.7 (C4).

3,4-dimethoxybenzaldehyde (43)

To a solution of NaOH (11.05 g, 0.276 mole) in H_2O (100 ml) was added 4-hydroxy-3-methoxybenzaldehyde (40.0 g, 0.23 mole) and the mixture stirred until the suspended material dissolved. The reaction mixture was cooled in an ice-bath, and dimethyl sulphate

(25 ml, 0.263 ml) was added dropwise over 1 hr. On completion of the addition, the mixture was refluxed with stirring for 2 hr.

The mixture was cooled and extracted into diethyl ether. The organic layer was washed 5 times with 4% NaOH, and once with H_2O, then dried over $MgSO_4$. The solvent was removed under reduced pressure to give a clear, colourless oil (33.0 g, 75%) which crystallised on standing. The crystals were recrystallised from Et_2O/pet. ether (40-60°C) to give white needles m.p. 40-42°C (lit. 42-45°C, Aldrich Catalogue).

^{1}<u>H NMR</u> (200 MHz, $CDCl_3$) δ: 3.77 (3H, s, OCH_3), 3.81 (3H, s, OCH_3), 6.75-7.35 (3H, m. Ar-H), 9.74 (1H, s, HC=O).

^{13}<u>C NMR</u> (50 MHz, $CDCl_3$) δ: 55.5 (OCH_3), 55.8 (OCH_3), 108.8 (C2), 110.4 (C5), 126.4 (C6), 130.1 (C1), 149.5 (C3), 154.3 (C4), 190.5 (HC=O).

<u>Compound 45</u>

The dithiane <u>42</u> (1.0 g, 3.106 mmol) was dissolved in anhydrous THF (Dried over $Na/Ph_2C=O$, 20 ml) in a 3-neck flask and cooled, with stirring to -78°C (dry ice/acetone).

n-BuLi, standardised by the method of Kofron (1976) (2.0 ml, 3.32 mmol) was added dropwise over 30 min, to give the 2-lithio-1,3-dithiane <u>44</u>. The mixture was stirred under N_2 at -78°C for 30 min, then a solution of compound <u>43</u> (0.50 g, 3.105 mmol) in anhydrous THF (5 ml) was added dropwise over 30 min. The mixture was allowed to warm to room temperature (ca. 4 hr) and poured into H_2O. The mixture was extracted with EtOAc and washed with saturated aqueous NaCl. The organic layer was dried over anhydrous $MgSO_4$ and the solvent removed under reduced pressure to give a yellow oil (1.5 g).

The oil was triturated with ethanol, with heating to give white crystals which were recrystallised from ethanol to give white plates (500 mg, 33%).

^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.80 (2H, m, $-CH_2-$), 2.65 (4H, m, $-SCH_2-$), 2.90 (1H, d, J = 6.0, β-OH), 3.54 (3H, s, OCH_3), 3.70 (3H, s, OCH_3), 3.81 (3H, s, OCH_3), 4.88 (1H, d, J = 6.0, Hβ), 6.20-6.90 (4H, m, ArH), 7.10-7.50 (7H, m, ArH).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 24.9 ($-CH_2-$), 27.3 (SCH_2), 27.4 (SCH_2), 55.5 (OCH_3), 55.8 (OCH_3), 56.1 (OCH_3), 66.5 (Cα), 70.9 (benzyl CH_2), 80.8 (Cβ), 109.2 (B2), 111.4 (A2), 113.0 (A5), 115.0 (B5), 120.9 (A6), 123.5 (B6), 127.3 (benzyl 3,5), 127.9 (benzyl 4), 128.6 (benzyl 2,6), 130.1 (A1), 130.2 (B1), 137.1 (benzyl 1), 147.6 (A3), 147.6 (B3), 149.0 (B4) 149.7 (A4).

Compound 46

The 2-lithio-1,3-dithiane 44 (1.0 g, 3.106 mmol) was formed by the method described previously for compound 45. 2,3-Dimethoxybenzaldehyde 12 (0.5 g, 3.106 mmol) in THF was added with stirring at -78°C. The mixture was allowed to warm to room temperature. After 4 hours, the mixture was poured into water, extracted with

EtOAc, and the organic layer dried over anhydrous $MgSO_4$. The solvent was removed under reduced pressure to give a yellow oil (1.5 g). The oil was triturated (with heating) with ethanol to give white crystals. These were used as seeds for the remaining material, which was crystallised from diethyl ether/pet. ether (40-60°C) to give yellow plates (970 mg, 64%).

^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.90 (2H, m,-CH_2-), 2.72 (4H, m, -SCH_2-), 3.33 (1H, d, J = 6.0, ß-OH), 3.63 (3H, s, OCH_3), 3.68 (3H, s, OCH_3), 3,78 (3H, s, OCH_3), 5.16 (2H, s, CH_2Ph), 5.38 (1H, d, J = 6.0, Hß), 6.40 (1H, dd, J = 5.9, 3.5, ArH), 6.80 (3H, m, ArH), 7.20 (1H, d, J = 2.3, H2) 7.25-7.50 (6H, m, ArH).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 24.9 (-CH_2-), 27.3 (SCH_2), 27.5 (SCH_2), 55.9, 56.1 (A3,B3-OCH_3), 60.8 (B2-OCH_3), 66.3 (Cα), 71.0 (benzyl CH_2), 75.7 (Cß), 112.4 (A2), 113.2 (B4), 114.8 (A5), 121.7 (A6), 122.4 (B6), 123.3 (B5), 127.4 (benzyl 3,5), 127.9 (benzyl 4), 128.6 (benzyl 2,6), 130.6 (B1), 131.0 (A1), 137.2 (benzyl 1), 147.5 (B2), 147.8 (A3), 149.1 (A4), 152.8 (B3).

Compound 49

Compound 45 (10 mg, 0.02 mmol) was reacted with neat $SOCl_2$ (0.5 ml) for 5 minutes. The $SOCl_2$ was removed under reduced pressure to give a yellow oil (8 mg).

^{1}H NMR (200 MHz, $CDCl_3$) δ: 3.89 (9H, s, OCH_3), 5.12 (2H, s, CH_2Ph), 5.16 (1H, s, Hß), 6.60-7.15 (3H, m, ArH), 7.20-7.50 (5H, m, ArH), 7.52 (2H, m, H2, H6).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 56.1 (OCH_3), 56.2 (OCH_3), 62.2 (Cß), 71.0 (benzyl CH_2), 110.2 (B2), 111.5 (A2), 111.7 (A5), 113.7 (B5), 121.1 (A6), 123.8 (B6), 127.3 (benzyl 3,5), 128.0 (benzyl 4), 128.7 (benzyl 2,6), 131.0 (B1), 131.4 (A1), 136.8 (benzyl 1), 149.1 (B3), 149.3 (A3), 150.2 (B4), 153.4 (A4), 190.1 (αC=O).

Reaction of 45 with $SOCl_2$/pyridine (Compound 59)

Compound 45 (20 mg, 0.041 mmol) was dissolved in $CHCl_3$ (2 ml). To this was added pyridine (4 µl, 0.049 mmol) and $SOCl_2$ (3.25 ul, 0.045 mmol) and the mixture stirred for 45 min. The mixture was poured into H_2O and extracted into $CHCl_3$. The organic layer was dried over $MgSO_4$ and the solvent removed under reduced pressure to give a clear, colourless oil (20 mg), which was identified as compound 59.

^{1}H NMR (200 MHz, $CDCl_3$) δ: 2.15 (2H, m, $-CH_2-$), 3.56 (3H, s, OCH_3), 3.62 (3H, s, OCH_3), 3.70 (4H, m, $-SCH_2-$), 3.80 (3H, s, OCH_3), 5.05 (2H, s, CH_2Ph), 6.50-6.90 (6H, m, ArH), 7.30-7.50 (5H, m, ArH).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 28.7 ($-CH_2-$), 32.1 (SCH_2), 55.8 (OCH_3), 70.9 (benzyl CH_2), 110.4 (B2), 113.1 (A2), 114.6 (A5), 115.1 (B5), 123.5 (A6), 123.5 (B6), 127.3 (benzyl 3,5), 127.8 (benzyl 4), 128.5 (benzyl 2,6), 129.9 (A1), 130.0 (B1), 134.1 (Cα)<->134.7 (Cß), 137.1 (benzyl 1), 147.3 (B3), 148.1 (B4), 148.1 (A3), 148.8 (A4).

Reaction of 45 with PPh_3/CBr_4

Compound 45 (20 mg, 0.041 mmole) was added to ether (5 ml). As dissolution of 45 was incomplete, a drop of dioxane was added. To this was added CBr_4 (27.2 mg, 0.082 mmol) and PPh_3 (21 mg, 0.082 mmol) and the mixture stirred for 3 hours. The mixture was poured into H_2O and extracted into $CHCl_3$. The organic layer was dried over $MgSO_4$ and the solvent removed under reduced pressure to give 59 as a clear yellow oil (also $CBr_4/Ph_3P{=}O$ and PPh_3 present). ^1H and ^{13}C NMR data as above for 59.

3,4-dimethoxybenzyl chloride (60)

3,4-dimethoxybenzyl alcohol (2.0 g, 11.9 mmol) was dissolved in $CHCl_3$ (20 ml). To this was added dropwise a solution of $SOCl_2$ (0.91 ml, 12.4 mmol) in $CHCl_3$ (20 ml) over 10 min. The mixture was stirred (vigorous evolution of gas) for 2 hr. The volatiles were removed under reduced pressure to give a royal blue oil (2.2 g, 100%). This was decolourised with activated charcoal to give 60 as a clear, colourless oil (since 60 darkened on exposure to light, it was kept in a light-tight container).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 46.7 (Cα), 55.8 (OCH_3), 110.0 (C2), 111.8 (C5), 121.2 (C6), 130.0 (C1), 149.1 (C3), 149.2 (C4).

2,3-dimethoxybenzyl chloride (61)

2,3-dimethoxybenzyl alcohol (2 g, 11.9 mmol) was chlorinated by the above method (see compound 60). Removal of the solvent gave a clear oil (2.2 g, 100%).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 41.2 (Cα), 55.8 (3-OCH_3), 61.2 (2-OCH_3), 113.0 (C4), 122.0 (C6), 124.2 (C5), 131.6 (C1), 147.5 (C2), 152.8 (C3).

2-benzyloxy-3-methoxybenzyl chloride (62)

2-benzyloxy-3-methoxybenzyl alcohol (1.0 g, 4.10 mmol) was chlorinated by the method for compound 60. Removal of the solvent gave 62 as a clear, colourless oil.

^{13}C NMR (50 MHz, $CDCl_3$) δ: 41.5 (Cα), 56.0 (OCH_3), 75.2 (benzyl CH_2), 113.2 (C4), 122.4 (C6), 124.5 (C5), 128.3 (benzyl 4), 128.5, 128.6 (benzyl 2,3,5,6), 132.0 (C1), 137.8 (benzyl 1), 146.3 (C2), 153.0 (C3).

Compound 63

The 2-lithio-1,3-dithiane 44 (1.0 g, 3.106 mmol) was formed by the method described previously for compound 45. 3,4-Dimethoxybenzyl chloride 60 (520 mg, 2.80 mmol was added dropwise with stirring at -78°C. The mixture was alowed to warm to room temperature. After 4 hours the mixture was poured onto water, extracted with EtOAc, and the organic layer dried over anhydrous $MgSO_4$, to give a yellow oil (1.50 g). The oil was triturated with EtOAc to give a brown oily solid (400 mg, 30%) which was shown to be compound 63.

^{1}H NMR (200 MHz, $CDCl_3$) δ: 2.04 (2H, m, -CH_2-), 2.75 (4H, m, -SCH_2-), 3.26 (2H, s, Hß), 3.62 (3H, s, OCH_3), 3.85 (3H, s, OCH_3), 3.90 (3H, s, OCH_3), 5.26 (2H, s, CH_2Ph), 6.12 (1H, d, J = 1.8, H2 or 2'), 6.5 (1H, dd, J = 1.8, 6.8, H6 or 6'), 6.73 (1H, d, J = 6.8, H5 or 5'), 6.80 (1H, d, J = 6.8, H5' or 5), 7.25-7.50 (7H, m, ArH).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 25.1 ($-CH_2-$), 27.5 ($-SCH_2-$), 55.3, 55.6, 55.7 (OCH_3), 51.1 (Cß), 59.8 (Cα), 70.7 (benzyl CH_2), 110.0 (A2), 111.7 (B2), 113.6 (A5), 114.0 (B5), 122.1 (A6), 123.2 (B6), 127.2 (benzyl 3,5), 127.8 (benzyl 4), 128.4 (benzyl 2,6), 133.4, 133.4 (A1, B1), 137.1 (benzyl 1), 147.3 (A3), 147.9 (B3), 148.9 (B4), 149.4 (A4).

Compound 64

The formation of 64 was accomplished as in the synthesis of 63, except that 2-benzyloxy-3-methoxybenzyl chloride 62 (720 mg, 2.80 mmol) added in place of 60. Workup gave a yellow oil (1.5 g). ^{1}H NMR showed a 50% yield of the addition product 64. The separation of 64 from 44 and 62 was difficult, as 64 could not be encouraged to crystallise from the reaction mixture. A small-scale separation by plc (eluted in $CHCl_3$) gave a 30% yield of 64.

^{13}C NMR (50 MHz, $CDCl_3$) δ: 27.9 ($-SCH_2-$), 32.3 ($-CH_2$), 44.1 (Cß), 56.0 (OCH_3), 60.0 (Cα), 71.0 (A4-benzyl CH_2), 74.1 (B2-benzyl CH_2), 111.6 (A2), 113.4 (A5), 113.4 (B4), 121.9 (A6), 122.6 (B6), 124.6 (B5), 127.4, 127.6, 127.9, 128.3, 128.6 (benzyl, 2,3,4,5,6,2',3',4',5',6') 129.6 (A1), 134.5 (B1), 137.3 (benzyl 1), 138.3 (benzyl 1'), 147.1 (B2), 147.2 (A3), 149.2 (A4), 152.6 (B3).

1-(4-benzyloxy-3-methoxyphenyl)-2-(3,4-dimethoxyphenyl)-ethan-1-one (65)

Compound 63 (100 mg, 0.212 mmol) was dissolved in THF/H_2O (5 ml:1 ml). To this was added $BF_3.Et_2O$ (70 µl) and the mixture stirred under N_2 for 1 hr. The mixture was extracted into $CHCl_3$ and washed with $NaHCO_3$. The organic layer was dried over anhydrous $MgSO_4$, and the solvent removed under reduced pressure to give 65 as a brown oil.

^{1}H NMR (200 MHz, $CDCl_3$) δ: 3.84 (6H, s, OCH_3), 3.90 (3H, s, OCH_3), 4.14 (2H, s, Hß), 5.20 (2H, s, CH_2Ph), 6.70-6.90 (5H, m, ArH), 7.20-7.50 (5H, m, ArH), 7.55 (2H, m, A2,A6).

^{13}C NMR (50 MHz, $CDCl_3$) δ:44.8 (Cß), 55.9,56.1 (OCH_3), 70.9 (CH_2Ph), 111.3 (B2)<->111.5(A2), 112.3 (A5)<->112.6 (B5), 121.5 (B6), 123.3 (A6), 127.2 (benzyl 3,5), 127.6 (A1), 128.2 (benzyl 4), 128.8 (benzyl 2,6), 130.1 (B1), 136.3 (benzyl 1), 148.1 (B3), 149.2 (A3), 149.7 (B4), 152.6 (A4),196.6 (α-C=O)

Mass Spectrum (probe, EI, 70 eV) m/z: 392 ($M^{+\cdot}$, 13), 242(13), 241(74), 151(23), 91(100). High resolution molecular ion at m/z 392.1611; calculated $M^{+\cdot}$ for $C_{24}H_{24}O_5$ = 392.1624.

1-(4-benzyloxy-3-methoxyphenyl)-2-(3,4-dimethoxyphenyl)-ethan-1-ol, (66)

Compound 65 (40 mg, 0.10 mmol) was dissolved in ethanol. To this was added $NaBH_4$ (20 mg, 0.5 mmol) and the reaction stirred overnight. The mixture was extracted into EtOAc, washed with NaCl, and the organic layer dried over $MgSO_4$. The solvent was removed under reduced pressure to give 66 as a clear, colourless oil (40 mg, 100%).

^{1}H NMR (200 MHz, $CDCl_3$) δ: 2.93 (2H, d, $J_{\alpha\beta}$ = 6.0, Hβ), 3.79 (3H, s, OCH_3), 3.84 (3H, s, OCH_3), 3.88 (3H, s, OCH_3), 4.77 (1H, t, J = 6.0, Hα), 5.15 (2H, s, CH_2Ph), 6.50-7.00 (6H, m, ArH), 7.20-7.50 (5H, m, ArH).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 45.7 (Cβ), 55.9, 56.0, 56.1 (OCH_3), 71.2 (CH_2Ph), 75.2 (Cα), 109.9 (A2), 111.4 (B2), 112.9 (B5), 14.0 (A5), 118.3 (A6), 121.6 (B6), 127.3 (benzyl 3,5), 127.9 (benzyl 4), 128.6 (benzyl 2,6), 130.6 (B1), 130.6 (A1), 137.2 (benzyl 1), 147.6 (A3), 147.9 (B3), 148.9 (B4), 149.8 (A4).

1-(4-hydroxy-3-methoxyphenyl)-2-(3,4-dimethoxyphenyl)-ethan-1-ol (67)

Compound 66 (30 mg, 0.076 mmol) was dissolved in methanol (20 ml), and debenzylated in the normal way to give 67 as a light yellow oil (20 mg, 87%).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 45.7 (Cβ), 55.9, 56.0 (OCH_3), 75.3 (Cα), 108.7 (A2), 111.4 (B2), 112.9 (B5), 114.2 (A5), 119.0 (A6), 121.6 (B6), 130.6 (B1), 136.0 (A1), 145.1 (A4), 146.6 (A3), 147.9 (B3), 148.9 (B4).

1-(4-acetoxy-3-methoxyphenyl)-2-(3,4-dimethoxyphenyl)-ethyl acetate (68)

Acetylation of 67 gave 68.

^{1}<u>H NMR</u> (200 MHz, $CDCl_3$) δ: 2.04 (3H, s, α-OAc), 2.30 (3H, s, Ar-OAc), 2.98 (1H, dd, $J_{\beta 1\alpha}$= 6.6, $J_{\beta_1\beta_2}$ = 13.9, $H\beta_1$), 3.10 (1H, dd, $J_{\beta_2\alpha}$ = 7.3, $J_{\beta_2\beta_1}$, = 13.9, $H\beta_2$), 3.767 (3H, s, OCH_3), 3.772 (3H, s, OCH_3), 3.772 (3H, s, OCH_3), 3.84 (3H, s, OCH), 5.87 (1H, dd, $J_{\alpha\beta_1}$ = 6.6, $J_{\alpha\beta_2}$ = 7.3, Hα), 6.50-7.00 (6H, m, Ar-H).

CHAPTER THREE

THE STEREOCHEMISTRY OF ß-5 LIGNIN MODEL COMPOUNDS

3.1 INTRODUCTION

In the course of our studies (Ralph, 1987a) on the reactions of ß-5 lignin model compounds with anthrahydroquinone and anthranol, we needed to know the stereochemistry of the lignin model compounds used. Although lignin is a racemic polymer, there is a large number of substructures possessing 2 adjacent asymmetric carbon atoms, Cα and Cß. This feature gives rise to erythro/threo stereoisomerism.

For compounds with two adjacent asymmetric carbon atoms, the erythro/threo nomenclature is a convenient way to assign relative stereochemistry. A problem exists however in assigning chemically similar groups, since the erythro/threo nomenclature is only valid for adjacent asymmetric carbons where there are two pairs of equivalent groups and the third pair is different. Hence for 1,2-diarylpropane-1,3-diols (representing ß-5 and ß-1 linkages), the two aromatic substituents and the two hydrogen atoms are logically chosen as the two chemically similar pairs; the two conformations are shown in the Fischer projections in Figure 1. For lignin models of the guaiacylglycerol-ß- guaiacyl ether type (representing the ß-0-4 linkage in lignin), the α-OH and the ß-OAr are chosen as one

---

Footnote: A paper detailing the majority of the work in this chapter has been accepted by Holzforschung for publication (Ede, 1987a).

equivalent pair, the other being the protons. The appropriate Fischer projections are therefore those shown in Figure 2. Some confusion about these descriptions is apparent in the literature. In a recently published paper (Chen, 1985), ß-1 model compound isomers were misassigned, since the assignments were based on the ß-ether erythro/threo nomenclature. The unambiguous R/S nomenclature is given in Figures 1 and 2.

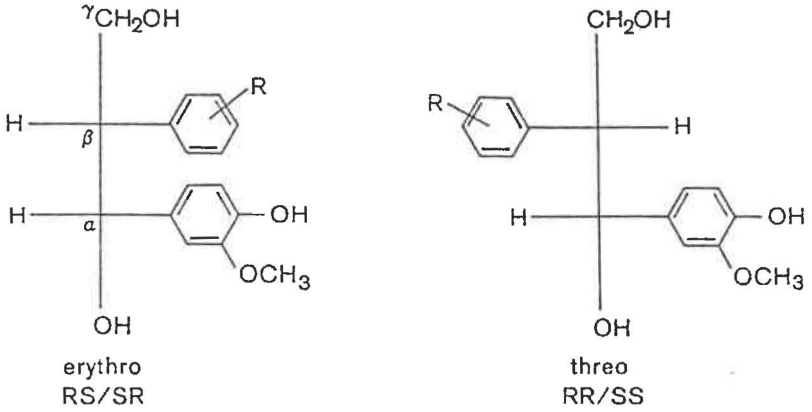


Figure 3.1. Fischer projections for ß-1 and ß-5 models

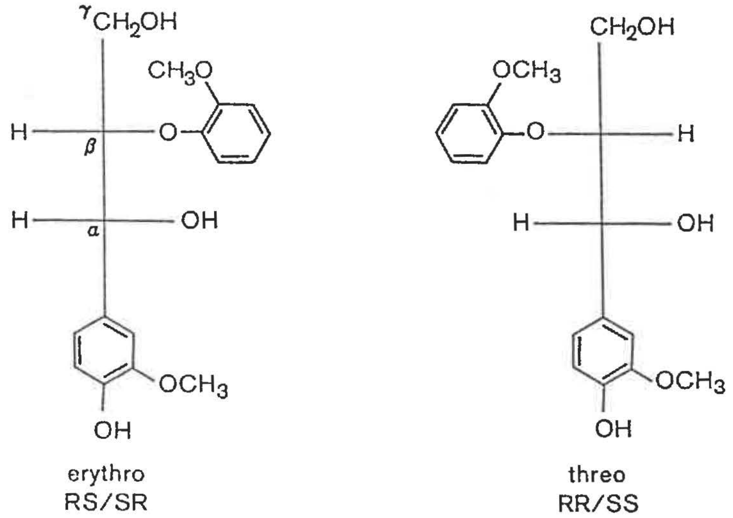


Figure 3.2. Fischer projections for ß-O-4 models

The stereochemistry of the propyl sidechains in the ß-5 model 2.23 synthesised by Brunow (1984), had been assigned as erythro based on comparisons of the ^{1}H NMR coupling constants of the tetra-acetate with a range of previously synthesised compounds

(Kristersson, 1980; Ahvonen, 1983). These assignments were, in turn, based on comparisons of ^{1}H NMR coupling constants with related compounds (Nakatsubo, 1975; Ferrand, 1975) whose stereochemistries were determined from NMR spectra of the corresponding phenylboronates or acetals.

While ^{1}H NMR is an excellent diagnostic tool in most cases, it is not always reliable for extrapolating stereochemical assignments over a number of syntheses. ^{1}H NMR coupling constants in aliphatic systems depend, in part, on the torsional angle between vicinal protons. If the molecule exists in an unusual conformation in solution, incorrect stereochemical assignments can result. Further evidence should be obtained to be certain of stereochemical assignments. The syntheses of the acetals (Ralph, 1983c) or phenylboronates (Nakatsubo, 1975) are simple and rapid, and by "locking" the molecule into a six-membered ring, the dihedral angles implied by the ^{1}H NMR coupling constants allow an unambiguous assignment in most cases.

This chapter discusses the synthesis and characterisation of phenylboronates <u>1</u>-<u>3</u> of the ß-5 lignin model compounds <u>2.17</u>, <u>2.18</u>, and <u>2.26</u> as a means of identifying the stereochemistry of these compounds. The preparation of phenylboronates or acetals is only possible if a 1,3-propanediol is present. For phenylcoumaran models such as dihydrodehydrodiisoeugenol <u>2.6</u>, which have two adjacent asymmetric carbons, some confusion as to the stereochemistry has been present in the literature. Conflicting stereochemical predictions have been derived from NMR (Ludwig, 1964) and chemical

(Aulin-Erdtmann, 1963) evidence. We sought to resolve this conflict unambiguously by an X-ray diffraction crystal structure determination of dihydrodehydrodiisoeugenol.

Although the chemical and NMR evidence for the stereochemistry of 2.26 confirms the *erythro* conformation, little is known of the conformations of the ß-C linked models. Along with the crystal structure of 2.6, an X-ray structure of the ß-C model 2.28 is presented. Although lignin is not a crystalline polymer, these structures may aid our understanding of the conformation of lignin sub-units.

3.2 RESULTS AND DISCUSSION

3.2.1 Synthesis of ß-5 Model Compounds

Compounds 2.17, 2.18, and 2.26 were synthesised as described in Chapter 2. All syntheses gave single, pure isomers. ^{1}H NMR spectra showed that the ß and γ proton resonances were obscured by the methoxyl resonances, particularly in compounds 2.18 and 2.26. More suitable spectral dispersion was obtained from ^{1}H NMR spectra of the acetates of 2.18 and 2.26, but an unambiguous assignment of stereochemistry of any of these was not possible based on NMR evidence, particularly without the other isomer on which to base comparisons. Dihydrodehydrodiisoeugenol 2.6 was obtained as described in Chapter 2.

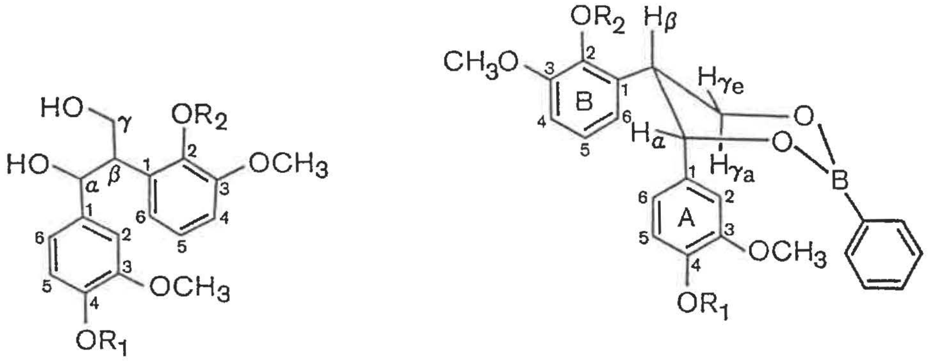
Footnote: Since compounds 2.17, 2.18, 2.26 and 1-3 contain no substituent in what in lignin units would be the 1 position on the B ring, the B ring is labelled starting from the ß-C linkage as in conventional nomenclature.

3.2.2 Synthesis of Phenylboronates

Phenylboronates 1-3 (see Figure 3) were synthesised from models 2.17, 2.18 and 2.26 by the method of Nakatsubo (1975). They were obtained as single isomers in quantitative yield.

3.2.3 Characterisation of Erythro Phenylboronates

200 MHz ^1H NMR spectra of 1-3 showed sufficient dispersion of the Hα, Hβ, and Hγ resonances for an unambiguous stereochemical assignment. For an ideal chair conformation, protons on adjacent carbons are oriented either axial-axial (with a 180° dihedral angle and J ∿ 10 Hz), axial equatorial (60°, J ∿ 3 Hz), or equatorial-equatorial (60°, J ∿ 3 Hz). In compounds 1-3, $J_{\beta\gamma_{eq}}$ = 4 Hz and $J_{\beta\gamma_{ax}}$ = 10-12 Hz. The αβ coupling constant suggests either an axial-equatorial or equatorial-equatorial orientation, but the large $J_{\beta\gamma_{ax}}$ indicates that Hβ must be axial, hence Hα must be equatorial. This leads to a unique (for phenylboronates of lignin model compounds) axial-equatorial arrangement of the aromatic rings A and B on Cα and Cβ and hence an erythro configuration.



1 $R_1 = R_2 = CH_2Ph$

2.23 $R_1 = R_2 = H$ 2.18 $R_1 = CH_2Ph$, $R_2 = CH_3$ 2 $R_1 = CH_2Ph$, $R_2 = CH_3$

2.17 $R_1 = R_2 = CH_2Ph$ 2.26 $R_1 = H$, $R_2 = CH_3$ 3 $R_1 = H$, $R_2 = CH_3$

Figure 3.3. β-5 lignin model compounds and phenylboronates

An interesting result of this configuration is seen in the ^1H NMR spectra. The A ring protons appear to be in the shielding region of the phenyl ring attached to the boron or the B ring, as evidenced by the unusual shifts in 2 of 6.11, 6.74, and 6.55 ppm for protons A2, A5, and A6 respectively. The B ring proton B6 is also extensively shielded (δ B6 = 5.92 ppm). This spectral dispersion of the aromatic protons allows correlation of the ^1H and ^{13}C chemical shifts by use of 2D-NMR. ^{13}C-^1H NMR shift correlation spectroscopy (Bax, 1981) allows assignment of the ^{13}C chemical shifts based on correlations with the appropriate proton signals. These can be assigned on the basis of their multiplicities and coupling constants (see Figure 4). In particular it is possible to distinguish between carbons A2 (111.19 ppm) and B4 (111.32 ppm) since proton A2 is a d, $\delta = 6.11$, $J_{26} = 2.1$ Hz and B4 is a dd, $\delta = 6.81$, $J_{45} = 6.0$ Hz, $J_{46} = 2.7$ Hz.

It is even possible from the 2D-spectrum of 2 to fully assign the methoxyl signals in the ^{13}C and ^1H spectra. This is aided by the shielding of (presumably) the A3-OCH_3 in the ^1H NMR spectrum, and a down-field shift of 5 ppm in the resonance of the sterically crowded B2 methoxyl in the ^{13}C NMR spectrum.

Since ^{13}C nuclei are relatively insensitive to the shielding effects of the diamagnetic aromatic ring currents, it is expected that the ^{13}C shifts in the non-complexed lignin models may also be assigned from this data.

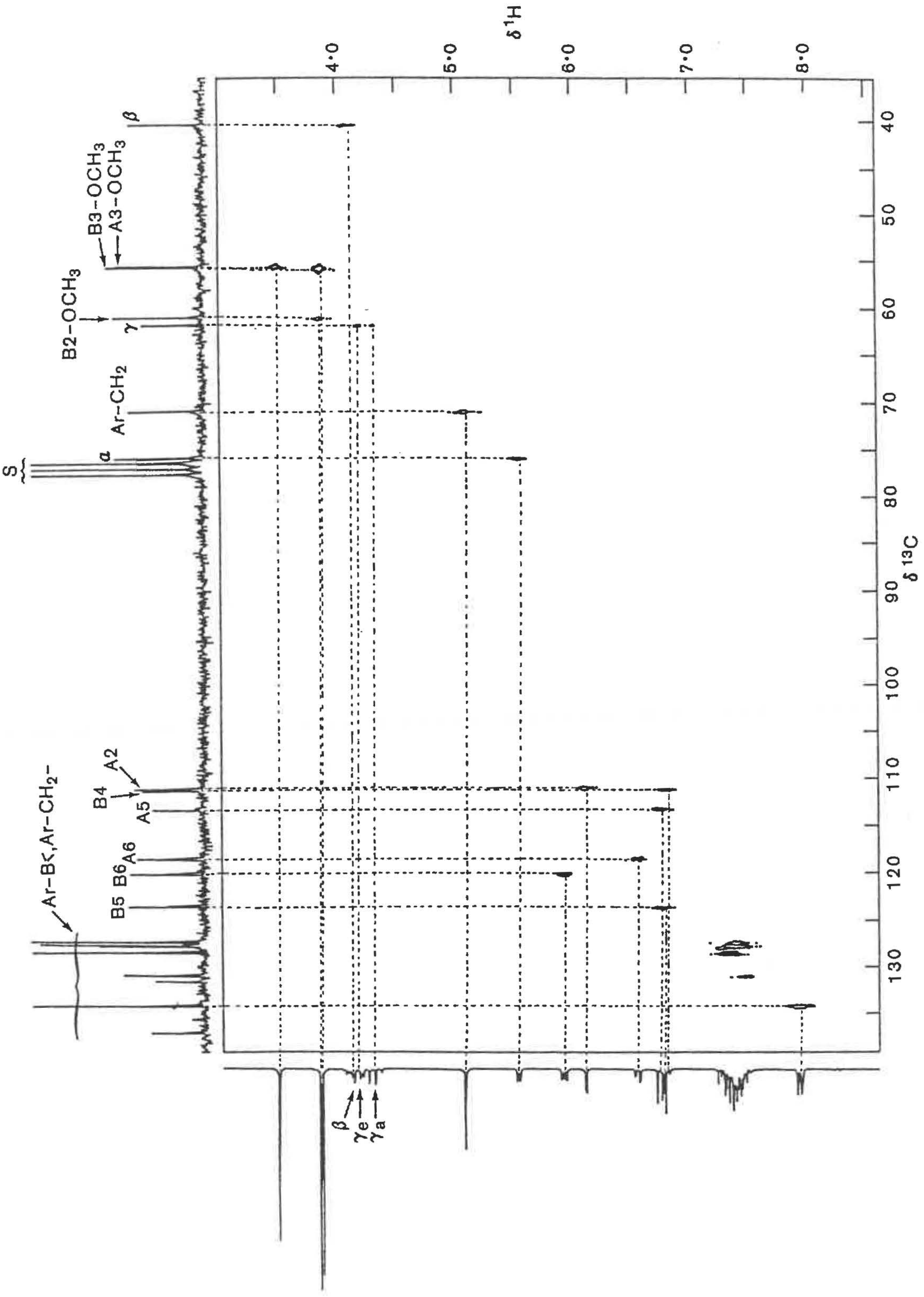


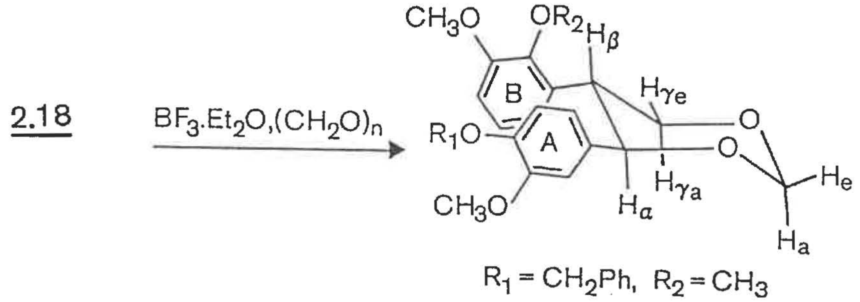
Figure 3.4. 2D ^{13}C-^{1}H shift correlation spectrum of 2.

3.2.4 Attempted Synthesis of threo-2.18

It was possible to obtain low yields of threo 2.18 by $NaBH_4$ reduction of α-ketone 4 (see experimental section), which was obtained by oxidation of erythro 2.28 with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ, Becker 1961).

$NaBH_4$ reduction of 4 in methanol/OH^- gave a 10:45:45 ratio of threo-2.18:erythro-2.18:erythro boric acid complex of 2.18. Reaction of the crude mixture with phenylboric acid gave 10:90 threo 2:erythro 2. It was not possible to effect the separation of the two isomers chromatographically as the threo isomer degraded on the silica gel.

It was thought that partial conversion of erythro to threo may be obtained by isomerising erythro 2.18 with $BF_3.Et_2O$ in the presence of paraformaldehyde to form the acetal (Ralph, 1983c; Brezny, 1978). ^1H NMR examination of the crude reaction mixture showed that >90% conversion to the threo acetal 5 had occurred. Although this compound was unstable on silica gel, it was possible to isolate it by preparative layer chromatography pure threo 5 (see Figure 5). Attempts to remove the acetal to give threo 2.18 by reaction of 5 with $FeCl_3/SiO_2$ (Kim, 1986) were not successful.



5

Figure 3.5. Synthesis of threo acetal 5.

3.2.5 Characterisation of threo-5

The major evidence for the threo conformation is the large (10 Hz) value for $J_{\alpha\beta}$ which is consistent with a diaxial arrangement of Hα and Hβ on the six-membered ring. The $^{13}C-^{1}H$ shift correlation spectrum of 5 confirmed the chemical shift assignments. In this case, it was shown that the shielded methoxyl resonance in the ^{1}H NMR spectrum was due to the B2-OCH_3 (cf compound 2).

3.2.6 Crystal Structure of Dihydrodehydrodiisoeugenol 2.6

Colourless needles of 2.6 suitable for a crystallographic study were obtained by recrystallisation from petroleum ether (100-120°C). Analysis (see Figure 6) showed that the crystal contained molecules of $C_{20}H_{24}O_4$ held together within the crystal by hydrogen bonds involving the hydroxyl group, as shown in the stereographic projection of the unit cell (Figure 7).

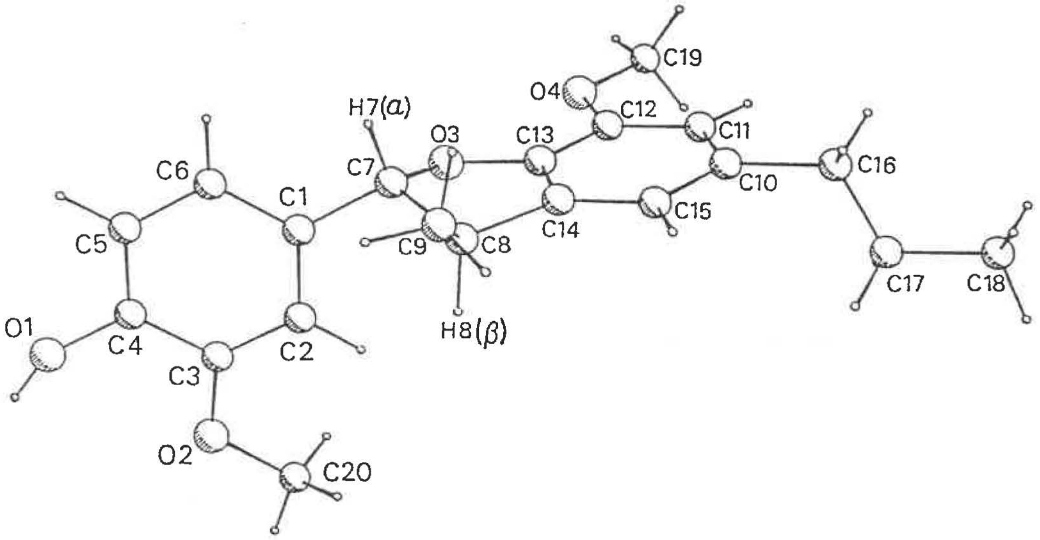


Figure 3.6. X-ray structure of 2.6.

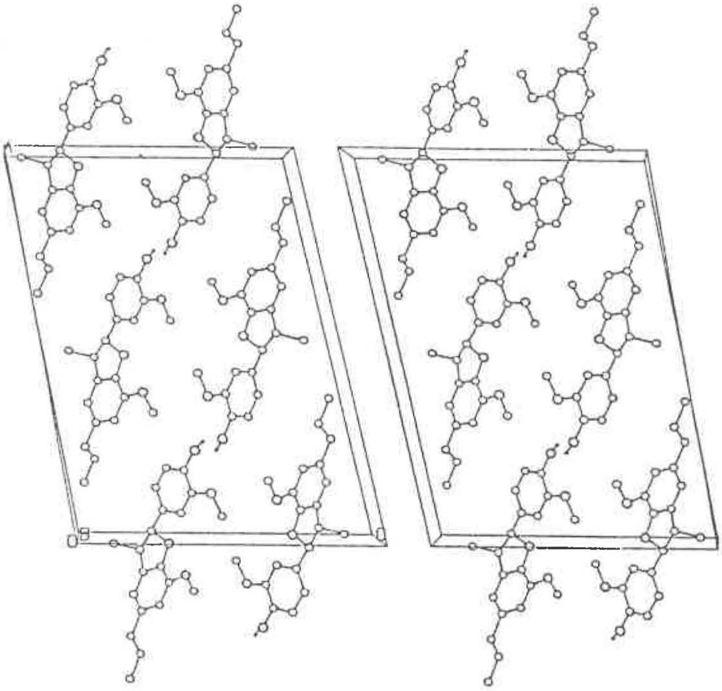


Figure 3.7. Stereographic projection of unit cell of <u>2.6</u>.

It is clear from Figure 6 that the dihydrobenzofuran ring of <u>2.6</u> is twisted from planar, giving rise to a torsional angle of ca. 145° for H7 and H8 (Hα and Hβ in conventional nomenclature). The <u>erythro</u> (transoid) stereochemistry is also clear. The torsional angle may explain the $J_{\alpha\beta}$ = 9.7 Hz observed in the ^{1}H NMR spectrum. Based on a simplistic Karplus treatment, a <u>threo</u> (cisoid) conformation would be expected from a large coupling constant (implying a dihedral angle of 0° or 180°). The Karplus equation however, was derived for substituted ethanes and is not valid for a highly substituted 5-membered ring containing a heteroatom. It should be noted that the solution conformation (giving rise to the ^{1}H NMR coupling constants) may not necessarily be identical to the solid-state arrangement.

3.2.7 Crystal Structure of 1-(4-hydroxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-propane-1,3-diacetate (2.28)

Colourless needles of 2.28 suitable for a crystallographic study were obtained from slow evaporation of chloroform. Analysis showed that the crystal contained molecules of $C_{22}H_{26}O_8$ held together within the crystal by hydrogen bonds involving the hydroxyl group, as shown in the stereographic projection of the unit cell. The molecules were oriented "head-to-tail" to achieve this arrangement.

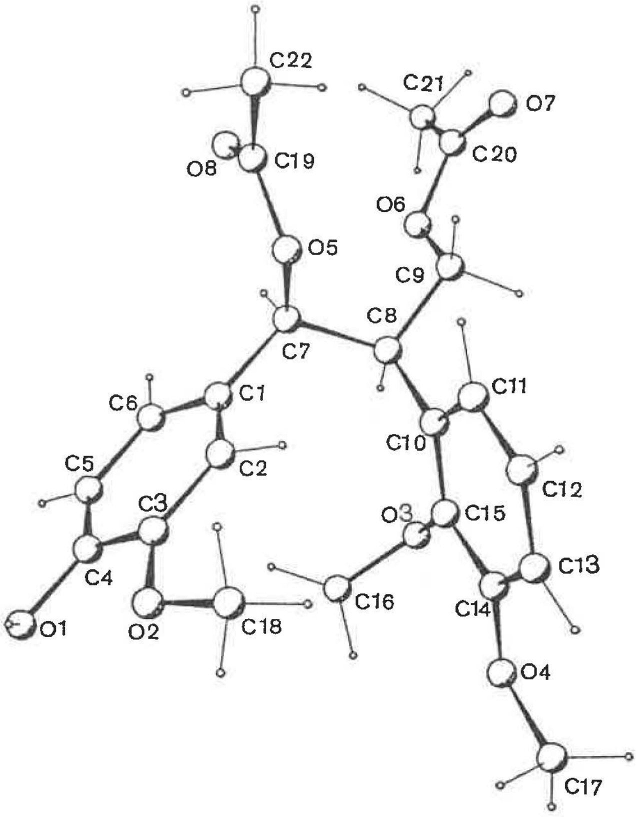


Figure 3.8. X-ray structure of 2.28 showing atom labelling.

The configuration of 2.28 is somewhat unusual, as it has adopted a folded arrangement. Simplistically a configuration would be expected with the 2 aromatic rings trans (see Newman projections in Figure 10) to minimise steric interaction, rather than that observed in the crystal structure.

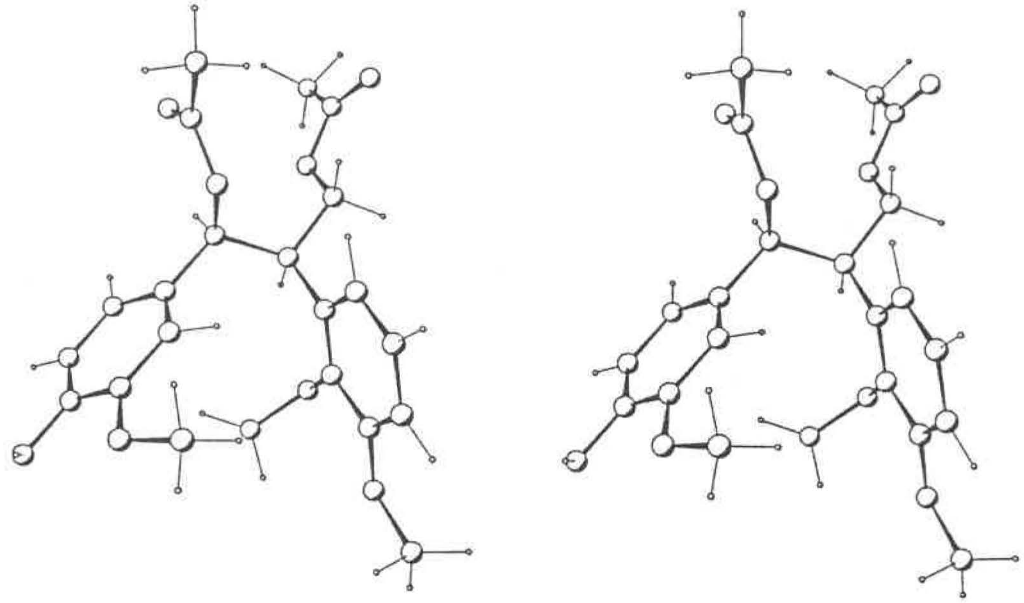
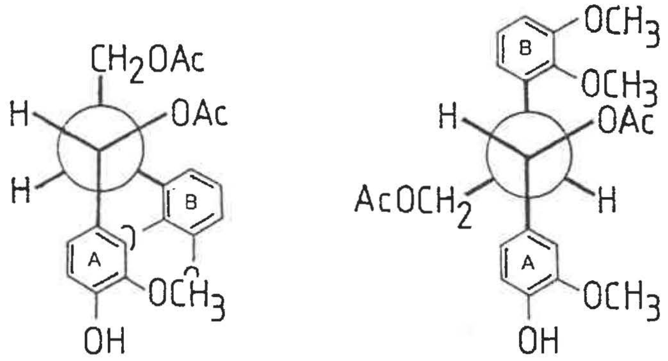


Figure 3.9. Stereographic projection of 2.28 showing "folded" structure.



Observed X-Ray Structure

Structure Minimising Aryl Group Interaction

Figure 3.10. Newman projections of 2.28.

3.3 CONCLUSIONS

The synthesis of the phenylboronates 1-3 of ß-5 lignin models 2.17, 2.18 and 2.26 has shown that the stereochemistry is indeed *erythro* as previously reported (Brunow, 1984). The evidence for the configuration (coupling constants in a 6-membered ring) is more conclusive than that obtained from non-rigid propane-1,3-diacetates. Unfortunately, final confirmation from the phenylboronate of an independently synthesised *threo* isomer was not available.

In the case of dihydrodehydrodiisoeugenol 2.6, where NMR evidence did not fit well with chemical evidence, the X-ray structure proved the chemically predicted *transoid* configuration.

3.4 EXPERIMENTAL

The ^{13}C-^{1}H shift correlation spectra (Bax, 1981) were obtained on a Bruker AC200 using the Bruker pulse program XHCORR. Parameters: 1 K data points in F_2 (^{13}C) domain, 256 data points zero-filled to 512 in F_1 (^{1}H) domain, recycle delay = 2 s, 96 scans for each experiment, with 256 experiments. Lorentzian-Gaussian resolution enhancement was applied in both domains. Correlation peaks were obtained for all non-quaternary carbons.

3.4.1 Crystal and Molecular Structure of 2.6

A colourless needle was obtained by recrystallisation from petroleum ether (100-120°C). Preliminary precession photography indicated a monoclinic space group. Lattice parameters were obtained from the setting angles of 25 reflections centred on an Enraf-Nonius CAD4 diffractometer using monochromated Mo-Kα X-radiation.

Crystal Data

$C_{20}H_{24}O_4$, Mr = 328; Monoclinic, space group $P2_1/a$ (a non-standard setting of $P2_1/c$), $\underline{a}$ = 22.229(3), $\underline{b}$ = 5.008(1), $\underline{c}$ = 16.811(2), ß = 103.60(1), V = 1819.1 $Å^3$ D_c = 1.197 g cm^{-3} for Z = 4. F(000) = 696e, (Mo-Kα) = 0.5 cm^{-1}, T = 23°C.

Intensity data were collected in the range $0.5° < \theta < 25°$ using an w-2θ scan technique. The data were corrected for Lorentz, polarisation and absorption (by an azimuthal scan method). Of the 2211 unique reflections 1140 had $I > 2\sigma(I)$ and were used in all calculations.

The structure was solved by direct methods (Sheldrick, 1976). In the final full-matrix least-squares refinement, non-ring atoms were assigned anisotropic temperature factors, ring atoms were treated isotropically, and hydrogen atoms were included in calculated positions with common isotropic temperature factors for each type of hydrogen. The refinement converged with R = 0.0694, R_w = 0.0692 where $w = 3.0[\sigma^2(F) + 0.001F^2]^{-1}$ with no parameter shifting by more than 0.1σ . A final difference map showed no peaks greater than 0.24 $eÅ^{-3}$.

Lists of bond lengths, bond angles, atomic positions, thermal parameters, hydrogen atom positions, and structure factors are included in the Appendix to this Thesis.

3.4.2 Crystal and Molecular Structure of 2.28

A colourless needle (0.30 x 0.15 x 0.10 mm) was obtained from slow evaporation of a chloroform solution. Preliminary precession photography indicated triclinic symmetry. The space group $P\bar{1}$ was assumed and confirmed by the successful refinement. Lattice parameters were obtained from the setting angles of 25 reflections centred on an Enraf-Nonius CAD4 diffractometer using unmonochromated Mo-Kα X-radiation (0.7107 Å).

Crystal Data

$C_{22}H_{26}O_8$, Mr = 418.44, triclinic, space group $P\bar{1}$,
$\underline{a}$ = 7.998(3), $\underline{b}$ = 16.460(2), $\underline{c}$ = 8.404(1), α = 99.49(1),
β = 99.17(2), γ = 86.16(2), V = 1068.2 $Å^3$, D_c = 1.276 g cm^{-3}
for Z = 2, D_o = 1.29 gcm^{-3}, F(000) = 444e, Mo-Kα) = 0.5 cm^{-1},
T = 20(1)°C.

Intensity data were collected in the range $1.5<\theta<18°$ using an w-2θ scan technique. The data were corrected for Lorentz, polarisation and absorption (by an azimuthal scan method). Some degradation of the crystal was observed under X-rays. Of the 2340 unique reflections, 1250 had $I>2\sigma(I)$ and were used in all calculations.

The structure was solved by direct methods (Sheldrick, 1976). In the final full-matrix least-squares refinement, the skeletal carbon atoms were treated isotropically, with the acetate methyls and carbonyls, the methoxyl methyls, the phenolic oxygen and the B3-methoxy oxygen were assigned anisotropic temperature factors. Hydrogen atoms were included in calculated positions with common isotropic temperature factors for each type of hydrogen. The phenolic hydrogen appeared as the highest peak in the penultimate difference map and was included, but not refined. The refinement converged with R = 0.0764, R_w = 0.0703, where $w = 2.34\ [\sigma^2(F) + 0.0006\ F^2]^{-1}$ with no parameter shifting by more than 0.15 e.s.d. A final difference map showed no peaks greater than 0.34 e $Å^{-3}$.

Lists of bond lengths, bond angles, thermal parameters, hydrogen atom positions and structure factors can be found in the Appendix.

3.4.3 Synthetic Methods

Compounds 2.17, 2.18, 2.6 and 2.28 were synthesised as described in Chapter 2.

Phenylboronates 1-3 were synthesised by the method of Nakatsubo and Higuchi (Nakatsubo, 1975).

Compound 1

^{1}H NMR (200 MHz, $CDCl_3$) δ: 3.51 (3H, s, A3-OCH_3), 3.90 (3H, s, B3-OCH_3), 3.96 (1H, ddd, $J_{\alpha\beta}$ = 4.9, $J_{\beta\gamma e}$ = 4.0, $J_{\beta\gamma a}$ = 12.2, Hβ), 3.98 (1H, dd, $J_{\gamma e\gamma a}$ = 12.2, $J_{\gamma e\beta}$ = 4.0, $H\gamma_e$), 4.19 (dd, $J_{\gamma a\gamma e}$ = 12.2, $J_{\gamma a\beta}$ = 12.2, $H\gamma_a$), 4.96 (1H, d, J = 11.3, B2-benzyl CH), 5.08 (2H, d, A4-benzyl CH_2), 5.12 (1H, d, J = 11.3 B2- benzyl CH), 5.37 (1H, br d, $J_{\alpha\beta}$ = 4.9, Hα), 5.88 (1H, dd,

J_{56} = 7.3, J_{46} = 2.1, B6), 6.09 (1H, d, J_{26} = 2.1, A2), 6.50 (1H, dd, J_{56} = 8.2, J_{26} = 2.1, A6), 6.75 (1H, d, J_{56} = 8.2, A5), 6.81 (1H, dd, J_{45} = 8.5, J_{56} = 7.3, B5), 6.84 (1H, dd, J_{45} = 8.5, J_{46} = 2.1, B4), 7.20-7.60 (13H, m, Ar-H), 7.90 (2H, dd, J = 7.3, J = 1.7, boron phenyl H2, H6).

^{13}<u>C NMR</u> (50 MHz, $CDCl_3$) δ: 40.5 (Cß), 55.7 (A3-OCH_3), 55.8 (B3-OCH_3), 62.0 (Cγ), 71.1 (A4-benzyl CH_2), 74.8 (B2-benzyl CH_2), 75.8 (Cα), 111.3 (A2, B4), 113.4 (A5), 118.6 (A6), 120.3 (B6), 123.7 (B5), 127.3 (A4-benzyl C3, C5), 127.7 (boron phenyl C3, C5), 127.8 (A4-benzyl C4), 128.0 (B2-benzyl C4), 128.2 (B2-benzyl C3, C5), 128.3 (B2-benzyl C2, C6), 128.5 (A4-benzyl C2, C6), 130.8 (boron phenyl C4), 131.3 (A1), 131.6 (B1), 134.1 (boron phenyl C2, C6), 137.1 (A4-benzyl C1), 137.5 (B2-benzyl C1), 145.8 (B2), 147.4 (A3), 148.6 (A4), 152.6 (B3).

<u>Mass Spectrum</u> (probe, EI, 70eV) m/z: 586 ($M^{\dot{+}}$, 3), 149(22), 121(11), 91(100. High resolution molecular ion at m/z 586.2539; calculated m/z for $C_{37}H_{35}O_6B$ = 586.2527.

<u>Compound 2</u>

^{1}<u>H NMR</u> (200 MHz, $CDCl_3$) δ: 3.49 (3H, s, A3-OCH_3), 3.84 (3H, s, B2-OCH_3), 3.86 (3H, s, B3-OCH_3), 4.07 (1H, ddd, $J_{\alpha\beta}$ = 4.2, $J_{\beta\gamma a}$ = 10.2, $J\beta_{\gamma eq}$ = 4.0, Hß), 4.19 (1H, dd, $J_{\gamma a\gamma e}$ = 10.5, $J_{\gamma e\beta}$ = 4.0, Hγ_e), 4.31 (1H, dd, $J_{\gamma a\gamma e}$ = 10.5, $J_{\gamma a\beta}$ = 10.2, γ_a), 5.07 (2H, s, benzyl CH_2), 5.53 (1H, br d, $J_{\alpha\beta}$ = 4.2, Hα), 5.92 (1H, dd, J_{46} = 2.7, J_{56} = 6.72, B6), 6.11 (1H, d, J_{26} = 2.1, A2), 6.55 (1H, dd, J_{56} = 8.3, J_{26} = 2.1, A6), 6.74

(1H, d, J_{56} = 8.3, A5), 6.77 (1H, dd, J_{56} = 6.7, J_{45} = 6.0, B5), 6.81 (1H, dd, J_{45} = 6.0, J_{46} = 2.7, B4), 7.20–7.60 (8H, m, Ar-H), 7.93 (2H, dd, J = 7.7, J = 1.6, H2, H6 on boron phenyl).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 40.5 (Cβ), 55.6 (A3-OCH_3) 55.8 (B3-OCH_3), 60.9 (B2-OCH_3), 61.9 (Cγ), 71.1 (benzyl CH_2), 75.9 (Cα), 111.2 (A2), 111.3 (B4), 113.5 (A5) 118.6 (A6), 120.1 (B6), 123.6 (B5), 127.3 (benzyl C3, C5), 127.7 (boron phenyl C3, C5), 127.8 (benzyl C4), 128.5 (benzyl C2, C6), 130.8 (A1), 130.9 (boron phenyl C4), 131.5 (B1), 134.1 (boron phenyl C2, C6), 137.1 (benzyl C1), 147.3 (B2), 147.4 (A3), 148.7 (A4), 152.6 (B3).

Mass Spectrum (probe, EI, 70eV) m/z: 510 ($M^{+\cdot}$, 17), 165(14), 164(100), 151(13), 149(33), 121(23), 97(14), 91(66). High resolution molecular ion at m/z 510.2239; calculated m/z for $C_{31}H_{31}O_6B$ = 510.2214.

Compound 3

^{1}H NMR (200 MHz, $CDCl_3$) δ: 3.53 (3H, s, A3-OCH_3), 3.87 (3H, s, B2-OCH_3), 3.88 (3H, s, B3-OCH_3), 4.11 (1H, ddd, $J_{\alpha\beta}$ = 4.4, $J_{\beta\gamma a}$ = 10.8, $J_{\beta\gamma e}$ = 4.0, Hβ), 4.16 (1H, dd, $J_{\beta\gamma e}$ = 4.0, $J_{\gamma a\gamma e}$ = 10.8, Hγ_e), 4.33 (1H, dd, $J_{\beta\gamma a}$ = 10.8, $J_{\gamma a\gamma e}$ = 10.8, Hγ_a), 5.49 (1H, brs, Ar-OH), 5.52 (1H, br d, $J_{\alpha\beta}$ = 4.4, Hα), 5.94 (1H, dd, J_{46} = 3.0, J_{56} = 6.4, B6), 6.115 (1H, d, J = 1.90, A2), 6.535 (1H, dd, J_{56} = 8.2, J_{26} = 1.9, A6), 6.77 (1H, d, J_{56} = 8.2, A5), 6.79 (1H, dd, J_{45} = 8.2, J_{56} = 6.4, B5), 6.82 (1H, dd, J_{45} = 8.2, J_{46} = 3.0, B4), 7.35–7.60 (3H, m, Ar-H), 7.945 (2H, dd, J = 7.7, J = 1.6, H2, H6 on boron phenyl).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 40.6 (Cβ), 55.7 (A3-OCH_3), 55.8 (B3-OCH_3), 61.0 (B2-OCH_3), 61.9 (Cγ), 76.0 (Cα), 109.9 (A2), 111.3 (B4), 113.6 (A5), 119.4 (A6), 120.1 (B6), 123.6 (B5), 127.7 (boron phenyl C3, C5), 130.3 (A1), 130.9, 130.9 (boron phenyl C4), 134.1 (boron phenyl C2, C6), 144.9 (A4), 145.6 (A3), 147.3 (B2), 152.6 (B3).

1-(4-benzyloxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-3-hydroxypropan-1-one (4)

Compound erythro 2 (500 mg, 1.179 mmole) was dissolved in dioxane (25 ml). To this was added DDQ (481 mg, 2.122 mmole) and the reaction was stirred overnight. The mixture was poured into ethyl acetate and extracted with saturated $NaHCO_3$ until no colour remained in the organic layer. The organic layer was then dried over $MgSO_4$, and the solvent removed under reduced pressure to give a pale orange oil (490 mg, 98%). This was crystallised from CH_2Cl_2/pet. ether to give pale orange crystals m.p. 74-76°C.

^{1}H NMR (200 MHz, $CDCl_3$) δ: 2.85 (1H, br s, -OH), 3.81 (3H, s, OCH_3), 3.83 (1H, dd, $J_{\gamma1\gamma2}$ = 11.1, $J_{\gamma1\beta}$ = 4.7, $H\gamma_1$), 3.85 (3H, s, OCH_3), 3.94 (3H, s, OCH_3), 4.27 (1H, dd, $J_{\gamma1\gamma2}$ = 11.1, $J_{\gamma2\beta}$ = 8.4, $H\gamma_2$), 5.11 (2H, s, benzyl CH_2), 5.19 (1H, dd, $J_{\beta\gamma1}$ = 4.7, $J_{\beta\gamma2}$ = 8.4, Hβ), 6.60-7.00 (4H, m, Ar-H), 7.20-7.40 (5H, m, Ar-H), 7.55 (1H, dd, J_{56} = 6.5, J_{26} = 2.0, A6), 7.57 (1H, d, J = 2.0, A2).

^{13}C NMR (50 MHz, $CDCl_3$) δ: 48.2 (β), 55.1 (OCH_3), 55.3 (OCH_3), 60.7 (B2-OCH_3, 64.0 (γ), 70.0 (benzyl CH_2), 110.9

(B4), 111.2 (A2), 111.7 (A5), 119.7 (B6), 122.9 (A6), 123.9 (B5), 126.8 (benzyl 3,5), 127.5 (benzyl 4), 128.1 (benzyl 2,6), 129.1 (A1), 130.4 (B1), 135.9 (benzyl 1), 145.7 (B2), 148.7 (A3), 152.0 (A4), 152.6 (B3), 198.1 (α-C=O).

Mass Spectrum (probe, EI, 70eV) m/z: 422 ($M^{+\cdot}$, 0.8), 242(11), 241(61), 164(13), 91(100). High resolution molecular ion at m/z 422.1738; calculated m/z for $C_{25}H_{26}O_6$ = 422.1729.

Compound 5

Compound erythro 2 (80 mg, 0.189 mmole) was dissolved in CH_2Cl_2 (5 ml). To this was added $BF_3.Et_2O$ (8 mg, 0.047 mmole) and paraformaldehyde (10 mg, 0.340 mmole) and the reaction was stirred for 2 hours at room temperature. The mixture was poured into $CHCl_3$ and washed with saturated $NaHCO_3$. The chloroform solution was dried ($MgSO_4$) and removed under reduced pressure to give a clear oil (80 mg, 98%). Preparative layer chromatography (60% ethyl acetate:pet. ether) gave threo-8 (37 mg, 46%).

^{1}H NMR (200 MHz, $CDCl_3$, ^{13}C correlations included) δ: 3.31 (3H, s, B2-OCH_3, 60.5), 3.74 (3H, s, OCH_3, 55.8), 3.77 (3H, s, OCH_3, 55.9), 3.78 (1H, ddd, $J_{\beta\gamma 1}$ = ?, $J_{\beta\gamma 2}$ = 3.3, $J_{\beta\alpha}$ = 9.8, β, 41.8), 3.83 (1H, dd, $J_{\gamma 1\gamma 2}$ = 9.7, $J_{\gamma 1\beta}$ = ?, $H\gamma_1$, 71.8, ($C\gamma$)), 4.11 (1H, dd, $J\gamma_2\gamma_1$ = 9.7, $J\gamma_{2\beta}$ = 3.3, $H\gamma_2$, 71.8 ($C\gamma$)), 4.77 (1H, d, $J_{\alpha\beta}$ = 9.8, α, 83.1), 4.99 (1H, d, J = 6.4, acetal H_{ax}, 94.1), 5.04 (2H, s, benzyl CH_2, 70.9), 5.31 (1H, d, J = 6.4, acetal H_{eq}, 94.1), 6.50-6.80 (5H, m, A2, B4, A5, A6, B6, 110.6, 111.0, 113.7, 119.2, 120.0), 6.99 (1H, dd, $J_{45} = J_{56} =$ 7.9, B5, 123.7), 7.20–7.40 (5H, m, benzyl Ar-H, 127.7, 128.0, 128.4).

^{13}C NMR (50 MHz, $CDCl_3$, non-correlated quaternary carbons)δ: 131.2 (A1), 133.0 (B1), 137.1 (benzyl C1), 147.5, 147.6 (B2, A3), 149.3 (A4), 152.9 (B3).

Mass Spectrum (probe, EI, 70 eV) m/z: 436 ($M^{\dot{+}}$, 5), 165(13), 164(100, 149(22), 91(27). High resolution molecular ion at m/z 436.1883; calculated m/z for $C_{26}H_{28}O_6$ = 436.1886.

CHAPTER FOUR

REACTIONS OF ß-5 LIGNIN MODEL QUINONE METHIDES WITH ANTHRAHYDROQUINONE AND ANTHRANOL

4.1 INTRODUCTION

A great deal of activity has been directed toward the study of the reactions of anthrahydroquinone (AHQ) and anthranol (reduction products of anthraquinone, AQ) with quinone methides of the ß-aryl ether type. It is primarily the reactions of this lignin unit which are responsible for the accelerated cleavage of the lignin macromolecule in alkaline-additive pulping.

Although there is considerable speculation (Poppius, 1984; Dimmel, 1985a) as to whether adducts between AHQ (or anthranol) and ß-ether quinone methides are intermediates in the catalytic cleavage of ß-ether bonds under soda-AQ pulping conditions, there is no doubt that such adducts are readily formed (Landucci, 1982).

ß-Aryl ether quinone methides are not the only quinone methides which can form under pulping conditions; any free-phenolic unit with an α-leaving group (OH, OAr, or OR) can form quinone methides (Miksche, 1980). Indeed, when anthranol, ^{13}C labelled at the 9

Footnote: A paper detailing the majority of the work in this chapter has been accepted by the Journal of Wood Chemistry and Technology for publication (Ralph, 1987a).

and 10 positions, was reacted in base with acetylated milled-wood lignin (conditions which generate lignin quinone methides readily at room temperature), anthranol-lignin adducts were obtained (Landucci, 1981a; Ralph, 1986a). Only two of a multiplicity of peaks in the C-10 region of the ^{13}C NMR spectrum could be attributed to adducts with ß-aryl ether units (Ralph, 1986a).

We wished to know if other quinone methides could also trap AHQ or anthranol. If so, it is of interest to determine, firstly, how the presence of AHQ and other species affects the reaction pathways of the ß-aryl units and, secondly, whether reactions involving ß-aryl quinone methides may help account for the considerable loss of "AQ" from the pulping cycle (Landucci, 1984).

The main objective of the work described in this paper was to determine if quinone methides from ß-5 linked structures react with AHQ and anthranol and to characterise any adducts formed. The results of this study and those of the reaction of ß-C-1 lignin model quinone methides have been published recently (Ralph, 1987a).

4.2 RESULTS AND DISCUSSION

4.2.1 Model Compounds

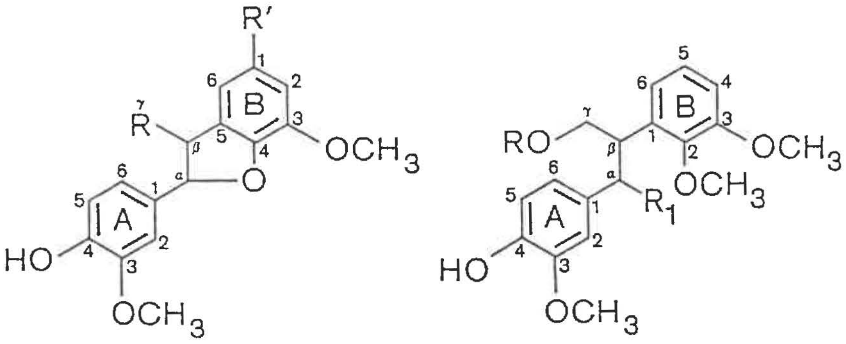
The most readily available phenylcoumaran models are dehydrodiisoeugenol 2.1 (Leopold, 1950) and its reduction product dihydrodehydrodiisoeugenol 2.6 (Fig. 1). Use of 2.6 rather than 2.1 removes the complication of further reactions of the vinyl side chain which are not characteristic of the phenylcoumaran moiety of lignin.

Although the use of these easily synthesised models is valuable in developing methods for the study of adduct formation, it is preferable to use a more representative model such as 2.24 which possesses the hydroxymethyl group present in most lignin side chains. The presence of this group markedly influences the course of important reactions. A model representing a 'ring-opened' ß-C-5 unit (which could not cyclise to a phenylcoumaran) was also required in our studies. Compound 2.26 and its derivatives were used for this study (Ralph, 1987, and Chapter 2).

A base-stable t-butyldimethylsilyl protecting group in compounds 4, 7, and 9, increased the stability of the quinone methides with respect to polymerisation and removed the possibility of retro-aldol reactions. In addition, this protecting group may prove to be a useful lignin derivatisation reagent. ^{29}Si NMR spectroscopy of trimethylsilylated spruce lignin has been shown to be a viable aid to lignin structural elucidation (Brezny, 1986).

4.2.2 Anthranol and AHQ Adducts with Quinone Methides of ß-5 Models

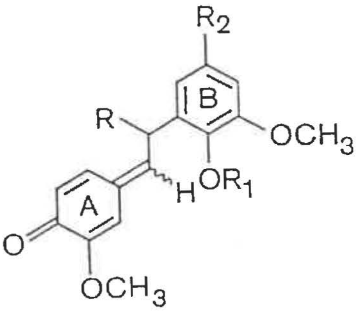
Alpha-aryl ethers such as compounds 2.1, 2.6, 2.24, 1 and 4 (Fig. 1) are known (Miksche, 1980) to reversibly generate quinone methides at a significant rate even at 10°C in 1M NaOH (Scheme 1). Therefore, attempts to form adducts from quinone methides 10-14 (Fig. 2) were made by addition of models 2.1, 2.6, 2.24, 1 and 4 directly to solutions of anthranol or AHQ in base. These reactions gave products as summarised in Table 1.



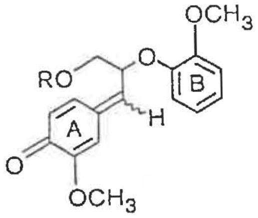
	R	R'
2.1	CH_3	$CH{=}CH{-}CH_3$
2.6	CH_3	$CH_2{-}CH_2{-}CH_3$
2.24	CH_2OH	H
1	CH_2OAc	H
4	$CH_2OSi^tBuMe_2$	H

	R_1	R
2.26	OH	H
5	Br	H
2.28	OAc	Ac
7	OH	Si^tBuMe_2
9	OAc	Si^tBuMe_2

Figure 4.1. Models and derivatives used.

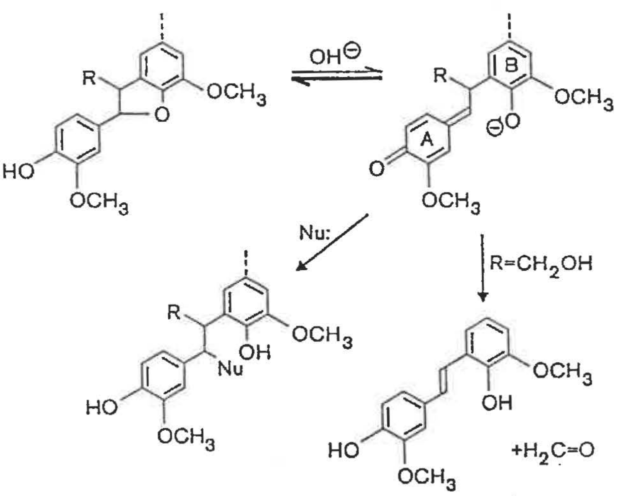


	R	R_1	R_2
10	CH_3	H	$CH{=}CH{-}CH_3$
11	CH_3	H	$CH_2{-}CH_2{-}CH_3$
12	CH_2OH	H	H
13	CH_2OAc	H	H
14	$CH_2OSi^tBuMe_2$	H	H
15	CH_2OH	CH_3	H
16	CH_2OAc	CH_3	H
17	$CH_2OSi^tBuMe_2$	CH_3	H



	R
18	H
19	Ac

Figure 4.2. Quinone methides.



21

Scheme 4.1. Reactions of phenylcoumarans.

The anthranol adduct 22 from dehydrodiisoeugenol 2.1 polymerised slowly on standing to give the polystyryl derivative 34. Polymerisation could be prevented by addition of trace quantities of butylated hydroxytoluene.

TABLE 4.1 - Approximate yield (%) data for adduct reactions.[a]

Model	Anthranol			AHQ		
	Adduct[b]	Starting material	Stilbene	Adduct	Starting material	Stilbene
2.1	22 70(97:3)	30	0	0	100	0
2.6	23 70	30	0	0	100	0
2.24	0	0	100	0	0	100
2.28	27 90(75:25)[c]	0	0	0	.	.
1	28 50(90:10)	50	0	-	-	-
4	30 50(80:20)	50	0	-	-	-
9	31 95(50:50)[d]	0	0	-	-	-

a Conditions: 2 eq anthranol or AHQ; 1M NaOH (except 0.3 M for 1 to minimize hydrolysis of the γ-OAc group); 50°C; 1 hr (15 min for 2.28).

b Ratio of erythro:threo isomers (in brackets) determined from H-1 NMR after acetylation.

c 75% yield after flash chromatography.

d 80% after flash chromatography. Isolated erythro 41% and threo 39% as pure fractions.

. Product not observed.

Generation of the quinone methide 15 from the ring-opened β-5 model 2.26 at moderate temperatures required the α-OH to be replaced with a better leaving group. Attempts to form 5, the α-bromide, from 2.26 using bromotrimethylsilane (Ralph, 1983c) were unsuccessful due to spontaneous loss of formaldehyde, and formation of stilbene 20 from the bromide. However, quinone methide 16 could be generated *in situ* from the free phenolic diacetylated model 2.28 in base. As there was no possibility of quinone methide 16 reverting to a phenylcoumaran by an internal cyclisation, the yield (Table 1) of anthranol adduct was substantially higher from model 2.28 than from the true phenylcoumarans 2.1, 2.6, 2.24, 1 and 4.

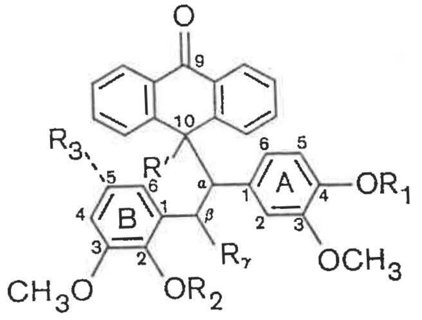
Silylated model 7 could be brominated using bromotrimethyl silane (Ralph, 1983c) in chloroform. Treatment of this solution with aqueous potassium carbonate gave relatively stable solutions of quinone methide 17. Alternatively, quinone methide 17 was generated from the free-phenolic α-acetate 9 in base. Reaction of anthranol with quinone methide 17 gave adduct 31 (after acetylation) in very high yield as a 50:50 mixture of *erythro* and *threo* isomers. Unlike the parent acetylated adducts 29, these were readily separated by tlc.

A further point is apparent from Table 1. Whereas anthranol adducts form readily from these quinone methides, attempts to form the corresponding AHQ adducts (e.g., R'=OH of 22, Fig. 3) using both aqueous and organic solvents, at temperatures ranging from 0°C to 80°C, were unsuccessful, presumably for a combination of steric and electronic reasons. It has been noted previously (Landucci, 1982) that AHQ adds less readily than anthranol to ß-aryl ether quinone methides and it has also been shown (Landucci, 1982) that, in competition studies, anthranol adducts are formed in overwhelming preference.

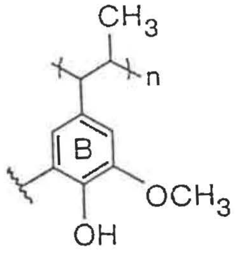
4.2.3 Stereochemistry and NMR Spectra of Adducts

Despite the high kinetic stereoselectivity observed (Landucci 1982; Poppius 1985a) for threo adducts from ß-ether quinone methides (e.g., 14-15), both adduct isomers can be detected from attack of anthranol on most of the ß-aryl quinone methides (Fig. 4; Table 1).

The ß-5 adducts 22-31 (Figure 3), like the ß-aryl ether adducts (Landucci, 1982; Ralph, 1983a, b; 1984) have fascinating NMR characteristics due to their conformations in solution. For example, in the erythro isomer of 29 (which is analogous to the threo isomer in ß-ether adducts because of the convention of group assignments, Figure 5) the A-ring is clearly situated over the anthracenyl ring system, as is evidenced by the highly shielded ring A methoxyl and the ring A protons (Figure 4). However, the minor threo isomer is quite unlike the erythro isomer (Ralph, 1983a) of ß-ether adducts in that ring A protons are more intensly shielded. The threo γ-acetate methyl chemical shift is also anomalous, appearing at $\delta 2.0$ compared with a normal shift of $\delta 1.8$. This methyl group is presumably in a deshielding region of the anthracenyl ring system and/or the other aromatic rings. In addition, the B-ring methoxyl protons experience substantial shielding, indicating their



	R'	R	R_1	R_2	R_3
22	H	CH_3	H	H	$CH=CH-CH_3$
23	H	CH_3	H	H	$CH_2-CH_2-CH_3$
24	H	CH_3	Ac	Ac	$CH=CH-CH_3$
25	H	CH_3	Ac	Ac	$CH_2-CH_2-CH_3$
26	H	CH_2OAc	H	H	H
27	H	CH_2OAc	H	CH_3	H
28	H	CH_2OAc	Ac	Ac	H
29	H	CH_2OAc	Ac	CH_3	H
30	H	$CH_2OSi^tBuMe_2$	Ac	Ac	H
31	H	$CH_2OSi^tBuMe_2$	Ac	CH_3	H



34

Figure 4.3. Adduct Structures

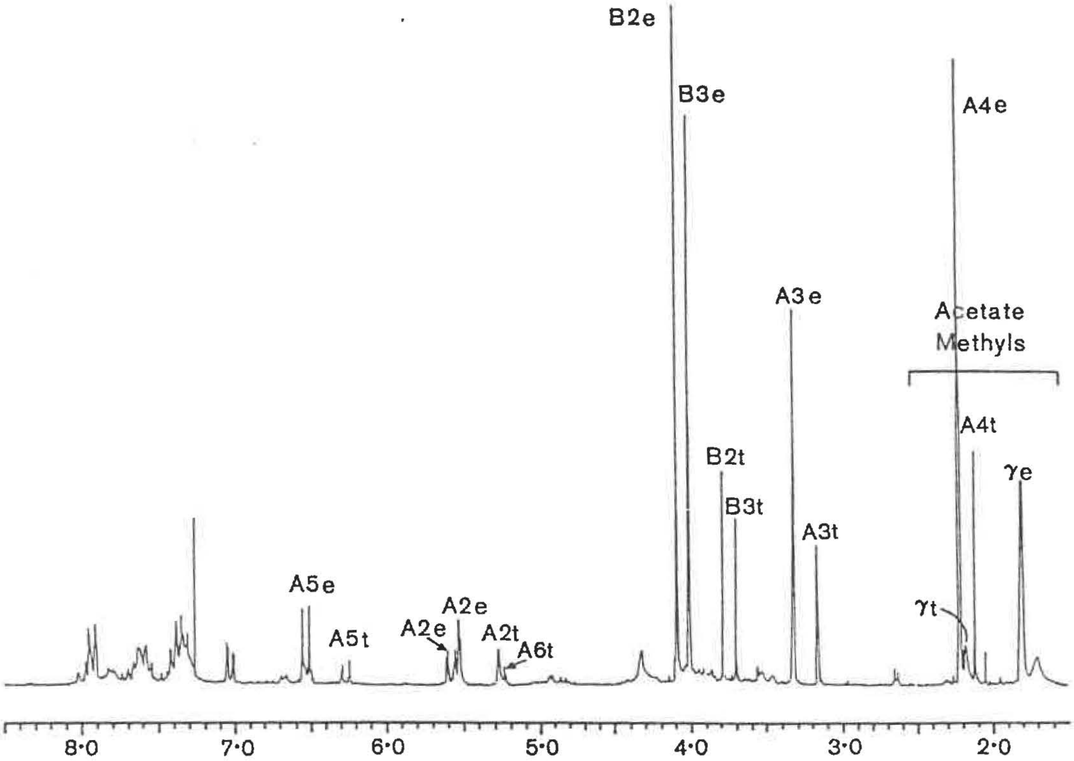


Figure 4.4. Partial 200 MHz ^1H NMR spectrum of ß-C-5 adducts 31 (t = threo, e = erythro)

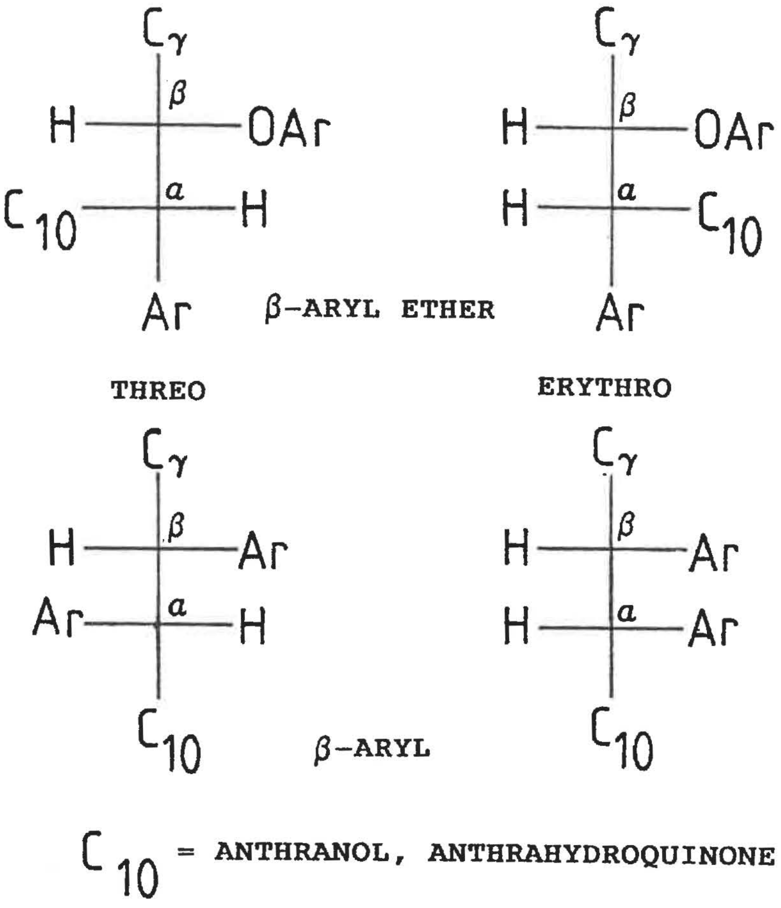
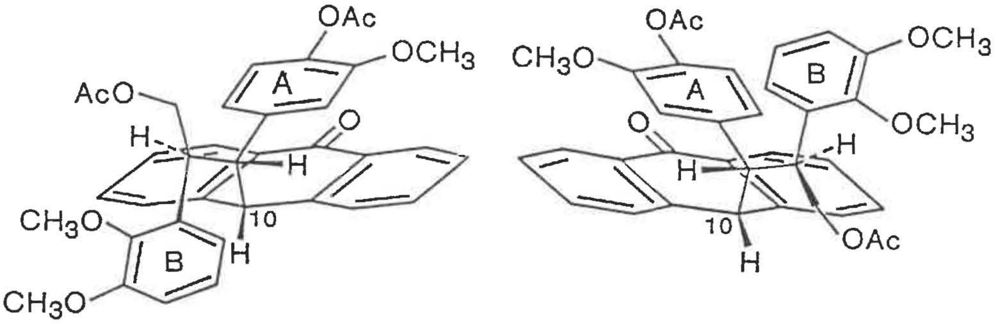


Figure 4.5. Adduct stereochemistries

positions within the shielding regions of the anthracenyl ring system and/or ring A. Conformations of erythro- and threo-28 postulated from the information in their spectra, are shown in Figure 6. Selected NMR data for these adducts are given in Tables 2 and 3.



erythro

threo

Figure 4.6. Postulated conformations of <u>erythro</u> and <u>threo</u> isomers of <u>28</u>

TABLE 4.2 - Selected ^{1}H NMR data for adducts

Adduct	Isomer$^{(1)}$	Solv.$^{(2)}$	MHz	Methoxyls			Acetate methyls			Aromatic protons			α	β	γ	10	tBu	MeSiMe
				A3	B3	B2	A4	B2		A2	A5	A6						
22	e	A	200	3.35	4.00	-	-	-	-	5.37	6.40	5.51	.	.	0.93	4.47		
25	e	A	200	3.29	3.93		2.22	2.47	-	5.48	6.53	5.48	(3.47-3.87)		0.89	4.48		
28	e	C	200	3.35	3.98	-	2.24	2.50	1.88	5.60	6.55	5.60	.	.	.	.		
	t	C	200	3.19	3.64	-	2.10	2.30	1.92	?	?	?	.	.	.	.		
29	e	C	200	3.28	3.94	4.10	2.15	-	1.70	5.50	6.50	5.55	.	.	.	.		
	t	C	200	3.08	3.60	3.72	2.10	-	2.02	5.28	6.22	5.20	.	.	.	.		
31	e	C	200	3.28	3.95	4.05	2.20	-	-	5.50	6.55	5.60	.	.	.	.	0.70	-0.30, -0.40
	t	C		3.15	3.55	3.65	2.00	-	-	5.35	6.21	5.20	.	.	.	.	1.00	0.04, 0.06

(1) e = *erythro*, t = *threo*

(2) C = $CDCl_3$, A = acetone-d_6

. Indicates resonances which are not resolvable due to coincident chemical shifts and/or to line broadening caused by hindered rotation.

TABLE 3 - Selected ^{13}C NMR data for adducts

Adduct	Isomer(1)	Solv.(2)	MHz	Methoxyls	Acetate methyls	$C\alpha$	$C\beta$	$C\gamma$	C10	C9	Acetate C=0	SiMe	Si^tBu
<u>22</u>	e	C	22.5	55.6, 56.0	-	62.0	33.9	21.6	45.9	183.6	-	-	-
<u>25</u>	e	C	22.5	55.5, 56.0	20.6	62.0	34.2	22.6	45.6	183.1	168.7	-	-
<u>28</u>	e	C	22.5	55.4, 56.2	20.6, 20.6, 20.6	58.4	38.4	67.7	45.1	182.9	167.8, 168.6, 171.0	-	-
	e	A	50	56.4, 56.4	20.4, 20.6, 20.6	58.6	39.3	68.1	45.6	183.0	168.4, 168.4, 168.5		
	t(3)	A	50	?	20.5, 20.8, .	58.1	.	67.7	45.9	182.9	168.5, 168.5, 168.5	-	-
<u>29</u>	e	C	50	55.7, 55.5, 61.2 (B2)	20.5, 20.6	59.1	37.9	67.5	45.1	183.1	168.6, 170.4	-	-
	t(4)	C	50	55.2, 55.6, 60.4 (B2)	20.4, 21.0	57.9	37.9	67.5	45.2	182.7	168.4, 171.1	-	-
	e	A	50	55.6, 55.9, 61.5 (B2)	20.4, 20.6	59.4	39.0	68.1	45.6	183.1	168.5, 170.5	-	-
	t	A	50	55.3, 56.1 60.7 (B2)	20.3, 21.0	58.4	37.5	68.0	45.5	182.9	168.3, 171.2	-	-
<u>31</u>	e	C	50	55.5, 55.6, 61.4 (B2)	20.5	58.4	40.7	65.9	45.1	183.3	168.6	-5.9, -6.0	25.8
	e	A	50	55.6, 55.9, 61.5 (B2)	20.4	58.7	41.9	66.7	45.6	183.2	168.5	-5.6, -5.7	26.2
	t(5)	C	50	55.3, 55.5, 60.5/.6 (B2)	20.5	56.8/57.7	39.2	65.8/67.3	44.7/44.9	182.9/183.1	168.5	-3.6, -5.8	25.9
	t	A		55.3, 55.7, 60.7 (B2)	20.3	58.8	40.0	66.6	45.2	183.1	168.4	-3.2, -5.7	26.2

(1) e = <u>erythro</u>, t = <u>threo</u>

(2) C = $CDCl_3$, A = acetone-d_6

(3) From a 90:10 e:t mixture

(4) From a 75:25 e:t mixture

(5) Two rotamers frozen out on NMR time scale

The ^{13}C NMR C-10 chemical shifts of these adducts in acetone-d_6 allow a more complete analysis of the C-10 region of the ^{13}C NMR of the anthranol-lignin adduct reported previously (Ralph, 1986a). Figure 7 is a highly expanded plot of the C-10 region of the anthranol-lignin adduct on which is shown the positions of ß-aryl ether, phenylcoumaran, and ß-C-1 adducts. There is little doubt that adducts between these three unit types account for most of the resonances in this region.

Several of the adducts exhibited hindered rotation phenomena (Landucci, 1982; Ralph, 1984) in their proton and ^{13}C NMR spectra. The effect of temperature on the spectra of these adducts was far more complex than that observed for certain ß-aryl ether adducts (Ralph 1984), and indicated that the behaviour was not simply due to rotation about a single bond. One compound, threo-31, was fully resolved at ambient probe temperature into two rotamers (60:40 ratio) on the ^{13}C NMR time-scale (Figure 8). The broader resonances from the major rotamer indicate that either the T_2 relaxation times are shorter or that further fluxional behaviour is occurring in the major rotamer that is not significant in the minor rotamer.

The observed stereoselectivity of anthranol attack could reasonably be attributed to the quinone methide conformations. Figure 9 shows the two major conformers expected (Ralph, 1984) for ß-aryl quinone methides. If the conformation does not significantly alter the charge density at the alpha carbon and R is sterically less demanding than Ar (as expected for R = Me, CH_2OH, CH_2OAc),

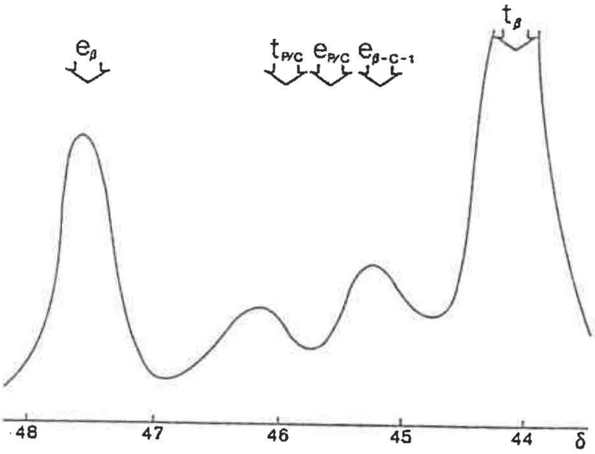


Figure 4.7. ^{13}C NMR (acetone-d_6) of the C-10 region of an anthranol-lignin adduct (Ralph, 1986a) and chemical shifts of model adducts (e = <u>erythro</u>, t = <u>threo</u>, ß = ß-aryl ether, P/C = phenylcoumaran)

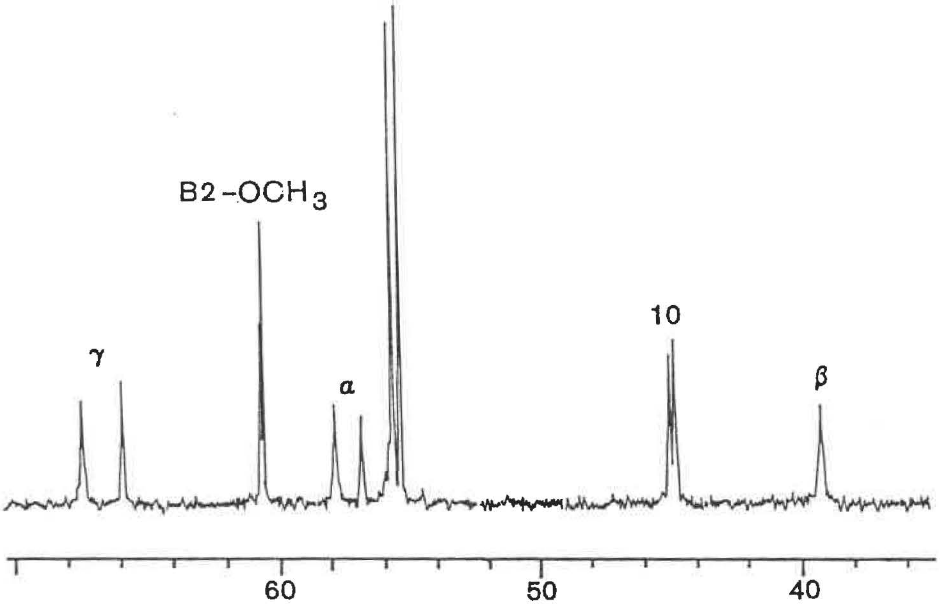


Figure 4.8. Partial ^{13}C NMR of adduct <u>threo</u> <u>31</u> showing hindered rotation

A would be the major conformer. Attack from the less hindered side would lead to the *erythro* adduct. As R becomes larger (e.g., $CH_2OSi^tBuMe_2$), rotamer B becomes significant, resulting in more *threo* product. This argument assumes partly that the reaction is under kinetic control. Further experiments have shown the possibility of thermodynamic control of the reaction. This is discussed in Section 4.2.6.

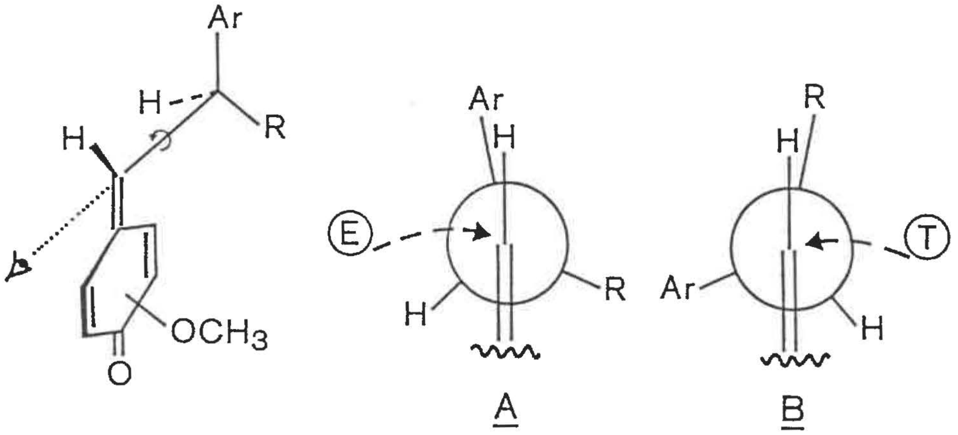


Figure 4.9. Major conformers of β-aryl quinone methides

For reasons that are not clear, these β-aryl quinone methides, particularly the γ-acetylated QMs, are markedly less stable toward polymerisation than β-aryl ether quinone methides and, at modest concentrations, are observed only transiently at room temperature. Attempts to characterise them by NMR techniques (Ralph, 1983) are discussed elsewhere (Ede, 1987b, Chapter 5).

4.2.4 The Phenylcoumaran Quinone Methide: Competition Between Anthranol Adduct Formation and the Reversal Reaction to the Phenylcoumaran

Formation of quinone methides from phenylcoumarans 2.1, 2.6, 2.24, 1, and 4 in base is clearly reversible (Scheme 1). The assumed steady state quinone methide concentration is too low to be detectable by conventional UV-visible or NMR spectroscopy. The reverse reaction to the phenylcoumaran must therefore be very rapid. Nevertheless, nucleophiles such as anthranol, obviously compete for the quinone methide.

In order to ascertain how effectively anthranol can compete with the quinone methide reversal reaction, the α-iodide 33 was prepared from dihydrodehydrodiisoeugenol, 2.6, by treatment with iodotrimethylsilane in chloroform. It was assumed that, on treatment with base, the phenolic TMS group would rapidly hydrolyse and that the quinone methide 11 would rapidly form by elimination of iodide. The phenylcoumaran 2.6 was isolated in high yield from such a reaction. Addition of the iodide 33 to a solution of anthranol in base and workup within 5 minutes gave a ratio of adduct 23 to phenylcoumaran 2.6 of approximately 10:90. Since only traces of adduct 23 were detected when phenylcoumaran 2.6 is reacted with anthranol under the same conditions for 5 minutes, it is concluded that anthranol attack is about 10% as rapid as the recyclisation reaction.

4.2.5 The Phenylcoumaran Quinone Methide: Competition Between Adduct Formation and the Retro-Aldol Reaction

During much of this work, quinone methides were most conveniently generated from free-phenolic acetates or t-butyldimethylsilylated compounds, but the use of these derivatives precludes one very important reaction - the retro-aldol elimination of formaldehyde. To relate the results of model studies to reactions involving lignin itself, it is essential that the model contains the hydroxymethyl group.

Despite its surprising effectiveness at trapping quinone methides (Ralph, 1985b) not even anthranol could compete against the retro-aldol elimination of formaldehyde from quinone methides 12 (Scheme 1) or 15 to give stilbenes. The reaction therefore follows the same course as in the absence of the additive (Scheme 1) (Gierer, 1970).

This point illustrates the pitfalls of using inappropriately substituted or derivatised models. Acetylated models (Landucci, 1982; Gierer 1979), or acetylated lignin itself (Landucci, 1981a; Ralph, 1986a) are frequently used to allow in-situ generation of quinone methides at room temperature. But the protection afforded to the hydroxymethyl group by acetylation means that formaldehyde loss by a retro-aldol reaction cannot compete in subsequent quinone methide reactions. This is not so critical in the case of ß-aryl ether quinone methides since anthranol and AHQ can add to quinone methide 18 efficiently before the retro-aldol reaction (to give the styryl ether) can occur (Ralph, 1985b). However, in phenylcoumaran and ß-C-1 models, the retro-aldol reaction entirely dominated the reaction of representative quinone methides 12 or 15 (with the ß-CH_2OH substituent) whereas adducts readily formed from the acetylated quinone methides 13 or 16, or the silylated derivatives 14 or 17. Thus, reactions on acetylated milled-wood lignin with anthranol, where adducts other than ß-ether adducts appear to be observed in the C-13 NMR spectra (Landucci, 1981a; Ralph, 1986) may not be representative of reactions of the underivatised quinone methides.

4.2.6 Reversibility of the addition of anthranol to the ß-C-5 lignin model quinone methides

The high stereoselectivity observed for the addition of nucleophiles to quinone methides has led to a belief that the addition is non-reversible. Predominantly *threo* isomers have been observed for the addition of amines (Ralph, 1983c), water in dioxane solution (Nakatsubo, 1976), and anthranol and AHQ (Landucci, 1982), to ß-ether lignin model quinone methides. Decreased stereoselectivity was observed when the addition of nucleophiles to the QMs was carried out under conditions which would form the more reactive carbonium ion instead. Ratios of *erythro*:*threo* in the products were typically 1:1 in these cases.

Recently it was observed that both *erythro* and *threo* adducts were formed on the addition of anthrone, 10-methylanthrone and 10-phenylanthrone to the quinone methide of 1-(4-hydroxy-3-methoxyphenyl)-2-(2-methoxyphenoxy)-1-propanol. As the amount of *erythro* isomer increased as the reaction time increased, the addition was assumed to be thermodynamically controlled, with the threo isomer being formed faster (Poppius, 1985a).

It was then necessary to determine if the ratio of isomers we observed from the addition of anthranol to the ß-C-5 lignin model QMs reflected kinetic or thermodynamic control of the reaction.

It became apparent from a simple NMR tube experiment that for QM 17, the addition of anthranol was reversible. Pure erythro adduct 32 was dissolved in $CHCl_3$ in an NMR tube. Two drops of 1 $mol\text{-}l^{-1}$ NaOD in D_2O were added and spectra were recorded over 24 hours. At the end of the time period, a small amount of the threo adduct 32 could be detected in the spectrum (Fig. 10). Over a period of days, the ratio of threo:erythro gradually increased, but at the same time the S/N of the adduct resonances decreased, along with an increase in the AQ resonances. Also noticeable was the formation of a white suspension in the aqueous layer. These observations are consistent with the erythro adduct reversing to anthranol and QM 17 with the anthranol oxidising to AQ, leaving QM 17 to gradually polymerise (see Scheme 2).

Further evidence for the thermodynamic control of the reaction was gained from examining the erythro:threo ratio observed from addition of QM 17 to anthranol; after 2 minutes reaction the ratio of erythro:threo was 9:1, after 1 hr the ration was 1:1.

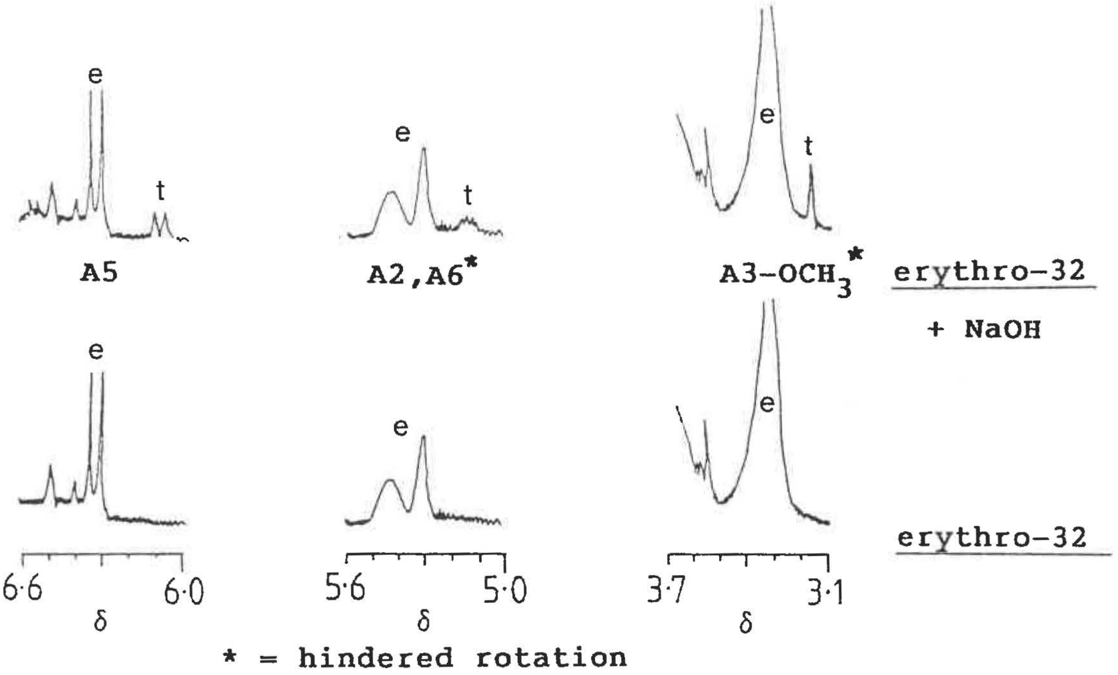
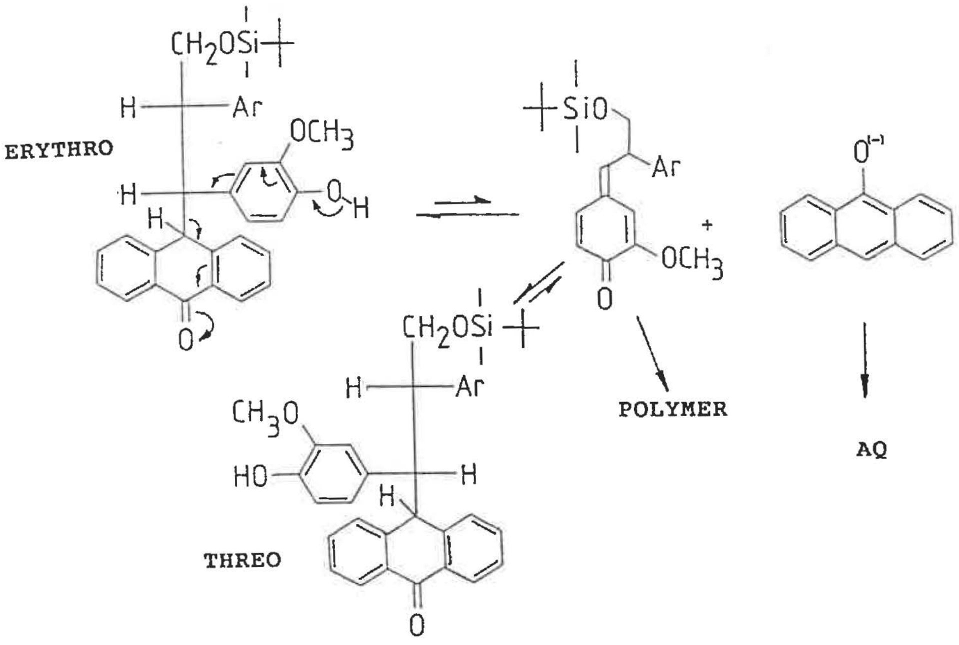


Figure 4.10. ^{1}H NMR spectra of erythro-32 before and after addition of NaOH.



Scheme 4.2. Reaction of adduct 32 with NaOH.

4.3 CONCLUSIONS

Adduct formation between ß-aryl quinone methides and anthranol, but not AHQ, occurs readily and reversibly, but only when the possibility of formaldehyde elimination from the quinone methide is removed. Consequently, the reactivity of lignin phenylcoumaran and ß-C-1 units in soda-AQ pulping is not expected to be altered by their additon reactions with AQ species. Conversely, it is not expected that AQ losses can be attributed to reactions of its reduction products with ß-aryl quinone methides.

4.4 EXPERIMENTAL

4.4.1 General Methods

Acetylations

Unless otherwise stated, acetylations were carried out following the method described in Chapter 2.

Preparation of TBDMS derivatives

The primary alcohol (1.0 eq), t-butyldimethylsilyl chloride (1.5 eq), and diazabicyclo[5,4,0]undec-7-ene (DBU, 1.4 eq) in CH_2Cl_2 (10 ml/mmole alcohol) were stirred for 40 minutes at 40°C (Aizpurua, 1985). The products were extracted into CH_2Cl_2 and washed three times with saturated aqueous NH_4Cl. The organic phase was dried over $MgSO_4$ and the solvent removed to give the silyl ethers in ca. 95% yield after purification.

Quinone Methides

Quinone methides 6-15 were generated *in situ* either from the free phenolic phenylcoumarans 2.1, 2.6, 2.24, 1 and 2, or from the free phenolic α-acetylated derivatives 2.29 and 5 (Landucci, 1982).

Anthrahydroquinone (AHQ and AHQ^{2-})

Solutions of AHQ^{2-} were prepared in aqueous 1 M or 0.3 M NaOH containing, or free from, sodium dithionite (Landucci, 1982).

Anthranol

Solutions of the anion of anthranol were prepared by refluxing a mixture of anthrone in 1 M or 0.3 M NaOH (20-50 ml) under nitrogen until dissolution was complete (about 1 hour). The solutions were then cooled to the required temperature.

AHQ or Anthranol Adducts

To a solution of AHQ or anthranol (2 eq) in base (at the temperature given in Table 1) was added the quinone methide precursor in solid form or as a solution in a small volume of CH_2Cl_2. After the stated time, the mixture was neutralised with 5% H_2SO_4 and extracted with $CHCl_3$ (2 X). The chloroform extract was dried over $MgSO_4$ and the solvent removed.

4.4.2 Synthesis of ß-5 Models

Unless described below, the lignin models were prepared according to the methods in Chapter 2.

2,3-dihydro-3-acetoxymethyl-2-(4-hydroxy-3-methoxyphenyl)-7-methoxy benzofuran (1)

Compound 2.25 (40 mg, 0.092 mmole) was dissolved in methanol (5 ml). To this was added pyrollidine (18.2 μl 0.37 mmole) and the reaction was stirred for 1 hr (Mansson, 1982). The mixture was extracted with $CHCl_3$ and washed with 5% H_2SO_4 and water. The organic layer was dried over $MgSO_4$ and the solvent removed under vacuum to give 1 as a clear, colourless oil (33 mg, 90% yield).

^{1}H NMR (200 MHz, $CDCl_3$ δ: 2.00 (3H, s, γ-$OCOCH_3$) 3.30 (1H, m, Hβ), 3.78 (3H, s, OCH_3), 3.88 (3H, s, OCH_3), 4.36 (1H, dd, $J_{\beta\gamma1}$ = 7.6, $J_{\gamma1\gamma2}$ = 11.1, γ_1), 4.47 (1H, dd, $J_{\beta\gamma2}$ = 5.5, $J_{\gamma1\gamma2}$ = 11.1, γ_2), 5.72 (1H, d, $J_{\alpha\beta}$ = 6.9, Hα), 5.80 (1H, s, Ar-OH), 6.8-7.2 (6H, m, Ar-H).

1-(4-benzyloxy-3-methoxyphenyl)-2-(2-benzyloxy-3-methoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol (2)

Compound 2.17 (200 mg, 0.40 mmole) was t-butyldimethylsilylated in the normal way. Workup gave 2 as a clear oil (250 mg, 100%).

^{1}H NMR : (200 MHz, $CDCl_3$): -0.09 (6H, s, $SiMe_2$), 0.86 (9H, s, ^{t}BuSi), 2.83 (1H, d, J = 3.7, α-OH), 3.67 (3H, s, OCH_3), 3.60-3.70 (3H, m, Hβ, Hγs), 3.86 (3H, s, OCH_3), 4.53 (1H, d, J = 11.1, benzyl CH), 4.93 (1H, d, J = 11.1, benzyl CH), 5.07 (1H, dd, $J_{\alpha\beta}$ = 4.6, Jα-OH = 3.7, Hα), 5.11 (2H, s, CH_2Ph), 6.50-7.10 (6H, m, ArH), 7.30-7.50 (10H, m, ArH).

1-(4-hydroxy-3-methoxyphenyl)-2-(2-hydroxy-3-methoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol (3)

Compound 2 was debenzylated in the normal way to give 3 as a clear oil (88%).

^{1}H NMR (200 MHz, CDCl$_3$) δ: -0.04 (6H, s, SiMe$_2$), 0.88 (9H, s, ^{t}BuSi), 3.48 (1H, m, Hβ), 3.60-3.90 (2H, m, (Hγ's), 3.78 (3H, s, OCH$_3$), 3.88 (3H, s, OCH$_3$), 5.20 (1H, d, $J_{\alpha\beta}$ = 6.5, Hα), 6.60-6.90 (6H, s, OCH$_3$).

2,3-dihydro-3-(t-butyldimethylsiloxymethyl)-(4-hydroxy-3-methoxyphenyl)-7-methoxybenzofuran (4)

Compound 3 was shaken with 5% H$_2$SO$_4$ to give 4 as a clear, colourless oil.

^{1}H NMR (200 MHz, CDCl$_3$) δ: 0.04, 0.06 3H, (2 x 3H, 2s, SiMe$_2$), 0.89 (9H, s, SiBu^t), 3.65 (1H, m, Hβ), 3.84 (3H, s, OCH$_3$), 3.90 (3H, s, OCH$_3$), 3.80-4.00 (2H, m, Hγ's), 5.55 (1H, d, $J_{\alpha\beta}$ = 5.8 Hz, Hα), 5.60 (1H, s, Ar-OH), 6.80-7.00 (6H, m, Ar-H).

^{13}C NMR (50 MHz, CDCl$_3$) δ: -5.31, -5.28 (SiMe$_2$), 18.3 (Me$_3\underline{\text{C}}$Si), 25.9 ($\underline{\text{Me}}_3$CSi), 54.2 (β), 56.0 (OCH$_3$), 65.5 (γ), 87.9 (α), 108.7 (A2), 112.1 (B4), 114.3 (A5), 117.1 (B6), 119.1 (A6), 121.2 (B5), 128.0 (A1), 133.7 (B1), 144.5 (B2), 145.7 (A4), 146.7 (A3), 148.3 (B3).

1-(4-hydroxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-1-bromo-propan-3-ol (5)

Attempted bromination of 2.26 using bromotrimethylsilane (Ralph, 1983) gave only the stilbene 20, presumably via HBr and formaldehyde elimination from bromide 5.

^{1}H NMR (60 MHz, $CDCl_3$) δ: 3.80 (9H, s, OCH_3), 6.40-7.20 (8H, m, ArH and vinyl H).

1-(4-benzyloxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol (6)

Compound 2.18 (100 mg, 0.244 mmol) was t-butyldimethylsilylated in the normal way. Workup gave 6 as a clear, colourless oil (123 mg, 96%).

^{1}H NMR (200 MHz, $CDCl_3$) δ: -0.03 (3H, d, SiMe), -0.02 (3H, s, SiMe), 0.85 (9H, s, ^{t}BuSi), 3.38 (3H, s, OCH_3), 3.63 (3H, s, OCH_3), 3.50-3.70 (2H, m, $H\gamma_1$, $H\beta$), 3.76 (3H, s, OCH_3), 3.92 (1H, dd, $J_{\gamma_2\beta}$ = 6.5, $J_{\gamma_1\gamma_2}$ = 9.3, $H\gamma_2$), 5.03 (2H, s, CH_2Ph), 5.12 (1H, d, $J_{\alpha\beta}$ = 5.1, $H\alpha$), 6.60-7.00 (6H, m, ArH), 7.10-7.60 (5H, m, ArH).

^{13}C NMR (50 MHz, $CDCl_3$) δ : -5.6 ($SiMe_2$), 18.2 (Me_3CSi), 25.9 ($Me_3\underline{C}Si$), 46.8 (Cβ), 55.7, 55.8 (OCH_3), 60.6 (B2-OCH_3), 64.8 (Cγ), 71.1 (CH_2Ph), 74.6 (Cα), 110.7 (B4), 110.8 (A2), 113.7 (A5), 119.0 (A6), 121.7 (B6), 123.4 (B5), 126.6 (benzyl 3,5), 127.3 (benzyl 4), 128.2 (benzyl 2,6), 132.7 (A1), 136.0 (B1), 137.3 (benzyl 1), 147.2 (A3), 147.7 (B2), 149.3 (A4), 152.6 (B3).

Mass Spectrum High resolution molecular ion not observed, but $M^{+\cdot}-H_2O$ measured at m/z = 520.2617; calculated m/z for $C_{31}H_{40}O_5Si$ = 520.2645.

1-(4-hydroxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol (7)

Compound 6 was debenzylated in the usual way to give 7 as a clear oil (97 mg, 96%).

^{1}H NMR (200 MHz, $CDCl_3$) δ : -0.049, -0.043 (2 x 3H, 2s, $SiMe_2$), 0.88 (9H, s, Bu^tSi), 3.65 (3H, s, OCH_3), 3.65 (1H, m, Hβ), 3.68-3.78 (2H, m, Hγ's), 3.76 (3H, s, OCH_3), 3.85 (3H, s, OCH_3), 5.14 (1H, d, J = 4.5 Hz, Hα), 5.55 (1H, s, ArOH), 6.60-7.00 (6H, m, Ar-H).

1-(4-benzyloxy-3-methoxyphenyl)-1-acetoxy-2-(2,3-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propane (8)

Compound 6 was acetylated in the normal way to give 8 as a clear oil (100%).

^{1}H NMR (60 MHz, $CDCl_3$ δ: 0.18 (6H, s, $SiMe_2$), 1.00 (9H, s, ^tBuSi), 2.04 (3H, s, α-OAc), 3.74 (3H, s, OCH_3), 3.70-4.00 (3H, m, Hβ, Hγ's), 3.85 (3H, s, OCH_3), 3.88 (3H, s, OCH_3), 5.30 (2H, s, CH_2Ph), 6.34 (1H, d, $J_{\alpha\beta}$ = 6.4 Hz, Hα), 6.80-7.40 (6H, m, ArH), 7.40-7.80 (5H, m, ArH).

1-(4-hydroxy-3-methoxyphenyl)-1-acetoxy-2-(2,3-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propane (9)

Compound 8 was debenzylated in the usual way to give 9 as a clear oil (88%).

^{1}H NMR (200 MHz, $CDCl_3$) δ: 0.15, 0.18 (2 x 3H, 2s, $SiMe_2$), 1.05 (9H, s, Bu^tSi), 1.98 (3H, s, α-$OCOC\underline{H}_3$), 3.82 (3H, s, OCH_3), 3.86 (1H, m, Hβ), 3.94 (3H, s, OCH_3), 3.90-4.10 (2H, m, Hγ's), 3.98 (3H, s, OCH_3), 6.00 (1H, s, Ar-OH), 6.34 (1H, d, $J_{\alpha\beta}$ = 7.8, Hα), 6.80-7.40 (6H, m, Ar-H).

Mass Spectrum High resolution molecular ion not observed, but $M^{+\cdot}$ - CH_3COOH measured at 430.2169; calculated m/z for $C_{24}H_{34}O_6Si$ = 430.2175.

4.4.3 Anthranol Adducts

Conditions, yields and *erythro*:*threo* ratios are given in Table 1; selected NMR data are given in Table 2 and ^{13}C NMR data in Table 3.

Adduct 22

Prepared from model 2.1. The *erythro* isomer was isolated by flash chromatography using chloroform as eluant. Acetylation gave adduct 24. On standing, compound 24 spontaneously polymerised, presumably to the styrene polymer 34 as indicated by the line broadening, the loss of the allylic methyl resonance, and the appearance of a new (broad) aliphatic methyl resonance (δ ca. 1).

Adduct 23

Prepared from model 2.6. The erythro isomer was isolated by prep. tlc using EtOAc:hexane as eluant. Acetylation gave adduct 25.

Adduct 26

Prepared from model 1. Attempts to separate threo and erythro isomers were unsuccessful.

Adduct 27

Prepared from model 2.28. Acetylation gave 29. Small scale separation on analytical tlc plates using multiple elution with EtOAc-hexane gave 300 μg pure erythro adduct.

Mass spectrum (probe, CI, isobutane) m/z: 595(($M+H^+$), 48), 416(13), 400(37), 356(11), 340(100), 238(11).

Adduct 28

Prepared from adduct 26.

Adduct 30

Prepared from model 4, followed by acetylation.

Mass spectrum (probe, CI, isobutane) m/z: 623(($M+H^+$), 64), 428(13), 368(59), 355(57), 326(15), 314(28), 299(16), 285(22), 283(18), 257(100), 243(48).

Adduct 31

Prepared from model 9, followed by acetylation. The ^{29}Si NMR spectra also showed hindered rotation features. Threo-31 ($CDCl_3$, 39.8 MHz) : δ 19.96, 19.99; erythro-31 δ 19.39 (broad).

Mass spectrum (probe, CI, isobutane) m/z: 667(($M+H^+$), 100), 472(13), 443(20), 340(72).

4.4.4 Competition for the Quinone Methide Between Anthranol Adduct Formation and Reversal to the Phenylcoumaran

Model 2.6 (160 mg, 1.0 eq) in $CDCl_3$ was treated with trimethylsilyl iodide (117 mg, 1.2 eq) for 3 minutes to give the α-iodide 33 (as evidenced by ^1H NMR, δ 5.5, $J_{\alpha\beta}$ ca. 10 Hz). This solution was rapidly added to a solution of anthranol (190 mg) in aqueous base (1 M NaOH), stirred for 5 minutes, then neutralised and extracted with $CHCl_3$, etc., as in the general method for adduct formation. The resultant product mixture was approximately 10% anthranol adduct 22 to 90% phenylcoumaran 2.6 by ^1H NMR.

4.4.5 Anthrone Adduct Reversibility

Adduct 32

Adduct erythro 31 (12 mg, 0.018 mmol) was dissolved in methanol. To this was added pyrollidine (36 µl, 0.072 mmol) and the reaction stirred for 1 hr. The mixture was extracted with $CHCl_3$ and washed with 5% H_2SO_4 and water. The solvent was removed under reduced pressure to give 32 as a clear oil (7 mg, 64%). ^1H NMR clearly showed the loss of the phenolic acetate resonance.

Isomerisation of adduct erythro 32

Adduct erythro-32 was dissolved in $CDCl_3$ in a 5-mm NMR tube, and the ^1H spectrum recorded. To this was added a drop of $NaOD/D_2O$ and the tube was shaken periodically over a period of 24 hours. The ^1H spectrum recorded after 24 hours showed the presence of a small (<5%) amount of the threo adduct 32.

After 1 week, the S/N of the adducts (erythro and threo 32) had decreased markedly from the initial spectra. The AQ resonances had increased significantly, and the white suspension formed in the aqueous layer indicated the presence of the QM polymer.

Reversibility of the Addition of Anthrone to QM 17

QM 17 (in $CDCl_3$) formed by the method of Ralph (1983) was added to a solution of anthranol in a 1:1 mixture of 1 mol l^{-1} NaOH and dioxane maintained at 40°C under oxygen-free N_2.

A sample was withdrawn after 2 minutes and extracted with $CHCl_3$. The organic layer was dried and the solvent removed. The resulting oil was acetylated in the usual way. ^1H NMR analysis showed a 9:1 ratio of erythro-31:threo-31. This procedure was repeted after 1 hr. ^1H NMR analysis showed a 1:1 ratio of erythro-31: threo-31.

CHAPTER FIVE

SYN AND ANTI LIGNIN MODEL QUINONE METHIDES: ASPECTS OF THEIR FORMATION, CHARACTERISATION AND DIFFERENTIAL REACTIVITY WITH AMINES

5.1 INTRODUCTION

It is well established that p-quinone methides (QMs) are key intermediates in alkaline-additive wood pulping reactions. They have also been implicated as the biosynthetic precursors of lignin, lignans, neolignans, and flavanoids (Taylor, 1967).

Quinone methides derived from lignin model compounds undergo addition reactions with nucleophiles (Scheme 1) such as water, hydroxide ion, hydrosulphide ion, alcohols, acids, amines, thiols anthranol, and anthrahydroquinone (Leary, 1977a, b; Hemmingson, 1975, 1979; Ralph 1983c). It is reactions of this type which are believed to be important in delignification reactions occurring in pulping processes.

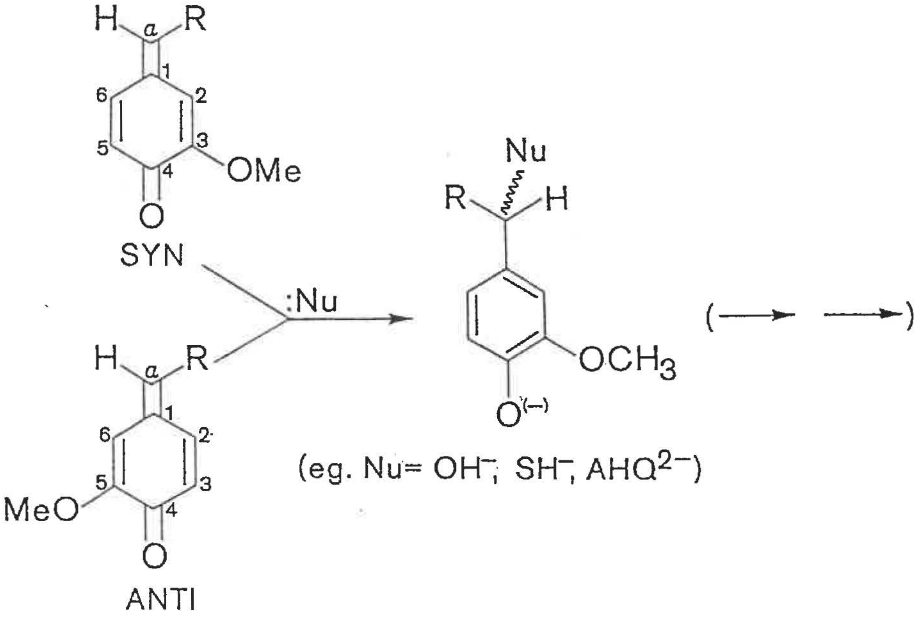
The characterisation of quinone methides has in general relied on the limited structural information available from UV spectroscopy, or the presence of stabilising groups on the methylenecyclohexadienone moiety to obtain species long lived enough

---

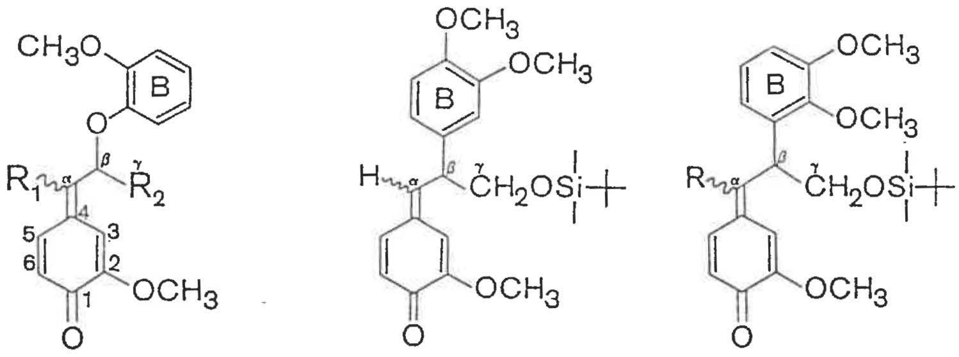
Footnote: Papers detailing the majority of the work in this chapter are in preparation for submission to the Journal of Organic Chemistry and Organic Magnetic Resonance (Ede, 1987b; Ralph 1987b).

for NMR studies (Grunanger, 1979). However, some lignin model quinone methides are surprisingly stable and are amenable to more informative study by both ^1H and ^{13}C NMR spectroscopy (Zanarotti, 1983, 1985; Ralph, 1983c,d).

Although the characterisation and reactivity of lignin model quinone methides have been well documented, the chemistry of the SYN and ANTI isomers (Fig. 1) of 2-methoxy substituted lignin model quinone methides (Ralph, 1983d) has received little investigation.



Scheme 5.1. Addition of nucleophiles to quinone methides.



	R_1	R_2
1	H	CH_2OH
2	H	CH_3
3	D	CH_2OH
4	D	CH_3
5	H	CH_2OAC

6

	R
7	H
8	D

Figure 5.1. Quinone methides.

This chapter deals with QMs derived from lignin model compounds representing the 1,2-diarylpropane-1,3-diol ("ß-aryl") and the 1-aryl-2-aryloxypropane-1,3-diol ("ß-aryl ether") moieties known to be present in wood lignin. The new ß-aryl QMs have been characterised by ^{1}H and ^{13}C NMR, and some previous ^{13}C NMR assignments corrected (Ralph, 1983d). Factors leading to the preferential (2:1) formation of the SYN isomer over the ANTI isomer of the ß-aryl ether and ß-aryl QMs have been evaluated. A simple NMR tube experiment was devised to determine the relative rate of addition of primary amines to the QM isomers.

5.2 RESULTS

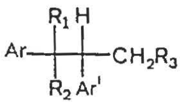
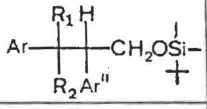
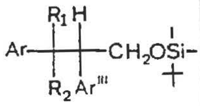
5.2.1 Lignin Model and Quinone Methide Syntheses

The 1-aryl-2-aryloxypropane-1,3-diol model derivatives 10-19 (Kratzl, 1959; Nakatsubo, 1975; Ralph, 1981, 1983c; Landucci, 1981b, 1982) and their quinone methides 1-5 were synthesised by previously described methods.

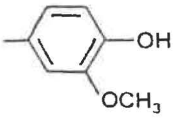
Compounds 23 and 24 (phenolic precursors of QM 6) were prepared by the following method: t-butyldimethylsilylation of *threo*-1-(4-benzyloxy-3-methoxyphenyl)-2-(3,4-dimethoxyphenyl)-propane-1,3-diol (Ralph, 1987) to give *threo*-1-(4-benzyloxy-3-methoxyphenyl)-2-(3,4-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol 21 followed by debenzylation to give *threo*-1-(4-hydroxy-3-methoxyphenyl)-2-(3,4-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol 22. Reaction of 22 with trimethylsilyl bromide gave a 1:1 mixture of 23 and 24. Compounds 25 and 26 were obtained by reaction of compound 4.7 with trimethylsilyl bromide. The α-deuterated α-bromides 30 and 31 were obtained by: $LiAlD_4$ reduction of compound 3.4 to give *erythro*-1-deuterio-1-(4-benzyloxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol 28, then debenzylation of 28 to give 29 *erythro*-1-deuterio-1-(4-hydroxy-3-methoxyphenyl)-2-(2,3-dimethoxyphenyl)-3-(t-butyldimethylsiloxy)-propan-1-ol). Reaction of 29 with trimethylsilyl bromide gave a 1:1 mixture of 30 and 31.

A synopsis of the reactions leading to the formation of QMs 1-9 is given in Table 1. It was shown by ^1H NMR that the phenolic

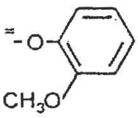
TABLE 5.1 - Phenolic precursors leading to QMs 1-9

Phenol structure	Entry	No.	Substitution R_1	R_2	R_3	Reaction conditions	QM	SYN:ANTI
	(a)	10	Br	H	OH	(i)	1	2:1
		11	H	Br	OH			
	(b)	12	Br	H	H	(i)	2	
		13	H	Br	H			
	(c)	14	Br	D	OH	(i)	3	
		15	D	Br	OH			
	(d)	16	Br	D	H	(i)	4	
		17	D	Br	H			
	(e)	18	OAc	H	OAc	(ii)	5	
		19	H	OAc	OAc			
	(f)	23	H	Br	-	(iii)	6	
		24	Br	H	-			
	(g)	25	H	Br	-	(iii) or (iv) or (v)	7	
		26	Br	H	-			
	(h)	4.9	OAc	H	-	(ii)	7	
	(i)	30	D	Br	-	(iii)	8	
		31	Br	D	-			
	(j)	32	-	-	-	(vi)	9	

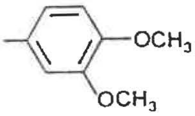
Ar =



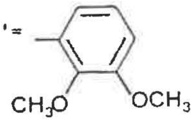
Ar'=



Ar''=



Ar'''=



(i) $NaHCO_3/D_2O/CDCl_3$ (ii) $NaOD/D_2O/CDCl_3$ (iii) $K_2CO_3/D_2O/CDCl_3$

(iv) $K_2CO_3/D_2O/CCl_4$ (v) $K_2CO_3/D_2O/C_6D_6$ (vi) Ag_2O/CCl_4

precursors were quantitatively converted to their quinone methides. The QMs were stable in solution for at least several hours, some for days. The QMs polymerised in the absence of solvent (Ralph, 1983c).

5.2.2 NMR Characterisation

The 200 MHz ^{1}H NMR spectra showed in all cases the presence of two isomers of the QMs in a ratio of 2:1 SYN-ANTI (± 5%). Assignments of the resonances for each isomer of QMs 1-5 have been reported previously (Ralph, 1983d). The relevant data for the new QMs 6-8 is reported in Table 2. A typical spectrum of the methylenecyclohexadienone/aromatic region of 7 is shown in Figure 2a. It was interesting to note the magnitude of the 5-bond coupling constant of 1.5 Hz between H6 and Hα in the ANTI isomer of 7 compared with that of 0.6 Hz for the SYN isomer. This coupling is analogous to 1,4-*trans* (^5J = 1.3 Hz) vs. 1,4-*cis* (^5J = 0.6 Hz) coupling in 1,3-butadiene (Harris, 1983). Considerable spectral simplification was evident in the spectrum of the α-deuterated QM 8 (Fig. 2b). The long-range coupling between H3, H5, H6, and Hα was removed as well as the loss of the Hα resonance.

A previous assignment of the ^{13}C NMR shifts of the SYN and ANTI isomers of QM 2 was shown to be incorrect, as a complete, unambiguous ^{13}C assignment of QM 2 was made from the correlations observed in a 2D NMR ^{13}C- ^{1}H shift correlation experiment (Bax, 1981). The 2D spectrum is shown in Figure 3. ^{13}C NMR spectra were obtained of QMs 7 and 8 (as mixtures of SYN and ANTI isomers). Comparison of the two spectra showed that the Cα signals of 7 (δ_{SYN} = 149.1 ppm, δ_{ANTI} = 148.7 ppm) were not present in the deuterated analogue 8 due to loss of signal from quadrupolar broadening, $^{13}C-^{2}H$ coupling and the loss of the heteronuclear NOE. The assignments were consistent with those from the 2D spectrum of 2. The ^{13}C assignments of 2, 7 and 8 are reported in Table 3.

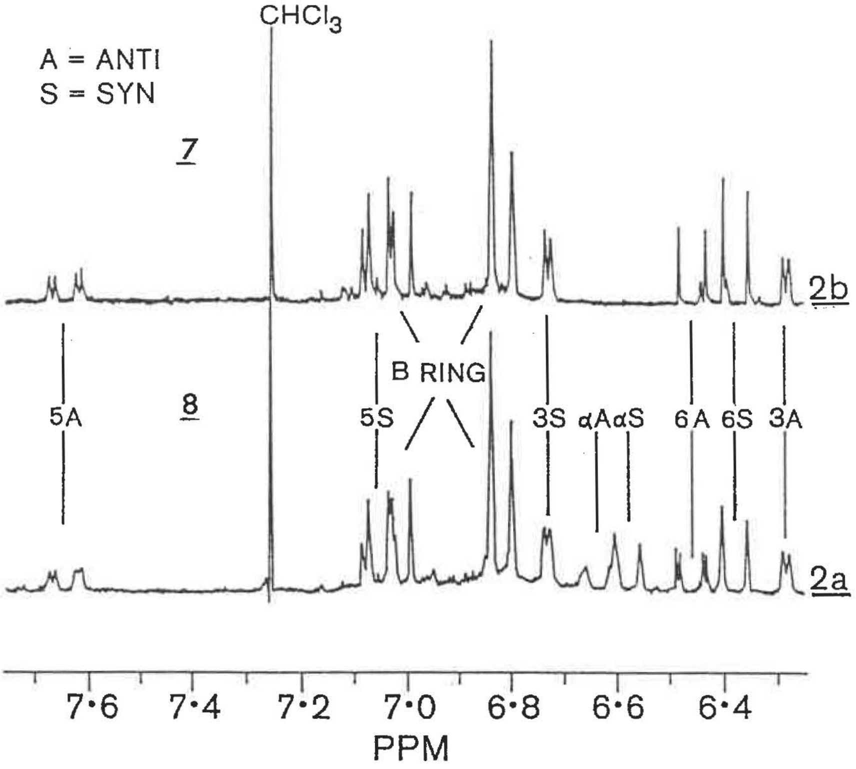


Figure 5.2. ^{1}H NMR spectra of 7 and 8.

TABLE 5.2. ^{1}H NMR data for QMs 6-8

QM	Me_2Si	$^{t}BuSi$	OCH_3	γ^{a}	β	α	H3	H5	H6	B ring	$J_{\alpha\beta}$	$J_{\beta\gamma_1}$	$J_{\beta\gamma_2}$	J_{35}	$J_{3\alpha}$	J_{56}	$J_{5\alpha}$	$J_{6\alpha}$
6 SYN	-0.02 -0.01	0.828	3.77 3.86 3.94	.	4.11^{m}	6.55^{dddd}	6.61^{dd}	7.08^{ddd}	6.42^{dd}	6.75-6.90	9.9	.	.	2.3	$< 0.3^{b}$	9.7	$< 0.3^{b}$	0.3
6 ANTI	-0.01	0.825	"	.	4.20^{m}	6.60^{dddd}	6.30^{dd}	7.58^{ddd}	6.48^{dd}	6.75-6.90	10.1	.	.	1.8	$< 0.3^{b}$	9.7	$< 0.3^{b}$	1.4
7 SYN	-0.01 -0.02	0.82	3.85 3.83 3.75	.	4.56^{m}	6.59^{dddd}	6.73^{dd}	7.06^{ddd}	6.39^{dd}	$6.82, 7.03^{c}$	8.6	.	.	2.2	0.5	8.2	$< 0.3^{b}$	0.5
7 ANTI	-0.01	0.81	"	.	4.63^{m}	6.64^{dddd}	6.29^{dd}	7.64^{ddd}	6.47^{dd}	$6.82, 7.03^{c}$	7.9	.	.	2.0	$< 0.3^{b}$	8.3	0.4	1.5
8 SYN	-0.01 -0.02	0.82	3.85 3.83 3.75	.	4.56^{dd}	-	6.73^{d}	7.05^{dd}	6.39^{d}	$6.82, 7.03^{c}$	-	6.5	6.8	2.3	-	9.5	-	-
8 ANTI	-0.01	0.81	"	a	4.63^{dd}	-	6.29^{d}	7.64^{dd}	6.47^{d}	$6.82, 7.03^{c}$	-	6.5	6.8	2.0	-	9.8	-	-

. not measurable; - coupling not present;
[a] Hγ resonances overlapped by methoxyl resonances;
[b] evidenced by broadening of appropriate signals;
[c] B ring resonances overlapping H6 SYN resonances.

TABLE 5.3 - ^{13}C NMR data for 2 and 7

QM	Me_2Si	^tBuSi	α	β	γ	OCH_3	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6
2 SYN	-	-	146.5	74.4	21.2	55.1, 55.8	181.0	153.1	104.1	132.0	141.6	128.5	151.1	146.9	112.3	122.9	120.8	117.7
2 ANTI	-	-	146.4	74.2	21.8	55.1, 55.8	181.2	152.8	111.9	131.8	132.5	129.7	151.1	146.9	112.3	122.9	120.8	117.9
7 SYN	-5.4	18.3, 25.8	149.1	41.9	66.47	55.1, 55.8	181.4	153.0	105.7	132.7	141.9	127.3	134.0	146.6	153.1	111.4	124.39	120.3
7 ANTI	-5.4	18.3, 25.8	148.7	41.7	66.53	55.1, 55.8 61.0	181.7	153.0	112.8	132.3	134.1	128.9	134.0	146.7	153.1	111.4	124.34	120.1

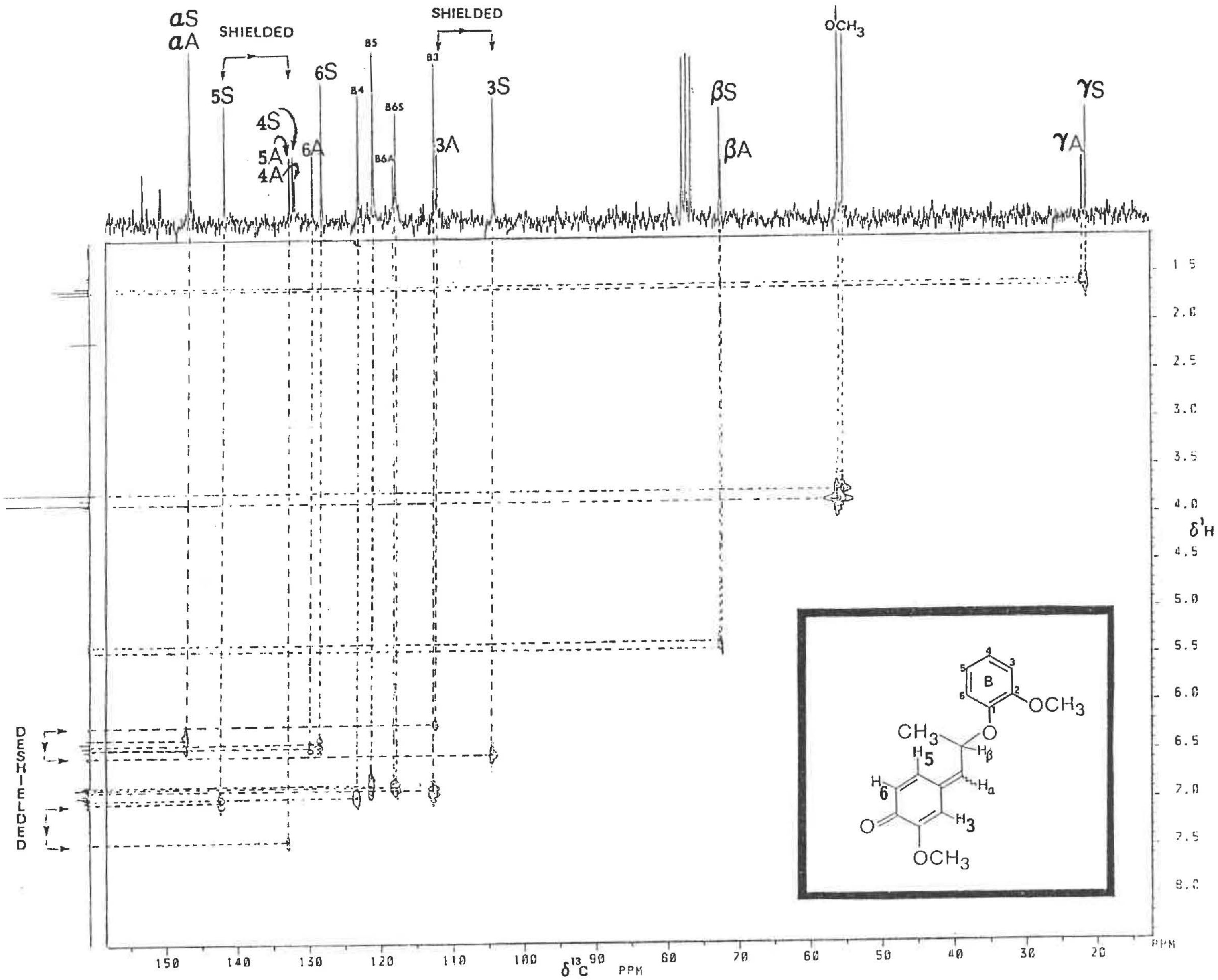


Figure 5.3. 13C-1H shift correlation spectrum of 2

5.2.3 Reactivity Study

The determination of the relative rates of addition of primary amines to QMs 3, 4, and 8 (each as a 2:1 mixture of SYN:ANTI isomers) was conveniently carried out by the ^1H NMR method described in the Experimental Section. This gave the ratio of each of the isomers of the QM present in solution after the addition of approximately 10 0.1 mole-equivalent aliquots of the amine. The results of these experiments are summarised in Table 4. Typical examples of the ^1H spectra obtained are shown in Figure 4. A graph showing the decrease in [QM] vs. moles amine added is shown in Figure 5.

TABLE 5.4 - Relative rates of addition of amines to QMs

QM	RNH_2	No. additions amine	k_{ANTI}/k_{SYN}
3	R = $(CH_2)_2OH$	13	1.3 ± 0.1
4	R = $(CH_2)_2OH$	7	1.4 ± 0.2
4	R = ^tBu	10	1.4 ± 0.2
8	R = $(CH_2)_2OH$	5	1.4 ± 0.3

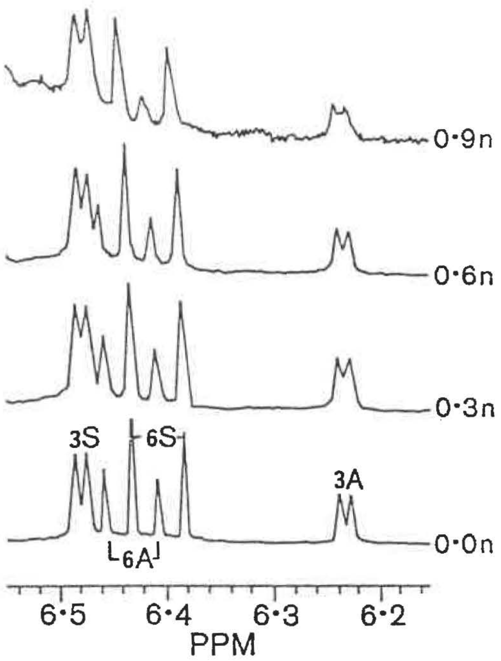


Figure 5.4. ^{1}H Spectra obtained from addition of ethanolamine to n mmole 4

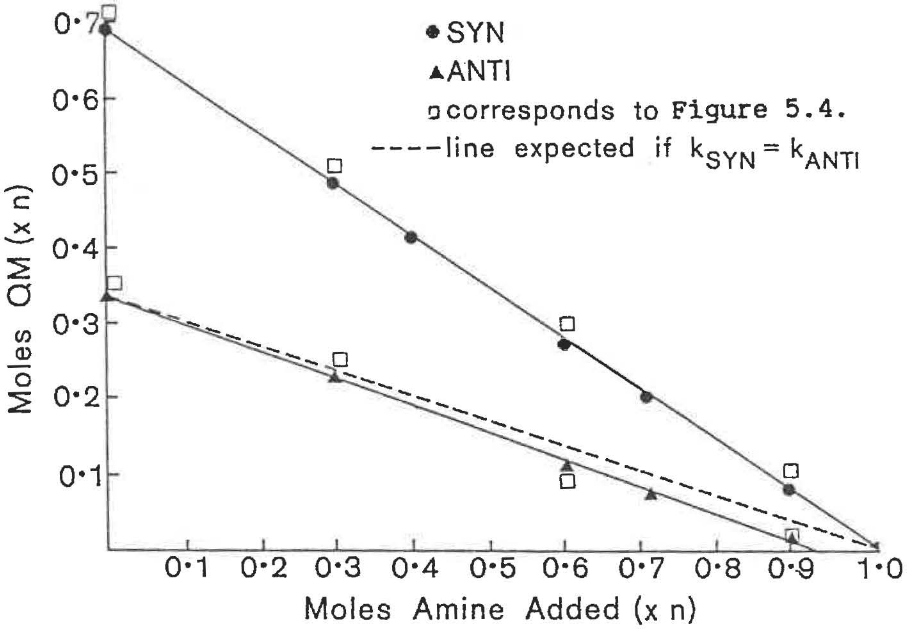


Figure 5.5. Plot of [QM] vs moles amine added to 4.

5.3 DISCUSSION

5.3.1 Quinone Methide Formation

It is widely believed that quinone methide formation is the rate-determining step in most alkaline-additive wood delignification reactions (Miksche, 1980), yet little is known of the detailed mechanism of quinone methide formation. Miksche (1980) has shown that at pH > 11, rate = k[phenolate anion] for 4-hydroxy-3-methoxy benzyl alcohols, and that at room temperature the rate of formation of quinone methides from the phenolate anions of these benzyl alcohols is negligible - a temperature of 110°C is required before $k = 10^{-3}\ \text{min}^{-1}$. The rate of formation of quinone methides of 4-hydroxy-3-methoxy benzyl acetates or bromides (formed at room temperature) is much faster (Ralph, 1983c,d) as the elimination of the acetate or bromide from the phenolate is more facile and at room temperature appears to be concommitant with phenolate ion formation. Other studies (Leary, 1977a,b; Hemmingson, 1975, 1979; Ralph, 1983c; Nakatsubo, 1976; Cook, 1956; Ivnas, 1961; Lindgren, 1963) have indicated the pH dependence of the mechanism of addition of hydroxy compounds to QMs (the reverse reaction of QM formation). At pH < 4 a benzylic carbonium ion is thought to be the key intermediate, whereas at intermediate pH a plurality of mechanisms (QM vs. carbonium ion) may exist.

A theoretical treatment (Murphy, 1981) has indicated that the 1,6-conjugate elimination (an example of which is QM formation) will have the opposite stereochemistry to that of the S_N2' and 1,4-conjugate eliminations, but the study dealt with 1,6-substituted hexa-2,4-dienes of defined cis/trans isomerism, rather than those with a conformationally mobile aromatic group within the conjugated system.

5.3.2 Quinone Methide Isomerism

None of the above mechanistic discussons aid in the determination of the origin of the 2:1 excess of SYN over ANTI isomers in 2-methoxy substituted QMs. From Table 1, however, several observations can be made:

(1) Comparison of entries (a)-(d) with (e) suggests a non-dependence of the ratio on the benzylic leaving group.

(2) The ratio was independent of the side-chain stereochemistry (entries (a) (i)). The ratio also remained unchanged whether the bromides were isomerically pure (>9:1 12-13) or 1:1 mixtures.

(3) QMs formed in $CDCl_3$, CCl_4, or C_6D_6 showed no variation in the SYN:ANTI ratio (entry (g)).

(4) The vinylogous quinone methide 2-methoxy-4-(prop-1,3-dienyl-cyclohexa-2,5-dienone 9 (formed via a free radical mechanism (Zanarotti, 1983)) gave the same 2:1 ratio of isomers as QMs 1-8 (entry (j)).

The above evidence suggests that the 2:1 SYN:ANTI ratio in these quinone methides is independent of both the side-chain on the methylenecyclohexadienone moiety, and, as far as can be ascertained, the solvent. It also appears, from VT ^1H NMR epxeriments, that the ratio is independent of temperature. There was no observable change in the 2:1 ratio of SYN 7 to ANTI 7 from -10 °C to 80 °C. A study (Berg, 1978) with some quinone methides with donor substituents on the exocyclic carbon has determined that low barriers to rotation about C4-C exist. This was clearly not the case for QMs 1-8. It was clear from the VT results that the ratio did not reflect a pair of interconverting isomers at equilibrium.

The clearly defined preference for the formation of the SYN isomer in these quinone methides can be accounted for by a range of mechanisms, but two in particular are of interest.

1. Product control: It has been noted (Ralph, 1983d) that the SYN isomers of QMs appeared (intuitively) to be more sterically crowded than the ANTI isomers based on possible interactions between the 2-OCH_3 and the ß substituents. However, since it was the SYN isomer which predominated in all QMs studied, the preference may have arisen instead from some unspecified electronic effects. Also reported was a steric interaction between Hß and H3 in the SYN isomer, and Hß and H5 in the ANTI isomer of the QMs. this interaction was manifested by:

   - Downfield shifts of the H3 SYN and H5 ANTI resonances relative to the resonances from the non-compressed protons H3 ANTI and H5 SYN in the ^1H NMR spectra.
   - Corresponding upfield shifts of the C3 SYN and C5 ANTI resonances, relative to the resonances from C3 ANTI and C5 SYN in the ^{13}C NMR spectra.
   - An homonuclear ^1H-^1H NOE enhancement of the H3 SYN and H5 ANTI resonances on irradiation of the Hß protons.

For QMs 1-8 the above steric interactions have been observed, but it is notable that for QMs 1-8 the downfield shift in the ^{1}H NMR resonance of H3 SYN relative to H3 ANTI is less than the downfield shift of H5 ANTI relative to H5 SYN. These differences are mirrored in the ^{13}C spectra, with the upfield shift of the C3 SYN resonance relative to C3 ANTI being less than that of C5 ANTI relative to C5 SYN. Allied to these observations are the results of the difference NOE experiment on QM 8 which showed a 15% enhancement of H5 ANTI compared to a 10% enhancement of H3 SYN on irradiaton of the Hβ protons. These results suggest that the extent of through-space interaction between Hβ ANTI and H5 ANTI is greater than that between Hβ SYN and H3 SYN, i.e., there is more steric crowding in the ANTI isomer compared to the SYN isomer.

The greater H5 ANTI/Hβ ANTI interaction must be attributed to a decrease in the internuclear distance between H5 and Hβ in the ANTI isomer compared to Hβ and H3 in the SYN isomer. Such a decrease could be achieved by a distortion of the cyclohexadienone ring; for example if the effect of the 2-methoxyl was to cause the C2=C3 bond to be longer than the C5=C6 bond (the use of a molecular model may aid the reader in visualising this effect), the ensuing distortion would cause a decrease in the H5-Hβ internuclear distance in the ANTI isomer only.

Thus, if the formation of the QMs was under product development control (House, 1972), the favoured transition state would be that leading to the more stable (less sterically crowded) SYN isomer. However, a 2:1 ratio of isomers does not suggest a large energy difference between the two forms, and since both isomers are obtained, the two transition states (between the phenolate and the two QM isomers) may well be able to interconvert through a common transition state, either by a rotation around the developing C4-Cα double bond (requires rotational freedom) or by a microscopic reversibility of the benzylic group elimination, i.e., if the leaving group were temporarily enclosed in a cage of solvating molecules, resulting in several addition-eliminations to give an equilibrium mixture followed by irreversible elimination of the leaving group to give the 2:1 SYN:ANTI ratio in the QMs.

2. Conformational Equilibrium Control: The crystal structures of 2.6 and 2.28 (which are closely related to the phenolic precursors of QMs 6 and 8) show that the orientation of the A ring and Cα is as shown in Figure 6. Since this is the lowest

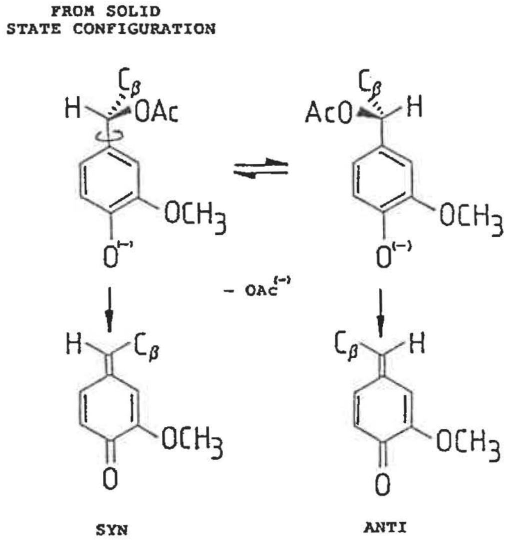


Figure 5.6. Low energy configurations of precursor compounds and their relationship to quinone methide isomers.

energy arrangement in the solid, it is likely (neglecting any unusual crystal packing interactions) that this conformation will also be a low energy rotamer in solution. Formation of the QM from the phenolate in the same conformation will give rise to the SYN QM. A rotation of 180° about C1-Cα in the phenolate (also likely to give a low energy rotamer) followed by QM formation will give rise to the ANTI QM. If the energy of the transition state of QM formation is lower than the transition state of C1-Cα rotation in the phenolate, the ratio of the QM isomers would reflect the relative populations of the phenolate rotamers, and the system would be under conformational equilibrium control (Zefirov, 1977).

In the case of phenols with benzylic bromides or acetates, the QM formation was qualitatively very fast, but the relative rates of rotamer interconversion vs. QM formation have not yet been determined.

5.3.3 Differential Reactivity

Previous kinetic studies (Leary, 1977a,b; Hemmingson, 1975, 1979; Nakatsubo, 1976; Cook, 1956; Ivnas, 1961; Lindgren, 1963) of the reactivity of QMs of this type with nucleophiles have either directly or indirectly measured the disappearance of the QM with time, but have not been able to distinguish between the reactions of the two QM isomers. Thus the previously determined rate constants have neglected the possibility of differing reactivities of the two isomers.

In this study, primary amines were chosen as the most suitable nucleophiles, since the rate of reaction with QMs has been (qualitatively) shown to be very fast, and under the slightly alkaline conditions used, irreversible (Ralph, 1983c). Alcohols and thiols react more slowly with QMs than primary amines (Ralph, 1985b), and do so reversibly (Ralph, 1985b; Miksche, 1980), and for these reasons were not considered. For a qualitative kinetic analysis, it was important that the product ratio reflects the kinetic ratio of the isomers.

The reactivity difference between the 2 isomers of 3, 4, and 8 was small but consistent. Since the addition of t-butylamine (a more hindered but also more basic amine than ethanolamine) to the QMs showed no observable change in the reactivity ratio, the reaction was probably not subject to steric limitations. The greater rate of addition of amines to the ANTI isomers may be related to the higher strain energy of these QM isomers compared to the SYN isomers. Greater relief of steric strain in the ANTI isomer may account for k_{ANTI} being greater than k_{SYN}. The addition of very hindered nucleophiles such as anthranol and anthrahydroquinone to QMs 1-4 proceeds so much more rapidly than most other common nucleophiles (Ralph, 1985), that the addition may be controlled by electronic effects or a different mechanism may be at play. Anthrahydroquinone will not however add to QMs 5-7 (Ralph, 1987a).

5.4 CONCLUSIONS

Quinone methides (2-methoxy-4-methylenecyclohexa-2,5-dienones) derived from 1,2-diarylpropane-1,2-diol lignin model compounds have been characterised by ^{1}H and ^{13}C NMR. These and other quinone methides have been shown to exist in solution as a pair of non-interconverting isomers, in a ratio of 2:1 SYN:ANTI. The isomeric composition has been shown to be independent of both the benzylic leaving group and the side-chain stereochemistry in the parent phenolic lignin model compounds. The reason for the predominance of the SYN isomer in these quinone methides was not obvious, but may have been a product controlled preference for the sterically less compressed SYN isomer, although the possibility existed that the system was under conformational equilibrium control, with the ratio of the QM isomers reflecting the relative populations of the solution-state rotamers of the precursor phenols.

It was shown by a simple NMR tube experiment that the ANTI (minor) isomers reacted with primary amines approximately 40% faster than the SYN isomers, possibly due to the greater relief of steric strain in the ANTI isomers.

The results obtained in this chapter have, in part, led to the necessity for some further studies to obtain a clearer understanding of the mechanism of QM formation, and the importance of the mechanism to pulping reactions.

The rates of formation of quinone methides from benzylic bromides and acetates should be quantified (possibly by stopped flow kinetics), and, if possible, a determination of the rates of formation of the SYN and ANTI isomers.

Determination of the energy barrier to rotation about the C1-Cα bond in the phenolate precursors and comparison with the energy of formation of the QM isomers would be a test of the conformational equilibrium control hypothesis.

It would be interesting to determine if QMs formed from benzyl alcohols exhibited the same 2:1 SYN:ANTI ratio, although, given the reversibility of OH^- addition to QMs, this would not be a trivial experiment.

Also of interest would be determining the relative addition rates of pulping additives (SH^-, AHQ^{2-}) to QMs - would they add to the SYN isomers faster than the ANTI isomers?

Lastly, a largely hypothetical question - would delignification be more efficient if all guaiacyl derived QMs were ANTI rather than if they were SYN?

5.5 EXPERIMENTAL

5.5.1 General Syntheses

The quinone methides were synthesised by one of two methods[12,13]. The parent alcohol (0.2-0.4 mmol) in $CDCl_3$ in a

5 mm NMR tube was treated with trimethylsilylbromide (1.1 mole equivalents) then shaken vigorously with saturated $NaHCO_3/D_2O$ (the formation of QMs 7 and 8 required saturated K_2CO_3). The aqueous layer was drawn off. Alternatively the QM in $CDCl_3$ could be prepared by shaking the alpha acetylated parent compound with a drop of $NaOH/D_2O$, then drawing off the aqueous layer. Dry, degassed QM 8, for NOE studies was formed by the first method, then filtered through anhydrous magnesium sulphate and degassed by the freeze-thaw method (Noggle, 1971) at 1 torr, and stored in a sealed tube.

5.5.2 Specific Syntheses

Compound 22

Debenzylation of 21 (13 mg, 0.024 mmol) dissolved in MeOH (5 ml) in the usual way gave 22 as a clear oil (11 mg, 100%).

^{1}H NMR (200 MHz, $CDCl_3$) δ: 0.11 (6H, s, $SiMe_2$), 0.95 (9H, s, Si^tBu), 1.65 (1H, br s, α-OH), 2.97 (1H, ddd, J_{β} = 8.3, $J_{\beta\gamma_1}$ = 4.2, $J_{\beta\gamma_2}$ = 8.3), 3.74 (3H, s, OCH_3), 3.75 (3H, s, OCH_3), 3.81 (3H, s, OCH_3), 4.02 (1H, dd, J = 4.2, $J_{\gamma_1\gamma_2}$ = 10.2, $H\gamma_1$), 4.11 (1H, dd, $J_{\gamma_2\beta}$ = 8.3, $J_{\gamma_2\gamma_1}$ = 10.2), 4.65 (1H, s, Ar-OH), 4.98 (1H, d, $J_{\alpha\beta}$ = 8.3, $H\alpha$), 6.40-6.80 (6H, m, ArH).

Compound 27

Reaction of compound 3.4 (80 mg, 0.187 mmol) with $LiAlD_4$ (16 mg, 0.37 mmol) in THF (dried over $Na/Ph_2C{=}O$, 10 ml) in the normal way gave 27 as a clear oil (75 mg, 94%).

^1H NMR (200 MHz, $CDCl_3$) δ: 3.69 (3H, s, OCH_3), 3.78 (3H, s, OCH_3), 3.85 (3H, s, OCH_3), 3.70-3.90 (3H, m, Hβ, Hγ's), 5.13 (2H, s, CH_2Ph), 6.70-7.10 (6H, m, ArH), 7.30-7.60 (5H, m, ArH).

Compound 28 (60 mg, 0.14 mmol)

Compound 27 was reacted with t-butyldimethylsilyl chloride in the normal way to give 28 as a clear, colourless oil (76 mg, 100%).

^1H NMR (200 MHz, $CDCl_3$) δ: -0.03 (3H, s, SiMe), -0.02 (3H, s, SiMe), 0.85 (9H, s, ^{t}BuSi), 3.38 (3H, s, OCH_3), 3.63 (3H, s, OCH_3), 3.5-3.9 (3H, m, Hβ, Hγ's), 3.76 (3H, s, OCH_3). 5.03 (2H, s, CH_2Ph), 6.60-7.00 (6H, m, ArH), 7.10-7.60 (5H, m, ArH).

^{13}C NMR (50 MHz, $CDCl_3$) δ: -5.6 ($SiMe_2$), 18.2 ($Me_3\underline{C}$ Si), 25.9 ($Me_3\underline{C}$ Si), 46.8 (Cβ), 55.7, 55.8 (A3,B3-OCH_3), 60.6 (B2-OCH_3), 64.8 (Cγ), 71.1 (CH_2Ph), 74.6 (t, $J_{C\alpha-D} = 21$, Cα), 110.7 (B4), 110.8 (A2), 113.7 (A5), 119.0 (A6), 121.7 (B6), 123.4 (B5), 126.6 (benzyl 3,5), 127.3 (benzyl 4), 128.2 (benzyl 2,6), 132.7 (A1), 136.0 (B1), 137.3 (benzyl 1), 147.2 (A3), 147.7 (B2), 149.3 (A4), 152.6 (B3).

Mass Spectrum High resolution molecular ion not observed,but $M^{+\cdot}-H_2O$) observed at m/z = 521.2700; calculated m/z for $C_{31}H_{39}O_5DSi$ = 521.2708.

Compound 29

Debenzylation of 28 (60 mg, 0.11 mmol) in MeOH in the usual way gave 29 as a clear, yellow oil (52 mg, 100%).

^{1}H NMR (200 MHz, $CDCl_3$) δ: -0.05 (3H, s, SiMe), -0.04 (3H, s, SiMe), 0.88 (9H, s, ^{t}BuSi), 3.00 (1H, br s, α-OH), 3.65 (3H, s, OCH_3), 3.76 (3H, s, OCH_3), 3.84 (3H, s, OCH_3), 3.65-3.84 (3H, m, Hß, Hγ's), 5.51 (1H, br s, ArOH), 6.65-7.00 (6H, m, ArH).

5.5.3 Characterisation

All NMR spectra were obtained on a Bruker AC200 FT spectrometer. 200 MHz ^{1}H spectra were recorded using 16K data points (resulting in J values accurate to 0.3 Hz), with Lorentzian-Gaussian resolution enhancement. The difference NOE experiment was carried aout using the Bruker pulse program NOEDIFF with a decoupler power of 60 µW, irradiation for 5 seconds and a delay after acquisition of 3 seconds. 50 MHz ^{13}C spectra were recorded using 32K data points with WALTZ-16 (Shaka, 1983) decoupling. Exponential line broadening (1 Hz) was applied to improve S/N. Multiplicity assignments were achieved with the DEPT (Doddrell, 1982) pulse sequence (θ = 135°). The heteronuclear shift correlation spectrum (Bax, 1981) was obtained using the Bruker pulse program XHCORR. Parameters were: τ_1 = 0.0037s, τ_2 = 0.00185s; sweep width in F_1 = 1250 Hz, in F_2 = 9615 Hz; 1024 data points in F_2, with 256 incremented experiments recorded in F_1 (with zero-filling to 512 data points). Ninety-six scans were recorded for each increment with Lorentzian-Gaussian resolution enhancement applied in both domains.

5.5.4 Reactivity Studies

The reactivity experiments were carried out in the following manner. The QM (0.02-0.04 mmol) in $CDCl_3$ or C_6D_6 was treated successively with approximately 10 0.1 mole equivalents of a solution of the amine in CCl_4 (200 µl/2 ml). For each addition, a ^1H spectrum was obtained and the SYN/ANTI ratio determined from the H 3,5 and 6 resonances. By scaling each resonance to the $CHCl_3$ peak (or methylene chloride added as an internal standard) a fair estimation of the amount of unreacted QM and hence the amount of reacted amine could be calculated. The low S/N ratios encountered at low [QM] made the accuracy of the electronic integrator on the spectrometer uncertain. For reproductibility, all integrations were performed from peak-height measurements. The amount of each isomer reacting for each addition could then be calculated, and hence a ratio for the isomers.

APPENDIX

I. ^{13}C NMR shift assignments of a range of lignin model compounds and precursors synthesised in this thesis.

Compound No.	Solv.	Methoxyls	α	β	γ	Acetate methyls	Acetate carbonyls			Benzyl			A Ring						B ring					
							1°	2°	Ar	CH_2	1	2-6	1	2	3	4	5	6	1	2	3	4	5	6
2.1@	C	55.9	93.7, 131.0[a]	45.6 123.4[a]	17.8 18.3[a]	-	-	-	-	-	-	-	133.3	109.0	146.6*	145.8	114.2	119.9	132.2	146.7*	144.1	122.1	132.1	109.4
2.3	C	55.6	145.0	123.0	167.7	-	-	-		-	-	-	127.0	109.5	148.1	146.7	115.2	114.8	-	-	-	-	-	-
2.6	C	55.7	93.4 37.9	45.6 24.9[a]	17.2 13.7[a]								132.7	108.8	146.5	145.5	113.9	119.7	132.0	145.2	143.6	115.2	136.1	111.6
2.11	C	56.1	190.2	-	-	-	-	-	-	75.1	137.6	128.3 128.6 128.7	130.0	153.2	151.1	118.1	124.4	119.0	-	-	-	-	-	-
2.13@	C	55.4	188.3	123.9	138.8	-	-	-	-	70.2 74.9	136.0 136.8	126.9, 127.6 128.1, 128.2	129.1	110.8	149.7	152.8	113.7	122.9	131.1	147.0	153.1	111.8	122.5	119.8
2.14@	C	55.8, 55.9 61.6	188.7	124.1	138.7	-	-	-	-	70.7	136.2	127.2 128.0 128.6	129.2	111.3	149.6	152.8	114.0	122.8	131.6	148.8	153.1	112.2	123.2	119.6
2.15@	C	55.7, 55.9	191.4	55.5	59.8	-	-	-	-	70.6 75.1	136.0 136.8	127.1, 128.1 128.5	128.8	110.5	149.6	152.4	112.5	123.2	130.0	146.5	153.0	112.0	124.4	117.0
2.16@	C	55.3, 55.4 60.5	191.0	54.9	59.5	-	-	-	-	70.2	135.6	126.8, 127.6 128.1	128.4	110.1	149.6	152.0	112.3	122.7	129.1	147.6	152.7	111.8	124.0	116.5
2.17@	C	55.5, 55.6	74.9	47.7	63.8	-	-	-	-	70.9 74.4	137.1 137.8	127.1, 127.7 127.8, 128.2 128.3	135.7	110.2	147.4	149.4	113.4	120.7	133.0	146.7	152.8	111.0	123.9	118.7
2.18@	C	55.6, 55.7 60.5	74.8	47.8	63.8	-	-	-	-	71.0	137.1	127.3 127.6 128.4	135.9	110.5	147.7	149.3	113.7	121.1	132.7	147.3	153.6	111.0	123.7	118.8
2.19	C	55.8, 55.9	75.3	42.3	64.8	20.9, 21.1	170.7	169.8		71.0 74.5	137.2 138.1	127.4, 128.0 128.5, 128.6	132.2	110.9	148.2	149.6	113.6	120.5	132.0	146.9	152.8	111.4	124.0	119.9
2.20	C																							
2.21	C	55.6	73.8d ^3J=3.7	75.6d ^2J=2	88.8d ^1J=174.2	-	-	-	-	70.7 74.5	137.0 137.1	127.1, 127.6 127.9, 128.1 128.2, 128.3	134.0	110.2	147.6	149.4	113.5	118.9	131.1,d ^2J=21.6	143.9,d ^3J=6.7	152.2	112.4	124.0	119.4,d ^3J=8.9

Compound No.	Solv.	Methoxyls	α	β	γ	Acetate methyls	Acetate carbonyls			Benzyl			A ring						B ring					
							1°	2°	Ar	CH2	1	2-6	1	2	3	4	5	6	1	2	3	4	5	6
2.22@	C	55.7, 55.8	72.5,d $^{3}J=7$	73.6,d $^{2}J=18$	86.7,d $^{1}J=178$	20.1, 20.8				70.8 74.3	136.9 137.8	127.2, 127.7 128.4, 129.5	129.5	111.3	148.1	149.2	113.4	120.3	129.6 $^{2}J=20$	114.0 $^{3}J=9$	152.0	112.8	123.1	118.8 $^{3}J=9$
2.23@	C,A,D		71.7	49.8	62.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2.24@	C	56.0	87.9	53.7	64.1	-	-	-	-	-	-	-	127.9	108.9	148.3	145.7	114.4	119.4	133.1	146.7	144.6	112.2	121.4	116.4
2.26@	C	55.7, 55.8	75.1	48.2	63.9	-	-	-	-	-	-	-	132.8	109.4	146.5	145.2	114.2	119.5	134.3	147.8	152.8	111.1	124.0	121.0
2.28	C	55.6, 55.8	75.5	42.1	64.7	20.7, 21.0	170.7	169.8	-	-	-	-	130.6	110.0	147.8	145.3	114.2	120.3	131.9	145.6	152.5	111.2	123.6	120.3
2.29	A	56.4	83.2	49.1	176.0	-	-	-	-	-	-	-	131.6	111.3	148.6	147.4	113.4	118.6	-	-	-	-	-	-
2.30	A	56.3	82.4	48.9	175.7	20.5	-	-	169.0	-	-	-	138.3	111.0	152.8	141.4	118.5	124.2	-	-	-	-	-	-
2.31	D	55.3	71.5	44.9	59.0	-	-	-	-	-	-	-	136.0	110.1	146.9	144.7	114.5	118.5	-	-	-	-	-	-
2.32	A	56.2	74.8	41.9	62.2	20.7, 20.4, 20.8	170.7	170.0	168.9	-	-	-	138.9	111.3	152.1	140.2	119.0	123.5	-	-	-	-	-	-
2.35	D	56.3	81.5	53.2	59.9	-	-	-	-	-	-	-	135.2	109.1	148.4	142.8	109.5	121.8	-	-	-	-	-	-
2.36	A	56.8	83.6	51.4	66.1	20.2, 20.6	170.9	-	168.1	-	-	-	?	110.9	153.7	143.1	(s) 117.5	123.2	-	-	-	-	-	-
2.37	A	56.1	86.4	54.8	72.0	-	-	-	-	-	-	-	133.8	110.5	148.1	146.5	115.5	119.5	-	-	-	-	-	-
2.39	A	56.1	86.0	55.2	72.4	20.5	-	-	169.0	-	-	-	139.9	110.9	152.1	141.7	118.5	123.4	-	-	-	-	-	-

Com-pound No.	Solv.	Methoxyls	α	β	γ	Benzyl				A Ring						B Ring						-SCH$_2$-	-CH$_2$-
						CH$_2$	1	2-6	r	1	2	3	4	5	6	1	2	3	4	5	6		
2.42	C	56.1	51.3	-	-	71.0	137.1	127.4, 128.0 128.7		132.3	11.4	148.3	149.7	113.8	120.1	-	-	-	-	-	-	32.3	25.2
2.43	C	55.5, 55.8	190.5	-	-	-	-	-		130.1	108.8	149.5	154.3	110.4	126.4	-	-	-	-	-	-	-	-
2.45	C	55.5, 55.8 56.1	66.5	80.8	-	70.9	137.1	127.3, 127.9 128.6		130.1*	111.4	147.6	149.7	113.0	120.9	130.2*	109.2	147.6	149.0	115.0	123.5	27.3, 27.4	24.9
2.46	C	55.9, 56.1 60.8	66.3	75.7	-	71.0	137.2	127.4, 127.9 128.6		131.0	112.4	147.8	149.1	114.8	121.7	130.6	147.5	152.8	113.2	123.3	122.4	27.3, 27.5	24.9
2.49	C	56.1, 56.2	190.1	62.2	-	71.0	136.8	127.3, 129.0 128.7		131.4	111.5	149.3	153.4	111.7	121.1	131.0	110.2	149.1	150.2	113.7	123.8	-	-
2.59	C	55.8	134.1	134.7	-	70.9	137.1	127.3, 127.8 128.5		129.9*	113.1	148.1	148.8	114.6	123.5	130.0*	110.4	147.3	148.1	115.1	123.5	32.1	28.7
2.60	C	55.8	46.7	-	-		-	-		130.0	110.0	149.1	149.2	111.8	121.2	-	-	-	-	-	- -	-	-
2.61	C	55.8, 61.2	31.2	-	-		-	-		131.6	147.5	152.8	113.0	124.2	122.0	-	-	-	-	-	- -	-	-
2.62	C	56.0	41.5	-	-	75.2	137.8	128.3, 128.5, 128.6		132.0	146.3	153.0	113.2	124.5	122.4	-	-	-	-	-	- -	-	-
2.63	C	55.3, 55.6, 55.7	59.8	51.1	-	70.7	137.1	127.2, 127.8, 128.4		133.4	110.0	147.3	149.4	113.6	122.1	133.3	111.7	149.9	148.9	114.0	123.2	27.5	25.1
2.64	C	56.0	60.0	44.1	-	71.0	137.3	127.4, 127.6, 127.9, 128.3, 128.6		129.6	111.6	147.2	149.2	113.4	121.9	134.5	147.1	152.6	113.4	122.6	124.6	32.3	27.9
2.65	C	55.9, 56.1	196.6	44.8	-	70.9	136.3	127.2, 128.2, 128.8		127.6	111.5*	149.2	152.6	112.3*	123.3	130.1	111.3*	148.1	149.7	112.6*	121.5	-	-
2.66	C	55.9, 56.0, 56.1	75.2	45.7	-	71.2	137.2	127.3, 127.9, 128.6		130.6	109.9	147.6	149.8	114.0	118.3	130.6	111.4	147.9	148.9	112.9	121.6	-	-
2.67	C	55.9, 56.0	75.3	45.7	-	-	-	- -	-	136.0	108.7	146.6	125.1	114.2	119.0	130.6	111.4	147.9	148.9	112.9	121.6	-	-

Compound No.	Solv.	Methoxyls	α	β	γ	Benzyl			A Ring						B Ring						Other	Si(CH$_3$)$_2$	Si$\underline{C}$(CH$_3$)$_3$	SiC($\underline{C}$H$_3$)$_3$
						CH$_2$	1	2-6	1	2	3	4	5	6	1	2	3	4	5	6				
3.1	C	55.7, 55.8	75.8	40.5	62.0	71.1 74.8	137.1 137.5	127.3, 127.8, 128.5 128.0, 128.2, 128.3	131.3	111.3	147.4	148.6	113.4	118.6	131.6	145.8	152.6	111.3	123.7	120.3	127.7, 130.8, 134.1[1]	-	-	-
3.2	C	55.6, 55.8 60.9	75.9	40.5	61.9	71.1	137.1	127.3, 127.8, 128.5	130.8	111.2	147.4	148.7	113.5	118.6	131.5	147.3	152.6	111.3	123.6	120.1	127.7, 130.9, 134.1[1]	-	-	-
3.3	C	55.7, 55.8 61.0	76.0	40.6	61.0	-	-	-	130.3	109.9	145.6	144.9	113.6	119.4	130.9	147.3	152.6	111.3	123.6	120.1	127.7, 130.9, 134.1[1]	-	-	-
3.4	C	55.1, 55.3 60.7	198.1	48.2	64.0	70.0	135.9	126.8, 127.5, 128.1	129.1	111.2	148.7	152.0	111.7	122.9	130.4	145.7	152.6	110.9	123.9	119.7	-	-	-	-
3.5	C	55.8, 55.9 60.5	83.1	41.8	71.8	70.9	137.1	127.7, 128.0, 128.4	131.2	110.6	147.6*	149.3	113.7	119.2	133.0	147.5*	152.9	110.1	123.7	10.0	94.1[2]	-	-	-
4.4	C	56.0	87.9	54.2	65.5	-	-	-	128.0	108.7	146.7	145.7	114.5	119.1	133.7	144.5	148.3	112.4	121.2	117.1	-	-5.31, -5.28	18.3	25.9
4.6	C	55.7, 55.8 60.6	74.6	46.8	64.8	71.1	137.3	126.6, 127.3, 128.2	132.7	110.8	147.2	149.3	113.7	119.0	136.0	147.7	152.6	110.7	123.4	121.7	-	-5.6	18.2	25.9
5.28	C	55.7, 55.8 60.6	74.6 t.J$_{C-D}$	46.8 = 21)	64.8	71.1	137.3	126.6, 127.3, 128.2	132.7	110.8	147.2	149.3	113.7	119.0	136.0	147.7	152.6	110.7	123.4	121.7	-	-5.6	16.2	25.9

* = Interconvertible

a = B4-position substituent

@ = 22.5 MHz, otherwise 50.1 MHz

C = CDCl$_3$

A = d$_6$-acetone

D = d$_6$-dmso

1 = phenylboronate aromatic carbons (3.1-3.3)

2 = acetal carbon (3.5)

II. Final positional and thermal parameters for compound 2.6

ATOM	X/A	Y/B	Z/C	U11	U22	U33	U23	U13	U12
C(1)	0.5688(3)	0.181(1)	0.3023(4)	0.047(2)					
C(2)	0.5670(3)	-0.015(1)	0.3594(4)	0.047(2)					
C(3)	0.6211(3)	-0.103(2)	0.4117(4)	0.048(2)					
C(4)	0.6780(3)	-0.006(2)	0.4051(4)	0.054(2)					
C(5)	0.6801(3)	0.187(2)	0.3486(4)	0.067(2)					
C(6)	0.6255(3)	0.284(2)	0.2967(4)	0.063(2)					
C(7)	0.5111(3)	0.288(1)	0.2478(4)	0.052(2)					
C(8)	0.4674(3)	0.085(2)	0.1947(4)	0.056(2)					
C(9)	0.4846(4)	0.024(2)	0.1138(5)	0.068(6)	0.113(8)	0.096(7)	-0.021(7)	0.009(5)	0.013(6)
C(10)	0.2985(3)	0.334(2)	0.1507(4)	0.058(2)					
C(11)	0.3071(3)	0.519(2)	0.2145(4)	0.058(2)					
C(12)	0.3664(3)	0.556(2)	0.2661(4)	0.052(2)					
C(13)	0.4137(3)	0.405(1)	0.2511(4)	0.045(2)					
C(14)	0.4060(3)	0.220(1)	0.1892(4)	0.050(2)					
C(15)	0.3476(3)	0.181(2)	0.1382(5)	0.064(2)					
C(16)	0.2340(3)	0.297(2)	0.0944(5)	0.054(5)	0.093(8)	0.108(7)	0.006(7)	-0.016(5)	0.003(5)
C(17)	0.1985(4)	0.085(2)	0.1148(6)	0.065(6)	0.16(1)	0.122(8)	0.015(8)	-0.011(6)	-0.032(7)
C(18)	0.1342(4)	0.052(3)	0.0601(6)	0.056(6)	0.15(1)	0.127(8)	-0.007(8)	-0.012(5)	-0.023(6)
C(19)	0.3308(4)	0.893(2)	0.3460(5)	0.074(6)	0.089(7)	0.088(7)	0.000(6)	0.028(5)	0.034(6)
C(20)	0.5692(4)	-0.385(2)	0.4882(5)	0.063(6)	0.090(7)	0.084(6)	0.022(6)	0.001(5)	-0.019(5)
O(1)	0.7310(2)	-0.100(1)	0.4552(3)	0.026(3)	0.101(4)	0.089(4)	-0.002(4)	-0.014(2)	0.003(3)
O(2)	0.6253(2)	-0.291(1)	0.4722(3)	0.046(3)	0.072(4)	0.068(4)	0.017(3)	-0.002(2)	0.003(3)
O(3)	0.4741(2)	0.4240(9)	0.2963(2)	0.050(1)					
O(4)	0.3802(2)	0.736(1)	0.3288(3)	0.065(3)	0.064(4)	0.060(3)	-0.004(3)	0.007(3)	0.014(3)
H(61)	0.756(0)	0.000(0)	0.484(0)	0.090(0)					

III. Final positional and thermal parameters of calculated hydrogen atoms of compound 2.6.

ATOM	X/A	Y/B	Z/C	Ui1
H(21)	0.5272(3)	-0.091(1)	0.3633(4)	0.090
H(51)	0.7202(3)	0.258(2)	0.3441(4)	0.090
H(61)	0.6276(3)	0.425(2)	0.2568(4)	0.090
H(71)	0.5270(3)	0.403(1)	0.2103(4)	0.070
H(81)	0.4685(3)	-0.096(2)	0.2171(4)	0.070
H(91)	0.4579(4)	-0.119(2)	0.0854(5)	0.130
H(92)	0.5280(4)	-0.032(2)	0.1236(5)	0.130
H(93)	0.4783(4)	0.186(2)	0.0799(5)	0.130
H(111)	0.2719(3)	0.622(2)	0.2235(4)	0.090
H(151)	0.3413(3)	0.049(2)	0.0941(5)	0.090
H(161)	0.2392(3)	0.265(2)	0.0389(5)	0.090
H(162)	0.2107(3)	0.463(2)	0.0953(5)	0.090
H(171)	0.2213(4)	-0.081(2)	0.1126(6)	0.090
H(172)	0.1942(4)	0.115(2)	0.1708(6)	0.090
H(181)	0.1141(4)	-0.110(3)	0.0741(6)	0.130
H(182)	0.1365(4)	0.044(3)	0.0027(6)	0.130
H(183)	0.1100(4)	0.209(3)	0.0685(6)	0.130
H(191)	0.3480(4)	1.011(2)	0.3923(5)	0.130
H(192)	0.3008(4)	0.771(2)	0.3609(5)	0.130
H(193)	0.3101(4)	1.001(2)	0.2988(5)	0.130
H(201)	0.5820(4)	-0.522(2)	0.5307(5)	0.130
H(202)	0.5398(4)	-0.464(2)	0.4413(5)	0.130
H(203)	0.5494(4)	-0.237(2)	0.5102(5)	0.130

IV. Bond lengths for compound 2.6

C(1)	---C(2)	1.379(8)	C(16)	---H(161)	0.98(0)
C(1)	---C(6)	1.386(8)	C(16)	---H(162)	0.98(0)
C(1)	---C(7)	1.489(8)	C(16)	---C(17)	1.41(1)
C(10)	---C(11)	1.395(9)	C(17)	---H(171)	0.98(0)
C(10)	---C(15)	1.389(9)	C(17)	---H(172)	0.98(0)
C(10)	---C(16)	1.53(1)	C(17)	---C(18)	1.517(9)
C(11)	---H(111)	0.98(0)	C(18)	---H(181)	0.98(0)
C(11)	---C(12)	1.409(8)	C(18)	---H(182)	0.98(0)
C(12)	---C(13)	1.367(8)	C(18)	---H(183)	0.98(0)
C(12)	---O(4)	1.365(8)	C(19)	---H(191)	0.98(0)
C(13)	---C(14)	1.375(8)	C(19)	---H(192)	0.98(0)
C(13)	---O(3)	1.382(7)	C(19)	---H(193)	0.98(0)
C(14)	---C(15)	1.390(8)	C(19)	---O(4)	1.434(8)
C(15)	---H(151)	0.98(0)	O(1)	---H(01)	0.829(5)

V. Bond angles for compound 2.6

C(2)	-C(1)	-C(6)	119.2(6)
C(2)	-C(1)	-C(7)	121.4(6)
C(6)	-C(1)	-C(7)	119.4(7)
C(11)	-C(10)	-C(15)	120.8(7)
C(11)	-C(10)	-C(16)	119.6(7)
C(15)	-C(10)	-C(16)	119.6(7)
C(10)	-C(11)	-H(111)	120.0(4)
C(10)	-C(11)	-C(12)	120.1(7)
H(111)	-C(11)	-C(12)	120.0(4)
C(11)	-C(12)	-C(13)	117.5(7)
C(11)	-C(12)	-O(4)	124.8(7)
C(13)	-C(12)	-O(4)	117.7(6)
C(12)	-C(13)	-C(14)	123.3(6)
C(12)	-C(13)	-O(3)	123.5(6)
C(14)	-C(13)	-O(3)	113.2(6)
C(8)	-C(14)	-C(13)	107.8(6)
C(8)	-C(14)	-C(15)	132.7(7)
C(13)	-C(14)	-C(15)	119.5(7)
C(10)	-C(15)	-C(14)	118.9(8)
C(10)	-C(15)	-H(151)	120.6(5)
C(14)	-C(15)	-H(151)	120.5(5)
C(10)	-C(16)	-H(161)	107.8(5)
C(10)	-C(16)	-H(162)	108.0(5)
C(10)	-C(16)	-C(17)	115.9(7)
H(161)	-C(16)	-H(162)	109.50(0)
H(161)	-C(16)	-C(17)	107.8(6)
H(162)	-C(16)	-C(17)	107.8(6)
C(16)	-C(17)	-H(171)	107.9(6)
C(16)	-C(17)	-H(172)	107.9(6)
C(16)	-C(17)	-C(18)	115.9(9)
H(171)	-C(17)	-H(172)	109.50(0)
H(171)	-C(17)	-C(18)	107.8(7)
H(172)	-C(17)	-C(18)	107.8(6)
C(17)	-C(18)	-H(181)	111.3(6)
C(17)	-C(18)	-H(182)	109.9(6)
C(17)	-C(18)	-H(183)	107.2(6)
H(181)	-C(18)	-H(182)	109.50(0)
H(181)	-C(18)	-H(183)	109.50(0)
H(182)	-C(18)	-H(183)	109.50(0)
H(191)	-C(19)	-H(192)	109.50(0)
H(191)	-C(19)	-H(193)	109.50(0)
H(191)	-C(19)	-O(4)	108.4(4)
H(192)	-C(19)	-H(193)	109.50(0)
H(192)	-C(19)	-O(4)	108.0(4)
H(193)	-C(19)	-O(4)	112.0(4)
C(4)	-O(1)	-H(O1)	122.2(6)

VI. Observed and calculated structure factors for 2.6

H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC
4	0	0	554	-559	2	3	0	144	150	14	0	1	245	228	-7	2	1	317	304	14	3	1	71	79
6	0	0	274	271	3	3	0	120	-115	16	0	1	115	-114	-5	2	1	268	-284	16	3	1	94	80
8	0	0	319	339	4	3	0	273	264	18	0	1	436	-394	-4	2	1	221	-221	-15	4	1	77	88
10	0	0	150	139	6	3	0	184	189	20	0	1	150	148	-3	2	1	265	271	-7	4	1	131	116
12	0	0	271	-274	9	3	0	53	-59	-18	1	1	253	255	-2	2	1	81	86	-5	4	1	114	121
16	0	0	253	245	10	3	0	179	183	-15	1	1	71	58	-1	2	1	133	-130	-4	4	1	80	83
18	0	0	156	-144	14	3	0	116	111	-14	1	1	93	-103	1	2	1	143	-157	-1	4	1	120	-134
20	0	0	313	-280	18	3	0	125	121	-12	1	1	360	-359	2	2	1	147	152	6	4	1	100	-121
3	1	0	194	-199	21	3	0	79	49	-10	1	1	171	174	3	2	1	411	-398	13	4	1	69	-69
4	1	0	429	417	1	4	0	138	-136	-9	1	1	260	241	4	2	1	204	-211	-11	5	1	87	99
5	1	0	283	-282	3	4	0	90	72	-7	1	1	130	-116	6	2	1	351	342	-7	5	1	116	-136
6	1	0	55	56	4	4	0	70	-80	-4	1	1	156	-151	7	2	1	250	-248	-4	5	1	100	-63
7	1	0	50	59	13	4	0	111	112	-3	1	1	949	-995	8	2	1	434	416	-3	5	1	115	98
9	1	0	284	253	15	4	0	87	97	-2	1	1	228	-247	9	2	1	75	-68	2	5	1	81	-70
10	1	0	80	64	4	5	0	92	73	-1	1	1	423	-406	10	2	1	210	207	9	5	1	135	-132
13	1	0	218	-220	6	5	0	82	65	0	1	1	1038	-1052	11	2	1	68	-52	-26	0	2	86	64
14	1	0	136	131	7	5	0	106	99	1	1	1	418	421	12	2	1	138	-138	-18	0	2	73	86
15	1	0	290	301	9	5	0	74	95	2	1	1	353	-367	14	2	1	66	78	-16	0	2	77	73
17	1	0	254	-252	11	5	0	78	-70	3	1	1	665	-683	16	2	1	167	166	-14	0	2	77	72
18	1	0	192	-164	13	5	0	97	-78	4	1	1	445	-443	18	2	1	70	62	-10	0	2	118	-116
21	1	0	65	37	-20	0	1	374	351	5	1	1	345	342	20	2	1	70	-47	-8	0	2	159	164
1	2	0	99	-100	-18	0	1	122	102	6	1	1	72	-74	-18	3	1	135	110	-6	0	2	778	-772
2	2	0	96	99	-16	0	1	360	-352	7	1	1	230	-241	-16	3	1	93	84	-4	0	2	214	-230
3	2	0	83	89	-14	0	1	89	-90	8	1	1	360	348	-9	3	1	86	-72	-2	0	2	1545	-1548
4	2	0	362	350	-12	0	1	358	-355	9	1	1	190	-173	-5	3	1	69	-6	0	0	2	901	-936
5	2	0	248	240	-8	0	1	261	-258	10	1	1	454	-431	-4	3	1	67	-75	2	0	2	59	-58
6	2	0	217	221	-6	0	1	367	375	16	1	1	138	141	-3	3	1	195	-193	4	0	2	223	233
7	2	0	234	224	-4	0	1	499	519	17	1	1	252	233	0	3	1	67	55	6	0	2	127	-120
8	2	0	352	-326	-2	0	1	577	-582	-18	2	1	131	-120	1	3	1	151	147	8	0	2	268	254
9	2	0	363	-350	0	0	1	670	-684	-17	2	1	93	93	2	3	1	349	-339	10	0	2	591	-516
10	2	0	107	-102	2	0	1	307	321	-15	2	1	64	51	4	3	1	138	-126	14	0	2	86	83
11	2	0	141	-146	4	0	1	673	661	-13	2	1	86	84	5	3	1	205	-203	16	0	2	95	115
12	2	0	62	53	6	0	1	330	336	-12	2	1	312	-303	7	3	1	86	84	18	0	2	270	238
13	2	0	98	105	8	0	1	322	298	-11	2	1	143	-141	8	3	1	109	109	-21	1	2	89	-90
18	2	0	113	-104	10	0	1	331	305	-10	2	1	67	-68	10	3	1	81	-66	-20	1	2	128	-110
1	3	0	57	-65	12	0	1	359	364	-9	2	1	189	-187	12	3	1	90	89	-19	1	2	190	177
-18	1	2	287	-278	-11	2	2	162	-146	5	3	2	50	-43	10	0	3	418	-405	-13	2	3	166	-157
-17	1	2	113	113	-10	2	2	84	64	8	3	2	66	-63	16	0	3	248	224	-12	2	3	118	94
-15	1	2	101	112	-9	2	2	52	-27	9	3	2	97	105	18	0	3	81	-67	-11	2	3	194	192
-14	1	2	223	237	-8	2	2	84	97	12	3	2	124	-124	-20	1	3	81	-80	-10	2	3	104	-103
-12	1	2	267	258	-7	2	2	213	196	16	3	2	124	-108	-19	1	3	178	-183	-9	2	3	85	-83
-11	1	2	100	113	-6	2	2	192	-180	21	3	2	75	12	-18	1	3	135	129	-8	2	3	102	107
-10	1	2	337	-330	-5	2	2	175	167	-11	4	2	75	82	-14	1	3	134	-143	-7	2	3	205	-204
-9	1	2	100	-83	-4	2	2	186	-183	-8	4	2	97	-73	-12	1	3	73	-60	-6	2	3	153	161
-8	1	2	369	-352	-3	2	2	60	-52	-7	4	2	99	-97	-11	1	3	207	-190	-5	2	3	121	-113
-7	1	2	156	160	-2	2	2	95	92	-1	4	2	149	153	-10	1	3	215	218	-4	2	3	169	-176
-6	1	2	319	309	-1	2	2	285	270	6	4	2	92	93	-9	1	3	370	376	-3	2	3	365	343
-5	1	2	129	-140	0	2	2	80	78	9	4	2	73	-97	-7	1	3	625	619	-2	2	3	474	476
-4	1	2	304	305	1	2	2	125	118	10	4	2	142	-144	-6	1	3	434	-437	-1	2	3	93	-86
-3	1	2	679	685	3	2	2	182	191	13	4	2	102	-107	-5	1	3	168	-168	1	2	3	205	226
-2	1	2	243	-260	4	2	2	49	43	-11	5	2	86	-96	-4	1	3	224	-222	2	2	3	309	-290
-1	1	2	389	389	5	2	2	138	-128	-6	5	2	85	88	-3	1	3	802	814	3	2	3	178	164
0	1	2	1046	-1039	7	2	2	122	128	-5	5	2	109	-104	-2	1	3	1873	1907	5	2	3	134	128
1	1	2	696	-690	9	2	2	152	145	-4	5	2	84	87	-1	1	3	141	138	6	2	3	155	-139
2	1	2	948	956	10	2	2	94	89	3	5	2	73	-44	0	1	3	453	475	7	2	3	332	335
3	1	2	275	-274	11	2	2	88	-72	9	5	2	74	71	1	1	3	131	-131	8	2	3	127	-115
4	1	2	179	185	12	2	2	128	133	-26	0	3	88	-48	2	1	3	687	-671	11	2	3	80	84
5	1	2	514	-497	15	2	2	264	-244	-22	0	3	101	-112	3	1	3	107	104	13	2	3	275	268
6	1	2	214	-203	16	2	2	83	-79	-20	0	3	417	-384	5	1	3	186	184	14	2	3	123	125
7	1	2	211	-201	18	2	2	212	191	-18	0	3	217	219	6	1	3	158	161	16	2	3	174	-155
8	1	2	275	-268	-19	3	2	70	66	-16	0	3	74	60	7	1	3	325	302	17	2	3	136	-124
9	1	2	496	-479	-12	3	2	140	142	-14	0	3	166	-163	8	1	3	285	271	-20	3	3	83	-68
10	1	2	162	174	-10	3	2	159	160	-12	0	3	53	46	9	1	3	246	248	-17	3	3	63	54
11	1	2	81	-87	-9	3	2	102	94	-10	0	3	121	139	11	1	3	365	-365	-16	3	3	119	-125
14	1	2	196	-183	-8	3	2	188	196	-8	0	3	388	-384	12	1	3	57	47	-12	3	3	78	-77
15	1	2	71	54	-5	3	2	121	123	-6	0	3	391	377	13	1	3	64	80	-11	3	3	174	185
18	1	2	235	222	-4	3	2	159	159	-4	0	3	901	-899	14	1	3	124	125	-10	3	3	144	-149
-16	2	2	125	119	-2	3	2	161	161	-2	0	3	1428	1464	15	1	3	350	-329	-9	3	3	77	66
-15	2	2	142	-150	0	3	2	101	-92	0	0	3	174	-178	17	1	3	199	-188	-5	3	3	89	104
-14	2	2	60	42	1	3	2	150	-132	2	0	3	896	-920	19	1	3	65	45	-3	3	3	77	-75
-13	2	2	208	213	3	3	2	165	158	4	0	3	281	-281	20	1	3	101	-84	-2	3	3	196	-194
-12	2	2	100	106	4	3	2	178	-179	8	0	3	374	370	-15	2	3	107	-123	-1	3	3	86	90

H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC
0	3	3	81	111	14	0	4	170	162	-12	2	4	76	-38	8	3	4	90	-92	10	0	5	345	-342
2	3	3	227	229	16	0	4	126	-134	-10	2	4	84	65	10	3	4	172	-174	12	0	5	194	193
3	3	3	102	96	-21	1	4	72	-66	-9	2	4	160	162	11	3	4	64	74	-14	0	5	208	-215
4	3	3	158	151	-20	1	4	240	216	-7	2	4	122	-129	13	3	4	64	-66	-21	1	5	139	147
6	3	3	255	-256	-19	1	4	99	-85	-6	2	4	217	-224	14	3	4	173	148	-19	1	5	135	128
8	3	3	100	-63	-18	1	4	87	-87	-4	2	4	86	-78	15	3	4	76	61	-18	1	5	77	-77
9	3	3	76	-102	-13	1	4	75	28	-3	2	4	560	-561	-12	4	4	102	-77	-17	1	5	74	93
11	3	3	104	-96	-11	1	4	92	87	-2	2	4	387	-402	-9	4	4	159	166	-16	1	5	61	59
12	3	3	163	153	-10	1	4	261	238	-1	2	4	129	-117	-6	4	4	93	112	-14	1	5	81	97
14	3	3	143	-157	-9	1	4	349	-346	1	2	4	213	-212	-5	4	4	226	-220	-12	1	5	121	-121
-10	4	3	131	-135	-8	1	4	54	68	2	2	4	206	-203	1	4	4	73	-66	-11	1	5	117	118
-9	4	3	157	-166	-5	1	4	530	-552	3	2	4	232	212	2	4	4	84	-91	-10	1	5	123	-116
-7	4	3	98	-124	-4	1	4	160	-171	4	2	4	59	-56	3	4	4	90	-91	-8	1	5	109	103
-4	4	3	121	-102	-3	1	4	600	-629	6	2	4	109	104	7	4	4	106	98	-7	1	5	53	-50
-3	4	3	165	161	-2	1	4	88	-88	7	2	4	228	-219	8	4	4	88	103	-6	1	5	209	222
-1	4	3	66	-72	-1	1	4	1330	1346	8	2	4	48	-45	13	4	4	97	69	-5	1	5	232	226
4	4	3	67	71	0	1	4	340	-360	10	2	4	115	-101	-7	5	4	119	111	-4	1	5	142	-162
6	4	3	85	-79	1	1	4	475	499	11	2	4	103	-63	-5	5	4	94	81	-3	1	5	267	260
11	4	3	222	207	2	1	4	325	329	12	2	4	71	-33	11	5	4	85	-41	-2	1	5	796	-799
17	4	3	90	-50	3	1	4	293	290	13	2	4	92	87	-26	0	5	72	65	-1	1	5	720	-706
6	5	3	76	85	4	1	4	143	-144	14	2	4	126	119	-22	0	5	97	106	0	1	5	240	231
-22	0	4	152	149	5	1	4	265	258	15	2	4	113	62	-20	0	5	199	198	1	1	5	138	-149
-20	0	4	113	-122	6	1	4	153	155	16	2	4	119	-107	-18	0	5	95	104	2	1	5	60	-75
-18	0	4	259	-283	7	1	4	351	340	17	2	4	129	152	-16	0	5	202	-207	3	1	5	160	-159
-16	0	4	181	174	8	1	4	296	-305	-9	3	4	111	-101	-14	0	5	172	-173	5	1	5	106	107
-12	0	4	189	-166	10	1	4	115	115	-8	3	4	89	-87	-12	0	5	112	108	6	1	5	107	-124
-10	0	4	461	-451	11	1	4	105	97	-7	3	4	70	-76	-10	0	5	817	768	7	1	5	181	-158
-8	0	4	168	162	13	1	4	102	106	-6	3	4	119	-111	-8	0	5	334	-320	8	1	5	316	-306
-6	0	4	287	-277	15	1	4	139	131	-4	3	4	87	-81	-6	0	5	264	-245	9	1	5	63	57
-2	0	4	791	843	16	1	4	243	-229	-3	3	4	73	71	-4	0	5	329	-341	11	1	5	69	67
0	0	4	188	-179	18	1	4	61	60	-1	3	4	137	139	-2	0	5	326	326	12	1	5	96	-84
2	0	4	529	546	19	1	4	122	-101	0	3	4	172	-166	0	0	5	871	-867	13	1	5	264	256
4	0	4	141	-145	-18	2	4	101	-98	1	3	4	133	-122	2	0	5	663	-653	20	1	5	64	-29
6	0	4	631	-622	-17	2	4	78	86	5	3	4	98	86	4	0	5	278	274	-21	2	5	91	-64
8	0	4	585	523	-14	2	4	244	-243	6	3	4	231	226	6	0	5	387	390	-20	2	5	122	-110
10	0	4	323	303	-13	2	4	144	135	7	3	4	116	-127	8	0	5	379	-362	-19	2	5	116	98
-16	2	5	102	89	-4	3	5	212	203	14	0	6	77	-70	-9	2	6	126	113	6	3	6	98	87
-15	2	5	103	115	-2	3	5	74	23	16	0	6	130	-109	-7	2	6	240	-238	7	3	6	118	112
-14	2	5	62	60	0	3	5	61	61	-22	1	6	167	-169	-6	2	6	200	-215	9	3	6	219	-222
-13	2	5	74	-65	1	3	5	73	88	-21	1	6	124	-124	-5	2	6	413	422	10	3	6	127	126
-12	2	5	146	-135	2	3	5	69	-86	-16	1	6	108	-111	-4	2	6	744	740	11	3	6	115	111
-10	2	5	201	-182	3	3	5	64	-56	-15	1	6	81	84	-3	2	6	104	87	14	3	6	136	-126
-9	2	5	57	-49	5	3	5	100	-117	-14	1	6	73	6	-2	2	6	389	406	15	3	6	68	-45
-7	2	5	81	56	7	3	5	107	102	-12	1	6	83	85	-1	2	6	194	-197	-12	4	6	73	-102
-6	2	5	96	124	8	3	5	153	171	-11	1	6	54	39	0	2	6	472	-428	-9	4	6	82	-99
-5	2	5	336	352	9	3	5	92	101	-10	1	6	172	-163	1	2	6	180	185	-6	4	6	81	-69
-4	2	5	353	-373	11	3	5	148	144	-9	1	6	462	462	2	2	6	82	-78	-5	4	6	136	136
-3	2	5	207	203	13	3	5	68	-87	-8	1	6	238	-219	3	2	6	86	98	1	4	6	101	85
-2	2	5	513	-542	14	3	5	92	-78	-7	1	6	87	-75	4	2	6	130	134	4	4	6	130	-146
-1	2	5	74	45	-12	4	5	141	156	-6	1	6	58	-54	5	2	6	136	141	6	4	6	143	-156
0	2	5	309	319	-11	4	5	93	98	-5	1	6	311	340	6	2	6	104	104	-1	5	6	82	-76
1	2	5	237	-244	-8	4	5	155	-165	-2	1	6	78	89	8	2	6	79	-68	-14	0	7	70	77
2	2	5	183	160	-7	4	5	161	168	-1	1	6	130	-153	9	2	6	96	102	-12	0	7	520	-529
3	2	5	319	-311	-6	4	5	77	-71	1	1	6	88	-99	10	2	6	145	-152	-8	0	7	190	191
4	2	5	112	-120	-4	4	5	107	98	4	1	6	124	127	11	2	6	71	63	-6	0	7	52	-56
5	2	5	201	-202	8	4	5	128	-144	5	1	6	95	-90	12	2	6	111	125	-4	0	7	92	100
6	2	5	121	-125	9	4	5	122	-119	6	1	6	330	307	13	2	6	147	-128	0	0	7	99	-101
7	2	5	79	-73	-1	5	5	107	108	7	1	6	77	77	15	2	6	161	-171	6	0	7	309	285
8	2	5	69	-70	-20	0	6	65	73	8	1	6	141	-144	16	2	6	99	-101	8	0	7	246	236
9	2	5	118	-125	-16	0	6	152	149	9	1	6	237	-235	-15	3	6	115	-114	10	0	7	47	9
12	2	5	71	-59	-14	0	6	67	47	13	1	6	111	-95	-12	3	6	71	53	12	0	7	163	189
13	2	5	176	-157	-12	0	6	62	49	14	1	6	120	117	-11	3	6	189	191	16	0	7	114	-99
14	2	5	114	-116	-10	0	6	101	-114	15	1	6	112	-97	-10	3	6	63	68	-21	1	7	135	-149
15	2	5	87	97	-8	0	6	129	134	17	1	6	111	137	-9	3	6	110	103	-18	1	7	83	89
16	2	5	254	222	-6	0	6	144	-161	18	1	6	74	-39	-8	3	6	90	-90	-17	1	7	72	-76
18	2	5	81	66	-4	0	6	214	-206	-22	2	6	102	-86	-5	3	6	76	-110	-16	1	7	136	130
-16	3	5	69	85	-2	0	6	141	-137	-19	2	6	154	-153	-3	3	6	68	52	-15	1	7	152	-158
-14	3	5	106	109	0	0	6	135	136	-18	2	6	147	156	-2	3	6	93	94	-14	1	7	53	-45
-13	3	5	100	-98	2	0	6	193	197	-17	2	6	141	-161	-1	3	6	70	-29	-13	1	7	85	-58
-11	3	5	141	-163	4	0	6	300	-307	-13	2	6	59	-53	1	3	6	66	57	-12	1	7	98	-87
-9	3	5	106	112	8	0	6	709	-665	-12	2	6	111	117	2	3	6	86	58	-11	1	7	103	-109
-8	3	5	86	93	12	0	6	168	-170	-11	2	6	59	-58	5	3	6	233	247	-9	1	7	145	-146

H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC	H	K	L	10FO	10FC
-8	1	7	199	185	-13	3	7	119	126	8	0	8	221	-242	-6	2	8	165	-154	4	5	8	67	-12
-7	1	7	58	-52	-12	3	7	118	114	10	0	8	179	195	-5	2	8	65	-61	-22	0	9	65	42
-6	1	7	95	-121	-11	3	7	166	-175	14	0	8	217	215	-4	2	8	468	-517	-18	0	9	96	114
-5	1	7	145	-137	-9	3	7	99	-91	16	0	8	92	65	-2	2	8	99	91	-12	0	9	229	236
-4	1	7	414	415	-8	3	7	209	-211	-23	1	8	81	98	-1	2	8	220	-231	-10	0	9	283	283
-3	1	7	538	527	-7	3	7	115	129	-22	1	8	98	98	0	2	8	111	114	-8	0	9	116	121
-2	1	7	167	-166	-6	3	7	133	-132	-17	1	8	65	-43	6	2	8	221	-236	-6	0	9	355	350
-1	1	7	240	263	-5	3	7	194	-210	-14	1	8	98	95	7	2	8	144	-145	-4	0	9	467	487
0	1	7	249	241	-3	3	7	86	90	-12	1	8	312	315	9	2	8	129	-126	-2	0	9	265	-267
3	1	7	81	-79	-2	3	7	154	-160	-11	1	8	144	-149	10	2	8	103	85	0	0	9	140	133
4	1	7	329	-323	0	3	7	69	-75	-10	1	8	99	105	13	2	8	138	128	2	0	9	146	-146
5	1	7	274	270	1	3	7	88	36	-9	1	8	69	-82	-21	3	8	84	58	6	0	9	191	-180
6	1	7	118	107	3	3	7	124	147	-7	1	8	368	-362	-14	3	8	66	-69	14	0	9	99	-93
7	1	7	71	75	5	3	7	157	-146	-6	1	8	227	221	-13	3	8	136	-128	-19	1	9	128	120
8	1	7	296	281	6	3	7	140	-153	-4	1	8	169	164	-12	3	8	146	-150	-13	1	9	102	-40
10	1	7	65	77	7	3	7	82	-93	-3	1	8	348	-329	-10	3	8	192	212	-12	1	9	56	52
12	1	7	66	41	8	3	7	144	-145	-2	1	8	187	-199	-8	3	8	237	266	-11	1	9	166	162
14	1	7	91	88	10	3	7	92	95	0	1	8	362	-360	-7	3	8	74	108	-10	1	9	122	-124
-22	2	7	111	125	12	3	7	187	176	1	1	8	85	75	-5	3	8	57	69	-8	1	9	77	48
-13	2	7	109	-94	-9	4	7	86	-95	2	1	8	167	162	-4	3	8	271	-270	-6	1	9	157	-160
-10	2	7	179	168	-7	4	7	133	-148	3	1	8	125	135	-3	3	8	56	-56	-5	1	9	160	-148
-8	2	7	75	59	-1	4	7	80	-86	4	1	8	224	237	-2	3	8	96	87	-4	1	9	65	-94
-7	2	7	154	-169	0	4	7	78	-82	5	1	8	167	-164	-1	3	8	124	-130	-3	1	9	127	-132
-5	2	7	429	-473	7	4	7	67	3	6	1	8	151	-147	1	3	8	129	-130	-2	1	9	300	297
-4	2	7	151	153	8	4	7	72	-65	8	1	8	95	-106	3	3	8	156	-157	-1	1	9	149	-148
-1	2	7	329	332	10	4	7	76	-66	9	1	8	136	131	4	3	8	128	-146	0	1	9	178	172
1	2	7	71	49	-7	5	7	78	-45	10	1	8	69	-58	7	3	8	112	110	1	1	9	156	-160
2	2	7	75	-16	-5	5	7	78	-69	11	1	8	124	124	9	3	8	85	79	2	1	9	90	-92
3	2	7	70	65	-3	5	7	79	-62	13	1	8	73	60	10	3	8	135	-122	5	1	9	123	120
4	2	7	55	-38	-20	0	8	121	125	14	1	8	147	-147	11	3	8	97	-79	6	1	9	224	-216
6	2	7	72	80	-14	0	8	111	131	-21	2	8	107	109	12	3	8	119	-93	7	1	9	162	-160
8	2	7	235	234	-12	0	8	417	427	-19	2	8	70	74	16	3	8	116	95	8	1	9	89	87
11	2	7	209	206	-10	0	8	108	-116	-13	2	8	147	153	-9	4	8	66	53	9	1	9	92	-88
14	2	7	193	-196	-8	0	8	115	-108	-12	2	8	100	121	-6	4	8	95	99	12	1	9	134	-130
15	2	7	115	118	-4	0	8	78	71	-8	2	8	57	39	-3	4	8	107	-113	13	1	9	140	-131
19	2	7	68	-32	6	0	8	36	325	-7	2	8	90	100	4	4	8	98	133	-17	2	9	77	66
-15	2	9	101	97	-6	0	10	70	70	-4	2	10	85	109	3	1	11	161	-152	-7	1	12	53	48
-13	2	9	126	-111	-4	0	10	118	123	-2	2	10	101	91	4	1	11	133	141	-6	1	12	78	70
-12	2	9	112	-111	-2	0	10	64	74	0	2	10	71	72	5	1	11	92	-92	3	1	12	140	132
-8	2	9	91	-66	0	0	10	48	50	1	2	10	100	-103	7	1	11	205	204	4	1	12	74	68
-7	2	9	237	278	2	0	10	386	383	2	2	10	124	-120	-15	2	11	92	83	5	1	12	89	-94
-6	2	9	192	179	4	0	10	60	55	4	2	10	157	158	-14	2	11	206	221	7	1	12	171	-165
-5	2	9	72	104	6	0	10	99	-96	5	2	10	178	171	-10	2	11	206	-236	8	1	12	111	-99
-4	2	9	198	204	10	0	10	88	80	6	2	10	385	394	-5	2	11	74	95	10	1	12	129	-144
-3	2	9	133	-130	12	0	10	156	-137	9	2	10	100	78	-4	2	11	93	-70	11	1	12	109	-96
-2	2	9	80	-50	14	0	10	154	-124	-6	3	10	153	-169	-3	2	11	77	-17	-13	2	12	112	-120
5	2	9	206	-214	-15	1	10	79	47	-7	3	10	157	-186	-2	2	11	66	-52	-9	2	12	146	184
6	2	9	194	-200	-14	1	10	147	-155	-6	3	10	66	79	-1	2	11	93	82	-8	2	12	117	-112
7	2	9	136	156	-12	1	10	209	-230	-3	3	10	170	182	0	2	11	66	47	-7	2	12	70	35
8	2	9	92	-89	-8	1	10	123	-118	8	3	10	125	117	1	2	11	110	103	-4	2	12	64	-23
11	2	9	92	-80	-7	1	10	76	-54	10	3	10	76	65	2	2	11	174	185	-3	2	12	102	76
12	2	9	109	121	-6	1	10	76	-80	10	4	10	76	68	5	2	11	175	-181	0	2	12	99	-88
13	2	9	73	-81	-5	1	10	206	195	-16	0	11	100	-104	10	2	11	64	34	1	2	12	94	95
-11	3	9	139	157	-4	1	10	67	-86	-14	0	11	145	-157	-6	3	11	284	-284	4	2	12	229	-239
-10	3	9	140	-159	-3	1	10	66	33	-12	0	11	116	-141	-5	3	11	115	135	-10	3	12	72	37
-9	3	9	140	-135	-1	1	10	102	-85	-10	0	11	167	-175	1	3	11	72	63	-9	3	12	87	79
-6	3	9	232	241	1	1	10	60	-43	-8	0	11	169	-194	2	3	11	108	-122	-8	3	12	131	122
-5	3	9	80	71	3	1	10	76	67	-6	0	11	402	-427	4	3	11	111	-123	-3	3	12	66	-56
-4	3	9	198	208	7	1	10	111	-99	-4	0	11	89	73	-6	4	11	94	-116	-2	3	12	90	-80
-3	3	9	173	-208	8	1	10	154	157	-2	0	11	218	230	9	4	11	97	-79	6	3	12	88	-69
4	3	9	160	163	10	1	10	73	54	2	0	11	196	-186	-22	0	12	101	117	-7	4	12	88	75
5	3	9	127	119	12	1	10	120	136	4	0	11	183	177	-6	0	12	163	180	-8	0	13	171	187
7	3	9	115	-122	15	1	10	78	-77	8	0	11	219	217	-4	0	12	293	-317	-4	0	13	62	-58
13	3	9	84	-78	-23	2	10	73	-54	12	0	11	173	160	-2	0	12	184	-179	2	0	13	63	-51
-13	4	9	91	54	-15	2	10	99	-102	14	0	11	86	106	2	0	12	116	102	4	0	13	168	165
-5	4	9	69	62	-14	2	10	184	-189	16	0	11	69	-52	6	0	12	171	-165	6	0	13	120	-121
-2	4	9	91	110	-13	2	10	97	102	-13	1	11	120	-108	8	0	12	76	67	8	0	13	69	-65
-22	0	10	80	-71	-11	2	10	108	102	-8	1	11	62	60	10	0	12	85	102	10	0	13	78	-65
-20	0	10	108	-121	-10	2	10	249	262	-7	1	11	88	92	12	0	12	87	64	12	0	13	82	-64
-18	0	10	152	-145	-9	2	10	135	-165	-6	1	11	82	92	-14	1	12	136	171	-13	1	13	84	-98
-10	0	10	72	-59	-6	2	10	104	115	-4	1	11	79	-82	-13	1	12	259	273	-12	1	13	177	-163
-8	0	10	51	8	-5	2	10	85	-77	-2	1	11	69	-95	-11	1	12	66	81	-7	1	13	128	119
-5	1	13	185	211	-4	3	13	83	89	-12	1	14	64	85	8	0	15	116	106	2	0	16	288	307
0	1	13	143	127	-3	3	13	80	96	-8	1	14	122	-123	-15	1	15	114	148	6	0	16	112	-118
4	1	13	292	-311	3	3	13	84	52	0	1	14	117	-116	-12	1	15	92	90	1	1	16	63	39
12	1	13	73	-83	4	3	13	68	58	5	1	14	200	213	-7	1	15	79	-106	3	1	16	102	-87
-16	2	13	80	-101	-9	4	13	84	-92	-5	2	14	67	-90	2	1	15	132	140	-7	2	16	111	145
-14	2	13	94	-126	-14	0	14	94	70	2	2	14	93	106	5	1	15	71	-80	-9	3	16	73	-13
-12	2	13	137	151	-12	0	14	118	-141	-7	3	14	96	86	11	1	15	81	41	-18	0	17	102	96
-11	2	13	130	-161	-8	0	14	179	-198	-8	4	14	97	-56	-6	2	15	74	62	0	0	17	81	84
-2	2	13	69	10	-4	0	14	70	115	0	0	15	64	82	-18	0	16	98	-81	0	0	18	109	-137
2	2	13	67	-63	8	0	14	77	-93	2	0	15	161	-181	-16	0	16	126	-131	2	0	18	98	-145
3	2	13	110	107	-16	1	14	133	-144	4	0	15	235	-238	-14	0	16	168	182	4	0	18	90	81
-7	3	13	72	-57	-15	1	14	118	-104	6	0	15	130	138	-12	0	16	67	141	2	1	18	98	-91

VII. Final positional and thermal parameters for compound 2.28

ATOM	X/A	Y/B	Z/C	ATOM	X/A	Y/B	Z/C
C(1)	0.006(1)	0.2565(5)	0.1121(9)	C(16)	-0.175(1)	0.0618(6)	-0.098(1)
C(2)	0.084(1)	0.2481(5)	-0.028(1)	C(17)	-0.296(2)	0.0327(7)	-0.618(1)
C(3)	0.225(1)	0.1965(5)	-0.0453(9)	C(18)	0.236(1)	0.2188(6)	-0.317(1)
C(4)	0.294(1)	0.1509(5)	0.077(1)	C(19)	-0.114(1)	0.4527(6)	0.244(1)
C(5)	0.219(1)	0.1595(5)	0.214(1)	C(20)	-0.606(1)	0.4126(7)	0.252(1)
C(6)	0.077(1)	0.2107(5)	0.232(1)	C(21)	-0.651(2)	0.4060(7)	0.414(1)
C(7)	-0.153(1)	0.3091(5)	0.132(1)	C(22)	-0.082(1)	0.5351(5)	0.206(1)
C(8)	-0.316(1)	0.2812(5)	0.0195(9)	O(1)	0.4329(8)	0.0987(4)	0.0596(8)
C(9)	-0.461(1)	0.3447(5)	0.035(1)	O(2)	0.3077(7)	0.1829(3)	-0.1794(7)
C(10)	-0.301(1)	0.2544(5)	-0.160(1)	O(3)	-0.3242(7)	0.1132(3)	-0.1359(7)
C(11)	-0.288(1)	0.3131(5)	-0.262(1)	O(4)	-0.3053(9)	0.0637(4)	-0.4507(7)
C(12)	-0.277(1)	0.2869(6)	-0.425(1)	O(5)	-0.1176(7)	0.3927(3)	0.1095(7)
C(13)	-0.283(1)	0.2047(6)	-0.495(1)	O(6)	-0.5008(8)	0.3496(4)	0.1995(7)
C(14)	-0.296(1)	0.1463(6)	-0.397(1)	O(7)	-0.654(1)	0.4648(5)	0.172(1)
C(15)	-0.302(1)	0.1722(5)	-0.231(1)	O(8)	-0.137(1)	0.4386(4)	0.3712(8)

VIII. Final positional and thermal parameters of calculated hydrogen atoms of compound <u>2.28</u>

ATOM	X/A	Y/B	Z/C	U11
H(21)	0.5272(3)	-0.091(1)	0.3633(4)	0.090
H(51)	0.7202(3)	0.255(2)	0.3441(4)	0.090
H(61)	0.6276(3)	0.425(2)	0.2568(4)	0.090
H(71)	0.5270(3)	0.403(1)	0.2103(4)	0.070
H(81)	0.4685(3)	-0 096(2)	0.2171(4)	0.070
H(91)	0.4579(4)	-0.119(2)	0.0854(5)	0.130
H(92)	0.5280(4)	-0.032(2)	0.1236(5)	0.130
H(93)	0.4783(4)	0.156(2)	0.0799(5)	0.130
H(111)	0.2719(3)	0.622(2)	0.2235(4)	0.090
H(151)	0.3413(3)	0.049(2)	0.0941(5)	0.090
H(161)	0.2392(3)	0.265(2)	0.0389(5)	0.090
H(162)	0.2107(3)	0.463(2)	0.0953(5)	0.090
H(171)	0.2213(4)	-0.081(2)	0.1126(6)	0.090
H(172)	0.1942(4)	0.115(2)	0.1708(6)	0.090
H(181)	0.1141(4)	-0.110(3)	0.0741(6)	0.130
H(182)	0.1365(4)	0.044(3)	0.0027(6)	0.130
H(183)	0.1100(4)	0.209(3)	0.0685(6)	0.130
H(191)	0.3480(4)	1.011(2)	0.3923(5)	0.130
H(192)	0.3008(4)	0.771(2)	0.3609(5)	0.130
H(193)	0.3101(4)	1.001(2)	0.2988(5)	0.130
H(201)	0.5820(4)	-0.522(2)	0.5307(5)	0.130
H(202)	0.5398(4)	-0.464(2)	0.4413(5)	0.130
H(203)	0.5494(4)	-0.237(2)	0.5102(5)	0.130

IX. Bond lengths for compound <u>2.28</u>

Bond Lengths (Å).

C(1) ---C(2)	1.40(1)	C(13) ---C(14)	1.39(1)	C(17) ---H(173)	1.08(0)
C(1) ---C(6)	1.39(1)	C(14) ---C(15)	1.39(1)	C(17) ---O(4)	1.42(1)
C(1) ---C(7)	1.50(1)	C(14) ---O(4)	1.36(1)	C(18) ---H(181)	1.08(0)
C(10) ---C(11)	1.41(1)	C(15) ---O(3)	1.397(9)	C(18) ---H(182)	1.08(0)
C(10) ---C(15)	1.38(1)	C(16) ---H(161)	1.08(0)	C(18) ---H(183)	1.08(0)
C(11) ---H(111)	1.08(0)	C(16) ---H(162)	1.08(0)	C(18) ---O(2)	1.413(9)
C(11) ---C(12)	1.38(1)	C(16) ---H(163)	1.08(0)	C(19) ---C(22)	1.49(1)
C(12) ---H(121)	1.08(0)	C(16) ---O(3)	1.433(9)	C(19) ---O(5)	1.362(9)
C(12) ---C(13)	1.38(1)	C(17) ---H(171)	1.08(0)	C(19) ---O(6)	1.182(9)
C(13) ---H(131)	1.08(0)	C(17) ---H(172)	1.08(0)	O(1) ---H(11)	0.970(6)

X. Bond angles for compound 2.6

```
Bond Angles  (degrees).

C(2)   -C(1)  -C(6)    117.5(8)      H(131)-C(13) -C(14)    120.7(6)      H(171)-C(17) -H(173)   109.50(0)
C(2)   -C(1)  -C(7)    122.4(7)      C(13)  -C(14) -C(15)   119.2(9)      H(171)-C(17) -O(4)     103.8(6)
C(6)   -C(1)  -C(7)    120.1(8)      C(13)  -C(14) -O(4)    124.8(9)      H(172)-C(17) -H(173)   109.50(0)
C(8)   -C(10) -C(11)   121.0(7)      C(15)  -C(14) -O(4)    116.0(8)      H(172)-C(17) -O(4)     102.4(7)
C(8)   -C(10) -C(15)   121.6(7)      C(10)  -C(15) -C(14)   122.6(8)      H(173)-C(17) -O(4)     121.6(6)
C(11)  -C(10) -C(15)   117.4(7)      C(10)  -C(15) -O(3)    118.7(7)      H(181)-C(18) -H(182)   109.50(0)
C(10)  -C(11) -H(111)  120.1(5)      C(14)  -C(15) -O(3)    118.5(7)      H(181)-C(18) -H(183)   109.50(0)
C(10)  -C(11) -C(12)   119.7(8)      H(161)-C(16) -H(162)   109.50(0)     H(181)-C(18) -O(2)     110.4(4)
H(111)-C(11)  -C(12)   120.2(5)      H(161)-C(16) -H(163)   109.50(0)     H(182)-C(18) -H(183)   109.50(0)
C(11)  -C(12) -H(121)  118.9(5)      H(161)-C(16) -O(3)     105.7(5)      H(182)-C(18) -O(2)     105.3(5)
C(11)  -C(12) -C(13)   122.2(9)      H(162)-C(16) -H(163)   109.50(0)     H(183)-C(18) -O(2)     112.6(5)
H(121)-C(12)  -C(13)   119.0(6)      H(162)-C(16) -O(3)     107.0(5)      C(22)  -C(19) -O(5)    111.7(8)
C(12)  -C(13) -H(131)  120.5(6)      H(163)-C(16) -O(3)     115.6(5)      C(22)  -C(19) -O(8)    126.3(8)
C(12)  -C(13) -C(14)   118.8(9)      H(171)-C(17) -H(172)   109.50(0)     O(5)   -C(19) -O(8)    121.9(9)
                                                                          C(4)   -O(1)  -H(11)    94.1(6)
```

XI. Observed and calculated structure factors for <u>2.28</u>

H	K	L	10FO	10FC
0	-13	2	78	-96
1	-13	2	173	169
2	-13	2	130	142
-6	-12	2	96	-129
-5	-12	2	86	100
-3	-12	2	162	-162
-2	-12	2	305	319
0	-12	2	166	-169
1	-12	2	88	76
2	-12	2	278	286
-2	-11	2	127	-128
-1	-11	2	104	120
3	-11	2	193	-199
4	-11	2	184	-200
5	-11	2	110	101
-5	-10	2	120	113
-2	-10	2	96	-91
-1	-10	2	274	-276
1	-10	2	200	196
2	-10	2	71	44
3	-10	2	193	-213
4	-10	2	116	120
-5	-9	2	101	102
-4	-9	2	96	103
1	-9	2	285	-284
2	-9	2	142	118
4	-9	2	76	90
-5	-8	2	133	-144
-4	-8	2	81	-86
-2	-8	2	303	-303
-1	-8	2	443	407
0	-8	2	147	121
1	-8	2	128	134
2	-8	2	167	167
3	-8	2	149	154
5	-8	2	72	-79
-8	-7	2	88	-94
-5	-7	2	84	-88
-4	-7	2	62	78
-3	-7	2	219	212
-2	-7	2	81	-74
-1	-7	2	123	-124
0	-7	2	119	-126
1	-7	2	179	-187
3	-7	2	62	42
5	-7	2	153	-162
-7	-6	2	95	-122
-6	-6	2	68	-79
-2	-6	2	246	242
-1	-6	2	138	138
0	-6	2	417	-389
1	-6	2	98	110
2	-6	2	152	132
3	-6	2	166	-172
4	-6	2	90	-107
6	-6	2	70	-20
-8	-5	2	162	161
-5	-5	2	136	135
-4	-5	2	127	138
-2	-5	2	57	-62
-1	-5	2	121	114
0	-5	2	443	-432
2	-5	2	61	-31
3	-5	2	338	358
-5	-4	2	152	-141
-4	-4	2	78	-112
-3	-4	2	113	-119
0	-4	2	160	168
1	-4	2	114	-120
2	-4	2	91	-98
3	-4	2	80	77
4	-4	2	62	66
6	-4	2	92	99
-5	-3	2	109	-112
-4	-3	2	89	-81
-2	-3	2	97	100
-1	-3	2	301	-294
0	-3	2	148	136
1	-3	2	85	104
3	-3	2	102	110
4	-3	2	110	-117
5	-3	2	124	-123
6	-3	2	135	-145
-4	-2	2	191	206
-3	-2	2	96	-111
-2	-2	2	70	71
-1	-2	2	251	242
0	-2	2	282	-280
1	-2	2	435	-445
2	-2	2	209	-218
3	-2	2	163	184
5	-2	2	152	159
-7	-1	2	99	106
-3	-1	2	126	-124
-2	-1	2	66	143
-1	-1	2	440	437
0	-1	2	689	682
1	-1	2	428	-417
2	-1	2	155	161
3	-1	2	163	-173
-8	0	2	78	-27
-7	0	2	74	106
-5	0	2	55	63
-2	0	2	142	-152
1	0	2	250	-259
2	0	2	95	100
3	0	2	68	76
-4	1	2	221	-219
-3	1	2	267	275
0	1	2	120	141
1	1	2	127	-150
2	1	2	174	-173
-6	2	2	91	82
-5	2	2	119	-104
-3	2	2	91	99
-2	2	2	254	-283
-1	2	2	61	110
0	2	2	84	80
1	2	2	227	-234
3	2	2	223	-232
4	2	2	151	147
6	2	2	106	148
-6	3	2	73	68
-5	3	2	112	112
-2	3	2	191	-191
-1	3	2	90	101
0	3	2	432	411
1	3	2	459	453
3	3	2	196	210
4	3	2	106	-105
-7	4	2	100	-119
-4	4	2	69	76
-3	4	2	156	157
-2	4	2	132	-141
-1	4	2	165	154
0	4	2	201	-210
1	4	2	110	-94
2	4	2	138	-128
-4	5	2	118	-126
-3	5	2	297	-289
-2	5	2	229	242
0	5	2	94	92
1	5	2	318	303
2	5	2	351	-341
3	5	2	263	-267
4	5	2	100	126
5	5	2	118	-120
-8	6	2	72	-47
-6	6	2	92	100
-2	6	2	149	-141
-1	6	2	276	-285
0	6	2	208	-200
1	6	2	103	117
2	6	2	68	-83
3	6	2	73	68
5	6	2	135	131
6	6	2	93	-97
7	6	2	76	102
-3	7	2	128	-135
-2	7	2	211	220
-1	7	2	135	122
1	7	2	202	182
2	7	2	134	134
-4	8	2	109	99
-3	8	2	94	-75
1	8	2	124	-142
2	8	2	288	278
4	8	2	166	-168
-6	9	2	146	-140
-4	9	2	156	149
-1	9	2	168	170
0	9	2	155	-149
1	9	2	207	-203
3	9	2	126	-117
4	9	2	178	-200
5	9	2	101	100
-2	10	2	128	-125
-1	10	2	109	-117
0	10	2	109	121
2	10	2	76	74
-3	11	2	124	117
-1	11	2	101	-114
1	11	2	82	-88
3	11	2	101	89
4	11	2	214	253
5	11	2	86	95
-4	12	2	161	-150
-1	12	2	145	154
0	12	2	167	161
1	12	2	91	84
2	12	2	130	-105
5	12	2	87	-100
-2	13	2	127	-122
1	13	2	116	-151
3	13	2	165	173
5	13	2	131	-145
-3	14	2	178	184
1	14	2	85	-71
2	14	2	110	-123
1	15	2	179	173
-2	16	2	72	63
-1	-15	3	73	47
0	-15	3	72	-102
1	-15	3	100	-119
-2	-14	3	96	-123
-1	-14	3	86	82
0	-14	3	195	200
1	-14	3	128	-137
2	-14	3	103	-120
3	-14	3	174	193
0	-13	3	130	147
3	-13	3	113	131
-2	-12	3	149	139
-1	-12	3	72	7
3	-11	3	262	-272
4	-11	3	143	-150
-5	-10	3	126	142
-2	-10	3	108	-106
-1	-10	3	288	-268
1	-10	3	110	116
3	-10	3	64	-93
4	-10	3	192	208
-5	-9	3	102	116
-4	-9	3	80	-55
-1	-9	3	167	164
4	-9	3	137	153
-5	-8	3	113	-123
-3	-8	3	140	-124
-2	-8	3	240	-230
-1	-8	3	283	265
0	-8	3	125	125
1	-8	3	75	-73
2	-8	3	64	84
3	-8	3	207	210
4	-8	3	77	-83
5	-8	3	167	-177
-8	-7	3	121	-121
-5	-7	3	159	-161
-4	-7	3	234	237
-3	-7	3	238	212
-2	-7	3	258	-243
-1	-7	3	140	144
1	-7	3	343	-327
3	-7	3	121	125
4	-7	3	186	-205
5	-7	3	201	-220
6	-7	3	108	127
-5	-6	3	101	-92
-3	-6	3	309	294
-1	-6	3	363	-345
0	-6	3	202	-195
1	-6	3	254	266
2	-6	3	130	-129
-8	-5	3	124	104
-6	-5	3	91	115
-3	-5	3	111	-114
-1	-5	3	202	-194
1	-5	3	365	370
2	-5	3	65	70
5	-5	3	236	248
-7	-4	3	170	-169
-5	-4	3	140	134
-4	-4	3	140	-133
-3	-4	3	216	-207
-2	-4	3	200	202
-1	-4	3	223	-225
1	-4	3	220	227
2	-4	3	148	-162
4	-4	3	84	93
6	-4	3	70	-62
-8	-3	3	115	-115
-4	-3	3	219	-216
-2	-3	3	192	188
0	-3	3	217	200
1	-3	3	68	-45
2	-3	3	214	-220
3	-3	3	235	224
5	-3	3	169	-185
6	-3	3	187	-206
-7	-2	3	99	101
-4	-2	3	144	158
-3	-2	3	57	73
-2	-2	3	466	466
-1	-2	3	244	-248
0	-2	3	293	-275
1	-2	3	265	-256
3	-2	3	62	-59
4	-2	3	80	88
7	-2	3	114	104
-7	-1	3	180	186
-6	-1	3	71	-36
-4	-1	3	122	-105
-3	-1	3	160	159
0	-1	3	112	120
2	-1	3	309	313
3	-1	3	96	-93
-6	0	3	186	-180
-5	0	3	155	145
-4	0	3	80	84
-3	0	3	320	-328
-2	0	3	136	-142
-1	0	3	77	65
0	0	3	329	-309
1	0	3	65	31
2	0	3	272	301
4	0	3	63	-55
5	0	3	125	126
7	0	3	69	-78
-8	1	3	120	106
-7	1	3	137	-152
-6	1	3	190	-196
-3	1	3	135	-120
-2	1	3	87	81
-1	1	3	370	381
1	1	3	311	-329
3	1	3	143	-142
4	1	3	80	44
8	1	3	74	-8
-8	2	3	82	-69
-6	2	3	65	80
-3	2	3	83	86
-2	2	3	273	-275
-1	2	3	505	511
0	2	3	257	234
1	2	3	66	-60
2	2	3	105	-116
3	2	3	89	-81
-8	3	3	98	-80
-6	3	3	224	222
-5	3	3	72	-47
-3	3	3	329	326
-2	3	3	258	-266
-1	3	3	367	-344
2	3	3	113	-115
3	3	3	305	328
-6	4	3	118	106
-5	4	3	209	-213
-3	4	3	89	88
0	4	3	99	101
2	4	3	283	-276
-4	5	3	104	-100
-3	5	3	165	-178
-2	5	3	172	-176
-1	5	3	154	-165
0	5	3	113	118
1	5	3	234	221
3	5	3	97	96
4	5	3	63	-58
-7	6	3	72	-70
-4	6	3	150	141
-2	6	3	173	177
2	6	3	121	-107
-3	7	3	108	-111
-2	7	3	165	162
-1	7	3	201	-211
0	7	3	124	119
1	7	3	213	211
-6	8	3	85	-87
-1	8	3	113	-111
0	8	3	93	-72

```
  H  K  L 10FO 10FC      H  K  L 10FO 10FC      H  K  L 10FO 10FC      H  K  L 10FO 10FC      H  K  L 10FO 10FC

  2  0  0  813 -833     -7  4  0   73  -73      2  8  0  349  359     -2-14  1   91   78      4 -9  1  142  135
  3  0  0  368  384     -6  4  0   90  -73      3  8  0  131  114      0-14  1  116 -106      5 -9  1   98  -74
  5  0  0  439 -453     -4  4  0  100 -102      4  8  0   90  101      2-14  1  174 -174      6 -9  1   85   61
  7  0  0   81  106     -3  4  0  381  386     -4  9  0   66   56      3-14  1   97  -91     -5 -8  1   93 -104
  8  0  0   65  -77     -2  4  0  137  131     -3  9  0  143 -146     -5-13  1  111  126     -4 -8  1   65  -56
 -8  1  0  161 -182     -1  4  0  293 -275     -2  9  0  389  373     -3-13  1  231 -237     -3 -8  1  275  267
 -6  1  0  235  257      1  4  0 1416 1373      1  9  0   60  -54     -1-13  1  133  147     -1 -8  1  301  295
 -5  1  0  185  183      2  4  0  296 -298      3  9  0  164 -167      3-13  1   80   90      0 -8  1  243  232
 -3  1  0  431  460      3  4  0   60  -64      4  9  0   82  -78      4-13  1  145 -128      2 -8  1   86  -67
 -2  1  0  347 -354      4  4  0  190  165      7  9  0   81  -48      5-13  1   90   85      5 -8  1   88   77
  1  1  0   86  106     -7  5  0   69  -99     -6 10  0   87  -64     -4-12  1  187  207     -6 -7  1   88   78
  2  1  0  678 -674     -3  5  0  195  193     -5 10  0   89   74     -3-12  1  102 -120     -4 -7  1  166 -154
  4  1  0  392  395     -2  5  0  144 -147     -4 10  0   90  -93     -1-12  1   63   59     -3 -7  1   59   62
  5  1  0  143 -144      1  5  0  403  401     -1 10  0   70  -59      1-12  1   89  -74     -2 -7  1  313 -306
  6  1  0  205 -219      3  5  0  275 -273      0 10  0   81  -78      2-12  1  184  175     -1 -7  1  231 -218
  7  1  0   98  123      5  5  0   89  -79      4 10  0   75  -87     -5-11  1  107 -127      0 -7  1   70  -75
 -6  2  0   90 -100     -5  6  0  107 -114      0 11  0   84   86     -3-11  1  122  139      1 -7  1  158  165
 -5  2  0  294  278     -4  6  0  316  311      2 11  0   61   50     -1-11  1   59  -72      2 -7  1   83  -74
 -4  2  0  557 -560     -3  6  0  197 -187     -2 12  0  134  139      0-11  1   76   89      3 -7  1  120  105
 -3  2  0   99 -111     -2  6  0  115  -91      1 12  0  109 -105      1-11  1   84  -71      4 -7  1  132  124
 -2  2  0  649  711     -1  6  0   77  -70      4 12  0   94   94      2-11  1   83  -87      5 -7  1  160 -158
  0  2  0  537 -520      0  6  0  141 -128     -4 13  0   93  -84      3-11  1   97  105     -7 -6  1  111 -135
  1  2  0  179 -177      1  6  0  385 -381     -2 13  0  116 -109      4-11  1   72 -107     -6 -6  1   67  -36
  2  2  0  180 -172      2  6  0  240 -229     -1 13  0  227  234     -4-10  1   96  -93     -3 -6  1  120  119
  3  2  0  299 -313      4  6  0  107  111     -4 14  0  108   63     -2-10  1  125 -136     -2 -6  1  359  353
  4  2  0  145 -166     -3  7  0   76   77     -3 14  0  106  -93      0-10  1  130  120     -1 -6  1  165 -190
  6  2  0   87   84     -2  7  0  262 -232      0 14  0   80  -72      3-10  1  143 -139      1 -6  1  135 -143
 -8  3  0  134  137     -1  7  0  100  100     -1 15  0  122  106      4-10  1  118 -109      2 -6  1  185 -177
 -6  3  0   93   68      1  7  0   93   90     -2 16  0   94  -57     -4 -9  1  186  189      4 -6  1  170  155
 -3  3  0  316 -365      2  7  0  164 -157     -1 16  0   89   89     -3 -9  1   66   68      5 -6  1  162 -169
 -2  3  0  262 -263      3  7  0  230  237      1-18  1  124 -112     -2 -9  1  178 -180     -4 -5  1  173 -189
 -1  3  0  366 -353      4  7  0  200 -217     -4-17  1   95  -79     -1 -9  1  408 -384     -3 -5  1  137  140
  2  3  0 1017  989     -2  8  0  235  229      1-16  1  151  156      0 -9  1   75   96     -2 -5  1   69 -100
  3  3  0  234 -223     -1  8  0  207 -202     -1-15  1   71  -68      1 -9  1  215 -205     -1 -5  1   86  -82
  4  3  0   86   79      0  8  0  278 -290      0-15  1  122  122      2 -9  1  161  153      0 -5  1  242 -223
  6  3  0   69   94      1  8  0  132  135     -5-14  1   64   59      3 -9  1   65   69      1 -5  1  494  488

  2 -5  1  186 -188      3 -1  1  608 -638      5  2  1   98  -81      5  6  1   81   93      1 12  1   80 -100
  3 -5  1  220  213      5 -1  1  367  373      6  2  1   97  108     -5  7  1   96  -73      2 12  1  177 -193
  6 -5  1  100 -117      7 -1  1  103 -133     -5  3  1  107   84     -4  7  1  247  230      4 12  1  107  101
 -4 -4  1   84  103      8 -1  1   87   80     -3  3  1  252 -262     -3  7  1   76  -58      1 13  1  130  127
 -3 -4  1  141  157     -7  0  1   73   71     -2  3  1  267  263     -2  7  1  421 -383      5 13  1  119 -130
 -2 -4  1  387  371     -6  0  1   74   65     -1  3  1  210  214     -1  7  1  470  445     -2 14  1  133  133
 -1 -4  1   78   77     -4  0  1   88   94      0  3  1  506 -511      1  7  1  338 -338     -1 14  1   66  -60
  0 -4  1  319 -310     -3  0  1  347 -368      1  3  1  390  405      2  7  1  243  238      0 14  1  166 -172
  1 -4  1  145  144     -2  0  1  310 -328      2  3  1  501  481      3  7  1  537  554      1 14  1  113 -128
  2 -4  1  193 -199     -1  0  1  341  356      3  3  1   94  -95      4  7  1  141 -152     -3 15  1   94 -109
  3 -4  1  110  121      0  0  1  700  684      6  3  1  133  123     -5  8  1  188 -183     -1 15  1  162  155
  4 -4  1   90   94      1  0  1  238 -250     -7  4  1   98 -117     -4  8  1   98   79      1 15  1   78  104
  6 -4  1   93  112      2  0  1  973  972     -5  4  1   98   98     -2  8  1  140  141      1 17  1  100  -73
  7 -4  1   75  -65      4  0  1  205 -222     -4  4  1  178 -174      0  8  1  244  242     -3-18  2   78  -19
 -3 -3  1  252 -259      8  0  1   74  -79     -3  4  1  375  368      1  8  1  164 -168      1-18  2  112 -111
 -2 -3  1  357  361     -8  1  1  114 -101     -2  4  1   98 -101      2  8  1  131  153      0-17  2   82  -95
 -1 -3  1  322 -325     -6  1  1   84  -90     -1  4  1   97 -102      3  8  1  172  177      1-17  2  113  115
  0 -3  1  443  426     -5  1  1  114  133      1  4  1  820  824      5  8  1  158 -165     -1-16  2   84   87
  2 -3  1  271 -267     -4  1  1  170  167      4  4  1  136 -131     -3  9  1  133  125      1-16  2   91   94
  3 -3  1  248 -263     -3  1  1  267  269     -7  5  1  132 -128     -2  9  1  123  120     -4-15  2  117  113
  4 -3  1   85  -91     -2  1  1   91  -76     -4  5  1  126  129     -1  9  1  167 -158     -2-15  2  151 -167
  5 -3  1   73  -82     -1  1  1  248  260     -2  5  1  227  207      2  9  1   93  109      0-15  2  161  168
  7 -3  1   95  111      1  1  1  577 -573      0  5  1  305 -320      3  9  1  106 -114      1-15  2  136 -130
 -5 -2  1   66   67      2  1  1  966 -977      1  5  1  319  302      4  9  1  160 -186      2-15  2  153 -174
 -3 -2  1  205 -202      3  1  1  264  283      2  5  1  189 -201     -1 10  1  127 -125     -6-14  2   91  115
 -1 -2  1  389 -391      5  1  1  173 -170      3  5  1  607 -594      0 10  1   63  -89     -3-14  2  110  130
  0 -2  1 1082-1063      7  1  1   79   92      4  5  1  203  224      2 10  1  119 -143     -1-14  2  115 -125
  1 -2  1  584  633      8  1  1   87  -94      6  5  1  124 -142      3 10  1  183 -196      0-14  2  151  160
  4 -2  1  253  253     -5  2  1   62  -73     -5  6  1   70   96     -1 11  1  223 -225      2-14  2  370 -392
  5 -2  1  319  299     -4  2  1  288 -279     -4  6  1  124  122      0 11  1  162  161      4-14  2   84   68
  6 -2  1  342 -347     -3  2  1  109 -107     -3  6  1  358 -323      3 11  1  129  133     -6-13  2  108  126
 -4 -1  1  201 -209     -2  2  1  532 -541     -2  6  1  201 -177      4 11  1  231  259     -5-13  2  102  101
 -3 -1  1  134 -146      0  2  1  251  245     -1  6  1  101  -98     -4 12  1  138 -129     -4-13  2  192 -186
 -2 -1  1 1035 1095      1  2  1  613 -599      1  6  1  150 -150     -3 12  1   94  100     -3-13  2  104 -140
 -1 -1  1  144  164      2  2  1  367  346      2  6  1  260 -274     -2 12  1   80   85     -2-13  2  110  131
  1 -1  1  126  150      3  2  1   81  -70      4  6  1  109  -71     -1 12  1  127  105     -1-13  2   97 -114
```

H	K	L	10FO	10FC
-5	9	3	73	-42
1	9	3	92	81
3	9	3	127	-137
4	9	3	93	-83
-3	10	3	81	54
-1	10	3	68	-78
2	10	3	156	173
3	10	3	86	71
-4	11	3	77	-91
-2	11	3	104	107
-1	11	3	70	79
0	11	3	90	-89
-4	12	3	94	-64
1	12	3	109	118
2	12	3	77	75
5	12	3	93	-72
0	13	3	165	-162
1	13	3	87	-89
-3	15	3	82	-71
0	-13	4	78	41
0	-12	4	80	62
1	-12	4	153	-148
4	-12	4	71	-19
-4	-11	4	94	-80
-3	-11	4	94	-94
1	-11	4	63	24
3	-11	4	86	-112
-5	-10	4	200	199
-3	-10	4	73	35
-1	-10	4	82	-79
0	-10	4	104	-109
4	-10	4	114	115
-4	-9	4	104	-87
-2	-9	4	131	113
-1	-9	4	162	157
1	-9	4	166	190
3	-9	4	145	-165
4	-9	4	106	113
-6	-8	4	113	112
-3	-8	4	191	-177
-2	-8	4	109	-114
1	-8	4	118	107
3	-8	4	75	-65
-6	-7	4	101	-104
-4	-7	4	119	112
-3	-7	4	74	92
-2	-7	4	116	-110
-1	-7	4	216	209
0	-7	4	235	-228
1	-7	4	129	-113
4	-7	4	132	-153
6	-7	4	76	67
-7	-6	4	99	92
-5	-6	4	82	-96
-4	-6	4	199	199
-3	-6	4	101	-109
-2	-6	4	146	-139
-1	-6	4	212	189
1	-6	4	100	-96
2	-6	4	103	94
3	-6	4	155	146
4	-6	4	148	-150
6	-6	4	116	119
-4	-5	4	239	243
-3	-5	4	147	-142
-2	-5	4	121	-119
-1	-5	4	129	-138
2	-5	4	166	176
3	-5	4	84	75
5	-5	4	143	132
-8	-4	4	91	-82
-7	-4	4	82	-84
-4	-4	4	169	-157
-3	-4	4	155	156
-1	-4	4	85	-71
0	-4	4	181	179
1	-4	4	159	157
2	-4	4	213	-217
3	-4	4	58	-54
6	-4	4	141	-118
-8	-3	4	103	-91
-6	-3	4	82	72
-2	-3	4	187	176
-1	-3	4	351	-324
2	-3	4	73	-78
4	-3	4	81	91
6	-3	4	113	-136
-6	-2	4	95	75
-4	-2	4	82	-73
-3	-2	4	287	280
-2	-2	4	419	407
-1	-2	4	186	-179
1	-2	4	269	-267
2	-2	4	107	-113
3	-2	4	74	83
5	-2	4	70	-72
6	-2	4	89	99
7	-2	4	136	135
-7	-1	4	231	228
-5	-1	4	91	-96
-3	-1	4	140	137
-2	-1	4	458	-422
0	-1	4	72	69
2	-1	4	184	180
3	-1	4	193	183
5	-1	4	97	-95
-7	0	4	70	-60
-6	0	4	167	-178
-3	0	4	75	87
-2	0	4	158	177
-1	0	4	475	-469
1	0	4	173	169
3	0	4	130	-114
4	0	4	95	110
6	0	4	90	-97
7	0	4	97	-74
-8	1	4	108	78
-7	1	4	176	-182
-5	1	4	105	84
-4	1	4	138	-139
-3	1	4	137	-115
-2	1	4	203	198
-1	1	4	397	391
0	1	4	197	-179
1	1	4	117	108
3	1	4	391	-415
5	1	4	123	152
7	1	4	94	-90
-5	2	4	368	360
-3	2	4	299	-278
-2	2	4	140	144
-1	2	4	449	425
0	2	4	404	-370
1	2	4	101	112
2	2	4	131	140
-6	3	4	246	236
-5	3	4	120	-98
-3	3	4	92	92
-1	3	4	86	-67
0	3	4	122	-117
1	3	4	337	-324
3	3	4	187	195
-5	4	4	314	-312
-4	4	4	126	-137
1	4	4	199	182
5	4	4	96	-86
-6	5	4	74	-78
-2	5	4	142	-145
4	5	4	75	-110
-5	6	4	73	-65
-4	6	4	343	342
-1	6	4	144	151
0	6	4	216	222
2	6	4	67	-60
-6	7	4	85	80
-5	7	4	187	181
-4	7	4	148	-130
-3	7	4	92	-103
-1	7	4	161	-140
4	7	4	69	92
-7	8	4	116	-106
-5	8	4	221	179
-4	8	4	209	-195
-3	8	4	209	-217
-2	8	4	119	125
-1	8	4	80	76
0	8	4	196	-203
2	8	4	118	107
3	8	4	119	-130
-6	9	4	97	-100
-4	9	4	125	115
-3	9	4	148	-149
2	9	4	176	177
4	9	4	137	-117
-6	10	4	85	-59
-4	10	4	137	138
-3	10	4	190	193
-2	10	4	216	-211
-1	10	4	97	76
0	10	4	104	120
1	10	4	97	-90
-3	11	4	130	110
-2	11	4	114	-98
2	11	4	98	-81
-3	12	4	115	-102
-2	12	4	77	-87
-3	13	4	123	97
-1	14	4	72	-41
-4	-15	5	102	75
-4	-14	5	110	114
-1	-14	5	111	71
-3	-13	5	80	98
-6	-12	5	72	24
-3	-12	5	136	-130
0	-12	5	105	108
1	-12	5	150	-151
-4	-11	5	101	96
-3	-11	5	75	-55
-2	-11	5	135	-152
-1	-11	5	92	-95
0	-11	5	145	142
1	-11	5	105	119
-3	-10	5	106	125
-2	-10	5	287	281
-6	-9	5	69	16
-5	-9	5	69	-42
-3	-9	5	189	-184
-1	-9	5	107	94
1	-9	5	86	85
3	-9	5	87	-99
-5	-8	5	108	90
-2	-8	5	121	-106
-1	-8	5	124	-136
0	-8	5	121	-120
2	-8	5	60	-38
-1	-7	5	166	152
0	-7	5	102	-100
1	-7	5	164	168
-4	-6	5	169	181
-3	-6	5	179	-189
0	-6	5	131	140
-8	-5	5	87	-59
-1	-5	5	90	78
1	-5	5	90	-92
4	-5	5	106	-79
-8	-4	5	100	-108
-4	-4	5	78	-71
-3	-4	5	100	-77
2	-4	5	80	67
4	-4	5	117	-129
-4	-3	5	88	84
-2	-3	5	226	218
-1	-3	5	262	-245
1	-3	5	147	-156
2	-3	5	85	79
-3	-2	5	92	87
-1	-2	5	125	128
0	-2	5	125	119
1	-2	5	73	62
-7	-1	5	82	60
-6	-1	5	115	-116
-5	-1	5	89	93
-2	-1	5	206	-191
1	-1	5	89	-89
2	-1	5	123	122
3	-1	5	115	116
5	-1	5	72	-86
-7	0	5	112	-103
-5	0	5	142	-130
-2	0	5	74	-41
-1	0	5	56	41
0	0	5	206	198
1	0	5	298	-275
3	0	5	76	78
5	0	5	98	-99
-6	1	5	69	-70
-1	1	5	301	291
0	1	5	123	-126
1	1	5	75	87
2	1	5	103	-115
3	1	5	80	-98
-5	2	5	174	139
-4	2	5	75	-67
0	2	5	61	-76
2	2	5	78	98
6	2	5	70	-61
-6	3	5	124	100
-5	3	5	175	-196
-4	3	5	148	144
0	3	5	93	-92
1	3	5	179	-177
4	3	5	71	64
-5	4	5	131	-136
-4	4	5	255	-241
0	4	5	102	118
1	4	5	194	192
2	4	5	138	-146
3	4	5	86	94
-6	5	5	73	73
-4	5	5	131	138
-3	5	5	146	148
-2	5	5	95	-99
0	5	5	124	134
4	5	5	103	-68
-6	6	5	82	-80
-4	6	5	279	258
-3	6	5	81	-83
-1	6	5	69	57
0	6	5	163	153
1	6	5	172	-176
3	6	5	89	85
6	6	5	102	115
-2	7	5	284	-263
0	7	5	183	197
1	7	5	87	-94
2	7	5	216	-214
3	7	5	135	139
4	7	5	84	77
5	7	5	80	-39
-6	8	5	79	68
-4	8	5	206	-191
-2	8	5	158	152
-1	8	5	222	-219
1	8	5	174	186
3	8	5	99	-117
4	8	5	163	174
-5	9	5	94	95
-4	9	5	189	-197
-2	9	5	310	304
1	9	5	203	209
3	9	5	105	-121
-3	10	5	126	115
0	10	5	157	-126
-3	11	5	75	-32
-3	12	5	111	-96
-2	12	5	105	-114
-1	13	5	158	164
-4	-15	6	118	112
0	-15	6	81	102
-5	-13	6	122	132
0	-13	6	178	-159
1	-13	6	131	-135
-5	-12	6	90	-91
-4	-12	6	112	-91
-3	-12	6	142	-145
-1	-12	6	108	102
2	-12	6	95	113
-3	-11	6	239	240
-1	-11	6	92	-88
3	-11	6	113	118
-5	-10	6	81	-62
-3	-10	6	236	229
-1	-10	6	109	111
2	-10	6	77	-108
3	-10	6	74	-88
-4	-9	6	73	94
-3	-9	6	180	-183
-2	-9	6	189	-189
-1	-9	6	69	-78
0	-9	6	71	82
-6	-8	6	79	-15
-2	-8	6	134	-121
-1	-8	6	108	131
-5	-7	6	76	70
-4	-7	6	161	-153
-3	-7	6	121	-122
-2	-7	6	272	251
0	-7	6	89	-78
1	-7	6	167	180
-4	-6	6	93	103
-3	-6	6	125	-106
-2	-6	6	217	215
2	-6	6	101	117
-7	-5	6	158	151
-4	-5	6	189	190
-2	-5	6	287	-291
1	-5	6	67	-49
2	-5	6	131	-127
-7	-4	6	88	79
-5	-4	6	172	-167
-3	-4	6	158	158
-2	-4	6	214	-194
-1	-4	6	262	-254
0	-4	6	252	260
1	-4	6	74	-79
2	-4	6	71	-58
3	-4	6	82	85
-6	-3	6	113	100
-4	-3	6	78	-73
-2	-3	6	124	107
0	-3	6	107	126
-5	-2	6	155	159
-3	-2	6	69	94
1	-2	6	129	126
-2	-1	6	123	124
-1	-1	6	178	-172
-7	0	6	81	-85
-6	0	6	99	71
-4	0	6	71	-57
-1	0	6	167	-166
0	0	6	81	-85
-5	1	6	102	103
-4	1	6	143	-147
-2	1	6	70	122
-1	1	6	153	155
0	1	6	68	-72
1	1	6	180	178
-6	2	6	68	66
-4	2	6	105	93
-1	2	6	81	-82
0	2	6	107	-112
2	2	6	162	165
-5	3	6	130	-123
-2	3	6	230	239
0	3	6	158	-160
2	3	6	96	-95
3	3	6	68	-67
4	3	6	67	-32
-4	4	6	172	-151
1	4	6	121	133
-4	5	6	216	224
-2	5	6	155	142
3	5	6	71	-70
-1	6	6	68	71
5	6	6	90	91
-2	7	6	149	-139
-1	7	6	126	126
0	7	6	93	-101
1	7	6	127	-130
2	7	6	86	83
-3	8	6	91	-76
0	8	6	104	99
1	8	6	97	-68
-3	9	6	110	117
-3	10	6	92	51
2	10	6	112	-102
-1	11	6	97	-82
2	-12	7	103	100
-3	-11	7	215	206
3	-11	7	74	54
-5	-10	7	82	-55
2	-10	7	82	-56
-2	-9	7	149	-137
-3	-8	7	113	-91
-2	-8	7	127	-139
-1	-8	7	170	162
3	-8	7	146	155
-3	-7	7	66	51
-2	-7	7	242	239
0	-7	7	129	114
2	-7	7	103	-93
4	-7	7	74	65
-6	-6	7	153	148
-5	-6	7	78	81
-4	-6	7	180	-168
-2	-6	7	314	298
-1	-6	7	115	-109
0	-6	7	219	-219
1	-6	7	198	202
3	-6	7	177	-185
-5	-5	7	134	128
-3	-5	7	76	-54
-2	-5	7	94	82
-1	-5	7	122	-125
0	-5	7	258	-275
3	-5	7	79	-84
-6	-4	7	125	-139
-5	-4	7	112	-112
-4	-4	7	131	100
-3	-4	7	140	-123
-2	-4	7	203	-176
-1	-4	7	64	70
0	-4	7	214	207
1	-4	7	120	-113
2	-4	7	73	111
-4	-3	7	135	143
-2	-3	7	137	-120
-1	-3	7	122	118
0	-3	7	177	167
-1	-2	7	251	245
0	-2	7	64	-41
1	-2	7	136	-148
0	-1	7	139	-125
1	-1	7	145	-157
2	-1	7	143	138
-4	0	7	89	-79
-3	0	7	170	178
-1	0	7	90	-97
2	0	7	92	-101
-4	1	7	87	-81
0	1	7	107	88
1	1	7	254	253
2	1	7	92	77
-4	2	7	227	214
1	2	7	167	-167
-5	3	7	93	-96
-1	3	7	137	127
0	3	7	74	97
2	3	7	132	-122
-6	4	7	102	66
-1	4	7	87	-93
-2	5	7	184	181
-2	6	7	84	-89
1	6	7	69	-10
0	8	7	70	66
-3	-10	8	85	-34
-2	-9	8	83	-73
-1	-7	8	126	98
0	-7	8	101	144
1	-7	8	83	-77
-2	-6	8	80	-47
-1	-6	8	141	-123
2	-6	8	88	-96
-5	-5	8	80	-60
-4	-5	8	105	-100
-2	-5	8	79	77
-1	-5	8	111	-104
0	-4	8	81	76
1	-4	8	77	87
-4	-3	8	79	53
-1	-3	8	73	75
0	-3	8	68	93
2	-3	8	85	-78
-2	-2	8	104	-90
-1	-2	8	71	86
1	-2	8	79	-73
0	-1	8	150	-137
1	-1	8	133	-135
-5	0	8	95	-77
-4	0	8	98	-77
0	0	8	73	48
1	0	8	123	112
2	0	8	79	24
-3	1	8	106	114
-1	1	8	177	-184
1	1	8	101	168
3	1	8	72	-19
-3	2	8	110	90
2	2	8	139	-149
3	2	8	113	-90
-3	3	8	109	-120
-4	4	8	76	37
-3	4	8	74	-44
-2	4	8	60	64
2	5	8	97	108
-4	-2	9	76	19
1	0	9	100	86

REFERENCES

Adler, E., Marton, J. and Falkehag, I. 1964. "The behaviour of lignin in alkaline pulping", Acta Chem. Scand. 18, 1311.

Adler, E. 1977. "Lignin chemistry - past, present, and future", Wood Sci. Tech. 11, 169.

Ahvonen, T., Brunow, G., Kristersson, P. and Lundquist, K. 1983. "Stereoselective syntheses of lignin model compounds of the ß-O-4 and ß-1 types", Acta chem. Scand. B37, 845.

Aizpurua, J.M. and Palomo, C. 1985. "1,8-Diazabicyclo[5.4.0] undec-7-ene (DBU): an effective base for the introduction of t-butyldimethylsilyl group in organic synthesis", Tet. Lett. 26(4), 475.

Algar, W.H., Farrington, A., Jessup, B., Nelson, P.F. and Vanderhoek, N. 1979. "The mechanism of soda-quinone pulping", Appita 33(1), 33.

Aulin-Erdtman, G. 1942. "The structure of dehydrodiisoeugenol", Svensk Kem. Tid. 54, 168.

Aulin-Erdtman, G., Tomita, Y. and Forsen, S. 1963. "Degradation of lignin and lignin model compounds. I. Configuration of dehydrodiisoeugenol", Acta Chem. Scand. 17, 535.

Bax, A. and Morris, G. 1981. "An improved method for heteronuclear chemical shift correlation by two-dimensional NMR", J. Mag. Res. 42(3), 501.

Becker, H-D. and Adler, E. 1961. "Zur oxydation mit chinonen", Acta Chem. Scand. 15(1), 218.

Bendall, M.R. and Pegg, D.T. 1983. "Complete accurate editing of decoupled carbon-13 spectra using DEPT and a quaternary-only sequence", J. Mag. Res. 53, 272.

Berg, U. and Sandstrom, J. 1978. "Barriers to rotation about the exocyclic carbon-carbon bond in some quinone methides with donor substituents on the exocyclic carbon", Acta Chem. Scand. B32, 41.

Berndtsson, I., Khanna, B. and Lundquist, K. 1980. "Synthesis of the erythro and threo forms of 1,2-bis(4-hydroxy-3-methoxyphenyl)-1,3-propanediol", Acta Chem. Scand. B34, 453.

Brezny, R. and Pufflerova, A. 1978. "Synthesis of 1,2-bis(4-hydroxy-3-methoxyphenyl- and 1,2-bis(3,4-dimethoxyphenyl)-1,3-propanediol", Coll. Czech. Chem. Comm. 43, 3263.

Brezny, R., Schraml, J., Kvicalova, M., Zeleny, J. and Chvalovsky, V. 1986. "Silicon-29 NMR spectroscopy in lignin chemistry - application to trimethylsilylated spruce dioxane lignin and related model compounds", Holzforschung 39(5), 297.

Brunow, G. and Poppius, K. 1981a. "A kinetic study on the mechanism of ß-0-4 ether cleavage in soda-anthraquinone pulping", Pap. ja Puu, 63(12), 783.

Brunow, G., Koskinen, L. and Urpilainen, P. 1981b. "Reversal of the direction of the asymmetric induction in the borohydride reduction of two propiophenone derivatives using a polymer-bound reagent", Acta Chem. Scand. B35(1).

Brunow, G. and Poppius, K. 1982. "Cleavage of ß-aryl ether bonds in phenolic lignin model compounds with anthrahydroquinone and anthrone", Acta Chem. Scand. 336(6), 377.

Brunow, G. and Lundquist, K. 1984. "A new synthesis of model compounds for the ß-5 structural unit in lignins", Acta Chem. Scand. B38(4), 335.

Brunow, G. 1985. Pers. Comm.

Buehler, G.A. and Pearson, D.E. 1970. "Survey of organic syntheses", Wiley-Interscience, New York.

Chen, C-L., Hise, R. and Gratzl, J. 1985. Synthesis of ß-lignin model compounds", J. Wood Chem. Tech. 5(3), 379.

Cook, G.D. and Norcross, B.E. 1956. "Oxidation of hindered phenols. V. The 2,6-di-t-butyl-4-isopropyland 4-sec-butylphenoxy radicals", J. Am. Chem. Soc. 78, 3797.

Dimmel, D.R. 1985a. "Electron transfer reactions in pulping systems (I): Theory and applicability to anthraquinone pulping", J. Wood Chem. Tech. 5(1), 1.

Dimmel, D.R., Perry, L.F., Palasz, P.D. and Chum, H.L. 1985b. "Electron transfer reactions in pulping systems (II): Electrochemistry of anthraquinone/lignin model quinone methides", J. Wood Chem. Tech. 5(1), 34.

Dimmel, D.R. and Schuller, L.F. 1986. "Electron transfer reactions in pulping systems (III): A study of steric effects in lignin model/AQ reactions", J. Wood Chem. Technol. 6(3), 345.

Doddrell, D.M. and Pegg, D.T. 1980. "Assignment of proton-decoupled carbon-13 spectra of complex molecules by using polarisation transfer spectroscopy. A superior method to off-resonance decoupling", J. Am. chem. Soc. 102, 6388.

Doddrell, D.M., Pegg, D.T., Brooks, W. and Bendall, M.R. 1981. "Enhancement of ^{29}Si or ^{119}Sn NMR signals in the compounds $M(CH_3)_nCl_{4-n}$ (M = Si or Sn, n = 4,3,2) using proton polarisation transfer. Dependence of the enhancement on the number of scalar coupled protons", J. Am. Chem. Soc. 103, 727.

Doddrell, D.M., Pegg, D.T. and Bendall, M.R. 1982. "Distortionless enhancement of NMR signals by polarisation transfer", J. Mag. Res. 48, 323.

Ede, R.M. 1984. "The synthesis of two new trimeric lignin model compounds and some aspects of lignin hydrogenolysis". MSc Thesis, University of Waikato.

Ede, R.M., Ralph, J. and Wilkins, A.L. 1987a. "The stereochemistry of ß-5 lignin model compounds", Holzforschung (accepted).

Ede, R.M., Ralph, J. and Main, L. 1987b. "Syn and anti lignin model quinone methides. Aspects of their synthesis, characterisation and differential reactivity with amines", J. Org. Chem. (submitted).

Ede, R.M., Ralph, J. and Main, L. 1987c. "Syn and anti lignin model quinone methides: Their differential reactivity with nucleophiles", Proc. Int. Symp. Wood and Pulp. Chem., Paris, 2, 171-173.

Faix, O. and Pfutze, E. 1980. "Soda-anthraquinone pulping", Holzforschung 34(1), 38.

Ferrand, G. and Huet, J. 1975. "Condensation of methylene diacetate with alkenes. IV. Stilbenes", Bull. Soc. Chim. Fr. 7-8, 1079.

Fieser, L.F. and Fieser, M. 1967. "Reagents for organic synthesis", John Wiley and Sons, New York, 1, 668.

Fleming, B.I., Kubes, G.J., MacLeod, J.M. and Bolker, H.I. 1978. "Soda pulping with anthraquinone - a mechanism", Tappi 61(6), 43.

Freudenberg, K. and Hubner, H.H. 1952. "Hydroxycinnamyl alcohols and their dehydration polymers", Chem. Ber. 85, 1181.

Freudenberg, K. and Dietrich, H. 1953. "Synthese des d,l-pinoresinols und andere versuche im zussamenhang mit dem lignin", Chem. Ber. 86(9), 1157.

Fujimoto, H., Nakatsubo, F. and Higuchi, T. 1982. "Synthesis of pinoresinol", Mok. Gak. 28(9), 555.

Fullerton, T.J. 1986. "The condensation reactions of lignin model compounds in alkaline pulping liquors." Submitted to J. Wood Chem. Tech.

Gellerstedt, G. and Gierer, J. 1968. "The reactions of lignin during neutral sulphite cooking. Part II. the behaviour of phenylcoumaran structures", Acta Chem. Scand. 22, 2029.

Gierer, J. 1970. "The reactions of lignin during pulping", Svensk Papp. 73(18), 571.

Gierer, J., Lindberg, O. and Noren, I. 1979. "Alkaline delignification in the presence of anthraquinone/anthrahydroquinone", Holzforschung 33, 213.

Gourang, I., Cassidy, R. and Dence, C.W. 1979. "Reduction products of anthraquinone", Tappi 62(7), 43.

Grunanger, P. 1979. In "Methoden der organischen chemie", edited by Mueller, E. and Bayer, O., G. Thieme Verlag, Stuttgart, VII/3b, 397.

Harkin, J. 1967. In "Oxidative coupling of phenols", edited by Taylor, W.I. and Battersby, A.R. Marcel Dekker, New York, Chapter 6, 243.

Harris, R.K. 1983. "Nuclear magnetic resonance spectroscopy - a physicochemical view", Pitman, London, 225.

Hemmingson, J.A. and Leary, G. 1975. "The chemistry of reactive lignin intermediates. Part 2. Addition reactions of vinyl substituted quinone methides in aqueous solutions", J. Chem. Soc. Perkin II, 1584.

Hemmingson, J.A. 1979. "A new way of forming lignin-carbohydrate bonds. Etherification of model benzyl alcohols in alcohol/water mixtures", Aust. J. Chem. 32, 225.

Hemmingson, J.A. 1982. "AQ pulping - a mechanism for 3-guaiacyl benzanthrone formation", J. Wood. Chem. Technol. 2(4), 417.

Heyl, F.W. and Herr, M.E. 1953. "Enamine derivatives of steroidal carbonyl compounds. II." J. Org. Chem. 75, 1918.

Holton, H.H. 1977. "Soda additive softwood pulping: a major new process", Pulp Paper Can. 78 T218.

Hooz, J. and Gilani, S.S.H. 1968. "A rapid mild procedure for the preparation of alkyl chlorides and bromides", Can. J. Chem. 46, 86.

House, H.O. 1956. "The rearrangement of α, β-epoxy ketones. III. The intramolecular nature of the rearrangement", J. Am. Chem. Soc. 78, 2298.

House, H.O. 1972. "Modern synthetic reactons" 2nd ed. Benjamin/ Cummings, California, p.61.

Ivnas, L. and Lindgren, B.O. 1961. "Nucleophilic substitution in 3-methoxy-4-hydroxybenzyl alcohol and 3,4-dimethoxybenzyl alcohol", Acta Chem. Scand. 15, 1081.

Katayama, Y. and Fukuzumi, T. 1978. "Enzymatic synthesis of three lignin-related dimers by an improved peroxidase-hydrogen peroxide system", Mok. Gak. 24(9), 664.

Kim, K.S., Song, Y.H., Lee, B.H. and Hahn, C.S. 1986. "Efficient and selective cleavage of acetals and ketals using ferric chloride adsorbed on silica gel", J. Org. Chem. 51, 404.

Kofron, w.g. and Baclawski, L.M. 1976. "A convenient method for estimation of alkyllithium concentrations." J. Org. Chem. 41(10), 1879.

Kratzl, K., Kisser, W., Gratzl, J. and Silbernagel, H. 1959. "Der ß-guajacylather des guajacylglycerins, seine umwandlung in coniferylaldehyd und verschiedne andere arylpropanderivate", Monatsch Chem. 90(6), 771.

Kratzl, K. and Miksche, G.E. 1963. "Einige beispeile zur spaltung von aryl-benzylathern in essigsaureanhydrid bei gegenwart katayltischer mengen H_2SO_4", Monatsch Chem. 94, 753.

Kristersson, P. and Lundquist, K. 1980. A new synthetic route to lignin model compounds of the 1,2-diaryl-1,3-propanediol type", Acta Chem. Scand. B34(3), 213.

Landucci, L.L. 1978. "Quinones in alkaline pulping", Tappi 63(7), 95.

Landucci, L.L. 1981a. "Formation of carbon-linked anthrone-lignin and anthrahydroquinone-lignin adducts." J. Wood Chem. Tech. 1(1), 61.

Landucci, L.L., Geddes, S.A. and Kirk, T.K. 1981b. "Synthesis of ^{14}C labelled 3-methoxy-4-hydroxy-α-(2-methoxyphenoxy)-ß-hydroxy-propiophenone, a lignin model compound", Holzforschung, 35, 67.

Landucci, L.L. and Ralph, J. 1982. "Adducts of anthrahydroquinone and anthranol with lignin model quinone methides. 1. Synthesis and characterisation", J. Org. Chem. 47(4), 149.

Landucci, L.L. and Ralph, J. 1984. "Anthraquinone losses during alkaline pulping", J. Wood Chem. Tech. 4(2), 149.

Leary, G., Miller, I.J., Thomas, W. and Woolhouse, A.D. 1977a. "The chemistry of reactive lignin intermediates. Part 5. Rates of reactions of quinone methides with water, alcohols, phenols, and carboxylic acids", J. Chem. Soc. Perkin II, 1737.

Leary, G. and Thomas, W. 1977b. "Reactive lignin intermediates. VI. Oxidation and coupling of isoeugenol with a quinone methide", Aust. J. Chem. 30, 2323.

Leopold, B. 1950. "Aromatic keto- and hydroxy-polyethers as lignin models. III." Acta Chem. Scand. 4, 213.

Lindgren, B.O. 1963. "Nucleophilic substitution in 3-methoxy-4-hydroxybenzyl alcohols and 3,4-dimethoxybenzyl alcohols." Acta Chem. Scand. 17, 2199.

Lowendahl, L. and Samuelson, O. 1977. "Carbohydrate stabilisation during kraft cooking with addition of anthraquinone", Svensk Papp. 80(17), 549.

Lowendahl, L. and Samuelson, O. 1978. "Carbohydrate stabilisation during soda pulping with addition of anthraquinone", Tappi, 61(2), 19.

Ludwig, C.H., Nist, B.J. and McCarthy, J.L. 1964. "Lignin. XII. The high resolution nuclear magnetic resonance spectroscopy of protons in compounds related to lignin", J. Am. Chem. Soc. 86, 1186.

Lundquist, K. and Miksche, G.E. 1965. "Nachweis eines neuen verknupfungsprinzips von guajacylpropaneinheiten in fichtenlignin", Tet. Lett. 25, 2131.

Mansson, P. 1982. "Selective deacetylation of aromatic acetates by aminolysis", Tet. Lett. 23(17), 1845.

Marmor, S. 1963. "The epoxidation of certain α,ß-unsaturated ketones with sodium hypochlorite", J. Org. Chem. 28, 250.

Miksche, G.E. 1980. In "Chemistry of delignification with oxygen, ozone, and peroxides", Uni Publishers Co., Tokyo, 107.

Murphy, W.S. and O'Mahony, B. 1981. "Stereochemistry of the vinylogous S_N2' reaction", Tet. Lett. 22, 585.

Nakatsubo, F. and Higuchi, T. 1975. "Synthesis of 1,2-diarylpropane-1,3-diols and determination of their configurations." Holzforschung 29(6), 193.

Nakatsubo, F., Sato, K. and Higuchi, T. 1976. "Enzymic dehydrogenation of p-coumaryl alcohol. IV. Reactivity of quinonemethide." Mok. Gak. 22, 29.

Nakatsubo, F. and Highuchi, T. 1979. "Syntheses of phenylcoumarans", Mok. Gak. 25(11), 735.

Noggle, J.H. and Shirmer, R.E. 1971. "The nuclear overhauser effect. Chemical applications", Academis Press, New York.

Nonni, A.J. and Dence, C.W. 1982. "The synthesis of 1,2-diarylpropane-1,3-diols via the Ivanoff reaction", J. Wood Chem. Technol. 2(2), 161.

Obst, J.R. and Landucci, L.L. 1986. "The syringyl content of softwood lignin", J. Wood Chem. Technol. 6(3), 311.

Payen, A. 1838. Compt. Rend. 7, 1057.

Pettit, G.R., Ghatak, U.R., Green, B., Kasturi, T.R. and Piatak, D.M. 1961. "Steroids and related natural products. IV. Reduction of lactones to cyclic ethers", J. Org. Chem. 26, 1685.

Poppius, K. 1984. "Studies on the cleavage of ß-aryl ether bonds in lignin model compounds effected by anthrone and its derivatives", Acta Chem. Scand. B38, 611.

Poppius, K. 1985a. "The stereochemistry of adduct formation between a lignin model quinone methide and anthrone, 10-methyl anthrone and 10-phenyl anthrone", Acta Chem. Scand. B39(10), 861.

Poppius, K. 1985b. "The "catalytic" effect of anthrone and anthrahydroquinone in cleaving ß-aryl ether bonds in lignin model compounds", J. Wood Chem. Tech. 5(2), 261.

Ralph, J. and Young, R.A. 1981. "Synthesis of the lignin model compounds threo-guaiacylglycerol-ß-guaiacyl ether and threo-veratrylglycerol-ß-guaiacyl ether", Holzforschung 29, 165.

Ralph, J. 1982. "Reactions of lignin model quinone methides and NMR studies of lignins." PhD Thesis. University of Wisconsin-Madison.

Ralph, J. and Landucci, L.L. 1983a. "Adducts of anthrahydroquinone and anthranol with lignin model quinone methides. 2. Dehydration derivatives. Proof of threo configuration", J. Org. Chem. 48(3), 372.

Ralph, J. and Landucci, L.L. 1983b. "Adducts of anthrahydroquinone and anthranol with lignin model quinone methides. 3. Independent synthesis of threo and erythro isomers", J. Org. Chem. 48(22), 3884.

Ralph, J. and Young, R.A. 1983c. "Stereochemical aspects of addition reactions involving lignin model quinone methides", J. Wood Chem. Tech. 3(2), 161.

Ralph, J. and Adams, B.R. 1983d. "Determination of the conformation and isomeric composition of lignin model quinone methides by NMR", J. Wood Chem. Tech. 3(2), 183.

Ralph, J., Landucci, L.L., Nicholson, B.K. and Wilkins, A.L. 1984. "Adducts of anthrahydroquinone and anthranol with lignin model quinone methides. 4. Proton NMR hindered rotation studies. Correlation between solution conformations and X-ray crystal structure", J. Org. Chem. 49, 3337.

Ralph, J. and Ede, R.M. 1985a. "Reactions of phenylcoumaran lignin model quinone methides with AHQ/anthranol", Proc. Int. Symp. Wood Pulp. Chem., Vancouver, 2 83.

Ralph, J. 1985b. "Lignin model quinone methides - facts and fallacies", presented at the 1985 Int. Symp. Wood Pulp. Chem., Vancouver.

Ralph, J. 1986a. "Adducts of anthrahydroquinone and anthranol with lignin model quinone methides. 9,10-^{13}C labelled anthranol-lignin adducts; examination of adduct formation and stereochemistry in the polymer", J. Wood Chem. Tech. 6(1), 73.

Ralph, J., Ede, R.M. and Wilkins, A.L. 1986b. "Synthesis of trimeric lignin model compounds composed of ß-aryl ether and phenylcoumaran structures", Holzforschung 40(1), 23.

Ralph, J., Ede, R.M., Robinson, N.P. and Main, L. 1987a. "Reactions of ß-aryl lignin model quinone methides with anthrahydroquinone and anthranol", J. Wood Chem. Tech. 7.

Ralph, J. and Ede, R.M. 1987b. "Lignin model quinone methides: ^{13}C NMR shift assignments by 2D ^{13}C-^{1}H shift correlation experiments. Submitted to Org. Mag. Res.

Remko, M. and Sekerka, I. 1983. "M.O. investigations on lignin model compounds", Z. Phys. Chem. 134, 135.

Robinson, N.P. 1985. "Synthetic studies of some 1,2-diarylpropane and phenylcoumaran lignin model compounds". MSc Thesis, University of Waikato.

Sarkanen, K.V. and Ludwig, C.H. 1971. "Lignins", Wiley, New York, 208.

Seebach, S. and Corey, E.J. 1975. "Generation and synthetic applications of 2-lithio-1,3-dithianes. J. Org. Chem 40(2), 231.

Shaka, A.J., Keeler, J. and Freeman, R. 1983. "Evaluation of a new broadband decoupling sequence WALTZ-16", J. Mag. Res. 53, 313.

Sheldrick, G.M. 1976. SHELX76 - Program for crystal structure determination", University of Cambridge, England.

Sjostrom, E. 1981. "Wood chemistry - fundamentals and applications", Academic, New York, 104.

Still, W.C., Kahn, M. and Mitra, A. 1978. "Rapid chromatographic technique for preparative separation with moderate resoltuion", J. Org. Chem., 43(14), 2923.

Storgard-Envall, C. and Dimmel, D.R. 1986. "Dissolving reactions of anthraquinone at high temperatures". J. Wood Chem. Technol. 6(3), 367.

Stork, G., Terrell, R. and Szmuszkovicz, J. 1954. "A new synthesis of 2-alkyl and 2-acyl ketones", J. Am. Chem. Soc. 76, 2029.

Taylor, W.I. and Battersby, A.R. (eds). 1967. "Oxidative coupling of phenols." Marcel Dekker, New York.

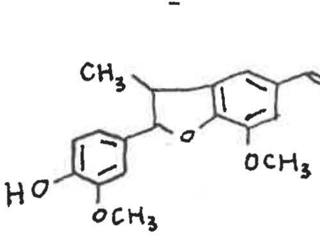
Wakselman, M. 1983. "1,4- and 1,6-Elimination reactions from hydroxy- and amino-substituted benzyl systems: chemical and biochemical applications", Nouv. J. Chim. 7(7), 439.

Zanarotti, A. 1983. "Synthesis and reactivity of lignin model quinone methides. Biomimetic synthesis of 8.0.4' neolignans", J. Chem. Res. (M) 2625.

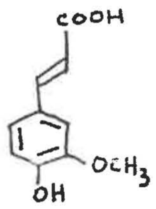
Zanarotti, A. 1985. "Synthesis and reactivity of vinyl quinone methides", J. Org. Chem. 50, 941.

Zefirov, N.S. 1977. "Stereochemical studies - XXI. General equation of relationship between products ratio and conformational equilibrium." Tetrahedron, 33, 2719.

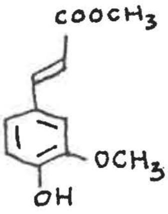
1



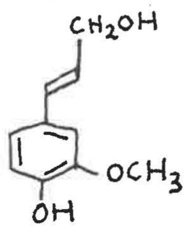
2



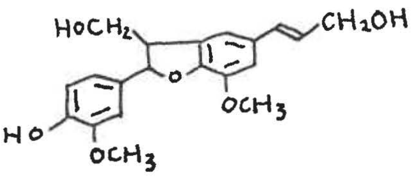
3



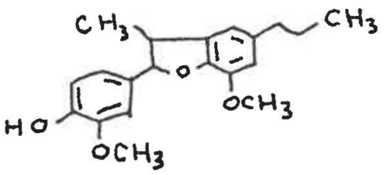
4



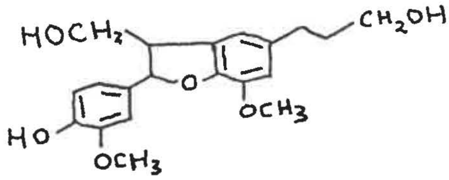
5



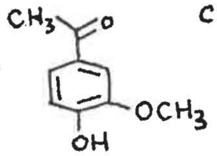
6



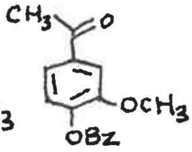
7



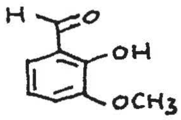
8



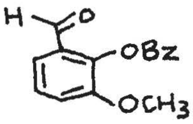
9



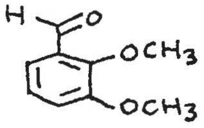
10



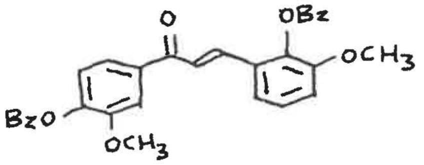
11



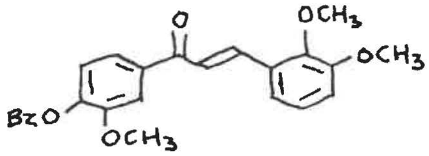
12



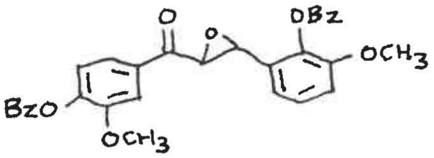
13



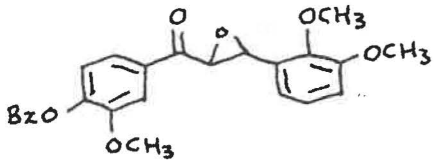
14



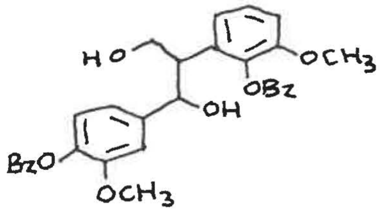
15



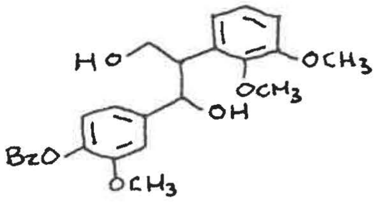
16



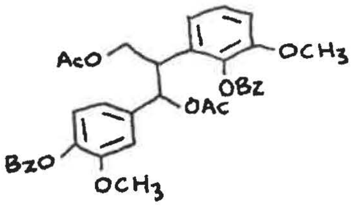
17



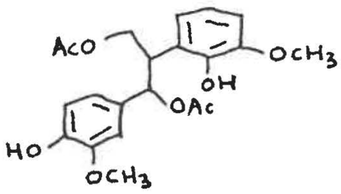
18



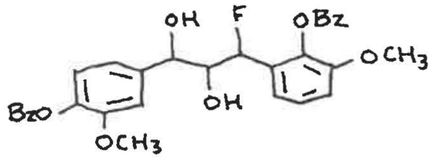
19



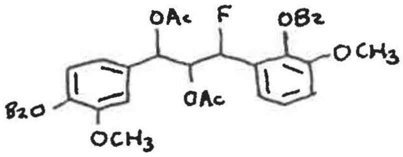
20



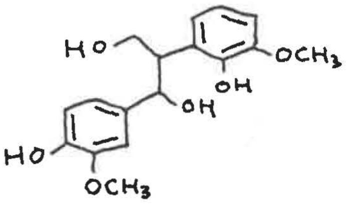
21



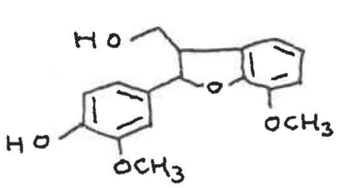
22



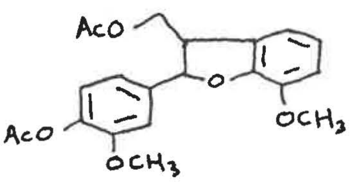
23



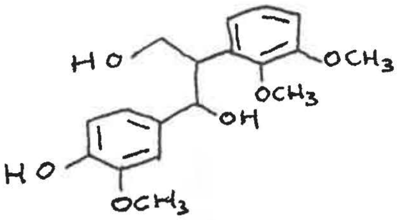
24



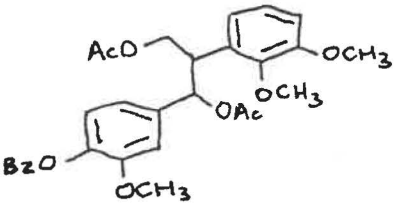
25



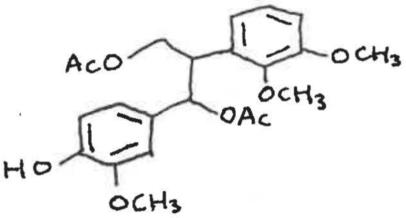
26



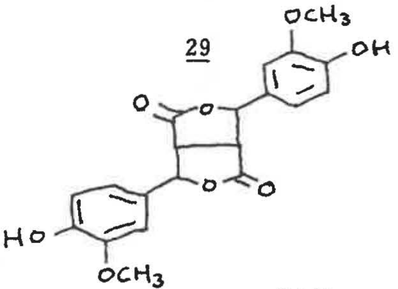
27



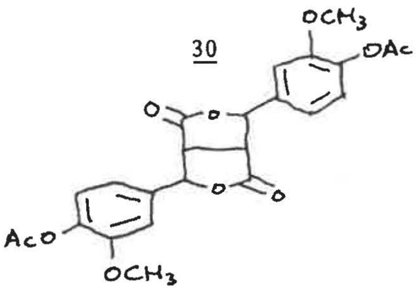
28



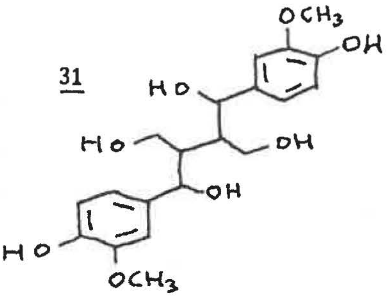
29



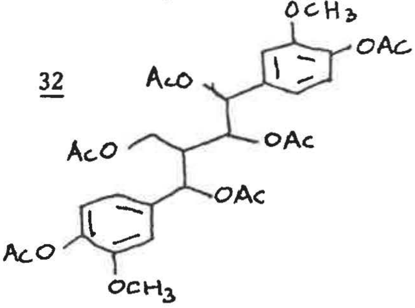
30



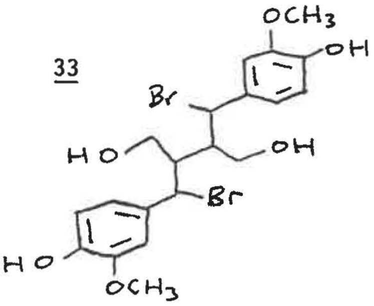
31



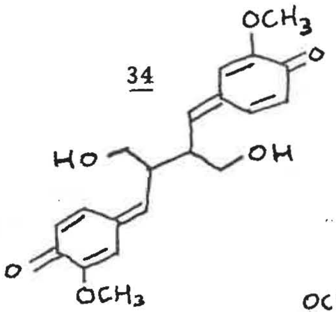
32



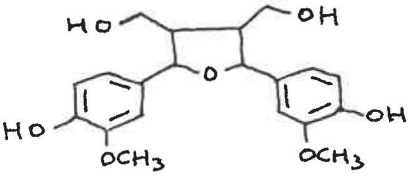
33



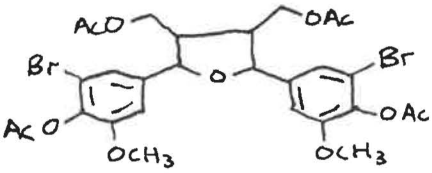
34



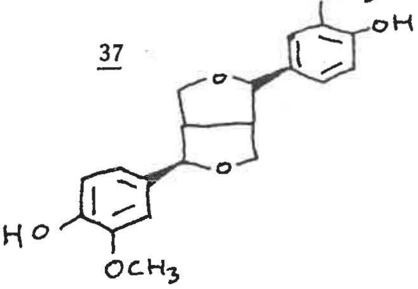
35



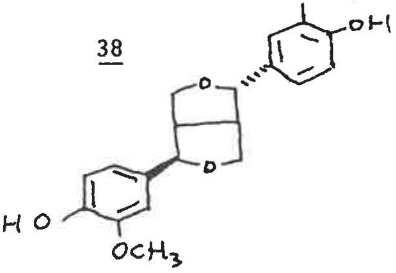
36



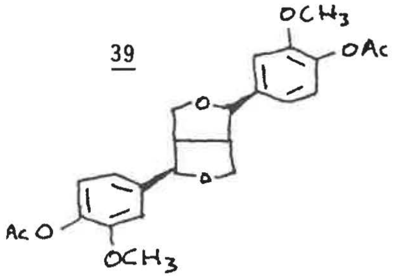
37



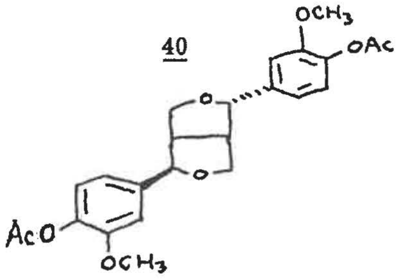
38



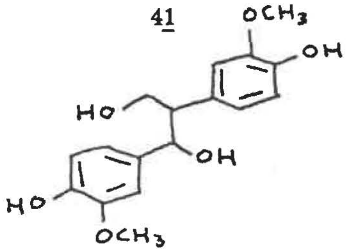
39



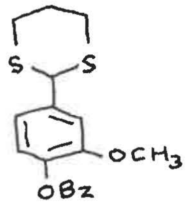
40



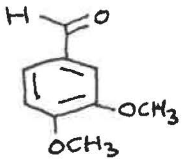
41



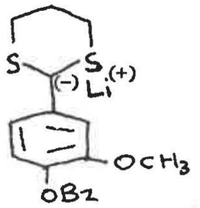
42



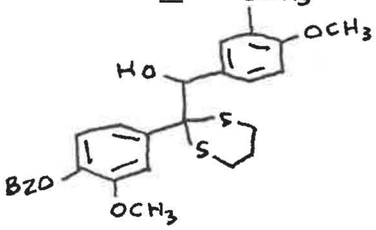
43



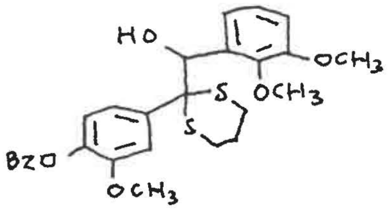
44



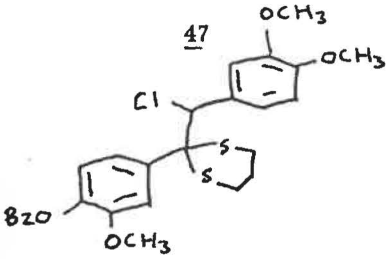
45



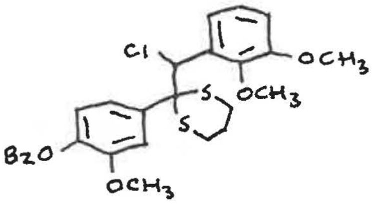
46



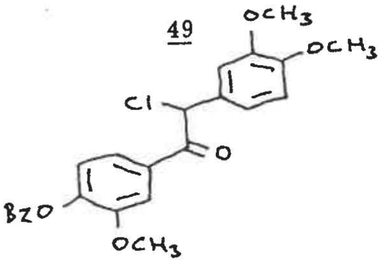
47



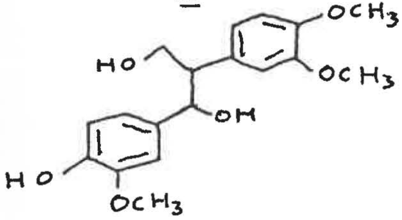
48



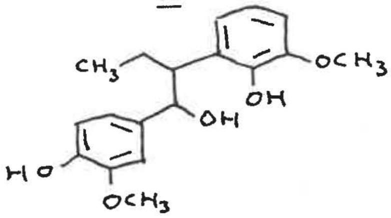
49



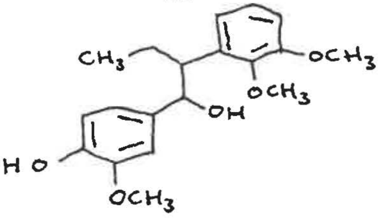
50



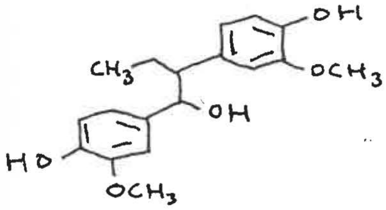
51



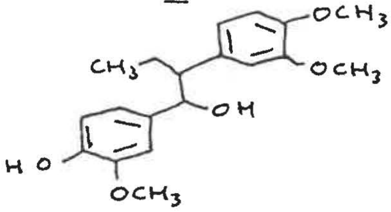
52



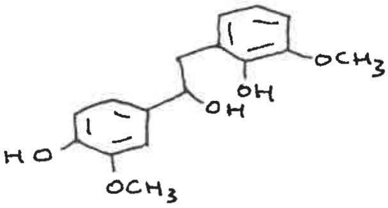
53



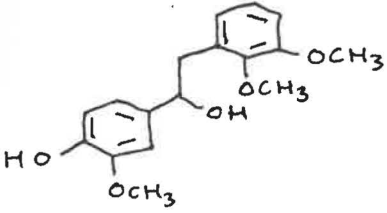
54



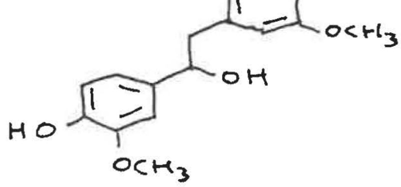
55



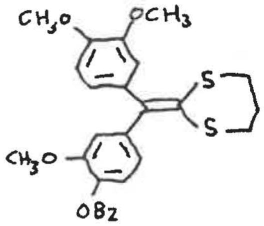
56



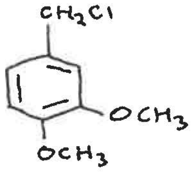
57



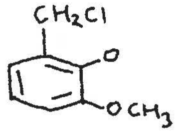
59



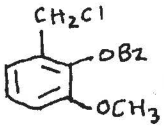
60



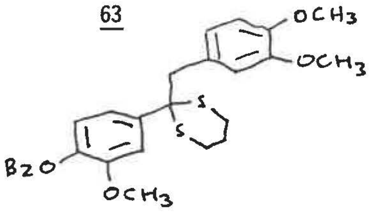
61



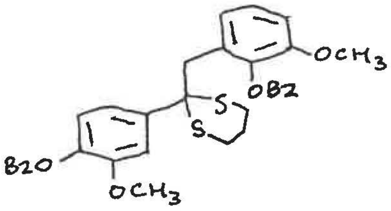
62



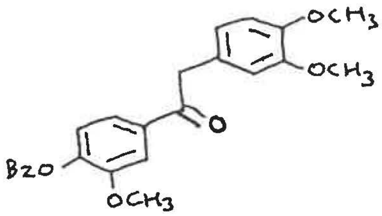
63



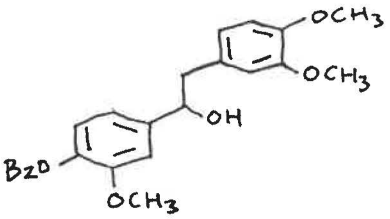
64



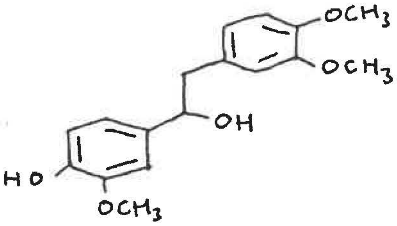
65



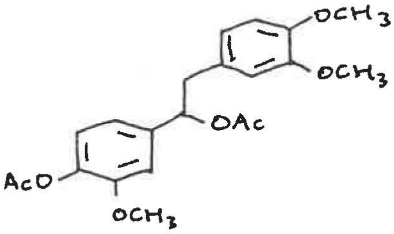
66



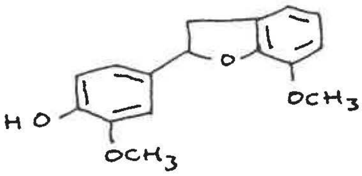
67



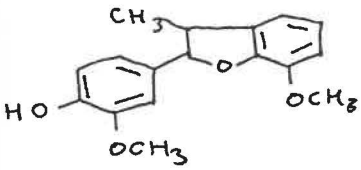
68



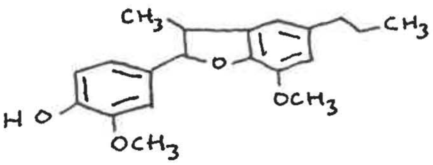
69



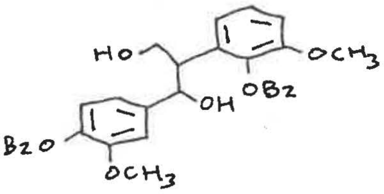
70



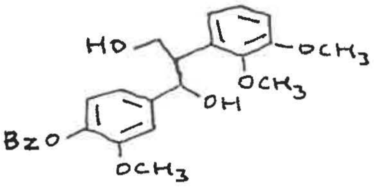
2.6



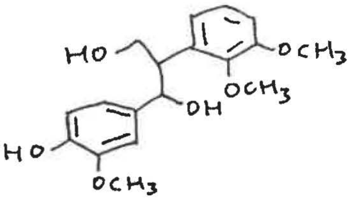
2.17



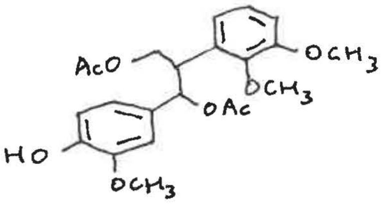
2.18



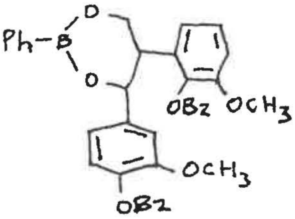
2.26



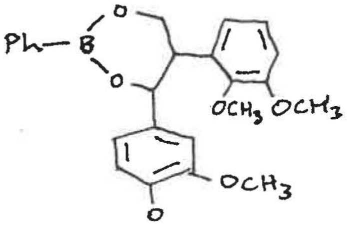
2.28



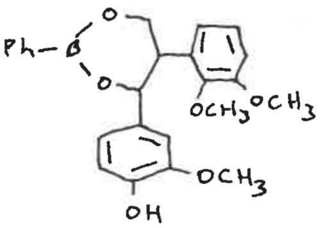
1



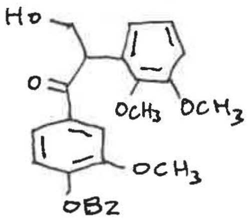
2



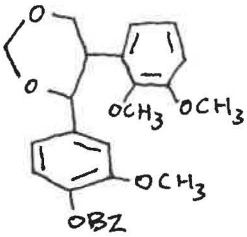
3



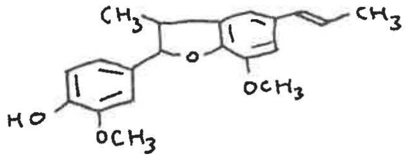
4



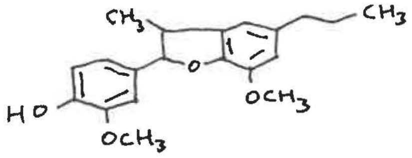
5



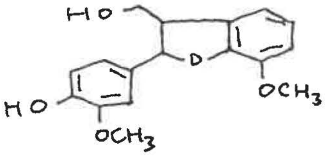
2.1



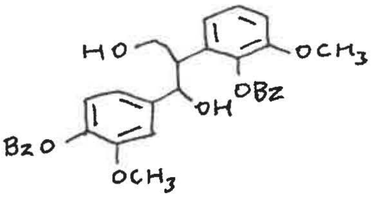
2.6



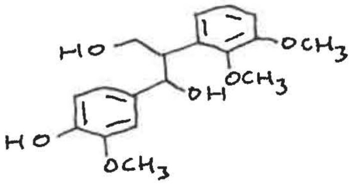
2.24



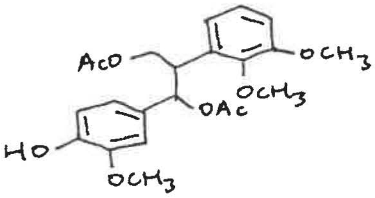
2.17



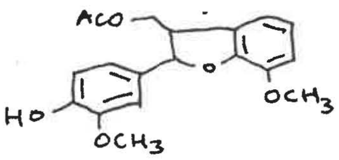
2.26



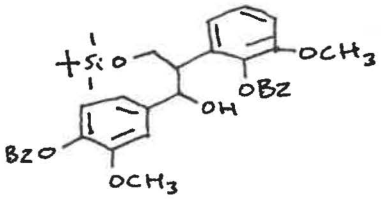
2.28



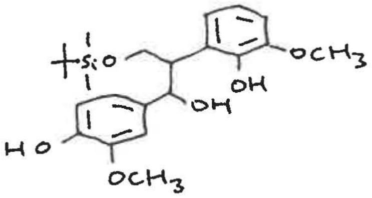
1



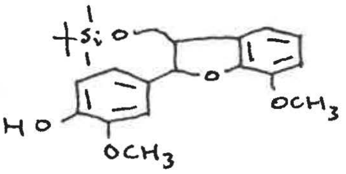
2



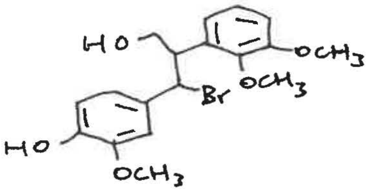
3



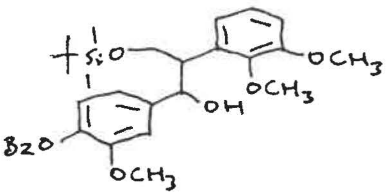
4



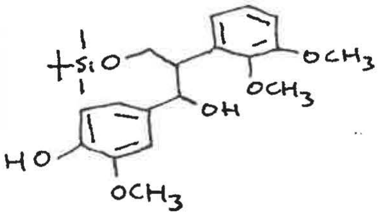
5



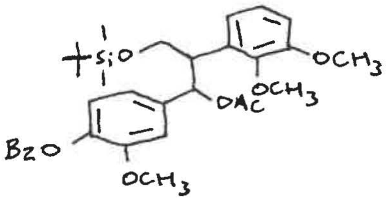
6



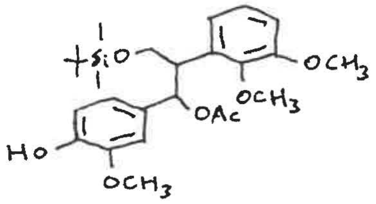
7



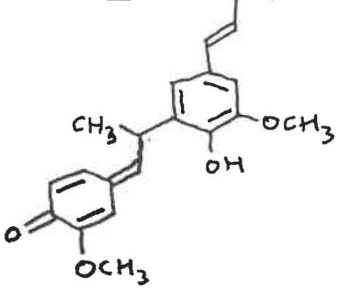
8



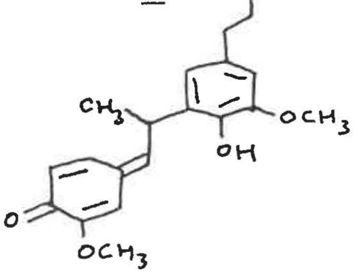
9



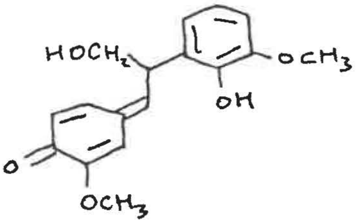
10



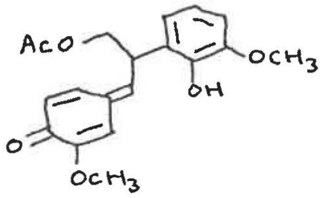
11



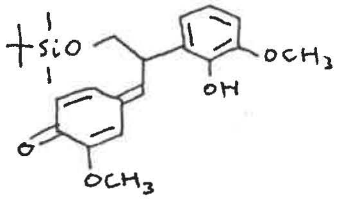
12



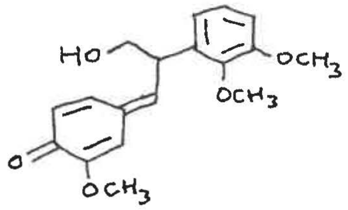
13



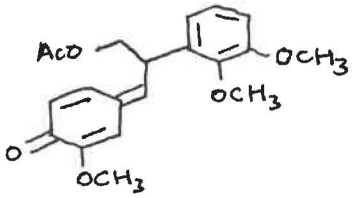
14



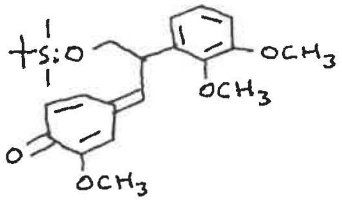
15



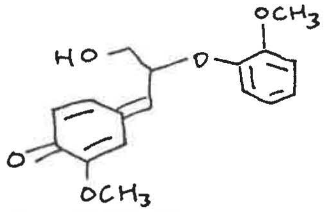
16



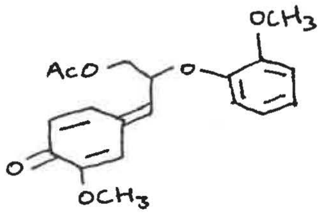
17



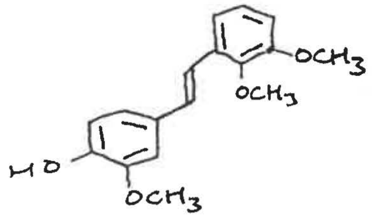
18



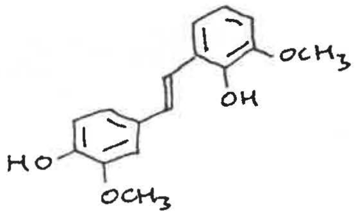
19



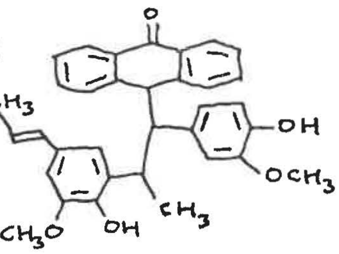
20



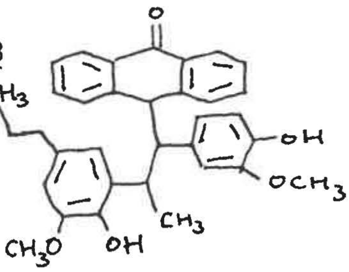
21



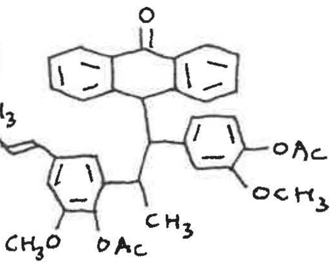
22



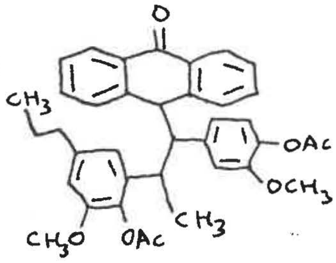
23



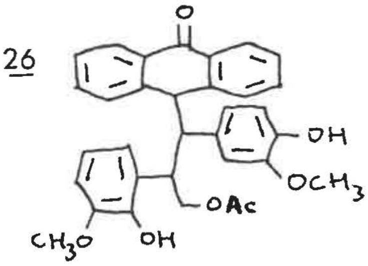
24



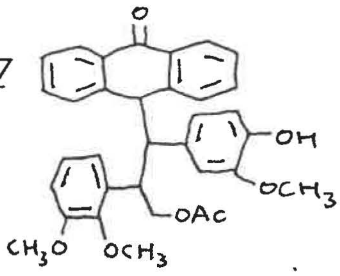
25



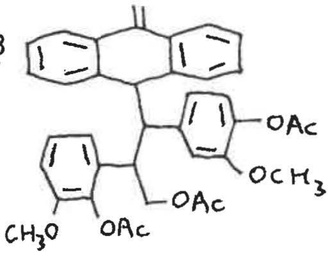
26



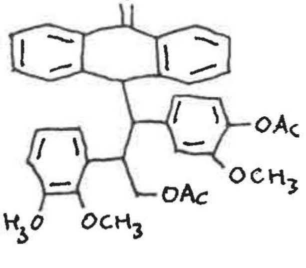
27



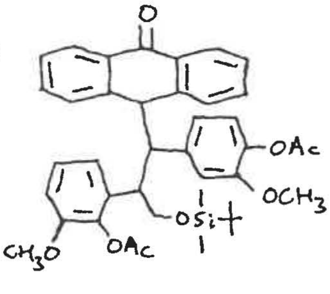
28



29

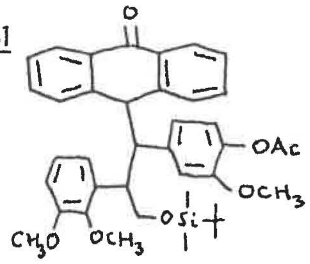


30

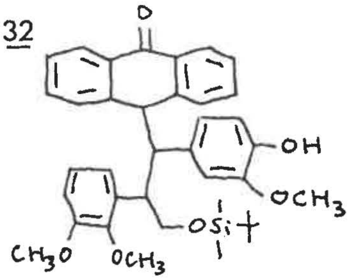


Compound Structures/Numbers - Chapter 4 (cont.)

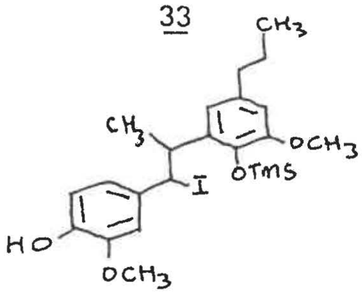
31



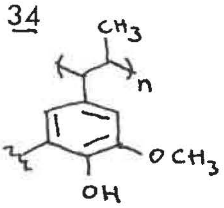
32



33

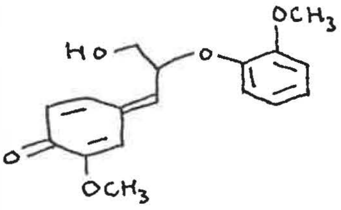


34

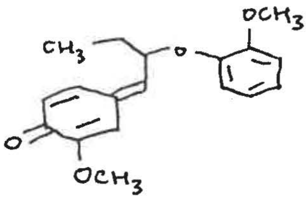


Compound Structures/Numbers - Chapter 5

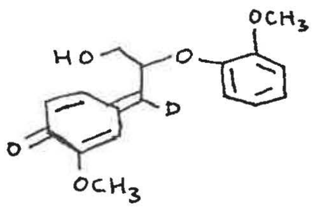
1



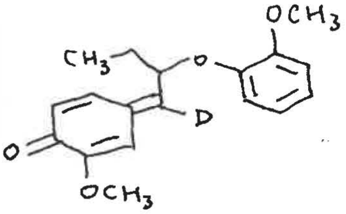
2



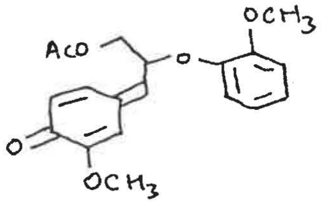
3



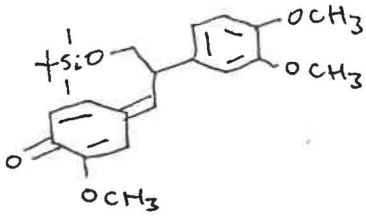
4



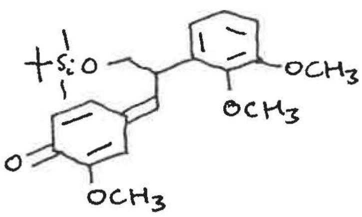
5



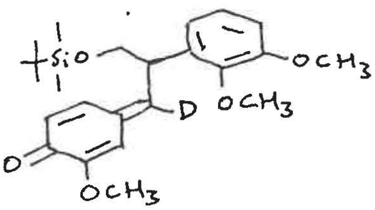
6



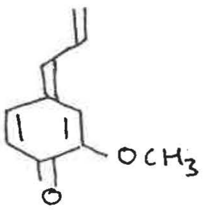
7



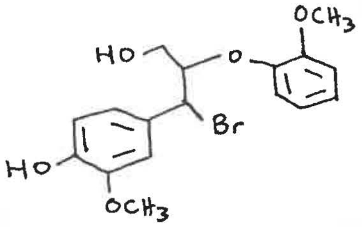
8

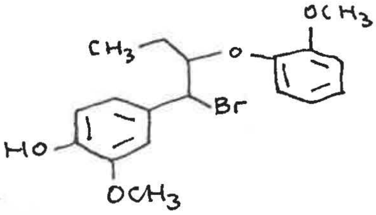


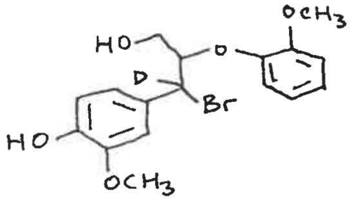
9



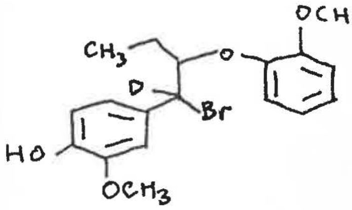
10 = threo, 11 = erythro. 12 = threo, 13 = erythro. 14 = threo, 15 = erythro



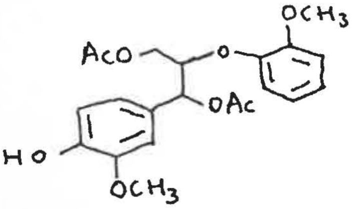




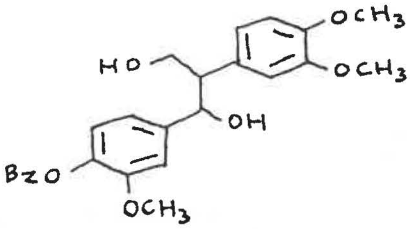
16 = threo, 17 = erythro. 18 = threo, 19 = erythro 20



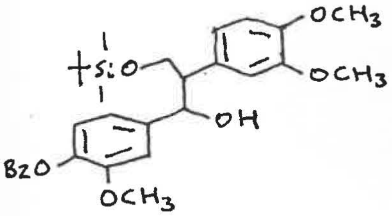
21



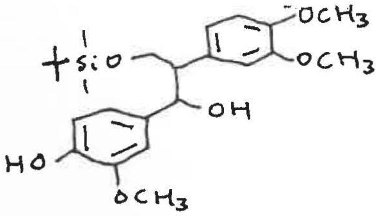
22



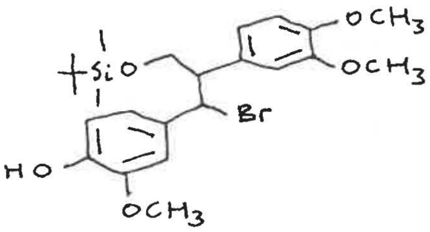
23 = threo, 24 = erythro



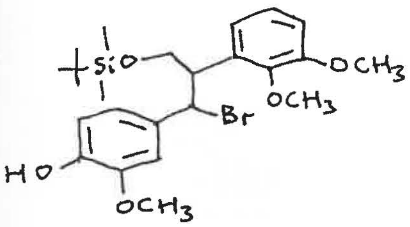
25 = threo, 26 = erythro



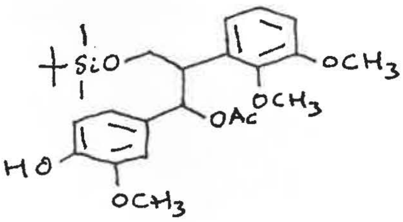
4.9



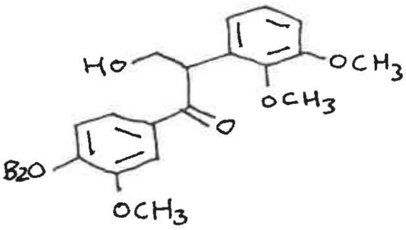
3.4



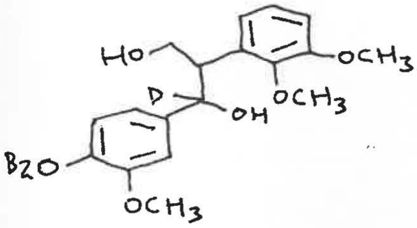
27



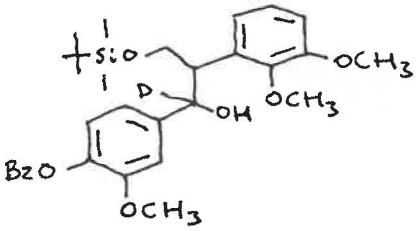
28



29



30



31