

THE SYNTHESIS OF FLOTATION  
COLLECTORS FOR CASSITERITE.

*Gregory Searle*

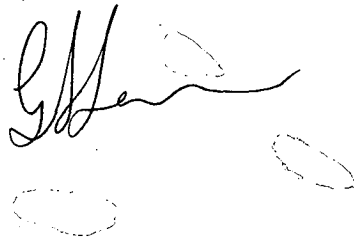
by

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Master of Science.

University of Tasmania  
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To the best of my knowledge this thesis contains no material which has been accepted for the award of any other degree or diploma in any University and contains no copy or paraphrase of material previously published or written by another person, except where due reference is made in the text.

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ABSTRACT

Aryl-substituted polycarboxylic acids and aryl-substituted phosphonocarboxylic acids (including polyphosphono / polycarboxylic acids) were synthesised using new and known techniques. These acids were prepared for evaluation as potential collectors and have been assessed by Aberfoyle Resources Pty. Ltd., for use in the flotation of cassiterite and other metal oxides. The acids represent a new structural group of collectors for use in this field. The structural chemical-physical features of the acids have been correlated with the flotation results obtained to optimise collector design.

Synthesis of the aryl-substituted polycarboxylic acids was carried out via established methodology to obtain thirty seven such acids, containing from one to four carboxylic acid functionalities per molecule. Various para-substituents were included to investigate the effect of both the hydrophilic and hydrophobic entities within the compounds on collector efficiency based on grade and net recovery of cassiterite. Some of these acids, notably some of the 2-(4-substitutedphenyl)propane-1,1,3-tricarboxylic acids, had not been reported previously in the literature.

The aryl-substituted phosphonocarboxylic acids prepared possessed similar structural characteristics to the acids above, with one or more of the carboxylic acid groups being replaced by phosphonic acid functionalities. Previously prepared acids of this class were, in general, poorly characterised prior to this work or not found in the literature. In this work particular use has been made of N.M.R. spectroscopy (<sup>31</sup>P, <sup>13</sup>C, <sup>1</sup>H) to elucidate and confirm the structure of the proposed collectors.

The flotation results for the two classes of collectors have

been compared and contrasted, and some structure-collector property relationships proposed. In general the new classes of collectors were found to be far superior to those collectors in current commercial use.



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I am especially grateful to Mr. N. Moony, late of Aberfoyle and now of Tasminex Ltd., whose insight initiated investigations into the subject of this thesis.

I wish to express my gratitude to the powers that be in the Aberfoyle hierarchy for funding my research through some difficult economic times (especially for tin).

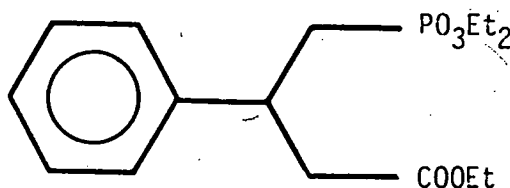
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Finally, I wish to thank Shirley, Aaron and Kiri for their support and patience during the past year or two.

AUTHOR'S NOTE.

Assessment of the collectors developed during the course of this work was carried out by Aberfoyle Services Pty. Ltd., Burnie, Tasmania, using the technique described, in general terms, in Appendix C. Unless otherwise stated the cassiterite ore used was that obtained from the Cleveland Tin Mine, Tasmania, being of the general composition stated in Appendix C. The use of the proposed collectors developed during the course of this work is subject to a Provisional Patent to Aberfoyle Ltd and the University of Tasmania (Appl. No. PH03082/85) and as such covered by the protective provisions applicable.

The organic nomenclature used within this thesis for the collectors is generally that denoted by IUPAC rules or that in common usage. Phosphonate esters, when incorporated with carboxylate esters are denoted as in the example below.



Triethyl 3-phenyl-4-phosphonobutanoate

The phosphonic / carboxylic acid analogue ~~would be named as~~ 3-phenyl-4-phosphonobutanoic acid.

To facilitate easier discussion, the collectors assessed in this study are denoted,  $\text{CrX}$ , where Cr stands for collector and X is an integer. Full correlation tables are given in Chapters 2, 3, and 5.

The terms "strong" or "powerful" collector refer to a collector that floats metal oxides at a rapid rate, usually giving a high first oxide concentrate (OC 1) recovery. A "weak" collector is one which floats metal oxide at a slower rate but is not necessarily non-selective for the metal oxide over the gangue. The "final recovery" and "final grade" refer to the cumulative recovery and grade at the end of the flotation test (OC 1 to 4).

#### SUPPLEMENTARY NOTE

Reference is made in the text, for example on pages 57 and 69, to hindered rotation or steric hindrance to rotation of functional groups causing non-equivalence of geminal protons. It should be noted that Jackman and Sternhell indicate that this is not correct. The non-equivalence is instead due to "components associated with unequal conformer population and to an irreducible component due to the low symmetry" of a  $\text{CH}_A\text{H}_B\text{U-CXYZ}$  system.

Jackman, L.M., Sternhell, S., Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry, 2nd Ed., Pergamon Press, Oxford, 1969, 373.

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" Phosphorus chemistry is the pits! "

Professor W.R. Jackson

Organic Chemistry

Monash Univeristy



## CHAPTER 1. General Introduction.

The aim of this study was to identify structural parameters that enhance collector activity in the flotation of metal oxides, particularly cassiterite. A number of reviews and texts have appeared in the literature on the chemistry of the froth flotation of cassiterite<sup>47 57 76 78</sup>. The history, and the process of flotation in general, are adequately covered in this literature.

Unlike sulfide ores, metal oxides are inherently hydrophilic and require a collector that will adsorb on the oxide surface and create the hydrophobicity required for the oxide to be collected in the froth during the froth flotation process. The mechanisms for the adsorption of collectors on metal oxides have been studied using various techniques<sup>49</sup>, most notably infrared spectroscopy. The definitive evidence for the chemical and physical adsorption of collectors on oxides came from Kuys<sup>74</sup> with his study of the adsorption of styrenephosphonic acid, and some of the collectors developed during the course of this study, on cassiterite using attenuated total reflectance and Fourier transform infrared spectroscopic techniques.

In general a collector may be any surface active agent that possesses some selectivity for the metal oxide over gangue material. Such selectivity is dependent on firstly, the composition of the hydrophilic unit (for example phosphonic acid or carboxylic acid) and secondly, the hydrophobic unit (for example an aliphatic chain or aromatic group).

A number of collectors, sometimes referred to as promoters, have been investigated over the past sixty years. These include the "sulphosuccinamates" and related compounds, alkyl- and aryl-phosphonic and arsonic acids, fatty acids and various derivatives, and other types including hydroxamic acids, sulfonates, sulfates, phosphates and cationic collectors. The

selectivity and efficiency of these collectors varies appreciably with ore type, although general trends exist that place phosphonic acids and arsonic acids as the more selective of the above collector types. Sulfosuccinamates and fatty acids (principally oleic acid), although less selective, enjoy significant cost advantages over many other collectors.

### 1.1 Fatty acids and related compounds.

Fatty acids ( $C_{7-22}$ ) first found use as collectors for haematite and magnetite<sup>47</sup>. These acids are strong collectors, showing low selectivity for metal oxides such as cassiterite but are depressed by the presence of calcium and ferric ions, and sulfides in the float. In 1967, Collins<sup>35</sup> stated that the only economically viable collectors were alkylphosphonic acids and oleic acid, although the depression by ions in solution was a limiting factor in the use of the latter. Fatty acids still play an important role in flotation in the U.S.S.R. where the ores are of simple composition, containing largely quartz as gangue<sup>104</sup>. The low cost and availability of these reagents has also prompted the use of these compounds in association with other collectors to reduce overall costs.

(Z)

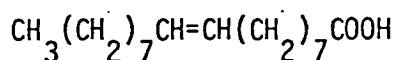


Figure 1.1 Oleic acid

Various derivatives of long chain carboxylic acids, including polycarboxylic acids, have been assessed as collectors with the results obtained showing increased selectivity and recovery<sup>23</sup>. Cyanamid (Aust.) Ltd. have marketed a polycarboxylic acid collector "S-3903", believed to be trisodium

N-(3-carboxyacryloyl)-<sup>55</sup>N-octadecylaspartate, that has found limited commercial use .

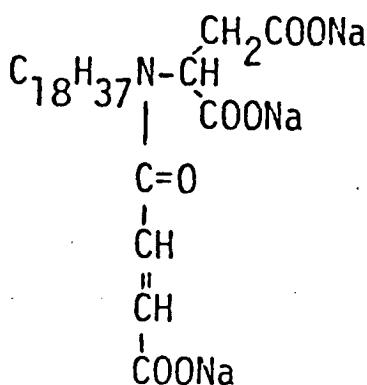


Figure 1.2 Trisodium N-(3-carboxyacryloyl)-N-octadecylaspartate

### 1.2 Sulfonates.

Alkyl- and alkylarylsulfonates have generally been found to be too surface active ( as evidenced by their high consumption by hydrophobic surfaces) to show any great selectivity for cassiterite or related oxides. Their activity is also greatly depressed by calcium and other ions in solution<sup>35</sup> .

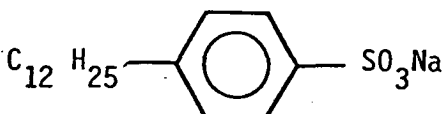


Figure 1.3 An alkylarylsulfonate

### 1.3 Sulfosuccinamates.

"Sulfosuccinamates" are inexpensive, exhibiting the characteristics of polycarboxylic acids and sulfonic acids and as such are moderately selective in the right conditions and very strong collectors. The predominately used collector of this type is tetrasodium N-(1,2-dicarboxyethyl)-N-octadecylsulfosuccinamate, which is marketed under a number of trade names, usually as an admixture with other components such as frothers. These trade names include Aeropromoter-845 and 860 (Cyanamid Australia Pty. Ltd.), Procol CA-540 (Allied Colloids), and Asparal F (Russian origin). This type of collector was first patented by Arbiter and Hin (Brit. Pat. 1,110,643) in 1967. It should be noted that the only apparent difference between these collectors and the former "Cyanamid S-3903" is sulfonation of the succinamate portion of the molecule. There are marked differences in the performance of these collectors where sulfonation provides increased collecting power and recovery.

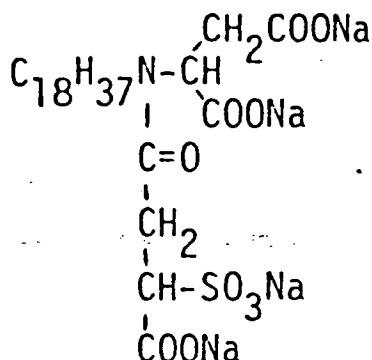


Figure 1.4

Tetrasodium N-(1,2-dicarboxyethyl)-N-octadecylsulfosuccinamate

The sulfosuccinamates have found widespread commercial use due to their low cost, low toxicity and biodegradability. Various tin mining operations such as Wheel Jane (England), Bolivian plants<sup>9</sup> and Cleveland Tin (Tasmania) have successfully utilized this type of collector for cassiterite flotation. Other plants at Rooiberg (S. Africa)<sup>26</sup> and Ardlethan (N.S.W.) have found this type of reagent unsatisfactory, in the latter case due to the high percentage of siliceous material in the ore<sup>32</sup>. Burt and coworkers<sup>27</sup> reported that "Procol CA-540" gave equivalent recovery and greater enrichment ratios than phosphonic acids (type unspecified), oleic acid and hydroxamic acids for tantalum oxides.

#### 1.4 Phosphates.

Alkyl and dialkyl phosphates have been found to be reasonably selective, although generally less so than alkylphosphonates.<sup>77 153</sup> As such their use has been limited.

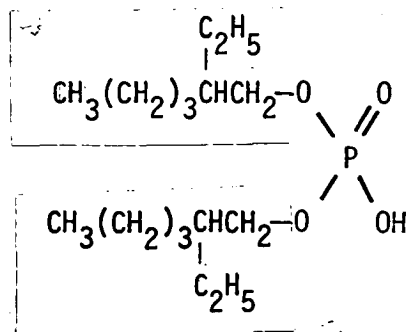


Figure 1.5 Di-(2-ethylhexyl)phosphate

#### 1.5 Arsonic acids.

Arsonic acids, principally p-tolylarsonic acid and benzylarsonic acid, are highly selective when compared with the previously mentioned collector types. Originally, the use of these compounds as collectors is thought to have been derived from the use of arylarsonic acids (for example 3-hydroxy-5-nitrophenylarsonic acid) as chelating agents for tin. The first use of p-toluenearsonic acid was recorded at Altenberg (D.D.R.) in the early 1960's where no apparent difference in the flotation efficiency of arylarsonic acids and arylphosphonic acids was found<sup>61</sup>. Wottgen and Rosenbaum<sup>152</sup> evaluated the use of alkylarsonic acids but found them to be less selective than their aryl counterparts.

Environmental considerations and high costs caused some users, and producers, to prefer other collectors<sup>139</sup>. Used at various times in a number of commercial applications, most notably Rooiberg (S. Africa)<sup>86</sup>, Renison and Cleveland (Tasmania), lack of supply and tailings disposal problems contributed to the demise of this collector type. Recently its use has been revived for cassiterite and wolframite in China<sup>30 154 157-161</sup>. Reassessment of this collector has also taken place in Australia by the Renison Tin Mine and Aberfoyle Ltd.

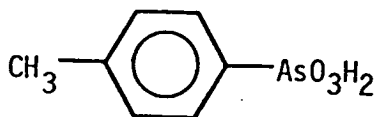


Figure 1.6 para-Toluenearsonic acid

#### 1.6 Phosphonic acids.

The use of phosphonic acids followed on from arsonic acids due to their chemical similarities. The phosphonic acids are less expensive and considerably less toxic than the arsonic acids<sup>35</sup>. In 1963, Kirchberg and Wottgen<sup>61</sup> evaluated a number of arsonic, phosphonic and antimononic acids (the latter showing little collecting ability) for the flotation of cassiterite. Their results showed alkylphosphonic acids to be less selective than their aryl counterparts, although Collins<sup>35</sup>, in an extensive review of flotation practice, preferred the alkylphosphonic acids for economic reasons. Styrenephosphonic acid (SPA) has become the most popularly used collector of this class due to the lower production costs compared with other arylphosphonic acids, styrene being a relatively cheap industrial product. This collector has found commercial application at Altenberg<sup>90</sup>, Renison, Cleveland, Ardlethan and in South Africa<sup>26 87</sup>.

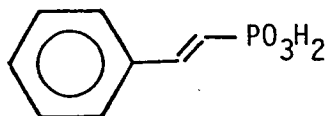


Figure 1.7 Styrenephosphonic acid (SPA).

Recently a number of "aminophosphonic acids" and "hydroxydiphosphonic acids" have appeared in the literature. Collins, in his patent<sup>36</sup>, showed that alkyl-substituted ( $C_7-C_9$ ) aminodi(methylenephosphonic acids) had approximately comparable selectivity and recovery to styrenephosphonic acid. The collector in Figure 1.8 has found commercial application at the Cornish Tin Mine (England), principally due to lower costs<sup>34</sup>.

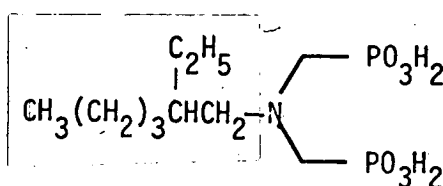


Figure 1.8 N-(2-ethylhexyl)iminodi(methylphosphonic acid)

The "hydroxydiphosphonic acids", in particular 1-hydroxyalkylidene-1,1-diphosphonic acids ( $C_7-C_9$ ) developed by Russian workers<sup>4 68 69 70 71</sup> are marketed under the trade name "Flotol-7,9". These collectors, according to Kotlyarevsky<sup>68</sup>, show considerably better selectivity than styrenephosphonic acid. Kotlyarevsky states that depression by calcium and other



ions is evident when these collectors are used, but as with most collectors, the addition of fluoride or fluorosilicate compensates for any suppression. However a recent report by Mosch and Becker<sup>90</sup> states that the performance characteristics of SPA could not be achieved with Flotol 7,9 or with several succinamate type collectors, for example, Aero promoter 845 (Cyanamid).

Kotlyarevsky and coworkers also proposed a novel approach for the flotation of cassiterite slimes (<0.01mm) with the use of donor-acceptor pi complexes as shown in Figure 1.9.

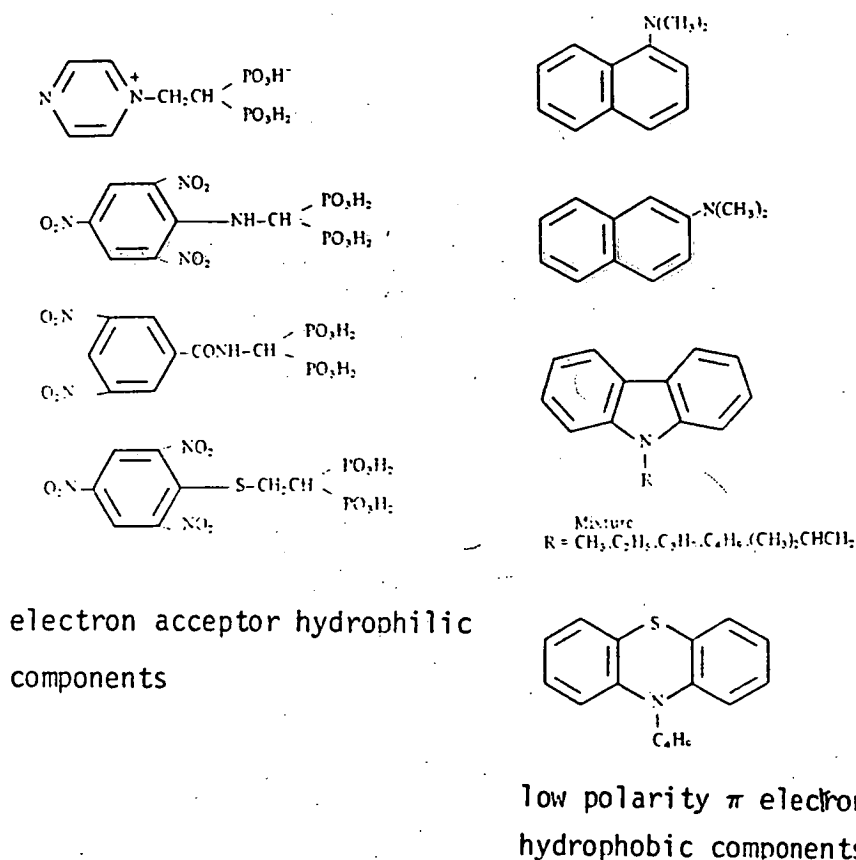


Figure 1.9 The use of donor-acceptor pi complexes as flotation collectors (from Kotlyarevsky<sup>68</sup>).

Although specific results are not given, Kotlyarevsky and coworkers state that the flotation results for the above are

comparable with those of the aforementioned hydroxydiphosphonic acids.

### 1.7 Cationic collectors.

Few reports of the use of cationic collectors in oxide flotation have been recorded<sup>76</sup>. This is due to the fact that the flotation of metal oxides generally takes place under acidic conditions. The pH of the float is usually close to the point of zero charge (referred to as P.Z.C.) of the metal oxide surface, when chemisorption is the major contributing factor in the flotation of the oxide<sup>76</sup>. Thus the use of cationic hydrophilic groups was not considered in this study.

A number of other collector types, including sulfates, phosphates, and amphoteric and cationic surfactants, have been investigated and a general overview of their chemistry and use, together with synthetic methods for their preparation, are presented in an earlier study by this author<sup>76</sup>.

### 1.8 Discussion.

To date phosphonic and arsonic acids have shown the most selectivity, their aryl derivatives being considerably more selective than the alkyl ( $C_7-C_9$ ) counterparts. Alkyldiphosphonic acids are also selective, possibly more so than the former collectors<sup>68</sup>. A study by Bochnia and Serrano<sup>23</sup> found that alkylpolycarboxylic acids were more efficient collectors than fatty acids. Other workers<sup>16 17 123 127 156</sup> have also evaluated polycarboxylic acids with similar findings. Bochnia and Serrano proposed that the greater activity of the alkylpolycarboxylic acids was due to the higher acidities of the carboxylic acid groups and the lower ability of association between collector molecules when the alkylcarboxylic acids were further substituted.

The effect of the aromatic ring with respect to flotation has not been satisfactorily explained. According to Osipow<sup>94</sup> the

aromatic ring has the same effect as three to four methylene carbons on physical factors such as critical micelle concentration. Thus styrenephosphonic acid can be equated with hexanephosphonic acid by these means. This correlates quite closely with the peak flotation activity of alkylphosphonic acids ( $C_6-C_9$ ). However the increased selectivity of arylphosphonic acids over alkylphosphonic acids is not explained by such a comparison.

Reagents containing aromatic rings, such as salicylic and gallic acids, arylsulfonates, partial esters of polycarboxylic acids with benzene rings incorporated in long aliphatic chains<sup>112</sup>, aryl-substituted long-chain carboxylic acids<sup>3</sup>, and some cationic collectors such as alkylpyridinium chloride have been examined as collectors. None of these reagents show notable selectivity for metal oxides in general.

The inclusion of the aromatic functionality confers some potential synthetic advantages due to the range of substituents and synthetic pathways that could be utilized to synthesise polyfunctional collectors. It was felt that further improvements to the selectivity of oxide collectors could be made by combining the aryl ring with polyacid functionalities.

The potential collectors examined during the course of this study consisted of aryl-substituted phosphonocarboxylic acids (Chapter 3) and aryl-substituted polycarboxylic acids (Chapter 2). They have been assessed with the aim of identifying structural features that improve collector selectivity for metal oxides, and in particular cassiterite.

Polycarboxylic acid functionalities had been shown to give increased activity over collectors such as oleic acid, and thus, were thought to be worthy of further investigation. Phosphonic acid functionalities were combined with carboxylic acids due to the former's current superiority over other acid functionalities, with the exception of arsonic acids, and their lower toxicity when compared to the arsonic acids. Preliminary

synthetic work by Barlow<sup>19</sup> on the aryldiarsonic acids indicated that these compounds were difficult to synthesise.

In the early stages of this study economic factors, such as cost of reagents and industrial application of synthetic methods, were not considered. The main aims of the investigation were to generate a new structural range of collectors in order to gain a better understanding of structure/flotation activity relationships for cassiterite.

To ascertain the effects of different substitution patterns on the physical properties of the collectors, the dissociation constants of a range of acids were determined and relationships between flotation activity and pKa were considered (see Chapter 4). Some mechanisms by which collectors adsorb are discussed with reference to mechanisms proposed by past workers in this field. Chapter 5 outlines the activity of each collector and discusses the general correlation of flotation activity with collector structural features.

## CHAPTER 2. Synthesis of Aryl-substituted Polycarboxylic Acids.

### 2.1 Introduction.

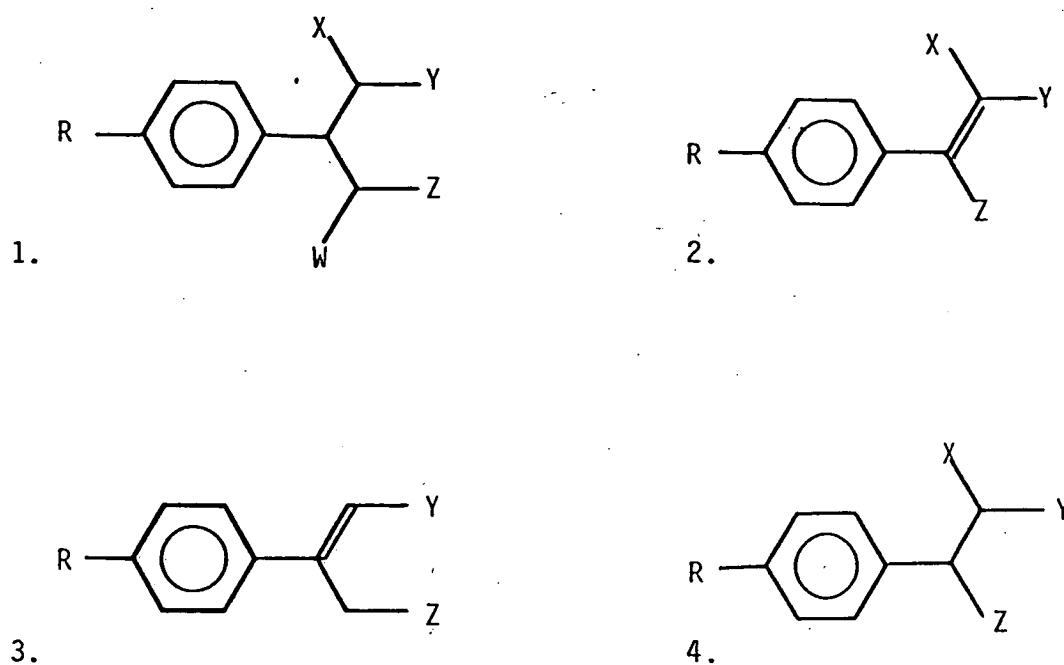
A number of aryl-substituted polycarboxylic acids have been investigated during the course of this study. Each of the acid types <sup>is</sup> based on known organic compounds although some of their derivatives are not reported in the literature. A total of thirty seven aryl-substituted polycarboxylic acids were synthesised or obtained commercially (see Table 2.1). Their activity as flotation collectors was assessed (see Chapter 5) with particular attention being paid to any trends apparent in this activity that could be correlated against structural features.

As there were innumerable structures incorporating a great many substitution patterns, only substitution in the 4-position of the aromatic ring was investigated, with the exception of 2-(3,4-dimethoxyphenyl)ethene-1,1-dicarboxylic acid (Cr9).

Substitution in the 4-position was thought to be advantageous from the point of view of increasing the hydrophobicity without hindering interaction of the acidic groups with the oxide surface. This type of substitution may not be essential, and 3- or 5- substitution or 3,5-disubstitution may provide results comparable to those obtained in this work.

The non-nitrogen containing polycarboxylic acids synthesised in this work are depicted in Figure 2.1 and Table 2.1. Nitrogen containing polycarboxylic acids are discussed in Chapter 2.4

With the exception of those polycarboxylic acids containing nitrogen, the compounds in this chapter are derived from 4-substituted benzaldehydes. Of these, the 4-alkylbenzaldehydes, and 4-methoxybenzaldehyde were obtained commercially (see Chapter 7). The method of Kostanecki and Scheider<sup>67</sup>, for the preparation of 4-ethoxybenzaldehyde, was used in the preparation



where R is alkoxy  $C_1$  to  $C_4$ , primary or secondary,  
or alkyl  $C_1$  to  $C_3$ , primary or secondary.

W, X, Y, Z are carboxylic acid groups ( $-COOH$ ) or H

Figure 2.1 General structures for the aryl-substituted polycarboxylic acids.

of 4-butoxy-, 4-propoxy- and 4-ethoxybenzaldehyde. This method was not suitable for the preparation of 4-(1-methylethoxy)benzaldehyde due to the competitive elimination of hydrogen bromide during the reaction. The method of Weygand and Gabler<sup>148</sup> was inappropriate due to the requirement of cyclohexanol as solvent. The method of Baddir<sup>15</sup> for the preparation of 3-(1-methylethoxy)benzaldehyde was found to be suitable for the 4-substituted derivative.

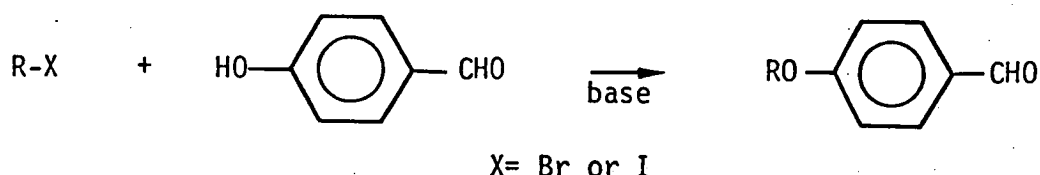


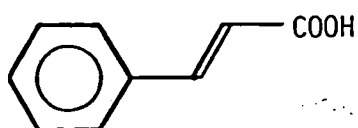
Figure 2.2 Synthesis of 4-substituted benzaldehydes.

In general the aryl-substituted polycarboxylic acids were ultimately obtained from their respective ethyl esters by hydrolysis. Both acidic and alkaline conditions were used. Alkaline hydrolysis (usually with 10% sodium hydroxide) was found to be advantageous when the 1,1-dicarboxylic acid structure was to be preserved. Acid hydrolysis, in particular the use of hydrobromic acid, was found to quantitatively decarboxylate the 1,1-dicarboxylate functionality to give the monocarboxylic acid.

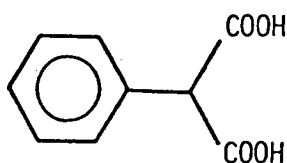




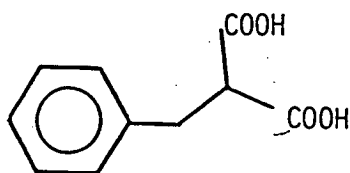
Listed below are a number of the aryl-substituted polycarboxylic acids obtained from commercial sources (see Chapter 7).



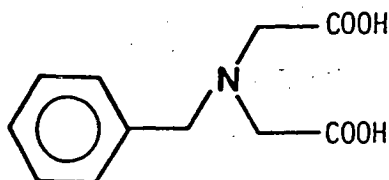
3-phenylpropenoic acid (cinnamic acid) (Cr1).



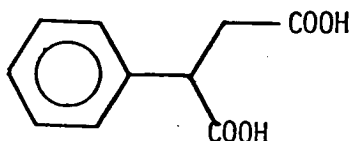
2-phenylpropanedioic acid (phenylmalonic acid) (Cr2).



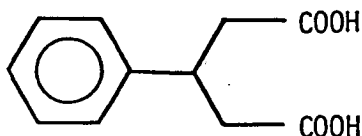
2-phenylethane-1,1-dicarboxylic acid (benzylmalonic acid) (Cr3).



N-phenylmethylinodiacetic acid (benzyliminodiacetic acid) (Cr33).



2-phenylbutanedioic acid (phenylsuccinic acid) (Cr19).



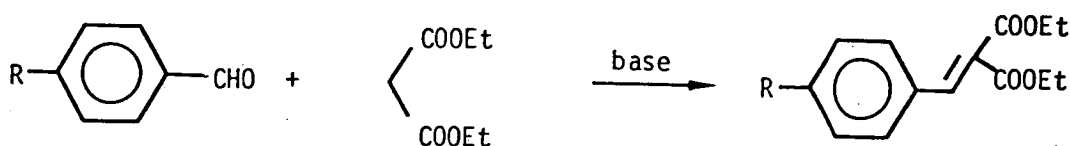
3-phenylpentanedioic acid (phenylglutaric acid) (Cr11).

The aryl-substituted polycarboxylic acids have been classified, for the purpose of discussion in this chapter, by their methods of synthesis. Chapter 2.2 contains compounds synthesised from a diethyl 2-(4-substitutedphenyl)ethene-1,1-dicarboxylate precursor. Chapter 2.3 deals with the Michael adducts from ethyl cinnamate and ethyl phenylpropiolate, while Chapter 2.4 discusses the syntheses of nitrogen containing acids based on iminodiacetic acid.

Where N.M.R. spectroscopy has been used to confirm structural assignments throughout Chapters 2 and 3, reference has been made to the work of Pretsch and coworkers<sup>165</sup> for the calculation of expected chemical shifts.

2.2      Synthesis      of      Derivatives      of      Diethyl  
2-(4-Substitutedphenyl)ethene-1,1-dicarboxylate      and      Related  
Compounds.

Diethyl 2-(4-substitutedphenyl)ethene-1,1-dicarboxylates were found to be a useful starting point for the synthesis of a number of polycarboxylic acids (see Figure 2.4). Synthesis of the esters was by Knoevenagel type condensation<sup>62</sup> of diethyl malonate and 4-substituted benzaldehyde similar to the method of Allen and Spangler<sup>6</sup> for the unsubstituted ester (Figure 2.3).



R	Yield
H	77%
Me	84%
Et	80%
MeO	78%
EtO	81%
di MeO #	54%

# MeO in 3 and 4 positions.

Figure 2.3 Diethyl 2-(4-substitutedphenyl)-ethene-1,1-dicarboxylates.

This procedure provided the required esters in moderately good yields, utilizing readily obtainable starting materials.

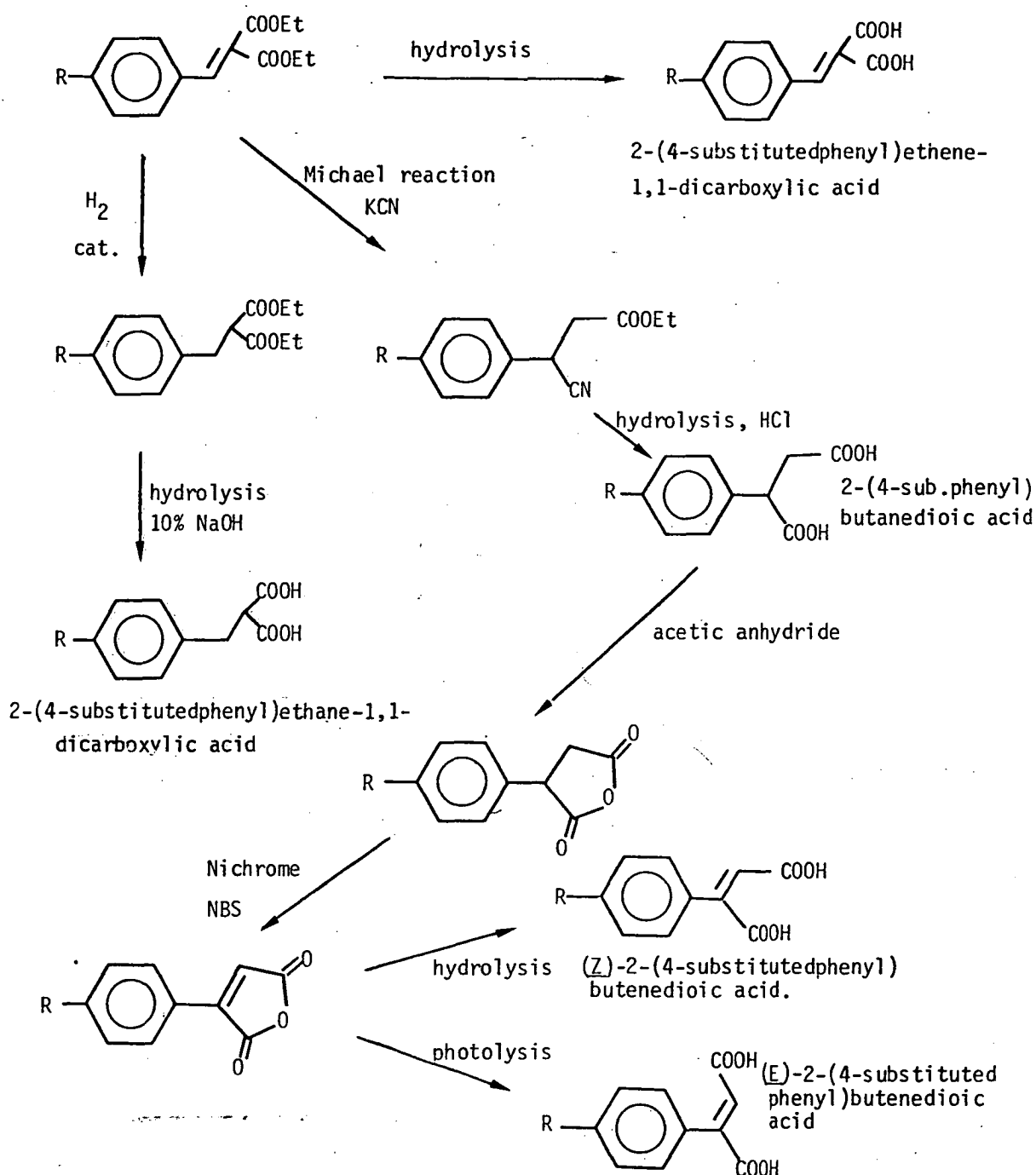


Figure 2.4 Synthesis of acids derived from diethyl 2-(4-substitutedphenyl)ethene-1,1-dicarboxylic acid.

Hydrolysis of these esters with ethanolic potassium hydroxide gave the corresponding dicarboxylic acids (Table 2.2) which were characterised by P.M.R. spectra and their melting points (see Chapter 7).

Table 2.2 Yields for the 2-(4-substitutedphenyl)ethene-1,1-dicarboxylic acids.

R	Yield	
H	92%	(Cr5)
Me	59%	(Cr6)
Et	78%	(Cr7)
MeO	66%	(Cr8)
* EtO	76%	(Cr10)
di MeO	45%	(Cr9)

\* not found in the literature

The above hydrolyses were not optimized. The low yields obtained, especially for Cr6 and Cr8 are apparently due to incomplete hydrolysis. In latter work it was found that better yields were obtained using 10% aqueous sodium hydroxide for the hydrolysis of the carboxylate esters.

Agarwal<sup>2</sup> reports a similar method utilizing malonic acid in the condensation with aromatic aldehydes to give the acid Cr7 in 75% yield. This provides a useful one step synthesis of these acids. For the purposes of this study the procedure in Figure 2.4 was utilized as the esters were needed for the syntheses outlined elsewhere in this chapter. Other suitable synthetic methods include that of Wallingford and coworkers<sup>144</sup>, utilizing alkylcarbonate and cinnamate esters, but this particular method was not investigated in this study.

2-(3,4-Dimethoxyphenyl)ethene-1,1-dicarboxylic acid (Cr9) was

the only disubstituted collector investigated during the course of this study. The acid had been reported previously by Jackson and Kenner<sup>58</sup> who obtained it by a method similar to that of Agarwal in 18% yield.

The unsaturated functionality within the esters in Figure 2.3 provided pathways to a number of aryl-substituted polycarboxylic acids. Hydrogenation of the ester by the method of Wojcik and Adkins<sup>149</sup> afforded the saturated ester, which on hydrolysis gave 2-(4-methylphenyl)ethane-1,1-dicarboxylic acid (Cr4) in 76% yield (see Figure 2.4). An alternative method for the synthesis of the above saturated ester is that of Fraisse-Jullien and Frejaville<sup>45</sup> using 4-methylbenzyl chloride, sodium ethoxide and diethyl malonate. For the non-substituted ester (R=H) they reported a yield of 68%.

The  $\alpha,\beta$ -unsaturated carbonyl structure of the esters in Figure 2.3 provides an ideal site for Michael addition<sup>81 82</sup>. The use of potassium cyanide as a donor by the method of Allen and Johnson<sup>5</sup> affords, on hydrolysis, the 2-(4-substituted phenyl)butanedioic acids (Cr19, Cr20). This reaction was utilized for the synthesis of 2-(4-methylphenyl)butanedioic acid (Cr20) in 74% yield from 2-(4-methylphenyl)ethene-1,1-dicarboxylate (see Figure 2.4). Although not examined in this work, other methods for the preparation of 2-(4-alkoxyphenyl)butanedioic acids have been reported by Avetisyan and Mndzhoyan<sup>14</sup>.

The synthesis of 2-phenylbutenedioic anhydride from 2-phenylbutanedioic acid (Cr19) was accomplished by the method of Miller<sup>84</sup> in 59% yield. The yields of (Z)-2-phenylbutenedioic acid (Cr22) and (E)-2-phenylbutenedioic acid (Cr21) were 90% and 76% respectively. They were obtained from the unsaturated anhydride, the latter by hydrolysis and photolysis by the method of Taylor and Strojny<sup>136</sup> (see Figure 2.4). The two geometrical isomers may be differentiated by their melting point and P.M.R. spectra. The methine proton resonance of the Z-form is found at  $\delta$  6.25 whilst for the E-form it is at  $\delta$  7.02.

Alternative methods for the synthesis of 2-(4-substitutedphenyl)butenedioic acids include the method of Rondestvedt and Filbey<sup>118</sup>, from the ethyl 4-substitutedphenylglyoxylate and condensation with ethyl cyanoacetate (Figure 2.5), or Reformatsky reaction with ethyl bromoacetate. The above workers state that their method and the method of Miller<sup>84</sup> is not suitable for the synthesis of 2-(4-methoxyphenyl)butenedioic acid. Ring bromination using Miller's method, and retrograde aldol degradation in Rondestvedt's method, are the limiting factors.

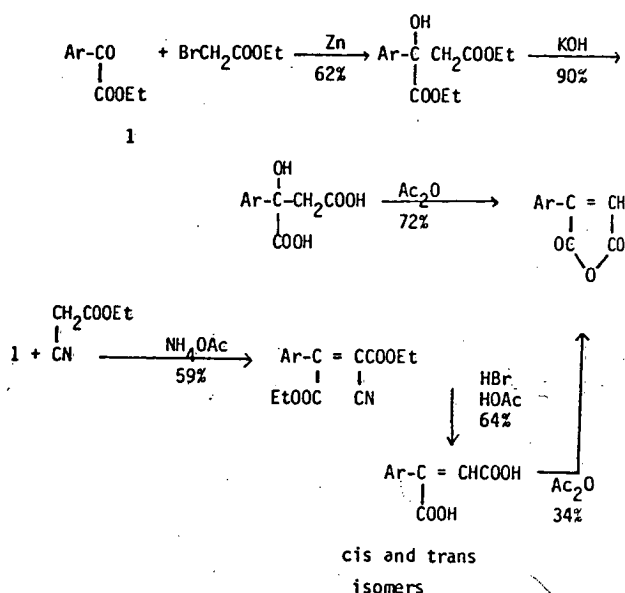


Figure 2.5 Alternative methods for the synthesis of 2-(4-alkylphenyl)butenedioic acids (Cr21, Cr22).

The methods suggested in Figure 2.5 may be useful in preparing 4-alkyl derivatives where the alkyl group is large and / or the preparation of 2-(4-alkylphenyl)butenedioic acid by the aforementioned methods is not suitable.

Other methods also include synthesis from benzenediazonium chloride and dimethyl maleate<sup>136</sup>, although yields using this method are very low.

The synthesis of 2-(4-methylphenyl)propane-1,1,3,3-tetracarboxylic acid (Cr32) by the method of Zalukaev<sup>155</sup> was

achieved by a "one pot" condensation-Michael reaction of two equivalents of 2,2-dimethyl-1,3-dioxane-4,6-dione with 4-methylbenzaldehyde to give the ester. Hydrolysis gave the required acid in 58% yield from the aldehyde (see Figure 2.6).

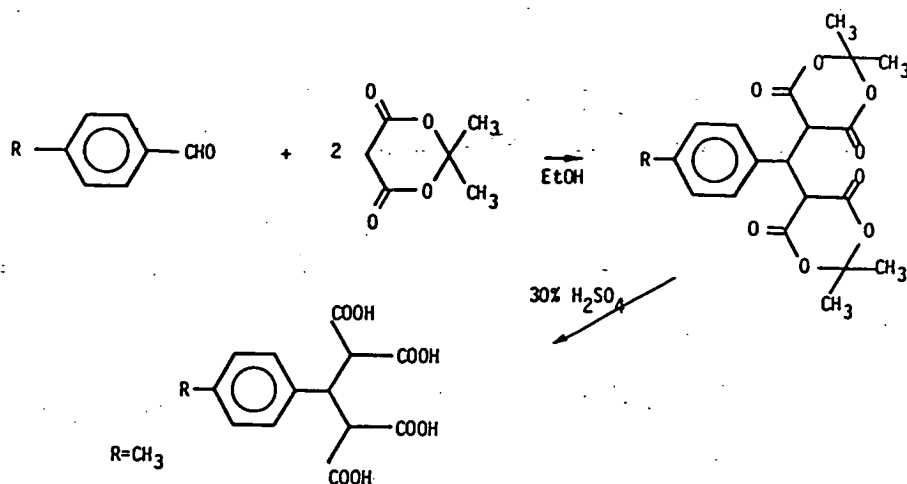


Figure 2.6 Synthesis of 2-(4-methylphenyl)propane-1,1,3,3-tetracarboxylic acid (Cr32).

An attempt to obtain the para-methoxy derivative using the same method proceeded to the condensation stage but failed to undergo Michael reaction under these conditions. This is thought to be due to the decreased electrophilic character of the Michael acceptor site para to the methoxy position in the aromatic ring. No further attempts were made to prepare the para-methoxy derivative by alternative methods.



2.3. Michael Reactions on Ethyl 3-(4-substitutedphenyl)-propenoates and Ethyl 3-(4-substitutedphenyl)propynoates.

In 1887 Michael<sup>81</sup> first reported base catalysed additions of diethyl malonate, and other related proton donor compounds, to unsaturated carbonyl compounds such as ethyl cinnamate (see Figure 2.7). Since that time many reviews on the general method<sup>56</sup> have been published in the literature.

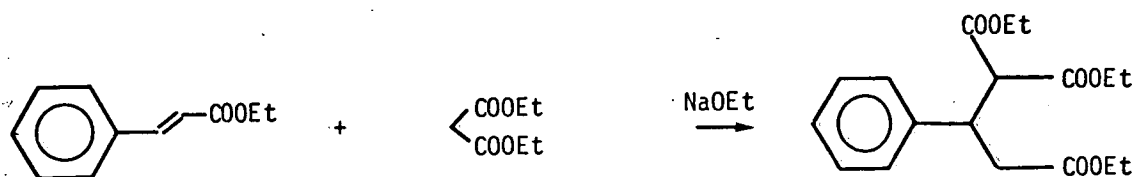


Figure 2.7 Michael reaction on ethyl cinnamate.

The acid (Figure 2.8) formed on the hydrolysis of the above triester was reported at a later date by Michael and Ross<sup>84</sup>.

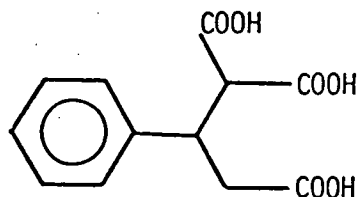


Figure 2.8 2-phenylpropane-1,1,3-tricarboxylic acid (Cr23).

A number of para-substituted derivatives of this acid were synthesised, as shown in Table 2.3.

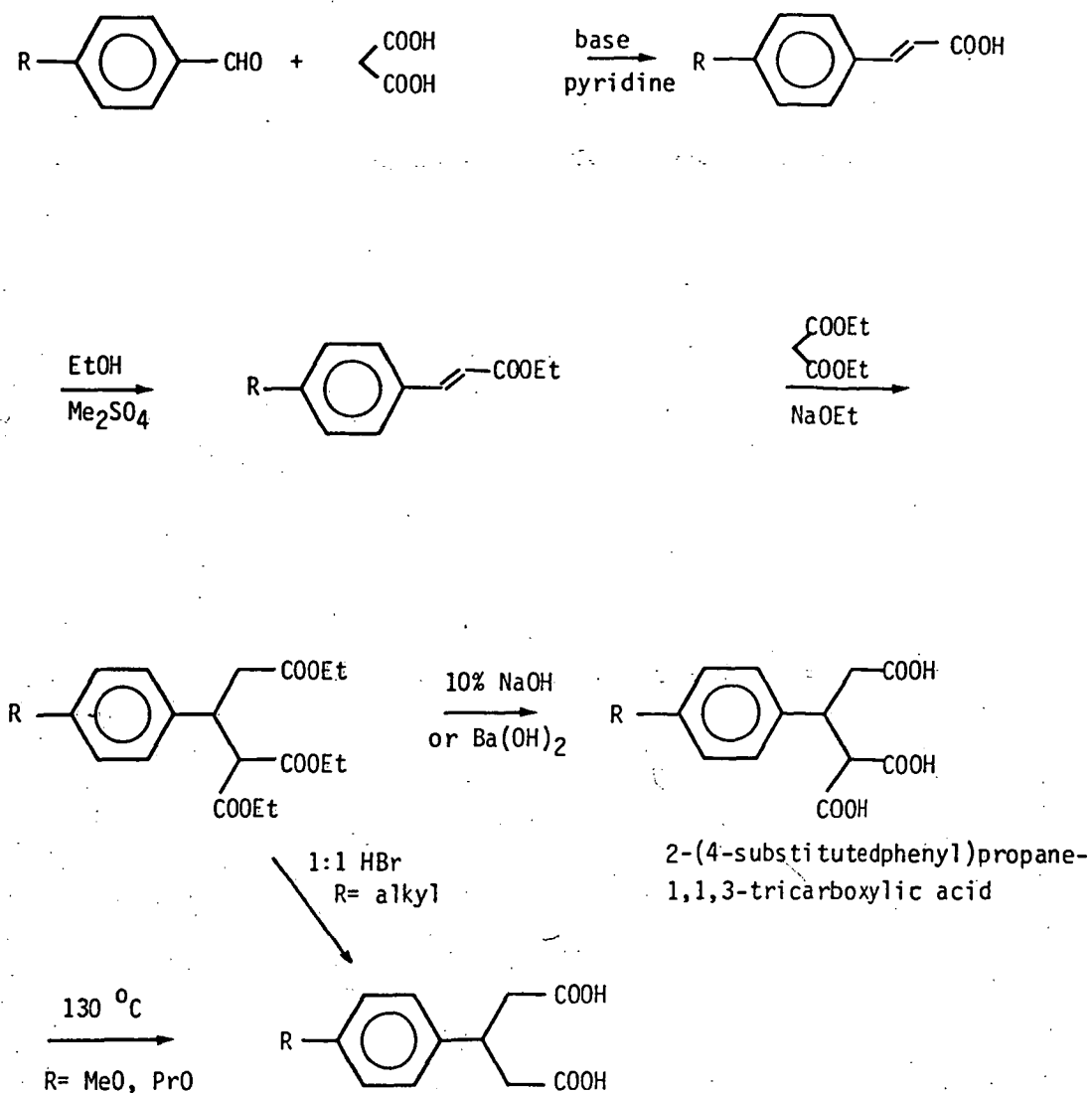


Figure 2.9 Synthesis of 2-(4-substitutedphenyl)propane-1,1,3-tricarboxylic acids and 3-(4-substitutedphenyl)pentanedioic acids.

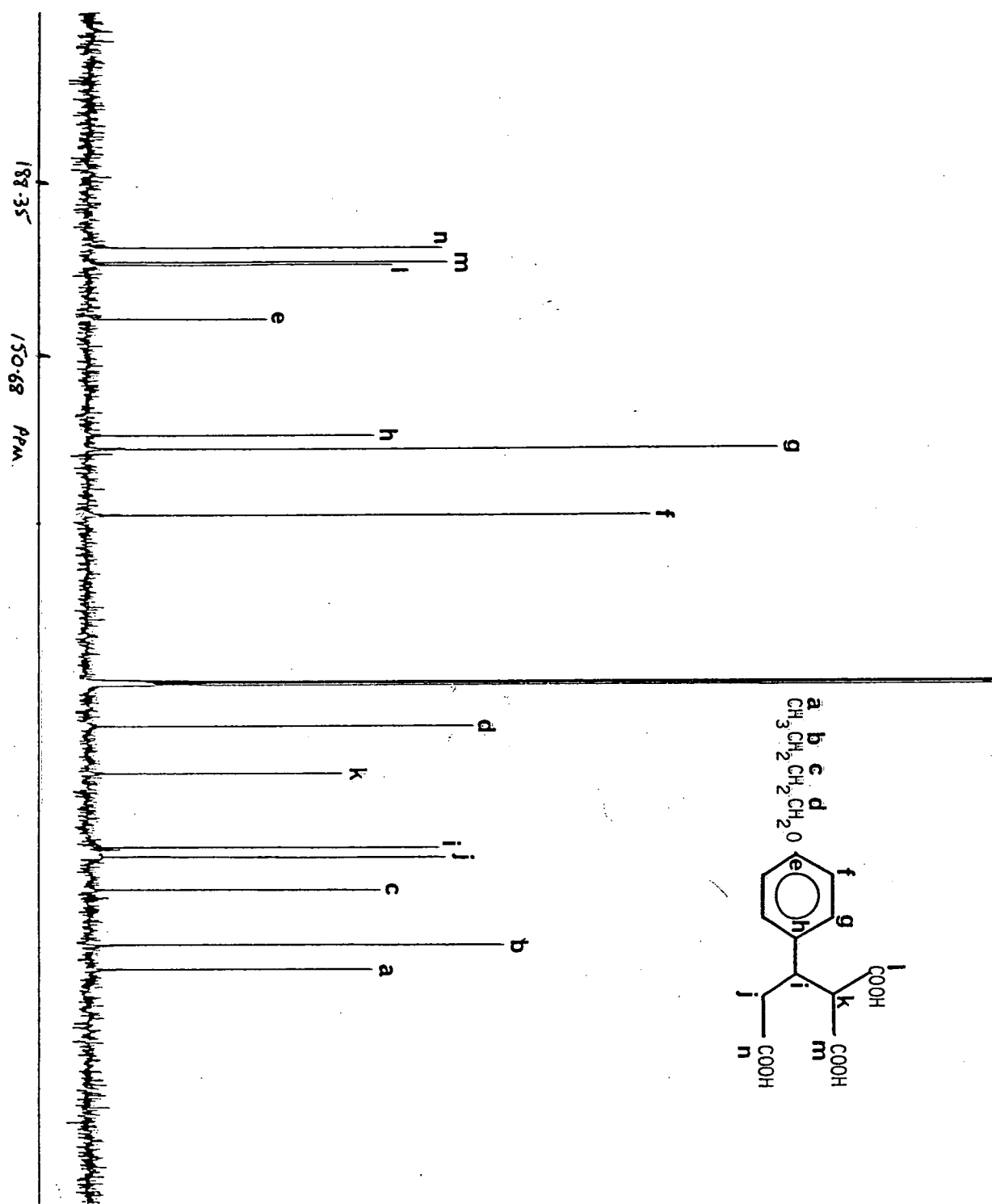


Figure 2.10  $^{13}\text{C}$  N.M.R. of 2-(4-butoxyphenyl)propane-1,1,3-tricarboxylic acid.

Table 2.3 Yields for 2-(4-substitutedphenyl)propane-1,1,3-tricarboxylic acids.

R	M.p. °C	Yield	
H	142-143	83%	(Cr23)
Me	168-170	92%	(Cr24)
Et	150-151.5	83%	(Cr25)
iPr	167-169	75%	(Cr26)
MeO	138-141	58%	(Cr27)
EtO	169.5	75%	(Cr28)
PrO	146-147	70%	(Cr29)
iPrO	158-159	76%	(Cr30)
BuO	140-141	72%	(Cr31)

A general reaction scheme for the synthesis of these tricarboxylic acids is given in Figure 2.9. A number of these acids were not found in the literature and they were characterised by high resolution P.M.R. (see for example Figure 2.11), in some cases <sup>13</sup>C N.M.R. (see for example Figure 2.10), as well as microanalysis (C, H). Melting points for these acids depended critically on the drying time used to free the acids of solvent and water. The above were dried for 4 to 5 hours at 0.5 mmHg. Excessive heating (>130 °C) of the crude acids, Cr23, Cr27 and Cr29 caused decarboxylation similar to that reported by Michael and Ross<sup>82</sup>. The ethoxy derivative (Cr28) only decarboxylated under more extreme conditions (>180 °C).

The most efficient means of hydrolysis of these esters was by refluxing until homogeneous with 10% aqueous sodium hydroxide solution. The use of acid hydrolysis was inappropriate since decarboxylation of the acid to the 3-(4-substituted phenyl)pentanedioic acid, and cleavage of the ether linkage in the case of the alkoxy-substituted acids occurred.

Due to the ease of decarboxylation and the poor reproducibility of the melting points of the carboxylic acids, P.M.R. spectra

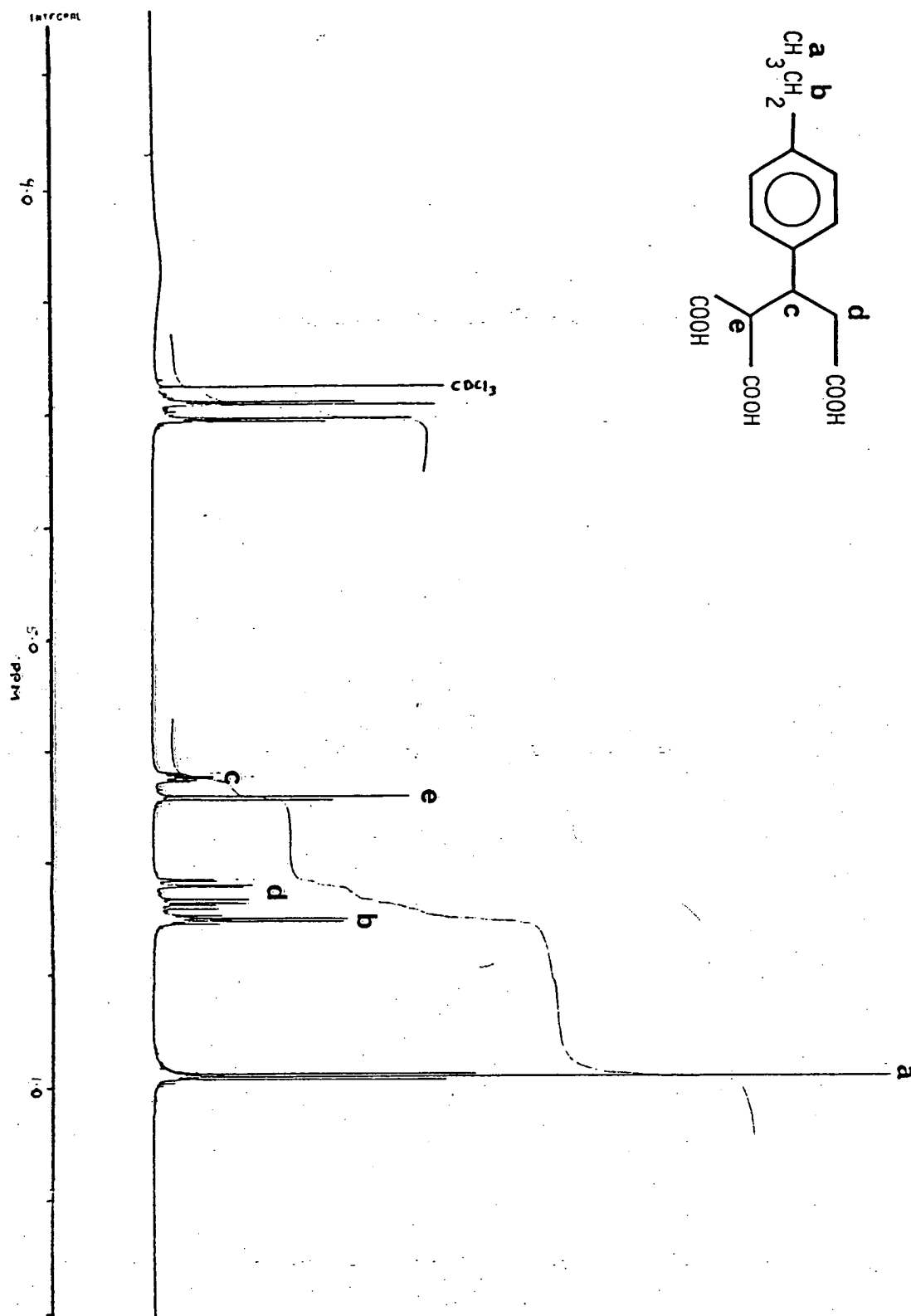


Figure 2. 11 P.M.R. spectrum of 2-(4-ethylphenyl)propane-1,1,3-tricarboxylic acid.

were considered to be the simplest and most reliable method of verifying structure. The triacids showed characteristic methine proton signals at approximately  $\delta$  3.6 and the methylene protons as a pair of doublets in the range  $\delta$  2.65-2.85. The product of decarboxylation, the 3-(4-substitutedphenyl)pentanedioic acids show only multiplets at  $\delta$  2.4-2.8 for the two pairs of methylene protons.

With increasing size of the substituted group in the 4-position of the aromatic ring the acids became less soluble in solvents such as ether. The butoxy derivative was virtually insoluble in ether, and also showed strong frothing power and high surface activity in aqueous solution.

The synthesis of the 3-(4-substitutedphenyl)pentanedioic acids (Cr11-Cr16)(Figure 2.12) was carried out by a number of different methods. 3-Phenylpentanedioic acid (Cr11) was available from commercial sources. This acid, the para-methyl (Cr12), and the para-ethyl (Cr13) derivatives were also prepared from their respective triesters (Figure 2.9) on hydrolysis with 1:1 aqueous hydrobromic acid.

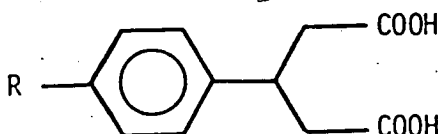


Figure 2.12 3-(4-Substitutedphenyl)pentanedioic acid.

The para-methoxy (Cr14) and para-propoxy (Cr16) derivatives were prepared on hydrolysis of the parent triester with barium hydroxide, followed by acidification and heating at 130 °C for several days. The use of hydrobromic acid caused cleavage of the ether functionality.

The para-ethoxy derivative (Cr15) was synthesised by the method of Smith and Kort<sup>132</sup> (for the methoxy derivative) from 4-ethoxybenzaldehyde and ethyl acetoacetate (Figure 2.13). Mndzhoyan and coworkers<sup>85</sup> have synthesised the para-alkoxy derivatives (C<sub>1</sub> to C<sub>5</sub>) using this method, and Smith and Shelton<sup>133</sup> have synthesised related thienyl- and furylpentanedioic acids.

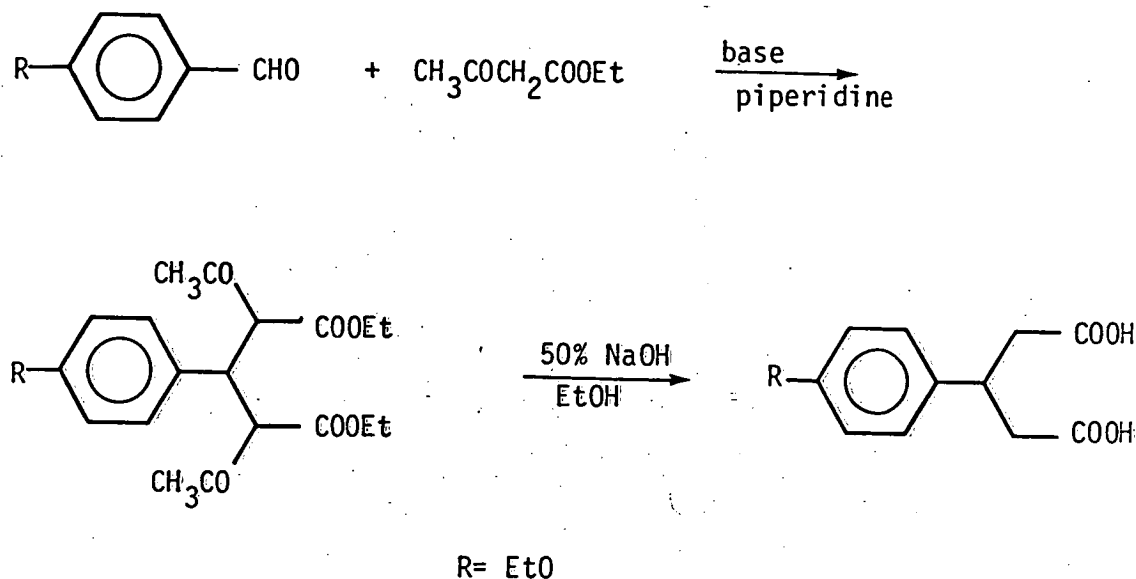


Figure 2.13. Synthesis of 3-(4-ethoxyphenyl)pentanedioic acid.

Table 2.4 Yields for the 3-(4-substitutedphenyl)pentanedioic acids.

R	Yield <sup>*</sup>	M.P.
Me	45%	158-158.5 °C (lit. 155 °C 161 °C)
Et	46%	119 °C (lit. 155 °C 121-122 °C)
MeO	40%	159 °C (lit. 58 °C 165 °C)
EtO	40%	122 °C (lit. 85 °C 130-132 °C)
iPrO	42%	118 °C (lit. 85 °C 98-100 °C)

\* from the para-substituted benzaldehyde.

The yields of acids in Table 2.4 were all approximately 40-45% irrespective of the method used. The method of Smith and Kort has the advantage of requiring fewer steps to obtain the acid, although in this work the triethyl 2-(4-substitutedphenyl)propane-1,1,3-tricarboxylates were required for the synthesis of the tricarboxylic acids (Cr23 to 31), thus making the decarboxylation approach acceptable.

To investigate the effect on flotation of incorporation of an unsaturated bond into the above acid structure, two unsaturated counterparts were prepared. The general approach for the synthesis of the previous tricarboxylate esters was used, with ethyl 3-(4-substitutedphenyl)propynoate as the Michael acceptor (Figure 2.14). The resultant esters were hydrolysed with 10% aqueous sodium hydroxide to give the acids in Table 2.5

Table 2.5. Yields for the 3-(4-substitutedphenyl)pentenedioic acids.

R	Yield	M.P.
H	62%	155-156.5 °C (lit. 22 °C 154-155 °C)
Me	55%	180-182 °C



There are a large number of early literature (1900-1935) reports<sup>22</sup> on phenylpentanedioic acids (phenylglutaconic acids) by Thorpe<sup>38 137</sup>, Ruheman<sup>120</sup>, Gidvani<sup>48</sup> and Dixit<sup>41</sup>.

The synthesis of the unsaturated tricarboxylic acid (Figure 2.14) was also attempted, but decarboxylation of the sodium salt occurred on acidification to pH 6. Decarboxylation at this pH was evidenced by very rapid evolution of carbon dioxide and substantial frothing.

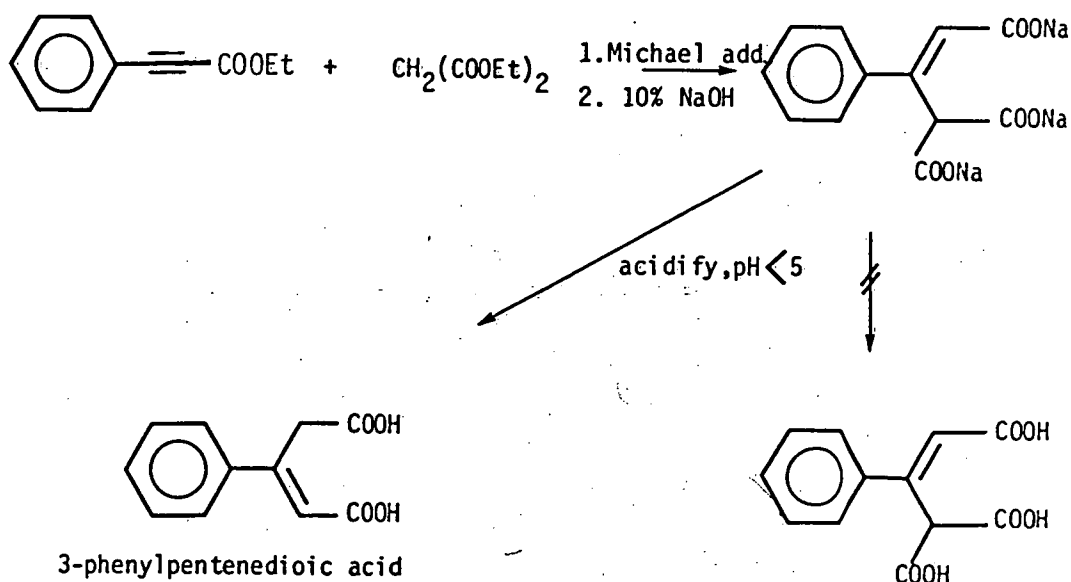


Figure 2.14 Attempted synthesis of 2-phenylpropene-1,1,3-tricarboxylic acid.

#### 2.4. The Synthesis of Nitrogen-Containing Aryl-substituted Polycarboxylic Acids.

There is some evidence that collectors based on N-alkyliminodi(methylphosphonic acid) and its aryl counterparts<sup>34</sup> are reasonably selective and have some commercial application. In the light of this, derivatives of N-phenyliminodiacetic acid were synthesised to investigate their collecting abilities. Unfortunately these acids proved to be unstable on standing for a period of days and decomposed to give dark oils.

The N-(4-substitutedphenyl)iminodiacetic acids were synthesised by the method of Pettit and Irving<sup>100</sup> as shown below.

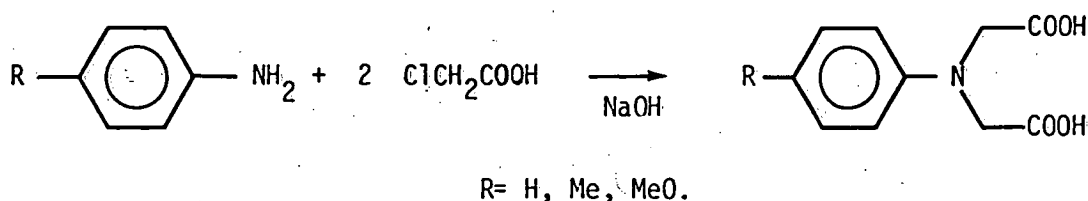


Figure 2.15 Synthesis of N-(4-substitutedphenyl)iminodiacetic acids.

N-Benzyliminodiacetic was obtained from commercial sources.

The results of the collector tests obtained for the use of the above compounds were far from impressive. To compensate for any effect of the basicity of the nitrogen atom on collector ability, N-benzoyliminodiacetic acid was also synthesised by the method of Cherkesov<sup>31</sup> (65% yield).

### CHAPTER 3. The Synthesis of Aryl-substituted Phosphonocarboxylic Acids.

#### 3.1 Introduction.

The aim of synthesising these mixed acids was twofold. Firstly to obtain a direct comparison of the flotation activity of polycarboxylic acids and phosphonocarboxylic acids of similar structure. Secondly, to ascertain whether these compounds would show more potential, in a general sense, as collectors for cassiterite and other metal oxides. Again, a great number of structural permutations are possible and only a selected number of structural types were examined, to provide a basis for further work.

The syntheses of aryl-substituted phosphonocarboxylic acids were based on reaction series similar to those outlined in the previous chapter. Condensation and / or Michael reactions gave the ethyl esters, and on hydrolysis of these esters using acidic or neutral conditions, gave the required phosphonocarboxylic acids.

The chemistry involved in the synthesis of phosphonocarboxylic acids, analogous in structure to those found in Chapter 2, also provided the opportunity for some new synthetic chemistry. A number of workers<sup>8 10 11 60 65 66 96 106 108 109 110</sup> have investigated the synthetic chemistry of phosphonocarboxylic acids and their esters over the last fifty years. Despite this, several target compounds of interest in this work have not been reported in the literature, most notably 3-phenyl-4-phosphonobutanoic acid and 3-phenyl-2-phosphonopropenoic acid. There were several reports of the attempted synthesis of the latter, although none were successful (see Chapter 3.2).

The synthesis of 3-phenyl-4-phosphonobutanoic acid seemed on first inspection to be straight forward. However a number of

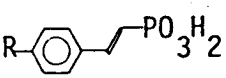
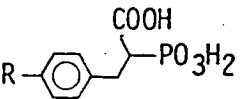
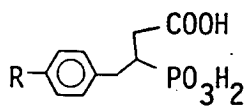
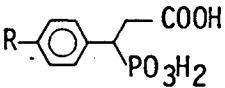
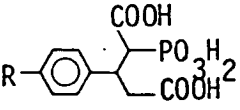
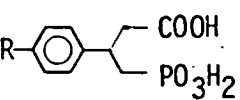
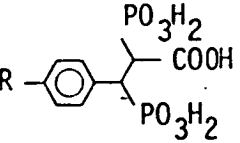
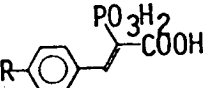
synthetic approaches were attempted with mixed success (Chapter 3.4). Along with these acids several other phosphonocarboxylic acids were synthesised and are represented in Table 3.1. The workup of phosphonocarboxylic acids, resultant on hydrolysis of their respective esters, was more difficult than that of the polycarboxylic acids. The phosphonocarboxylic acids were not soluble in the usual organic solvents and were usually obtained by evaporation of the aqueous phase after washing with dichloromethane to remove any unhydrolysed or partially hydrolysed esters. In general, only hygroscopic gums or foams were obtained in this way. These gums were characterised using N.M.R. techniques.

In some cases only the non-substituted derivatives were prepared and assessed due to the limited time available for the assessment of these proposed collectors. It was thought that correlation between the flotation data of phenyl-substituted phosphonocarboxylic, and polycarboxylic acids (Chapter 2) would provide sufficient indication of the relative effectiveness of these collector types.

It was unclear from literature reports on the investigations into the use of styrenephosphonic acid as a collector whether the para-substituted derivatives of this acid had been assessed as collectors, and therefore, whether these compounds were more active in their collecting abilities. In fact, the para-methyl derivative was found not to have been reported in the literature at all although other derivatives such as the para-ethyl and -butyl analogues have been reported<sup>65</sup>. The compound 4-methylstyrenephosphonic acid was synthesised using the method of Anisimov et al.<sup>7</sup> (for styrenephosphonic acid) and its collecting ability assessed and compared with styrenephosphonic acid (see Chapter 5).

The syntheses of the aryl-substituted phosphonocarboxylic acids were generally of three types. Firstly those syntheses incorporating condensation or a similar reaction on benzaldehyde using triethyl phosphonoacetate as described in Chapter 3.2.

Table 3.1 Correlation table for aryl-substituted phosphono-carboxylic acids.

	H	R Me
	S.P.A.	38
	39	
	40	
		41
	42	46
	43	
	44	
	45	

Secondly, Michael reactions on ethyl cinnamate using phosphorus based Michael donors (Chapter 3.3) and thirdly, Michael reactions on  $\alpha,\beta$ -unsaturated phosphonates and related schemes for the synthesis of 3-phenyl-4-phosphonobutanoic acid and related compounds (Chapter 3.4).

### 3.2 Aryl-substituted Phosphonocarboxylic Acids Derived from Triethyl 3-Phenyl-2-phosphonopropenoate.

Due to the selectivity shown by 2-(4-substituted-phenyl)ethene-1,1-dicarboxylic acids (Cr5 to Cr10) and 2-(4-substitutedphenyl)ethane-1,1-dicarboxylic acids, it was envisaged that the phosphonocarboxylic acid analogues of these dicarboxylic acids would provide an interesting comparison and perhaps superior collecting abilities for cassiterite.

The first report of 3-phenyl-2-phosphonopropanoic acid was by Arbusov and Razumov<sup>10</sup> as a hygroscopic solid (m.p. 137-141 °C).<sup>66</sup> Later the acid was also reported by Kosolapoff and Powell<sup>66</sup> (m.p. 150-152 °C) as being, "not noticeably hygroscopic". The former authors obtained the phosphonocarboxylic acid by acid hydrolysis (hydrochloric acid) in a sealed tube (130 °C) while the latter authors used acid hydrolysis at atmospheric pressure for 7 hours. An attempt in 1972 by Robinson, Li and Addison<sup>116</sup> via acid hydrolysis at atmospheric pressure, resulted only in the dephosphonated product, cinnamic acid (m.p. 47-48 °C).

In the present work triethyl 3-phenyl-2-phosphonopropenoate was prepared by two methods. Firstly, that of Robinson and coworkers<sup>115</sup> involving hydrogenation of triethyl 3-phenyl-2-phosphonopropenoate, and secondly, by the method of Kosolapoff and Powell<sup>66</sup> from benzyl chloride and triethyl phosphonoacetate. Yields for the two methods were 46 and 21%, respectively. The latter procedure had the advantage of being a rapid synthesis, recovering most of the unreacted starting materials, while the method of Robinson took one week for the synthesis of the unsaturated ester precursor.

Hydrolysis of triethyl 3-phenyl-2-phosphonopropanoate was carried out using the method of Kosolapoff and Powell to give colorless hygroscopic needles of the required phosphonocarboxylic acid in 89% yield (see Figure 3.1). The acid was identified by P.M.R., I.R. and <sup>31</sup>P N.M.R. spectroscopy. (see Figure 3.2).

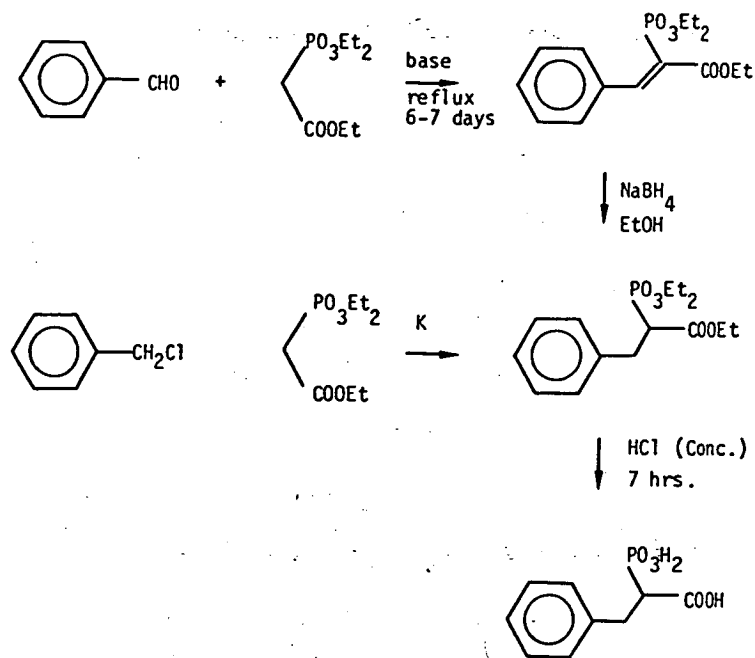


Figure 3.1 Synthesis of 3-phenyl-2-phosphonopropanoic acid.

The unsaturated analogue of this acid was also of considerable interest. There have been several reports in the literature of attempted synthesis, most notably those of Pudovik and Lebedeva<sup>108</sup>, Patai and Schwartz<sup>96</sup> and Robinson, Li and Addison<sup>116</sup>. Pudovik and Lebedeva (1956) reported their successful hydrolysis of triethyl 3-phenyl-2-phosphonopropenoate to the phosphonocarboxylic acid (m.p. 132 °C) in 37-40% yield by hydrolysis with hydrochloric acid. This was later disputed, firstly by Patai and Schwartz (1959) and then by Robinson (1972), both reporting that only cinnamic acid, resulting from dephosphonation, was obtained on hydrolysis under acidic or alkaline conditions.



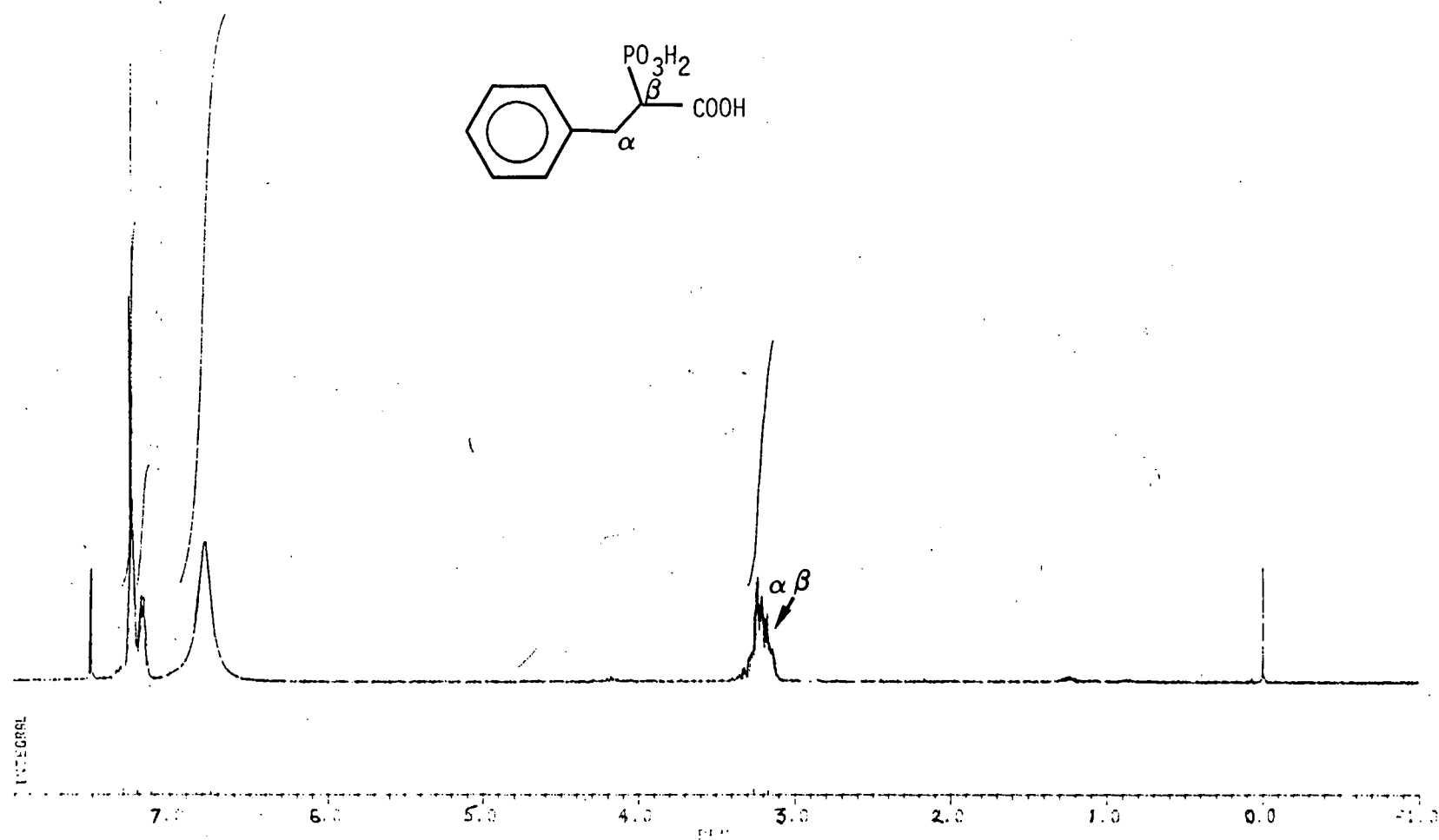


Figure 3.2 P.M.R. spectrum of 3-phenyl-2-phosphonopropanoic acid

To avoid the harsh conditions imposed during reflux in acidic or alkaline hydrolysis, the use of mild hydrolysis via the trimethylsilyl ester intermediate was considered. There are a number of reports on the use of trimethylsilyl halides in the hydrolysis of phosphonates<sup>28 89 92</sup> and carboxylates<sup>54 59 92</sup>. In an initial trial reaction on diethyl 2-phenylethene-1,1-dicarboxylate, trimethylsilyl iodide in acetonitrile was used to obtain the analogous dicarboxylic acid in 88% yield after recrystallization. Similarly, triethyl 3-phenyl-2-phosphonopropanoic acid was hydrolysed to give a yellow oil, that would not solidify unlike the hydrochloric acid hydrolysate. The barium salt of the acidic product had an I.R. spectrum superimposable on that of the barium salt of the previously prepared 3-phenyl-2-phosphonopropanoic acid. The P.M.R. spectrum confirmed hydrolysis had occurred to give the phosphonocarboxylic acid and also showed the presence of acetonitrile and water even after 24 hours under vacuum (0.5mmHg). This presumably prevented solidification.

With the success of these reactions, a similar procedure was attempted on triethyl 3-phenyl-2-phosphonopropenoate (92:8 E:Z isomeric mixture). The E-isomer is characterised by a doublet at  $\delta$  8.06 ( $J_{\text{P-H}}^3 = 24\text{Hz}$ ) while the Z-isomer gives a doublet at  $\delta$  8.58 ( $J_{\text{P-H}}^3 = 45\text{Hz}$ ) in the P.M.R. spectrum for the vinylic proton. Preliminary attempts using this method resulted in the synthesis of the monoethyl ester, ethyl 3-phenyl-2-phosphonopropenoate (see Figure 3.3), in varying yields of up to 74%. This ester was soluble in dichloromethane and easily separated from any acid present.

To obtain the required 3-phenyl-2-phosphonopropenoic acid (see Figure 3.4) in good yield, it was necessary to add further trimethylsilyl iodide after 12 hours and heat for a further 12 hours at 85°C. A similar procedure also gave the best yields for the saturated analogue. The I.R. spectrum of the phosphonocarboxylate esters, even after repeated distillation from CaH<sub>2</sub>, showed the presence of small amounts of water which was not apparent with diethyl 2-phenylethene-1,1-dicarboxylate,

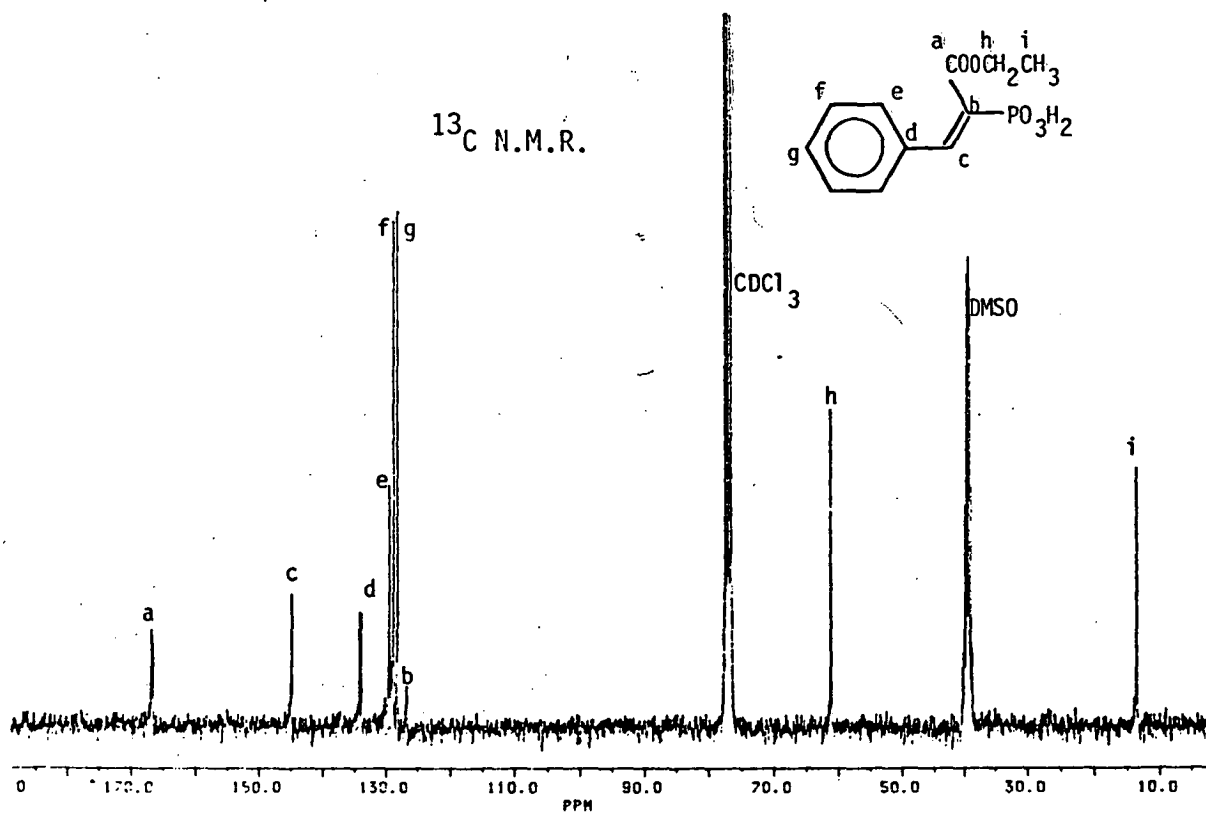
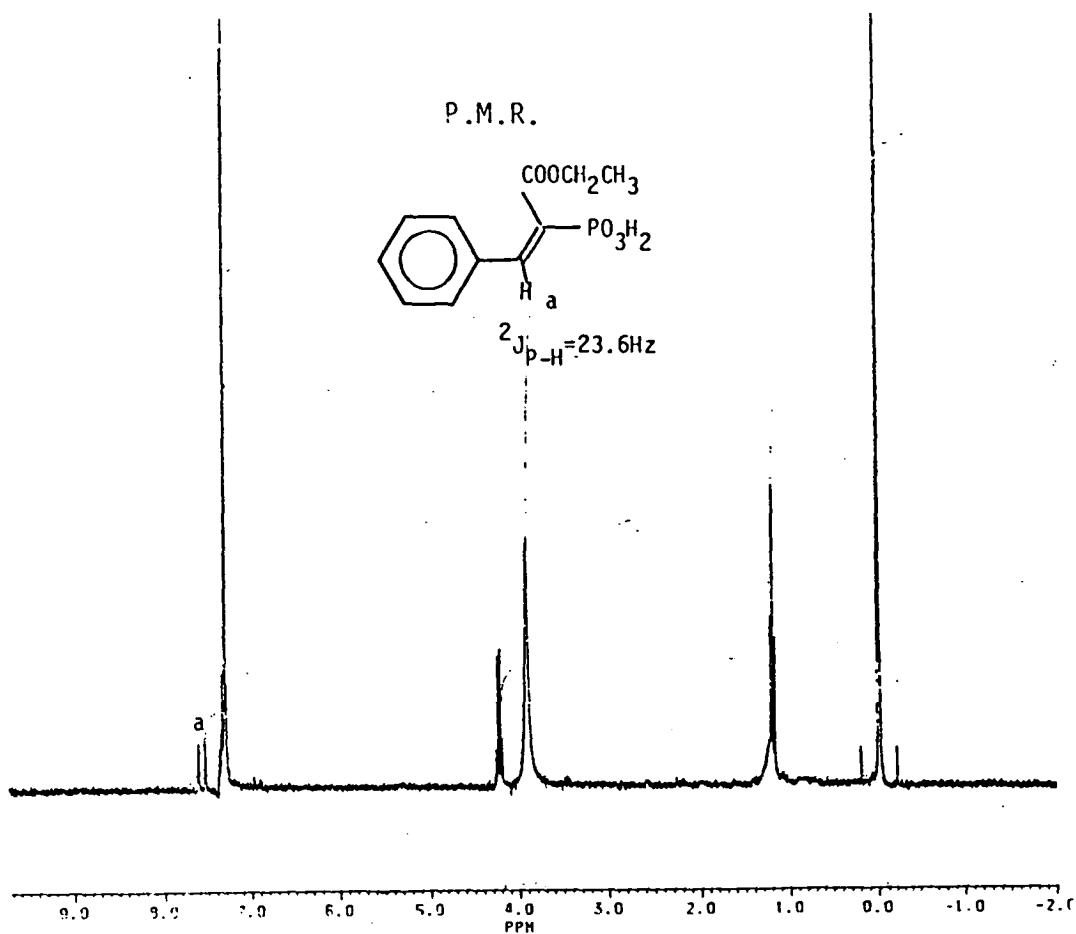


Figure 3.3 P.M.R. and  $^{13}\text{C}$  N.M.R. spectra of ethyl (E)-3-phenyl-2-phosphono propeneoate.

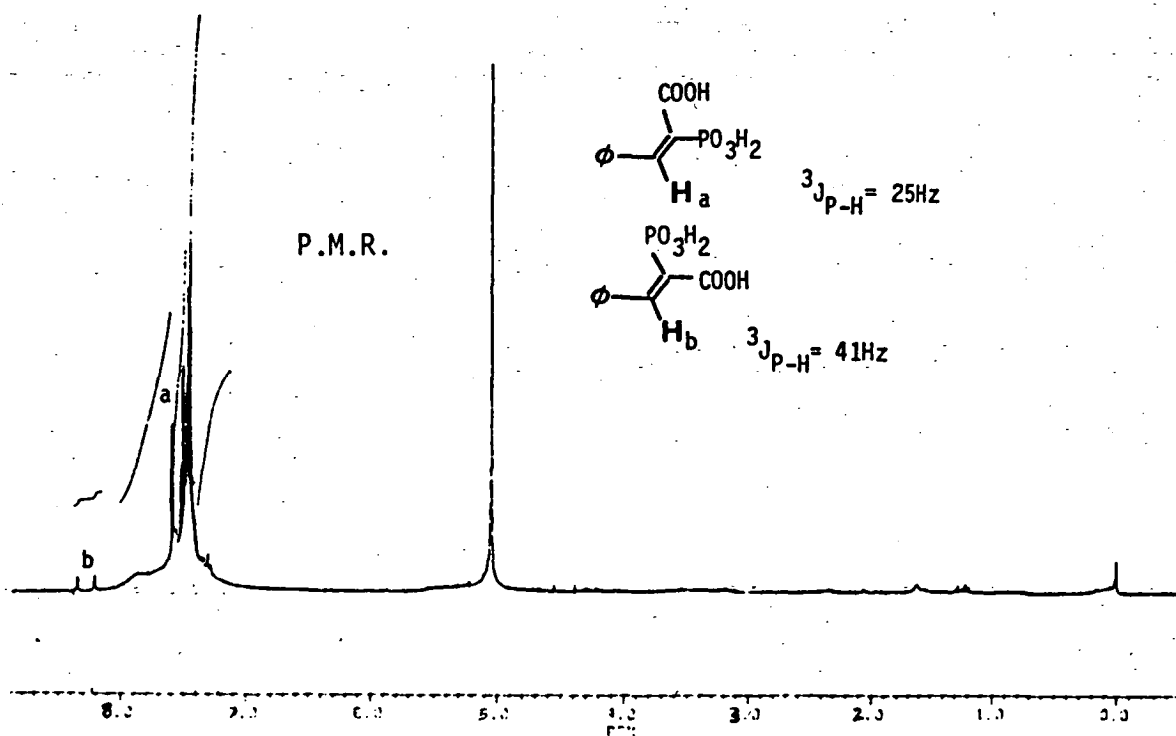
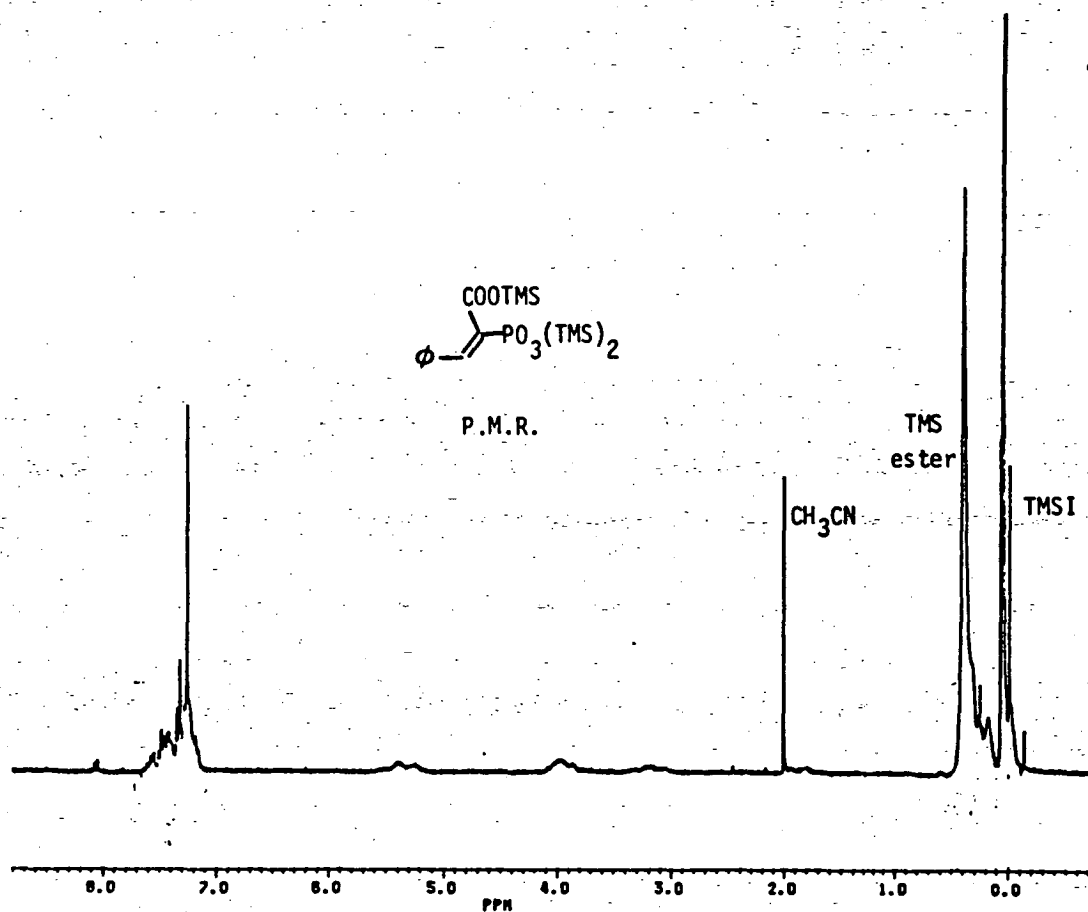


Figure 3.4 P.M.R. spectra of 3-phenyl-2-phosphonopropenoic acid and its tris (trimethylsilyl) ester.

as described earlier. This was presumably why additional trimethylsilyl iodide was needed for complete reaction. A sample of the crude reaction product, obtained prior to hydrolysis with water, gave the P.M.R. spectrum of tris(trimethylsilyl) 3-phenyl-2-phosphonopropenoate ( $\text{CH}_3\text{-Si}$  at  $\delta$  0.35, see Figure 3.4). Upon quenching with  $\text{D}_2\text{O}$  and washing with dichloromethane  $^{13}\text{C}$ ,  $^{31}\text{P}$ , and  $^1\text{H}$  N.M.R. spectra were recorded (see Figure 3.4 and 3.5). The P.M.R. spectrum of cinnamic acid displays a doublet for the methine proton at 6.42ppm. This feature was absent from the spectrum of the products obtained above. The  $^{13}\text{C}$  N.M.R. and  $^{31}\text{P}$  N.M.R. spectra both support the presence of the phosphonic acid group. On standing, crystals of cinnamic acid slowly formed from the solution, indicating decomposition of the phosphonocarboxylic acid. All attempts to isolate the pure acid by evaporation of the aqueous phase resulted in dephosphonation to give cinnamic acid. However, a hydrated barium salt was obtained and this exhibited an IR spectrum supporting the presence of both carboxylate ( $1403$  and  $1544\text{ cm}^{-1}$ ) and phosphonate ( $1049$  and  $1091\text{ cm}^{-1}$ ) groups; a satisfactory elemental analysis was obtained on this salt.

The assessment of this acid as a flotation collector was carried out by dissolving a known quantity of the tris(trimethylsilyl) ester in water to give a 1% solution of the acid immediately prior to carrying out the flotation test.

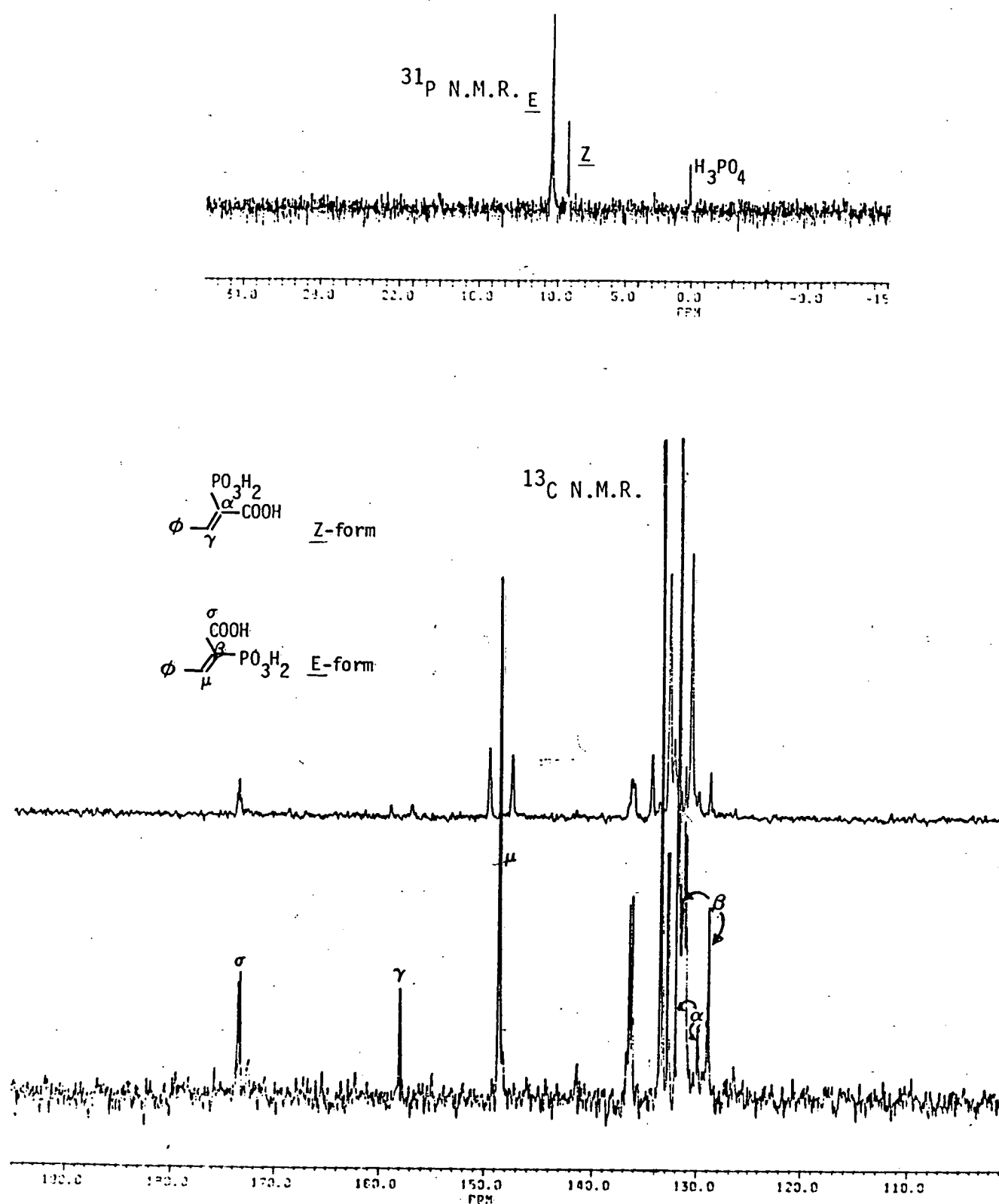


Figure 3.5 <sup>31</sup>P and <sup>13</sup>C N.M.R. of 3-phenyl-2-phosphonopropenoic acid.

### 3.3 Michael Reactions on $\alpha,\beta$ -Unsaturated Carboxylates for the Synthesis of Aryl-substituted Phosphonocarboxylic Acids.

A number of aryl-substituted phosphonocarboxylic acids were prepared via Michael addition on ethyl cinnamate, ethyl phenylpropynoate, or their derivatives, using diethyl phosphite or triethyl phosphonoacetate as Michael donors.

A method similar to that of Pudovik<sup>105</sup> and Kamai<sup>60</sup> for the synthesis of 3-phenyl-3-phosphonopropanoic acid, was used for the synthesis of 3-(4-methylphenyl)-3-phosphonopropanoic acid (m.p. 221-223 °C). This compound and its triethyl ester have not been reported in the literature.

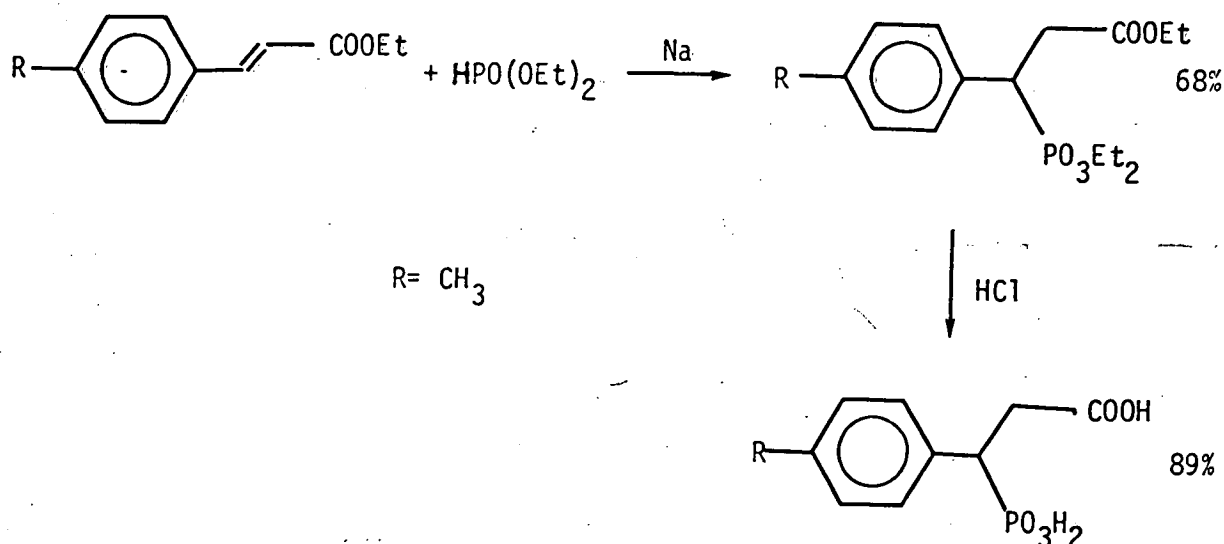


Figure 3.6 Synthesis of 3-(4-methylphenyl)-3-phosphonopropanoic acid

One attempt was made to synthesise 2-(4-methylphenyl)-2-phosphonoethane-1,1-dicarboxylic acid by acid hydrolysis of the respective tetraethyl ester. However, this resulted in

decarboxylation and formation of 3-(4-methylphenyl)-3-phosphonopropanoic acid.

3-Phenyl-2,3-diphosphonopropanoic acid was prepared similarly using ethyl phenylpropynoate as the Michael acceptor, followed by acidic hydrolysis as in Figure 3.7.

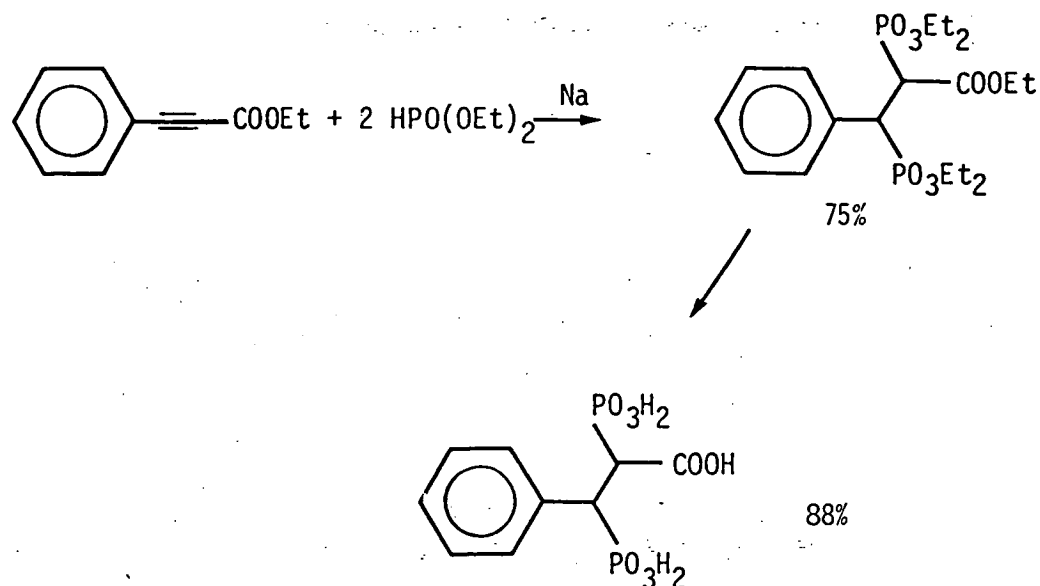


Figure 3.7 Synthesis of 3-phenyl-2,3-diphosphonopropanoic acid.

The above acid had been previously reported by Pudovik and Yarmukhametova<sup>110</sup> although their yield for the ester was somewhat lower (50% compared with 75% obtained in this work). No yield was given for the acid by these workers. Both acid and ester were formed as diastereomeric mixtures as evidenced by their<sup>31</sup>P N.M.R. spectra (Figure 3.8). The<sup>31</sup>P resonances, along with the P.M.R., indicated that the molecule had not dephosphonated. It was interesting to note that one diastereomer exhibited a<sup>3</sup>J<sub>P-P</sub> coupling constant of 71Hz whilst the coupling constant for the other diastereomer was close to zero. Pudovik found that the melting point of the acid was 113-115°C. The acid obtained in this work was in the form of hygroscopic colorless needles, melting point 209-215°C - a more realistic melting point considering the size of the molecules and the extent of



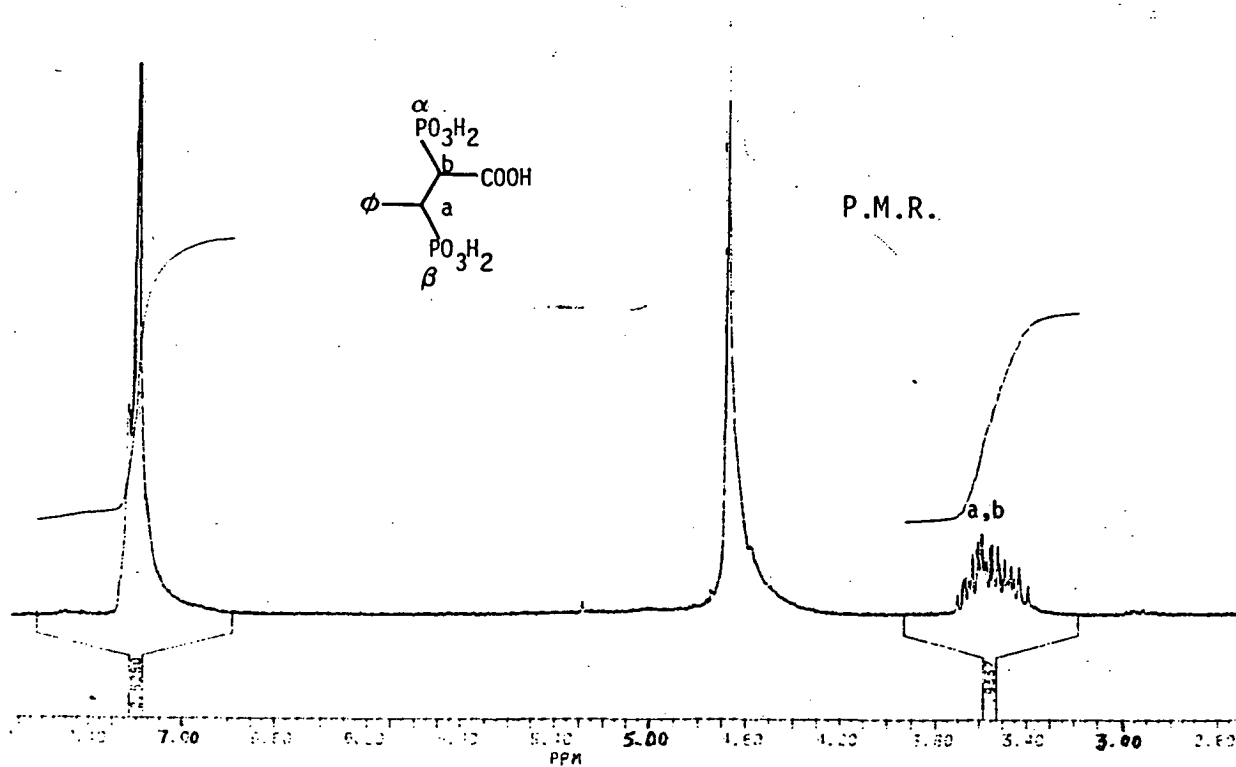
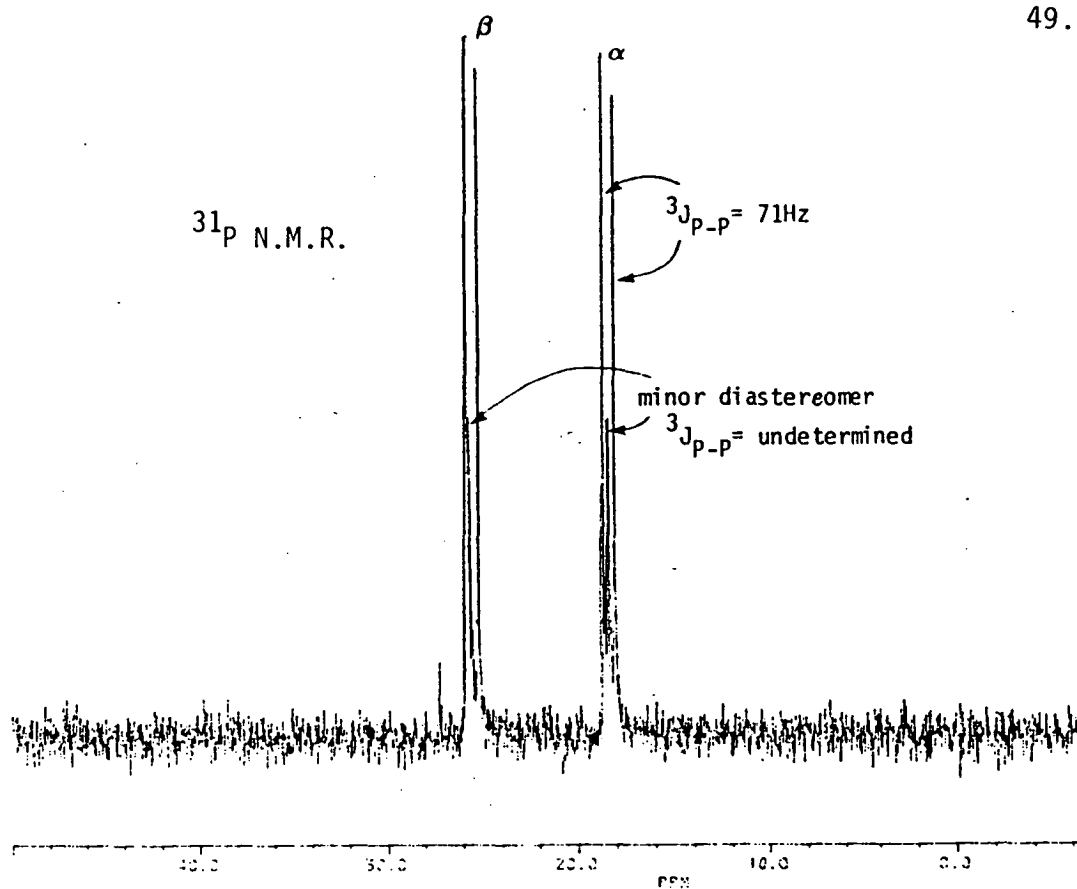


Figure 3.8 P.M.R. and  $^{31}\text{P}$  N.M.R. spectra of 3-phenyl-2,3-diphosphono propanoic acid.

hydrogen bonding expected in this acid.

Tetraethyl 3-phenyl-2-phosphonopentanedioate had been reported in the literature by a number of workers<sup>10 44 107 151</sup>. However, the analogous acid is only reported in a paper by Worms and Blum<sup>151</sup> but this report contains no supporting evidence of structure, nor clear description of preparative method. This acid was of interest due to the excellent flotation results obtained for the analogous tricarboxylic acid (see Chapter 5).

The tetraethyl ester was prepared by the method of Pudovik and Lebedeva<sup>107</sup> resulting in a mixture of diastereomers (approximately 2:1 ratio). Due to the hindered rotation of the ester groups, the P.M.R. spectrum of this ester shows well defined individual proton resonances and was thus readily interpreted. This ester was hydrolysed with aqueous 1:1 concentrated hydrochloric acid to give the corresponding acid. It was important to ascertain whether dephosphonation had taken place as noted for some  $\alpha$ -phosphonocarboxylic acids by other workers<sup>96 116</sup>. Due to the diastereomeric nature of the acid, the P.M.R. spectrum of the hydrolysate was relatively complex and difficult to assign with certainty.

To ascertain the relative proton couplings a COSY N.M.R. spectrum was obtained on this acid (see Figure 3.9). The resultant spectrum is a contoured two dimensional J-coupling correlation enabling identification of J-coupled signals<sup>20</sup>. The spectrum in Figure 3.9, illustrating the region 2.5 to 3.8ppm, contains the methylene and methine protons of the diastereomeric mixture. Following the arrows used in Figure 3.9, the relationships between J-coupled protons can be ascertained. While one of the diastereomers shows geminal coupling between <sup>1</sup>a and <sup>1</sup>b protons the other does not.

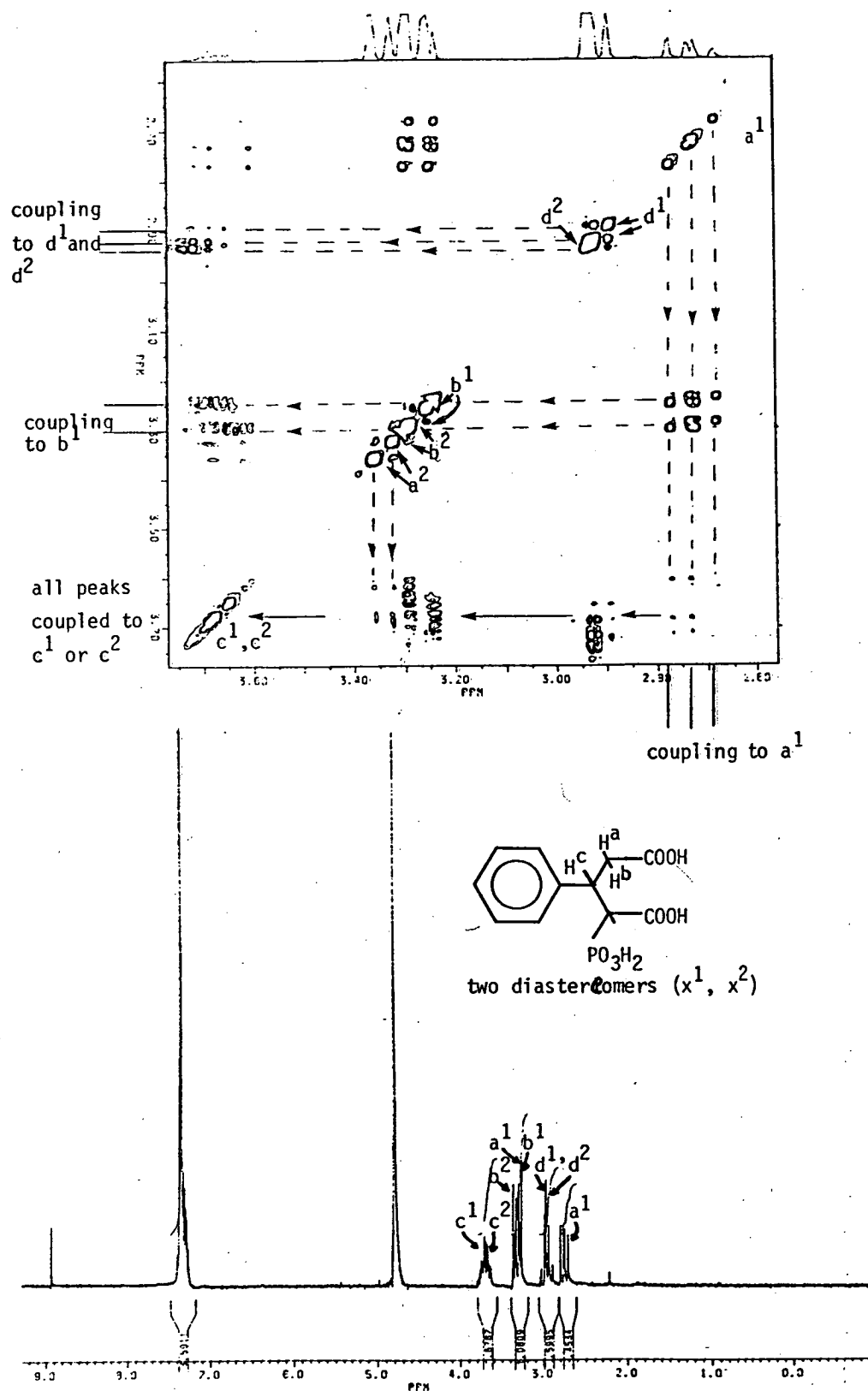


Figure 3.9 P.M.R. spectra of 3-phenyl-2-phosphonopentanedioic acid, including C O S Y plot.

The acid was thus determined to be 3-phenyl-2-phosphonopentanedioic acid. It was interesting to note that 1,1-phosphonocarboxylic acids are more stable to acidic hydrolysis than their dicarboxylic acid counterparts (see Chapter 2.3).

As this acid was obtained successfully the synthesis of the para-methyl derivative was also attempted as it had become apparent that para-substitution on the aromatic ring was desirable for greater flotation efficiency. The ester was obtained in similar yield and hydrolysed to give a hygroscopic gum. This gum was found to be a mixture of the expected 3-(4-methylphenyl)-2-phosphonopentanedioic acid and 3-(4-methylphenyl)pentanedioic acid, in the ratio 80:20. The reason for decomposition of this acid on hydrolysis is not evident given that the same conditions for hydrolysis were used as those used for 3-phenyl-2-phosphonopentanedioic acid. The 3-(4-methylphenyl)pentanedioic acid would be expected if decomposition was to occur. Most of the dicarboxylic acid contaminant was removed by preferential solubility of the phosphonocarboxylic acid in water. The resultant phosphonocarboxylic acid was estimated to be to be approximately 95% pure by P.M.R..

### 3.4 Michael Reactions on Esters of Styrenephosphonic Acid and its Derivatives and the Synthesis of 3-Phenyl-4-phosphonobutanoic Acid.

As already mentioned in the introduction to this chapter, one of the synthetic target compounds was 3-phenyl-4-phosphonobutanoic acid (Cr43). To obtain this product a number of synthetic pathways were considered.

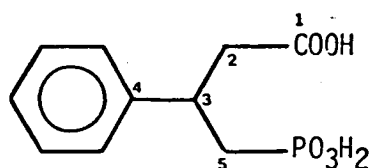
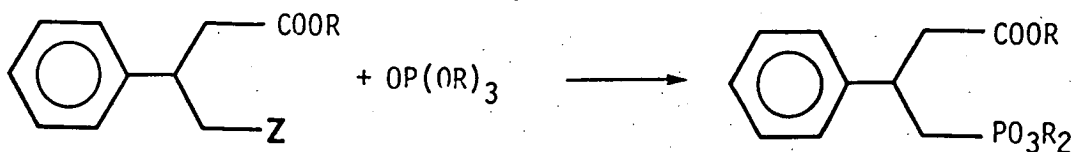


Figure 3.10 3-phenyl-4-phosphonobutanoic acid (Cr43).

Retrosynthetic analysis of the target molecule gives a number of possible disconnections and hence synthetic pathways. Firstly, a pathway utilizing a C<sub>5</sub> - P bond connection is possible by an Arbusov reaction as in Figure 3.11.



where **Z** is Cl, Br, or other  
equivalent functionality.

Figure 3.11. Arbusov reaction for the synthesis of 3-phenyl-4-phosphonobutanoic acid.

The use of phenylglyoxal as a potential precursor was also investigated, however the synthesis of the diethyl acetal was made difficult by hydration of phenylglyoxal on preparation and storage. The acetal prepared by the method of Torrey and coworkers<sup>138</sup> was difficult to separate from the hemiacetal impurity resulting from the presence of hydrate during acetalation. However, the most limiting factor was the difficulty experienced by Torrey in dehydrating the Reformatsky reaction product (10% yield, see Figure 3.12).

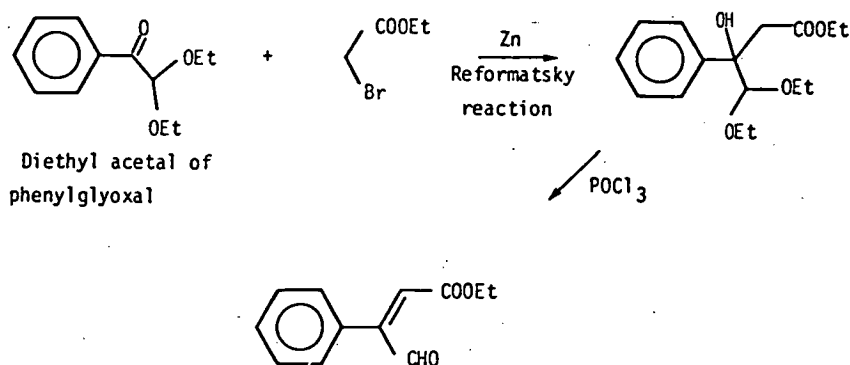


Figure 3.12 Method of Torrey and coworkers for the synthesis of ethyl  $\alpha$ -formylcinnamate.

A similar connection is possible via 3-phenyl-2-butenolide,<sup>42</sup> easily prepared by the method of Epstein and Sontag.  $\gamma$ -butyrolactones have been reported to undergo an Arbusov reaction with triethyl phosphite at high temperature to give triethyl 4-phosphonobutyrate in 12% yield<sup>80</sup>. The low yield for this step is compensated for by the high yields of the precursor and the one-step synthesis. This reaction was attempted on 3-phenylbutyrolactone but no Arbusov product was obtained (by P.M.R.).

Arbusov reactions are also reported on similar  $\alpha$ -halogenated substrates, in particular the brominated analogue<sup>80</sup>. Ethyl 4-bromo-3-phenylbutanoate was synthesised from 3-phenylbutyrolactone using trimethylsilyl bromide to form the brominated trimethylsilyl ester and transesterification with

ethanol to give the required product, ethyl 4-bromo-3-phenylbutanoate (Figure 3.13). Reaction of this with triethylphosphite gave triethyl 3-phenyl-4-phosphonobutanoate in 11% yield, the remainder of the bromo-ester reverting to the lactone. The reaction conditions have not been optimised.

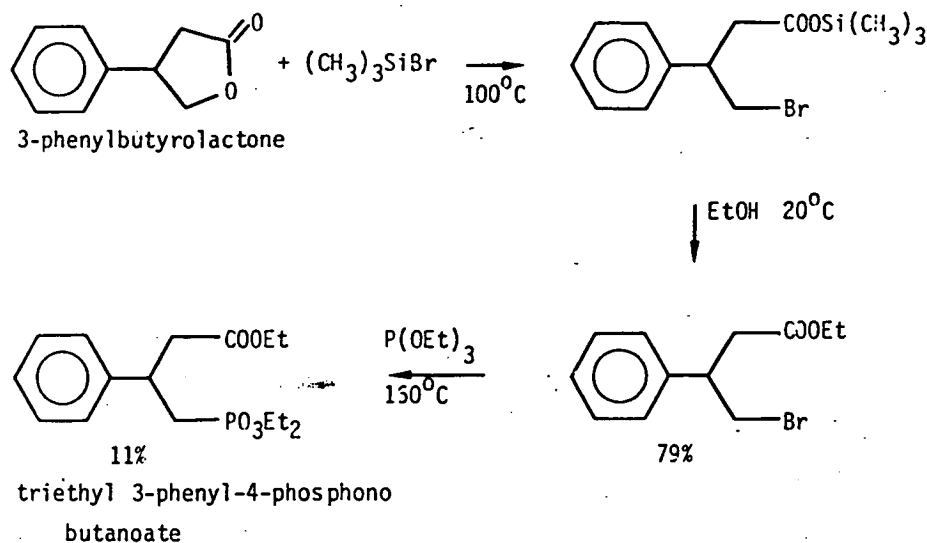


Figure 3.13 Synthesis of triethyl

3-phenyl-4-phosphonobutanoate from 3-phenylbutyrolactone.

Neither ethyl 4-bromo-3-phenylbutanoate nor triethyl 3-phenyl-4-phosphonobutanoate have been previously described in the literature. The former was obtained in crude form only (90-95% pure). Its structure was verified by P.M.R. and mass spectroscopy. The P.M.R. spectrum exhibits a characteristic doublet of doublets at  $\delta$  2.99 and 2.68 for the two methylene protons adjacent to the carboxylate ester. A geminal coupling constant of 15.9Hz and coupling to the methine proton of 5.9 and 8.4Hz respectively, produced a markedly different coupling pattern to that obtained for the lactone ( $J_{\text{H-H geminal}} = 18.0\text{Hz}$ ,  $J_{\text{H-H methine}} = 9.5\text{Hz}$ ). A molecular ion peak was not observed in the mass spectrum due to debromination corresponding to a 191 m/e peak.

Triethyl 3-phenyl-4-phosphonobutanoate, obtained as a yellow oil, was characterised using the usual spectroscopic techniques. The P.M.R. and  $^{13}\text{C}$  N.M.R. were assigned as shown in Figure 3.14.

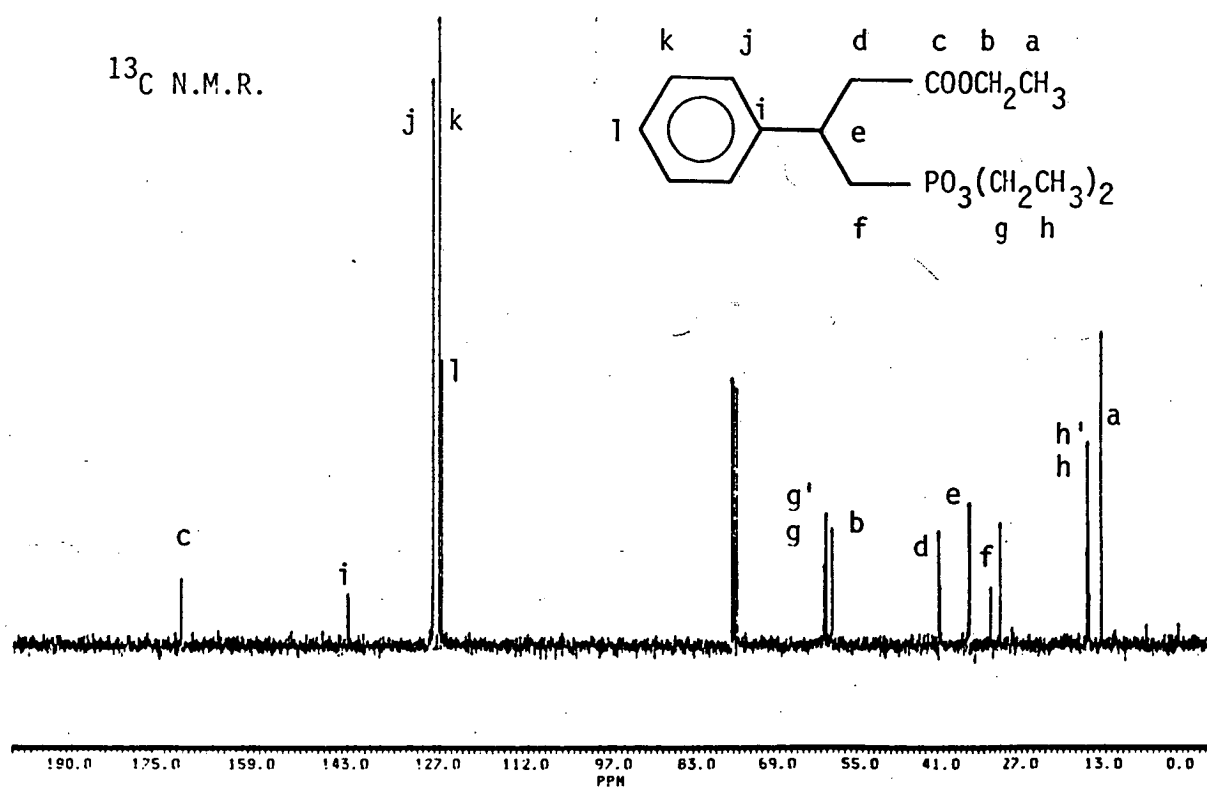
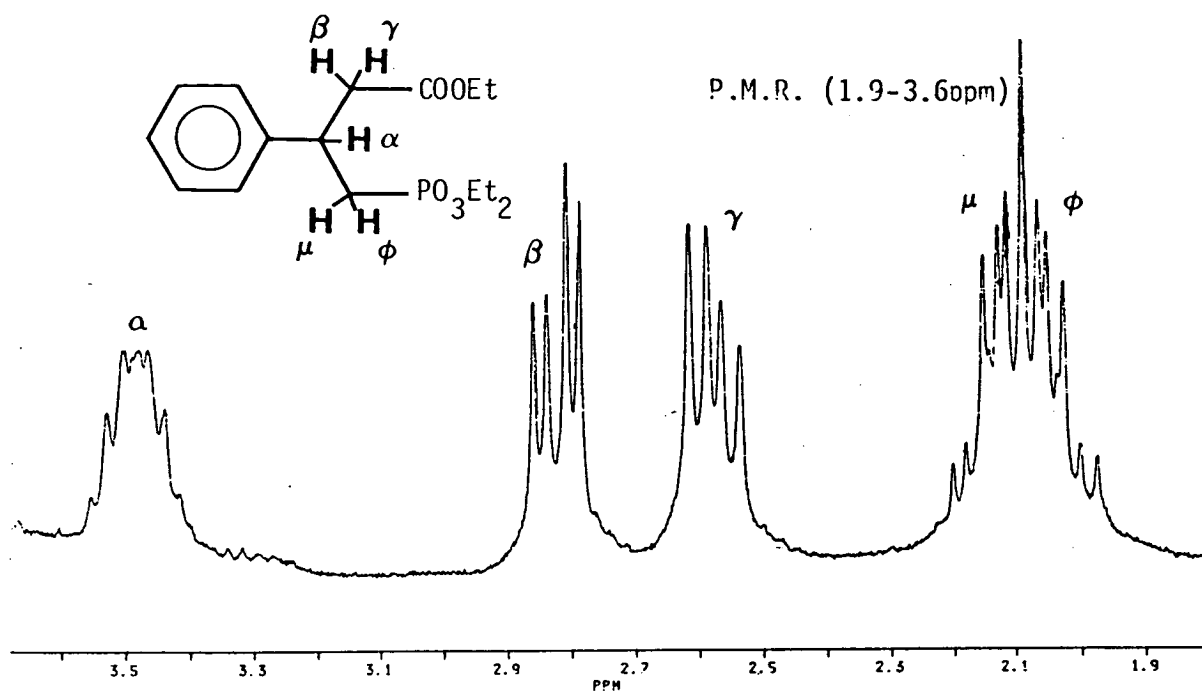


Figure 3.14 P.M.R. and  $^{13}\text{C}$  N.M.R. spectra of triethyl 3-phenyl-4-phosphonobutanoate



The triethyl ester showed a markedly different splitting pattern for the methylene protons adjacent to the phosphonate group when compared with the analogous acid (see Figure 3.26). The hindered rotation of the ethyl ester groups provided different magnetic environments for each of the methylene protons in the triethyl ester rather than the equivalent environments observed for the acid. The ester therefore gave two sets of doublet of doublet of doublets (resulting from splitting by the geminal proton, the proton on the adjacent carbon, and the phosphorus atom), while the acid with no geminal coupling exhibited only one doublet of doublets, the latter resulting from splitting by phosphorus and the adjacent methine proton only. The high resolution mass spectrum exhibited a molecular ion (328.1441) and the usual fragmentation pattern (loss of OEt, CO, O etc.)

Disconnection of the  $C^3 - C^5$  bond (see Figure 3.10) offers an alternative pathway to the required triethyl ester. This would involve Michael addition of a methylphosphonate anion to ethyl cinnamate. Methylphosphonate anions have been used at  $-70$  to  $-89$  °C<sup>43 83</sup>, with active acceptors. However, a Michael reaction using ethyl cinnamate as an acceptor at this temperature would be inappropriate due to thermodynamic considerations. A Michael reaction was attempted between tetraethyl methylenediphosphonate and ethyl cinnamate, but only starting materials were recovered.

An alternative disconnection is that between the  $C^3$  and  $C^4$  carbon atoms. Such a disconnection could only be utilized through a Friedel-Crafts reaction of benzene and triethyl 3-halogenated-4-phosphonobutanoate. This approach was considered to be inappropriate due to the electron withdrawing nature of the carboxylate and phosphonate groups as well as unfavourable steric factors.

Disconnection between the  $C^2 - C^3$  bond presented interesting possibilities. Michael addition to vinylphosphonate esters is well documented<sup>109</sup> and thus a Michael reaction on diethyl

styrenephosphonate was thought to be possible although no similar reactions are reported in the literature. The effect of the aromatic ring on Michael addition to the  $\alpha,\beta$ -unsaturated phosphonate was expected to result in lower yields than those for the reaction on diethyl vinylphosphonate (viz. reactivity of methyl acrylate and methyl cinnamate<sup>56</sup>). This is due to the conjugating effect of the delocalised electrons of the aromatic ring, and steric interference at the reactive site.

Several attempts at this reaction using various procedures gave no indication of the Michael reaction proceeding. Therefore the reaction was either not taking place at all due to steric constraint or the reaction equilibrium strongly disfavoured the products. To overcome the latter effect several alternatives were available. For example, the use of another electron withdrawing group substituted adjacent to the phosphonate was considered since this may increase the stability of the carbanionic intermediate (see Figure 3.15). Precedent exists for this since Pudovik and coworkers<sup>111</sup> investigated Michael-type additions to triethyl 3-phenyl-2-phosphonopropenoate using diethyl thiophosphite as a Michael donor with some success.

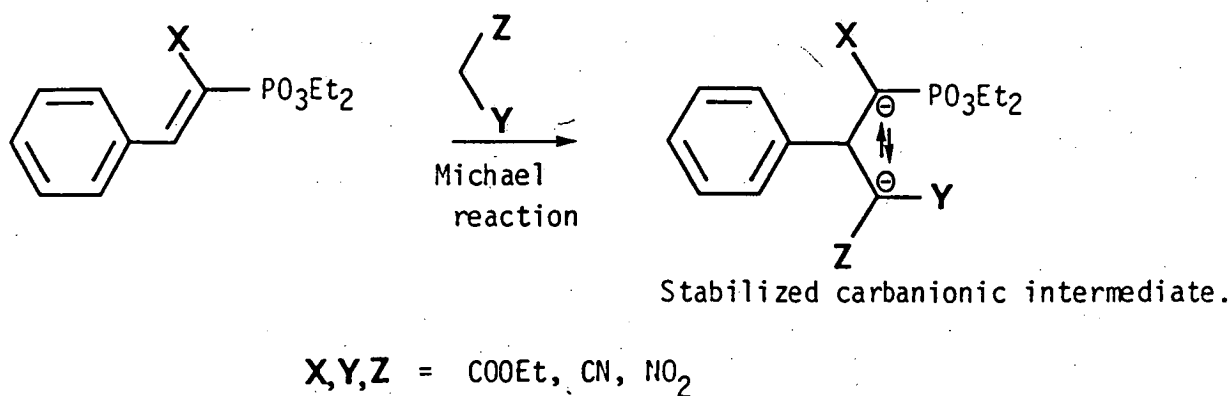


Figure 3.15 Use of electron withdrawing substituents to facilitate Michael reaction on styrenephosphonate esters.

The above alternative presented some synthetic difficulties since to obtain the required product the additional group had to be selectively eliminated once the Michael reaction was complete. This negated the possibility of using carboxylate or nitrile substituents as no method could be envisaged for such selective removal. The use of a nitro group would have been desirable from this point of view as it may be removed by use of tributyltin hydride<sup>163</sup>. However, work carried out by Vasilieva and coworkers<sup>140</sup> on the preparation of diethyl 1-nitro-2-phenylethenephosphonate indicated that this product was not obtained as expected on condensation of benzaldehyde and dimethyl nitromethylphosphonate as only the addition reaction took place. Also, when condensation was forthcoming with the use of 4-nitrobenzaldehyde the condensate dephosphonated. Thus this approach would have required considerable investigation into the causes of the observations above. The synthesis of diethyl nitromethylphosphonate also would have required some considerable expenditure of time<sup>94 98</sup>.

In an effort to reduce the electron density in the double bond, and thus facilitate nucleophilic attack, the use of iron carbonyl complexes was considered. These had been successfully utilized by Ross<sup>113 114 119</sup>, with Michael reactions on tetracarbonyl(methyl cinnamate)iron, and it was considered that the analogous reaction may take place with the diethylstyrenephosphonate analogue. Tetracarbonyl(dimethyl styrenephosphonate)iron, yellow needles (m.p. 81°C) was found to be stable in a cool dark environment. This compound has not been previously reported.

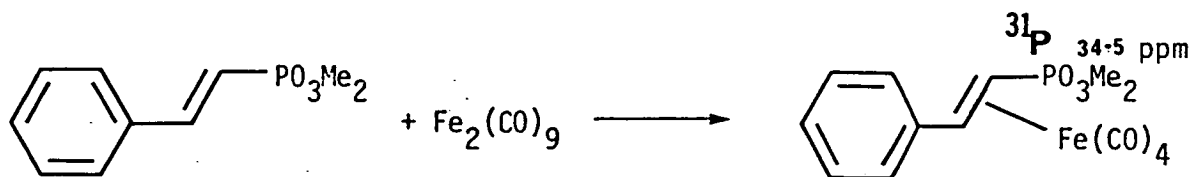


Figure 3.16 Synthesis of tetracarbonyl(dimethylstyrenephosphonate)iron(III).

This complex displayed a significant upfield shift of the two methine protons in the P.M.R. spectrum. For dimethylstyrenephosphonate their proton signals were observed at 7.51 and 6.25ppm, and for the complex at 3.23 and 4.79 ppm (300MHz, 4mg/ml). The P.M.R. spectrum of the complex varied with concentration and the strength of the applied field (see Figure 3.17). It was of interest to note that the  $J_{\text{P-H}}^2$  coupling-constant was reduced by the formation of the complex from 16Hz to 4.3Hz while  $J_{\text{P-H}}^3$  remained unchanged.

Unfortunately, the complex proved unstable in solution when the Michael reaction was attempted. No adduct was obtained from a number of attempts at this reaction at temperatures between  $-5^\circ\text{C}$  (freezing point of the hexamethylphosphoramide solvent) and  $40^\circ\text{C}$ . The Michael reaction on tetracarbonyl(methyl cinnamate)iron proceeded best at  $0^\circ\text{C}$  (contrary to Ross's findings where higher temperatures were required) in 70% yield (by N.M.R.). Decomposition of the phosphonate complex during reaction was marked by the formation of a deep red coloration in the reaction mixture.

With the failure of this reaction, ways of decreasing the effect of the aromatic ring were considered. As previously mentioned diethyl vinylphosphonate undergoes Michael reaction readily; but

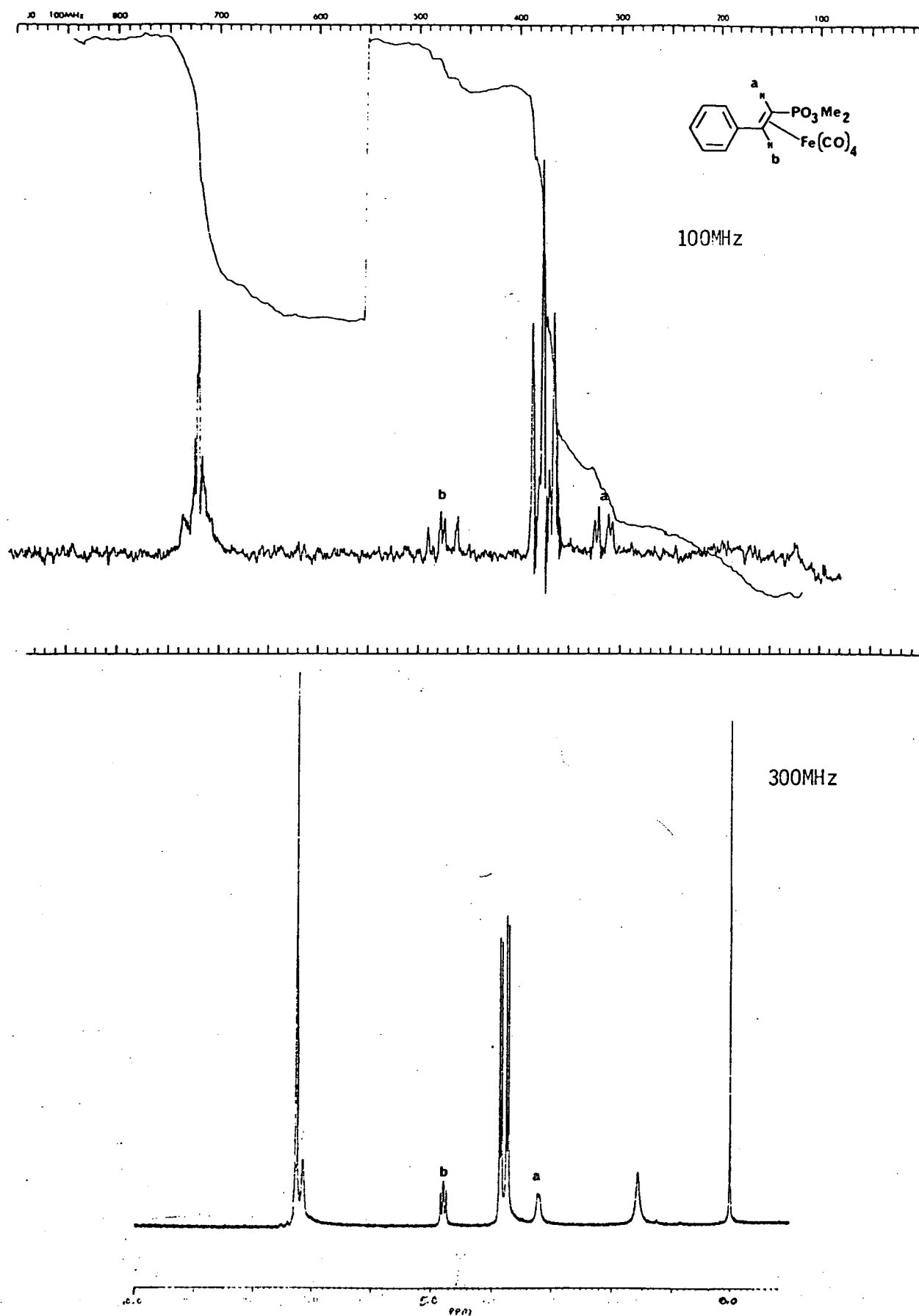


Figure 3.17 P.M.R. spectra of tetracarbonyl(dimethyl styrene phosphonate)iron(III)

the effect of substitution of the benzene ring has both steric and electronic effects on the reaction. To reduce the electronic effect, substitution of a nitro group in the para position was considered. The effect of this substitution would be to deactivate the ring reducing the electron donating and conjugating effect of the aromatic group on the adjacent unsaturated bond (see Figure 3.18).

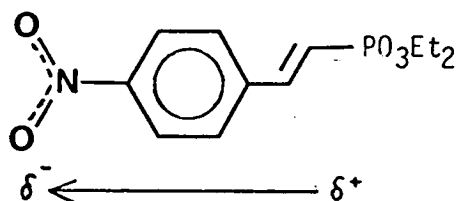


Figure 3.18 Electronic charge distribution in diethyl 4-nitrostyrenephosphonate

Since the compound 4-nitrostyrene undergoes Michael addition at the terminal carbon due to the capacity of the nitrated benzene ring to stabilize the carbanionic intermediate a similar competitive Michael reaction was envisaged with diethyl 4-nitrostyrenephosphonate. Thus a product from the latter reaction, as well as the required Michael reaction, may be obtained.

The synthesis of diethyl 4-nitrostyrenephosphonate (88% yield) was carried out using a method similar to that of Wadsworth and Emmons<sup>143</sup> for the preparation of diethyl styrenephosphonate. The former compound had been previously reported by Wada and Oda<sup>142</sup>, however their method of synthesis, from diethyl vinylphosphonate and 4-nitrobenzenediazonium chloride, gave only a 17% yield.

Michael reaction on this ester using ethyl cyanoacetate as a donor gave 15% of the required product, triethyl

2-cyano-3-(4-nitrophenyl)-4-phosphonobutanoate (adduct A), and 37% of the competitive adduct triethyl 2-cyano-4-(4-nitrophenyl)-3-phosphonobutanoate (adduct B) (Figure 3.19). The reaction was accompanied by the formation of a dark red coloration, most likely due to formation of the aci-nitro salt, which decomposed on quenching with glacial acetic acid. The use of sulfuric acid to quench the reaction reduced the yield of both adducts.

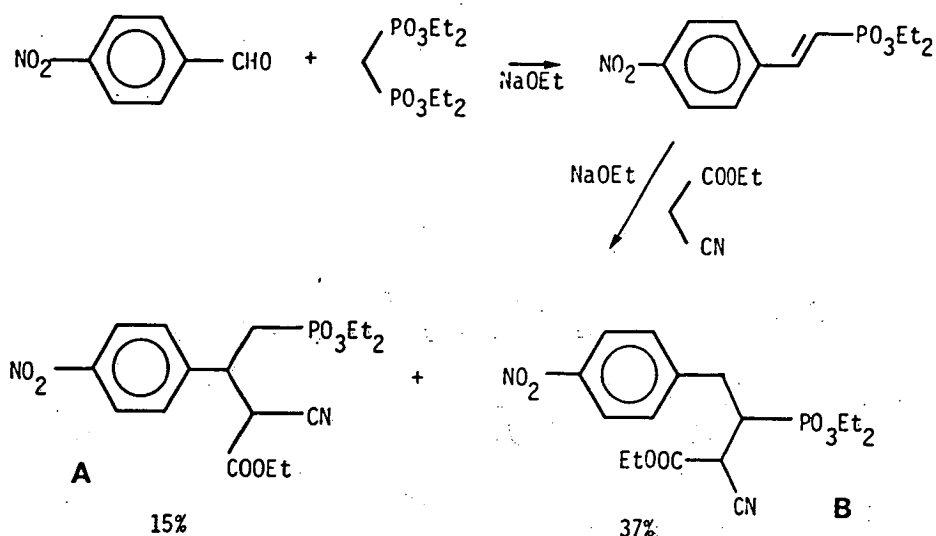


Figure 3.19 Michael reactions on, and the synthesis of, diethyl 4-nitrostyrenephosphonate.

Some difficulty was experienced in separating the two products from the precursor. Distillation of the crude product was attempted but decomposition resulted due to the high boiling point of the nitrated products. Separation by thin layer chromatography was possible using multiple development techniques.

The two adducts were easily differentiated by their P.M.R. spectra. As may be seen from Figures 3.20 and 3.21, the chemical

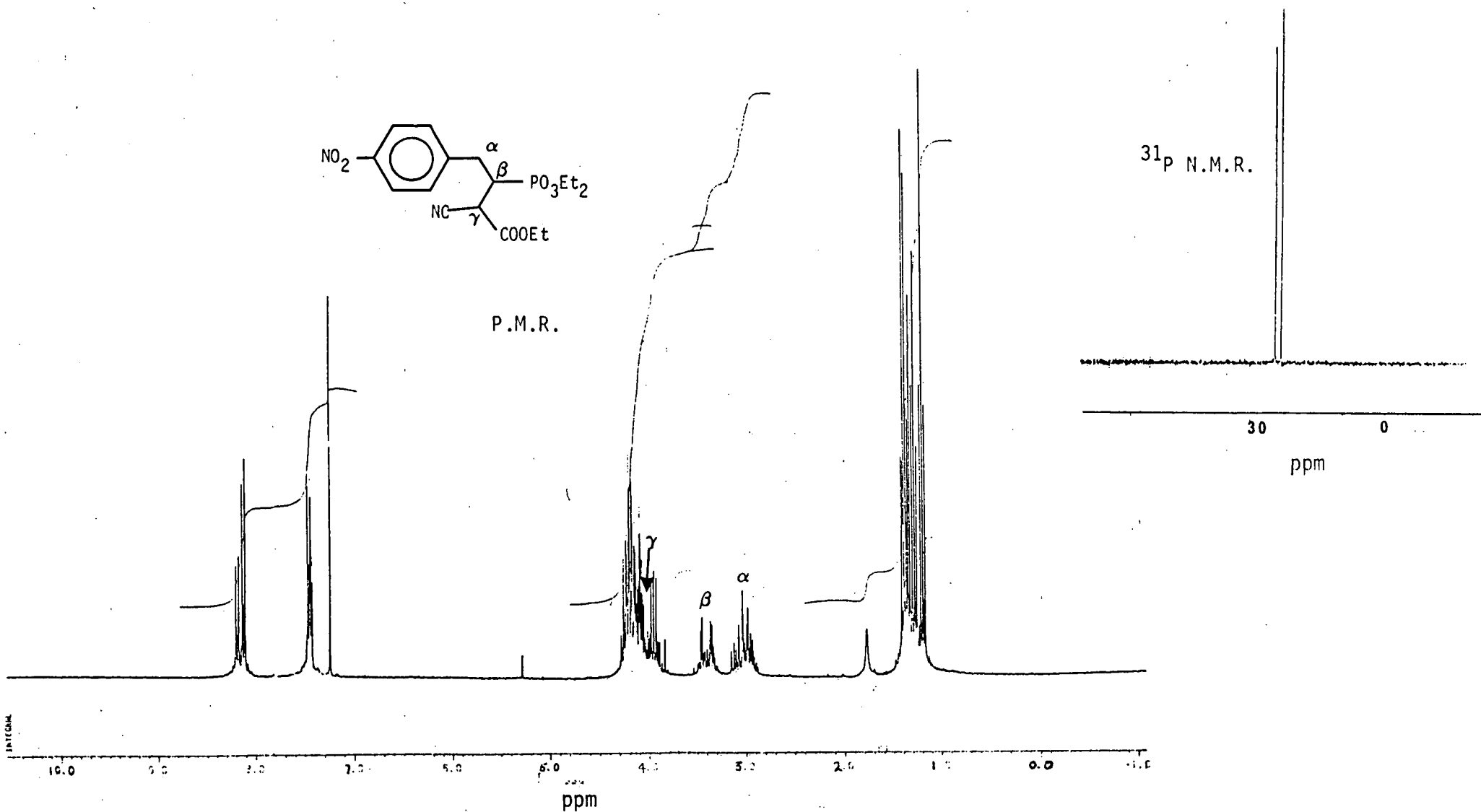


Figure 3.20 P.M.R. and  $^{31}\text{P}$  N.M.R. spectra of triethyl 2-cyano-4-(4-nitrophenyl)-3-phosphonobutanoate



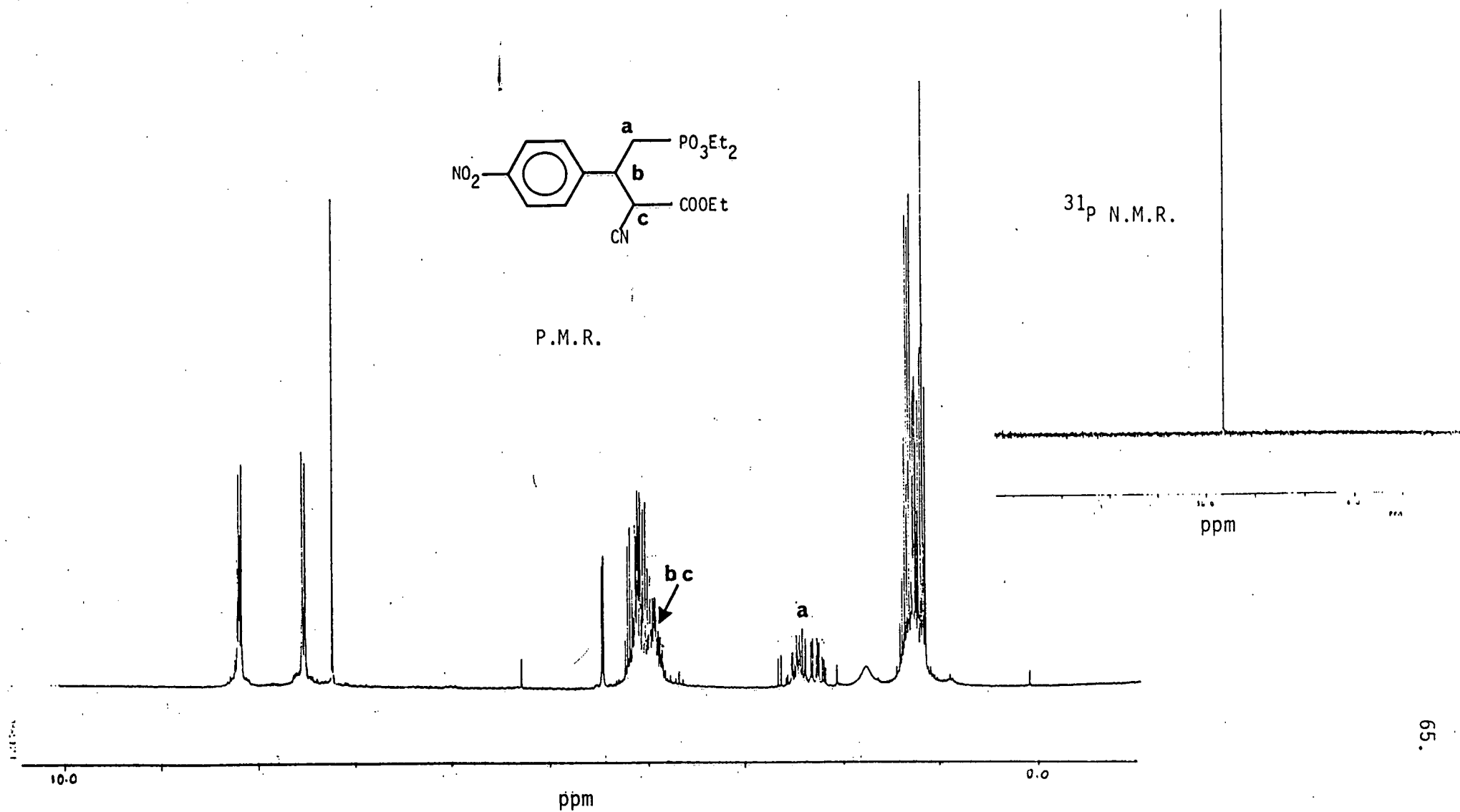


Figure 3.21 P.M.R. and  $^{31}\text{P}$  N.M.R. spectra of triethyl 2-cyano-3-(4-nitrophenyl)-4-phosphonobutanoate

shifts of the methylene protons in each adduct are markedly different. The benzylic protons of adduct B occur in the range 2.85-3.2ppm, and the methylene protons of adduct A (adjacent the phosphonate group) in the range 2.1-2.7ppm. The P.M.R. spectra of the adducts are complex as each adduct is composed of diastereomers due the presence of two chiral centres (see Figure 3.21). The <sup>31</sup>P N.M.R. spectrum of adduct B shows a peak for each diastereomer (approximately equal intensity) while adduct A gives just a single peak (Figure 3.21). The latter observation is due to the methylene carbon between the phosphorus atom and the chiral carbon negating the difference in the chemical shifts seen for the two diastereomers in adduct A. In adduct B the phosphonate is directly adjacent to a chiral centre. No attempt was made to separate the diastereomeric mixtures, and characterisation was limited to P.M.R., I.R., high resolution M.S. and refractive index measurement.

Characteristic fragmentation patterns in the mass spectra were evident for each adduct. Adduct B gave a base peak of 286 (100%) corresponding to a retro-Michael fragmentation, while adduct A gave an ion at 152 (100%) ( $\text{CH}_3\text{-CH}_2\text{-PO}_3\text{Et}_2$ ) (see Figure 3.22).

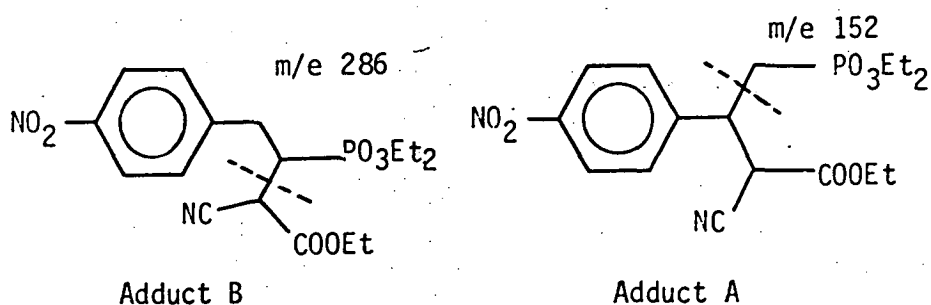


Figure 3.22 Fragmentation patterns of Michael adducts.

To remove the nitro group prior to hydrolysis of the esters adduct B was hydrogenated using 5% Pd on charcoal at atmospheric pressure. The amine thus formed was deaminated via its diazonium hydrochloride salt to give triethyl 2-cyano-4-phenyl-3-phosphonobutanoate in 51% yield. The mass spectrum of this

compound deserves comment as an auto-ionisation effect was encountered on attempts to determine the molecular ion by high resolution mass spectroscopy. Apart from this, the fragmentation pattern was similar to that observed for the nitro derivative.

To eliminate the formation of diastereomers the Michael reaction was repeated using diethyl malonate as the donor. The same difficulty was encountered in separation of the products using chromatographic techniques. A small amount of tetraethyl 3-(4-nitrophenyl)-2-phosphonopropane-1,1-dicarboxylate (adduct C) was separated by medium pressure column chromatography and characterised. The molecular ion was very weak in comparison with the previous adducts. A similar splitting pattern to that observed for adduct B was observed. Due to the larger multigram scale of the reaction, further reactions were performed on the mixture of both adducts and starting material.

The amine was obtained in a manner similar to that described with the ethyl cyanoacetate adduct. The diazotisation was carried out in 32% hypophosphorus acid, rather than proceeding via the hydrochloride salt<sup>63 124</sup>. This method was found to be more efficient. An attempt to separate the products by distillation resulted in the separation of diethyl phenylethanephosphonate from the denitrated adducts although the latter were not resolved. To determine the amount of denitrated adduct in the distillate mass spectroscopy / gas chromatography proved to be useful (see Figure 3.23).

The two denitrated adducts were then resolved using P.T.L.C. (multiple development). Tetraethyl 3-phenyl-2-phosphonopropane-1,1-dicarboxylate was obtained as an oil while tetraethyl 2-phenyl-3-phosphonopropane-1,1-dicarboxylate was obtained as transparent platelets. The P.M.R. of the latter (Figure 3.25) showed well resolved peaks for the protons associated with the ethyl ester groups indicating hindered rotation of the ester groups and a relatively rigid structure. This hindered rotation also caused splitting of the d carbon atom in the <sup>13</sup>C N.M.R. spectrum, since the psuedo-chirality of the hindered structure

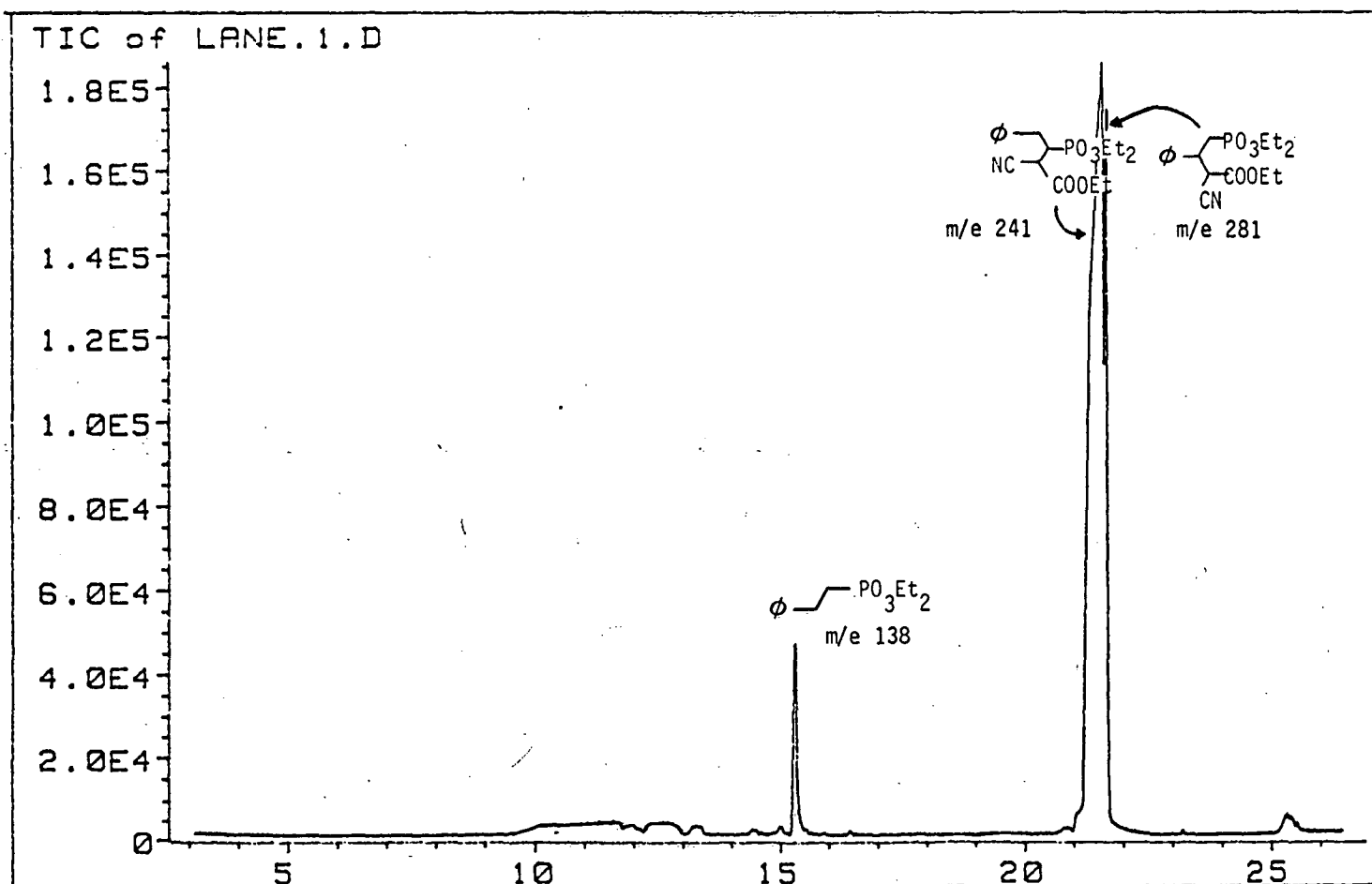


Figure 3.23 Gas chromatography / mass spectroscopy of denitrated Michael adducts and precursor.  
(parent ions given)

meant that the carboxylates would experience different fields (see Figure 3.25). The P.M.R. and  $^{13}\text{C}$  N.M.R. spectra of tetraethyl 3-phenyl-2-phosphonopropane-1,1-dicarboxylate are shown in Figure 3.24.

Both of these tetraethyl esters were hydrolysed in 1:1 aqueous solution of concentrated hydrochloric acid. The products were 3-phenyl-4-phosphonobutanoic acid (Cr43) obtained as a glass (97% yield) and 4-phenyl-3-phosphonobutanoic acid (Cr40) as a foam (88% yield). Both acids were characterised by  $^1\text{H}$ ,  $^{13}\text{C}$ ,  $^{31}\text{P}$  N.M.R. (see Figures 3.26 and 3.27). Mass spectra were not obtained due to expected facile decarboxylation. The barium salt of Cr40 was subject to analysis and I.R. spectroscopy. The small amount of Cr43 was needed for evaluation of this acid as a collector, therefore the barium salt of this acid was not prepared. It is noteworthy that the P.M.R. of the latter acid shows methylene proton signals adjacent to the phosphorus as an apparent doublet of doublets. The two protons experience the same field (no geminal coupling) with  $J_{\text{P-H}} = 18.2\text{Hz}$  and coupling to the benzylic proton ( $J = 6.7\text{Hz}$ ). The difference between the P.M.R. of the acid and its diethyl ester (see Figure 3.14) is due to the less hindered rotation of the acid groups when compared with the sterically hindered ester functionalities.

Unfortunately, the yield of 3-phenyl-4-phosphonobutanoic acid (Cr43), the initial target compound, was low (426mg for 10g of diethyl 4-nitrostyrenephosphonate). However, the other acid obtained was of interest and also not previously reported in the literature. The conditions for the reactions have not been optimised but yields obtained also reflect substantial mechanical losses in numerous attempts at separation of the adducts.

In summary, this work demonstrated that Michael reactions on substituted styrenephosphonates are possible and further work on other derivatives may improve the yields. Further work may involve different conditions for the Michael reaction or alternative methods for negating the effect of the aromatic ring

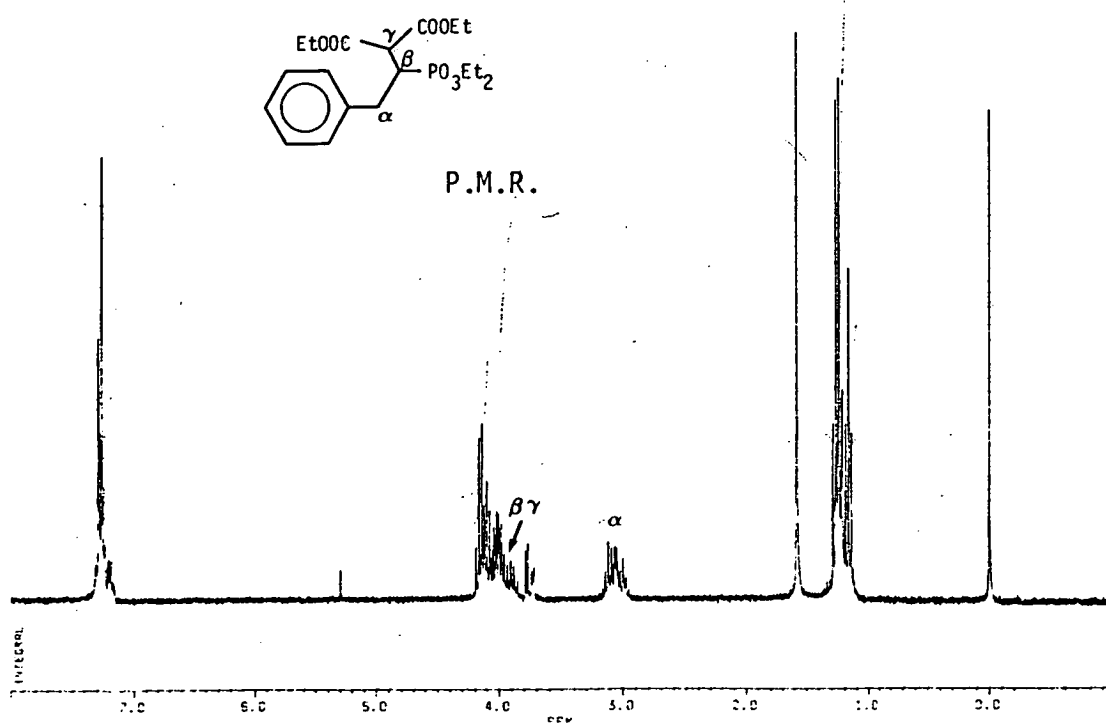
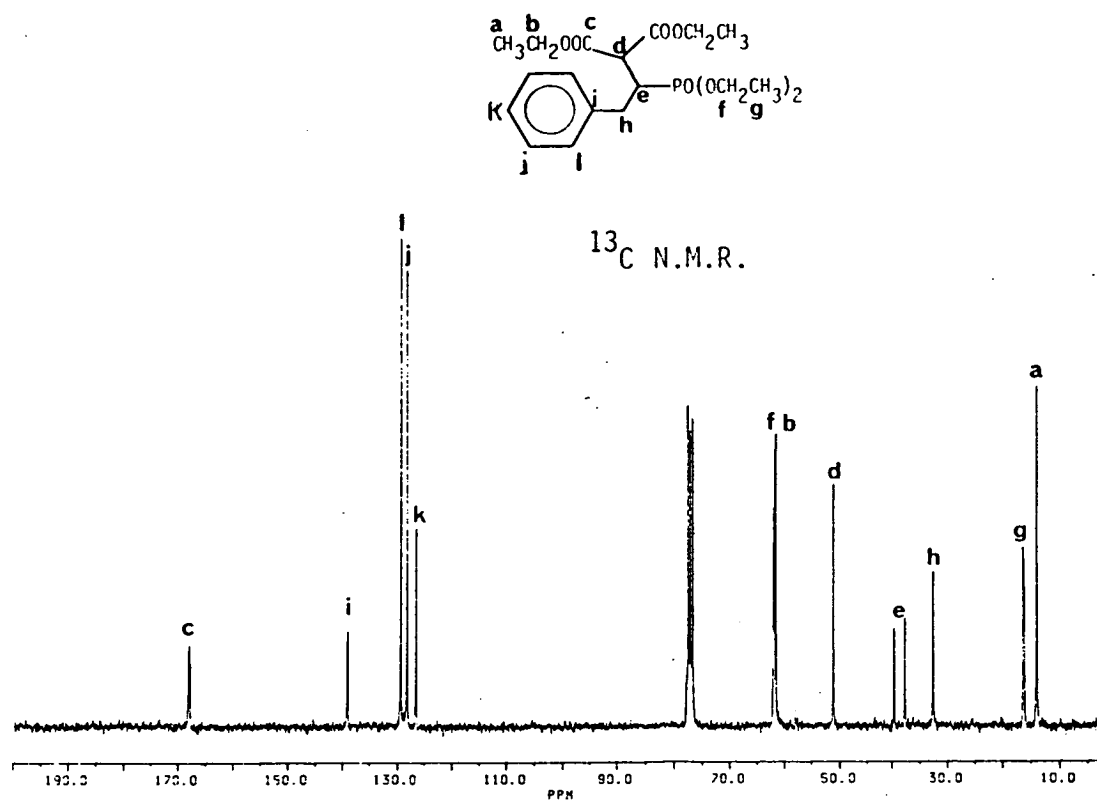


Figure 3.24 P.M.R. and  $^{13}\text{C}$  N.M.R. of tetraethyl 3-phenyl-2-phosphono propane-1,1-dicarboxylate.

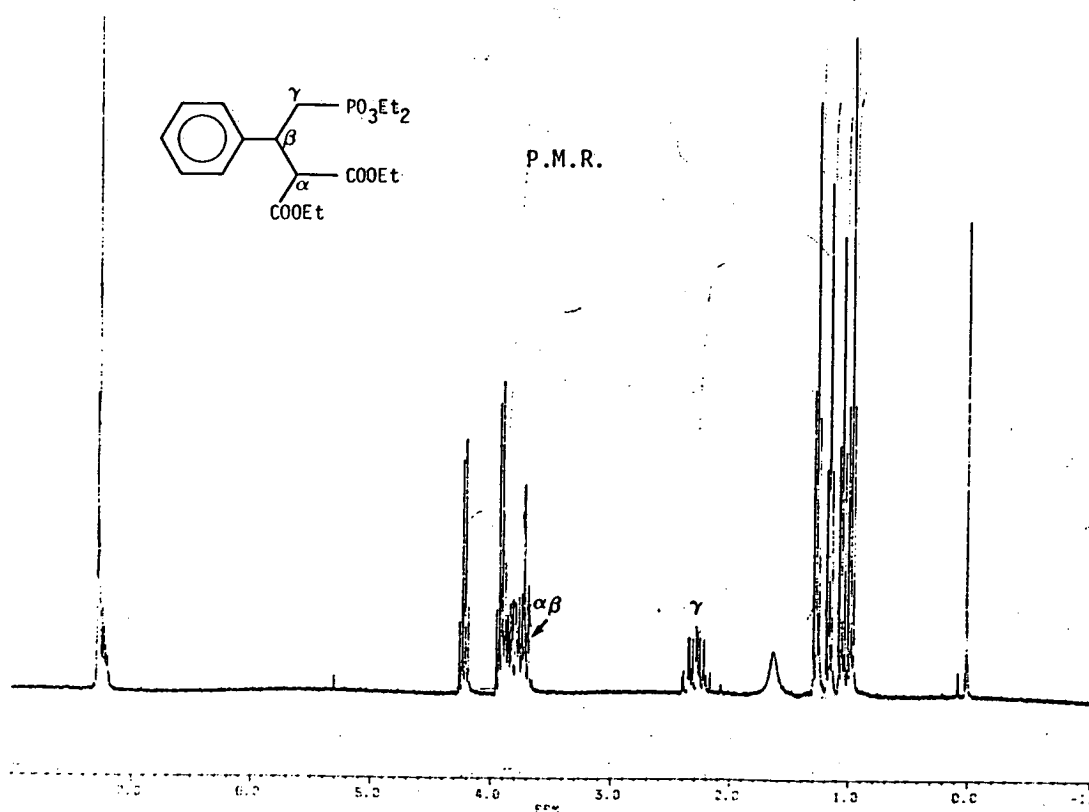
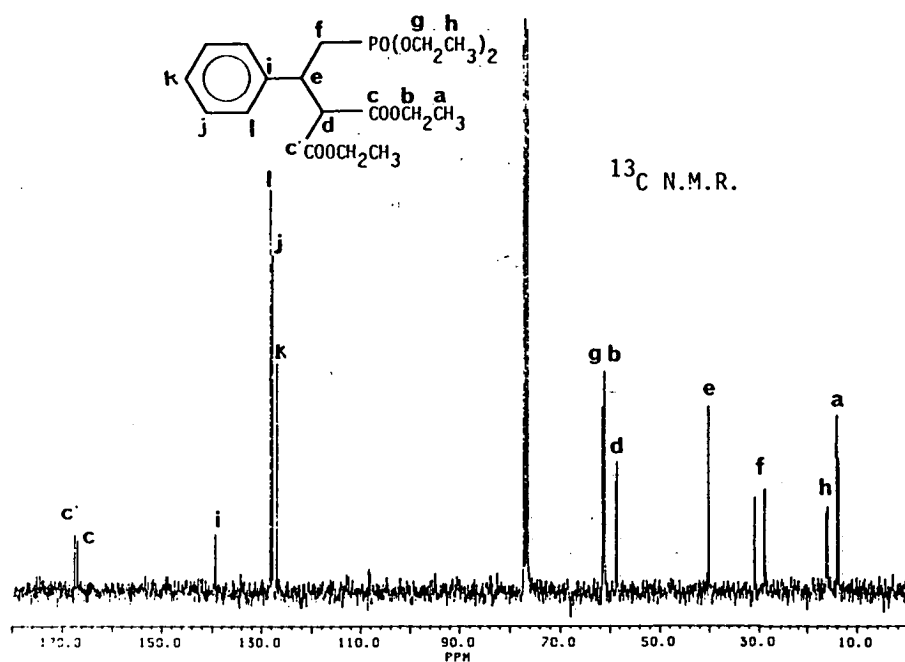


Figure 3.25 P.M.R. and <sup>13</sup>C N.M.R. of tetraethyl 2-phenyl-3-phosphonopropane-1,1-dicarboxylate

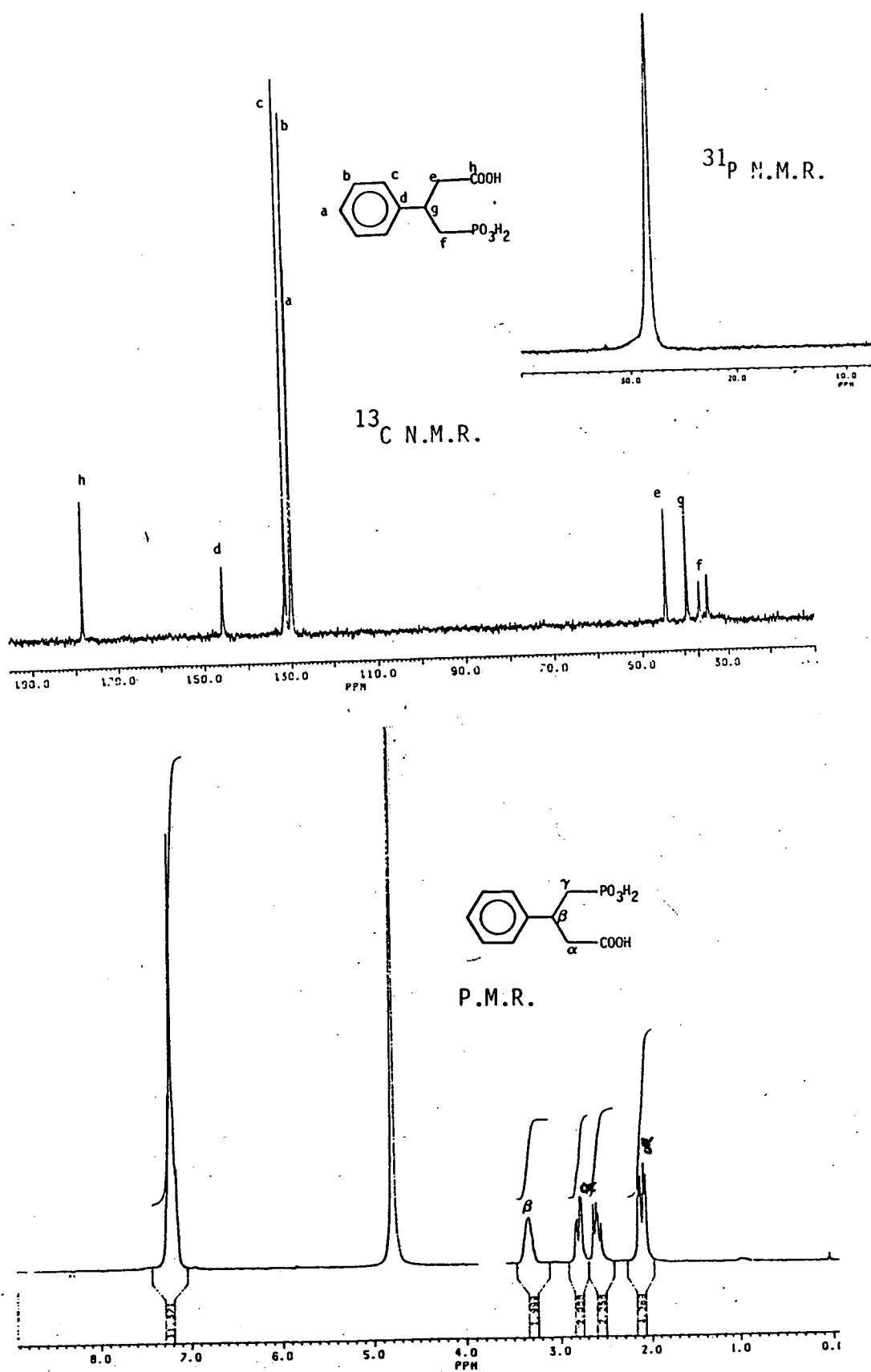


Figure 3.26 N.M.R. spectra of 3-phenyl-4-phosphonobutanoic acid.



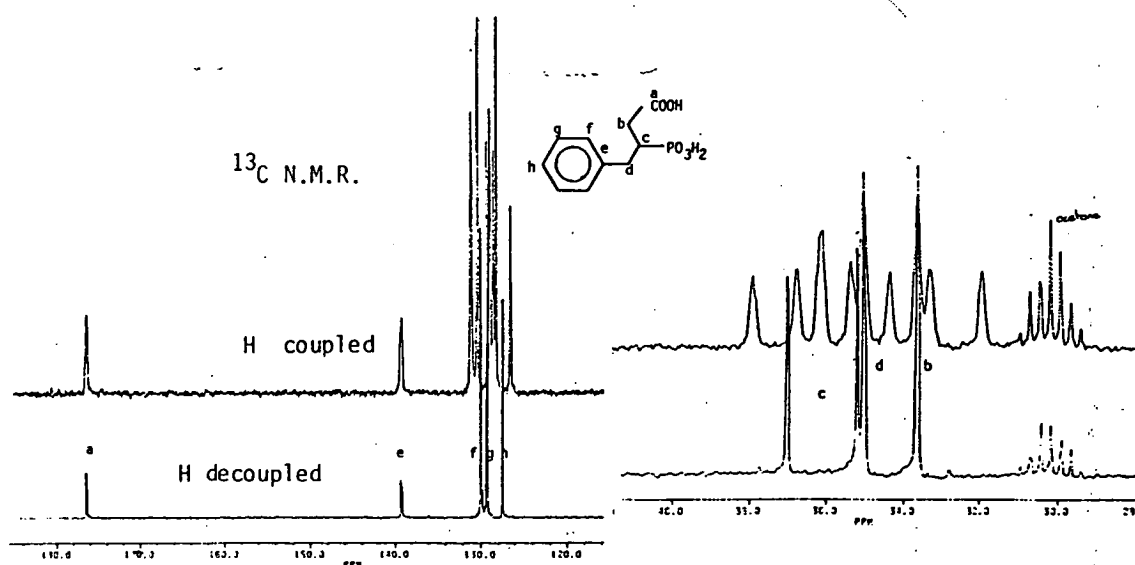
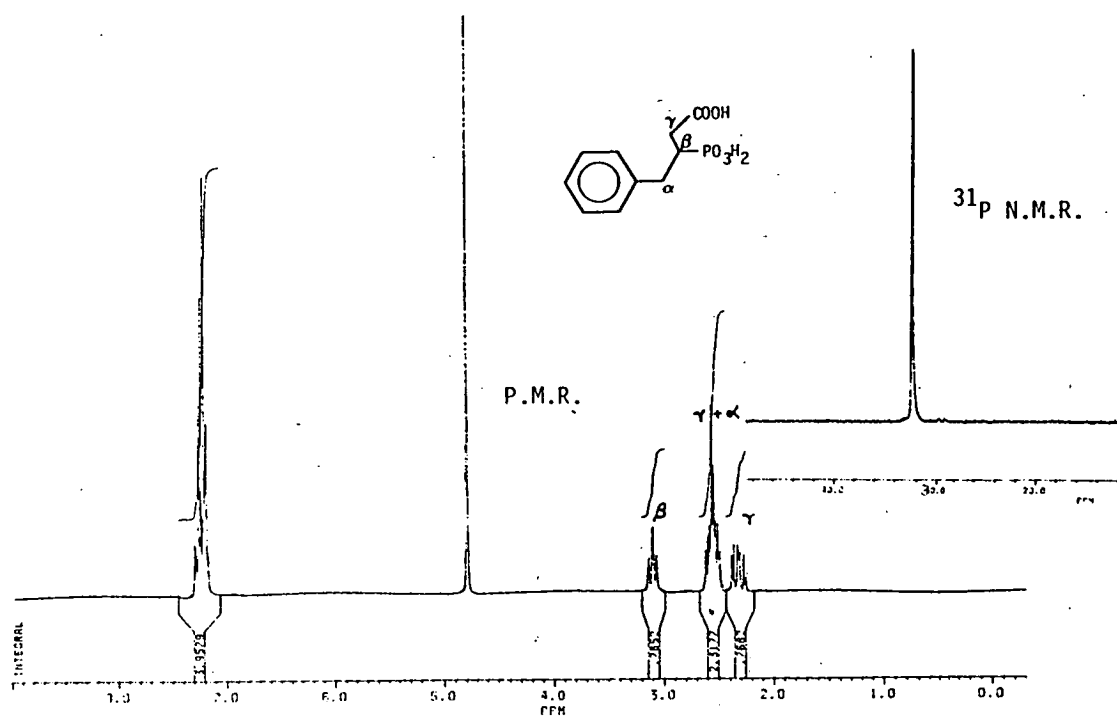


Figure 3.27 N.M.R. spectra of 4-phenyl-3-phosphonobutanoic acid.

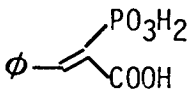
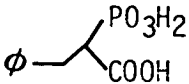
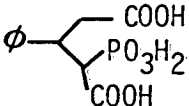
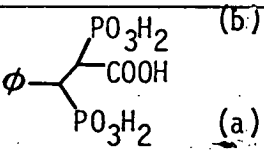
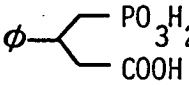
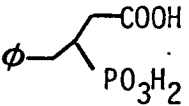
on the  $\alpha,\beta$ -unsaturated phosphonate entity.

Thus, two methods were found for the synthesis of the esters of 3-phenyl-4-phosphonobutanoic acid (Cr43). Firstly, via an Arbusov reaction using 4-bromo-3-phenylbutanoate and triethylphosphite and secondly, by a Michael reaction on diethyl 4-nitrostyrenephosphonate. Yields in both cases were unfortunately low. However, the former method provided the by-product 3-phenylbutyrolactone that could be recycled, and the latter method gave a second Michael reaction product that was hydrolysed and assessed as a collector.

### 3.5 <sup>31</sup>P N.M.R. Spectra of Phosphonocarboxylic acids.

During the course of the work performed for this part of the study it became evident, when dealing with the phosphonocarboxylic acids, that the <sup>31</sup>P chemical shift for the phosphonate group could be used as an indication of the substitution pattern adjacent to this group. The chemical shifts obtained for the acids and esters studied are presented in Table 3.2. The peak at highest field (9.3ppm) is observed for the unstable 3-phenyl-2-phosphonopropenoic acid containing a conjugated  $\alpha,\beta$ -unsaturated bond and an  $\alpha$ -carboxylic acid. The saturated analogue displayed a <sup>31</sup>P resonance considerably further downfield (19.9ppm), while other additionally substituted phosphonocarboxylic acids displayed signals at characteristic intermediate fields. The <sup>31</sup>P chemical shift was therefore a useful tool for the elucidation and confirmation of structures for the phosphonocarboxylic acids.

Table 3.2  $^{31}\text{P}$  N.M.R. chemical shifts for the phosphono-carboxylic acids.

STRUCTURE	$^{31}\text{P}$ Chemical Shift (ppm)
	10.4, 9.3
	19.9
	15.4, 14.6
	(a) 25.8, 25.6 (b) 18.4 18.4
	28.3
	32.5

CHAPTER 4. Dissociation Constants and Mechanisms of Adsorption  
for Some of the Cr Series Collectors.

To investigate the chemistry of the Cr series collectors in solution, and the effect of this on their adsorption on surfaces, acid dissociation constants of a number of the collectors were determined with the use of an automated equilibrium titrator. (For further information on this system see Chapter 7.9).

The results obtained are displayed in Table 4.1. They may also be correlated with respect to structure as in Figure 4.1. The pKa values determined in this study were slightly lower than those found for analogous acids in the literature, presumably due to the use of 1M sodium chloride as an electrolyte for the determinations in the work presented here.

Several points of interest arise from the acid dissociation constants obtained for the collectors assessed during this work. Firstly, substitution in the para-position of the aromatic ring has little effect on the dissociation constant of the carboxylic acids. Secondly, 1,1-dicarboxylic acids have one fully dissociated acid entity and one partially dissociated acid, at equilibrium, at the pH at which the flotation of cassiterite is carried out (pH 4.5). Thirdly, the effect of an adjacent double bond is to further reduce the pH at which both acids are dissociated, presumably due to the decreased electron density of the carboxylate group adjacent the conjugated double bond.

Table 4.1 Dissociation constants in 1M NaCl for some Cr series collectors.

COLLECTOR	$pK_{a1}$	$pK_{a2}$	$pK_{a3}$
Cr28	$4.866 \pm 0.022$	$3.975 \pm 0.014$	$1.530 \pm 0.034$
Cr36	$8.629 \pm 0.016$	$1.375 \pm 0.027$	
Cr19	$4.618 \pm 0.016$	$3.230 \pm 0.008$	
Cr2	$4.525 \pm 0.025$	$1.474 \pm 0.028$	
Cr11	$4.547 \pm 0.019$	$3.641 \pm 0.010$	
Cr3	$4.733 \pm 0.027$	$2.056 \pm 0.018$	
Cr5	$4.021 \pm 0.021$	less than 2	
Cr23	$4.878 \pm 0.014$	$3.980 \pm 0.010$	$1.841 \pm 0.012$
Cr27	$4.939 \pm 0.016$	$4.017 \pm 0.013$	$1.629 \pm 0.025$
Cr25	$4.919 \pm 0.016$	$4.020 \pm 0.012$	$1.742 \pm 0.018$
Cr24	$4.924 \pm 0.015$	$4.023 \pm 0.012$	$1.780 \pm 0.016$
Cr41	$7.252 \pm 0.015$	$4.288 \pm 0.030$	less than 2

Table 4.2 Literature values for the pK<sub>a</sub>'s of various organic acids.

Acid	pK <sub>a</sub> 's		Ref.
phenylethene-1,1-dicarboxylic acid	2.39	5.50	146
(in 50% EtOH)	4.0	6.70	86
malonic acid	2.83	5.69	46
succinic acid	4.16	5.61	145
maleic acid	1.83	6.07	145
glutaric acid	4.34	5.41	46
fumaric acid	3.03	4.44	145
octane-1,1-dicarboxylic acid	2.99	6.21	131
undecane-1,1-dicarboxylic acid	3.93	5.84	24
tetradecane-1,2-dicarboxylic acid	4.67	5.35	24
undecane-1,3-dicarboxylic acid	4.46	5.52	24
tetradecane-1,2,2-tricarboxylic acid	3.81, 5.04, 8.86		24
tetradecane-1,1,6,6-tetracarboxylic acid	2.44, 3.42, 5.95, 7.89		24
p-toluenearsonic acid	3.77	8.73	64
styrenephosphonic acid	2.00	7.10	29
CA540	2.3	5.8	125

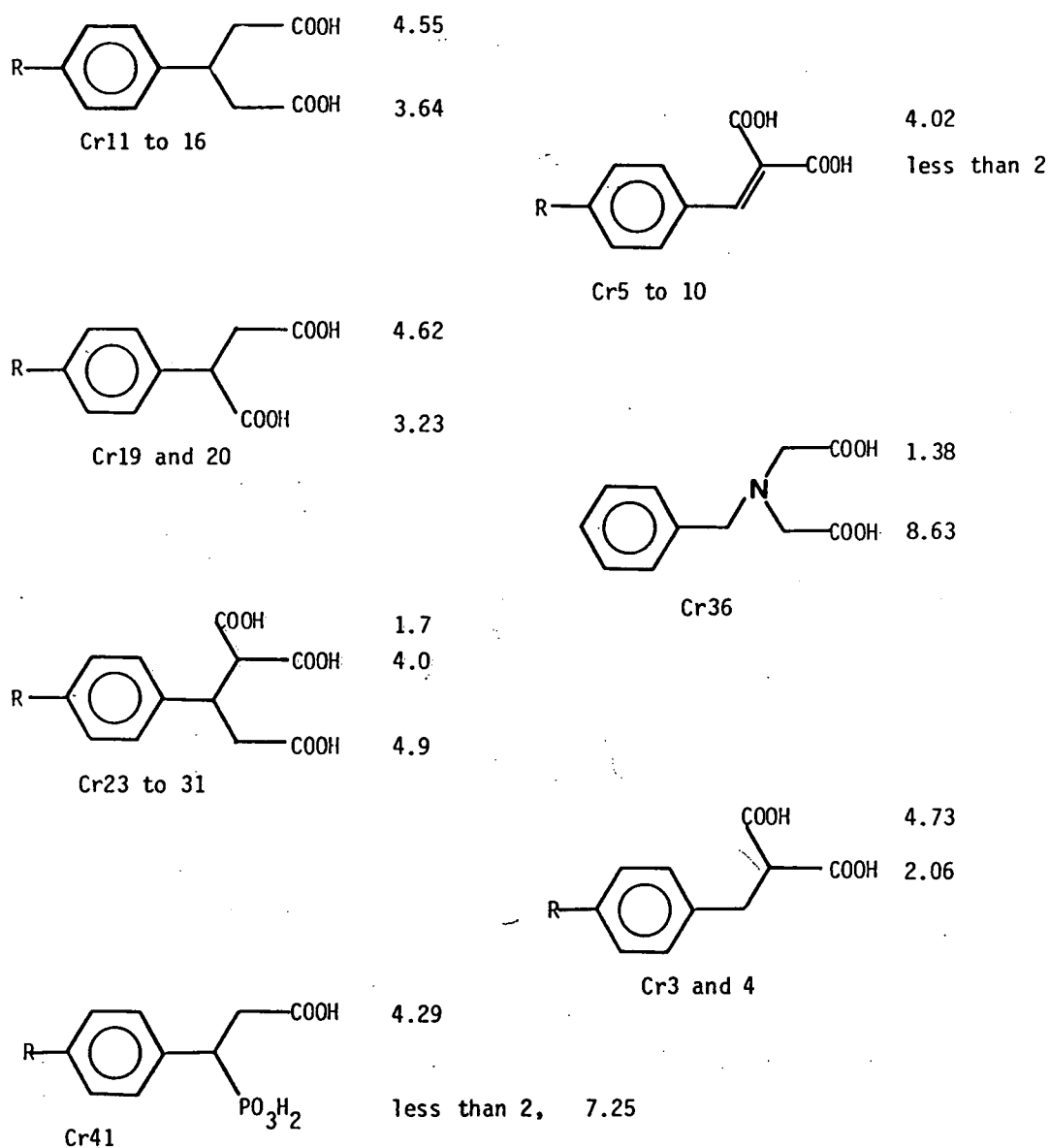


Figure 4.1 Dissociation constants for various acids.  
Structural correlation.



The  $pK_a$ 's of polycarboxylic acid Cr36 indicated that the second proton is associated with the nitrogen atom to give a structure more like that in Figure 4.2.

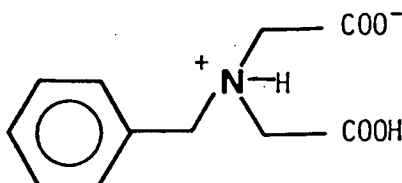


Figure 4.2. N-Benzyliminodiacetic acid.

At pH 4.5 the phosphonocarboxylic acids investigated contain a monoprotic phosphonic acid group and a partly dissociated carboxylic acid group. Work carried out by Kuys<sup>74</sup> using attenuated total reflectance Fourier transform infrared spectroscopy indicated that the carboxylic acids and phosphonic acids formed salt-like complexes at the oxide surface during the adsorption process. The formation of these salts and the information on dissociation constants, indicated that the protonated acid species in solution must deprotonate during adsorption via a dehydration mechanism as illustrated in Figure 4.3. Salient points from Kuy's work included the absence of phosphorus - oxygen double and single bonds in the phosphonate - cassiterite chemisorbed complex. Rather, a delocalised doubly negatively charged phosphonate anion entity exists. Mossbauer spectroscopy of tin(IV) phosphonates indicated an ionic character, supporting a salt-like structure<sup>103</sup>.

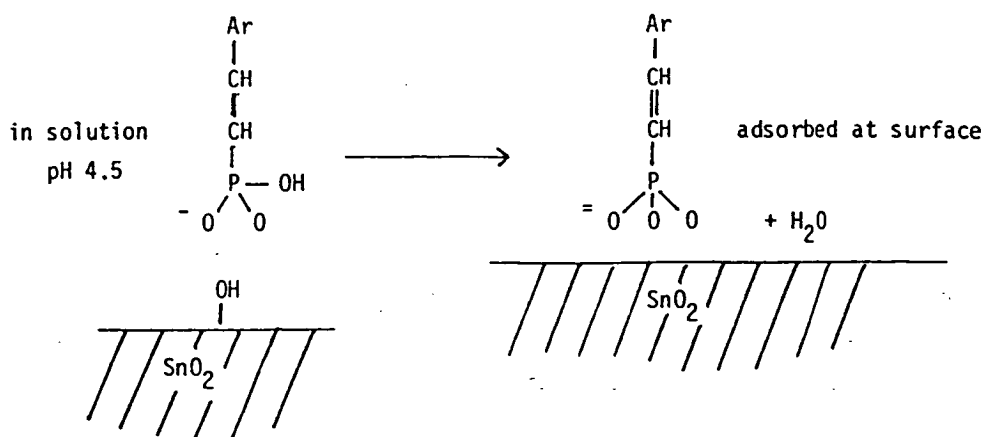


Figure 4.3 Adsorption of collectors on cassiterite.

This mechanism of dehydration on adsorption is supported by the recent work of Farrow, Houchin and Warren<sup>43</sup>. However, their interpretation of their results included the formation of six-membered ring complexes between the phosphonate and tin atom in the cassiterite matrix (Figure 4.4).

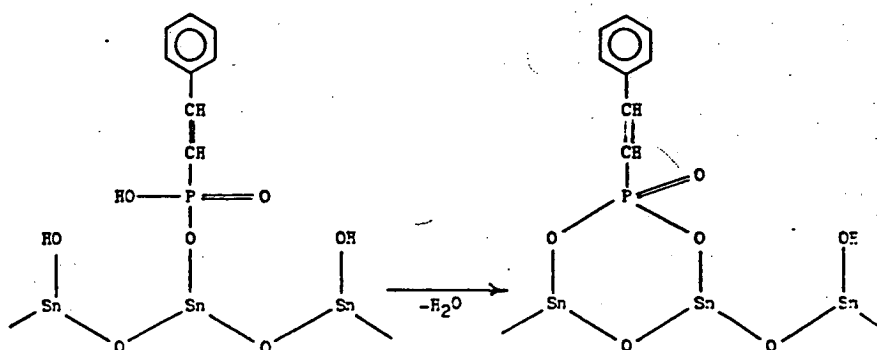


Figure 4.4 Farrow, Houchin and Warren's proposed phosphonate-cassiterite complex.

The above structure seems inconsistent with the delocalised doubly negatively charged phosphonate anion entity proposed from Kuys' work. Rather, a partially ionic chemisorbed entity as in Figure 4.3 is most likely.

In the case of the polycarboxylic acids, some protonated

carboxylate species were observed in the F.T.I.R. spectrum of the acid-cassiterite adsorption complex. This indicated the presence of a hydrogen bonding interaction as part of the adsorption process in a reversible adsorption mechanism. The carboxylic acid entity is apparently in an equilibrium between protonation and complex or salt formation, where hydrogen bonding is perhaps the initial step of the adsorption mechanism.

Kuys' analysis of results was incomplete due to the complexity of the spectra. He did not identify the bonding mode existing at the surface other than to say the  $\nu_{\text{C-O}}$  values for the polycarboxylic acids "are in the general range associated with unidentate co-ordination". However, a review by Deacon and Phillips<sup>40</sup> on carboxylate complexation concluded that  $\nu_{\text{C-O}}$  values  $>200\text{cm}^{-1}$  were generally associated with unidentate or unsymmetrical bidentate bridging ligand. They stressed that there was no unequivocal example of a unidentate acetato complex with this value less than  $200\text{cm}^{-1}$ . Also, all acetato complexes with  $\nu_{\text{C-O}} < 150\text{cm}^{-1}$  (or  $171\text{cm}^{-1}$  for ionic compounds) contain chelating or bridging carboxylate groups.

Considering these interpretations and Kuys' results, as shown in Table 4.3, further conclusions may be made.

Table 4.3 Infrared results from the adsorption of collectors on cassiterite<sup>74</sup>.

Collector	No. of COOH groups	$\nu_{\text{C-O}}$ $\text{cm}^{-1}$
Cr20	2	174
Cr12	2	162
Cr24	3	176
Cr28	3	188, 212

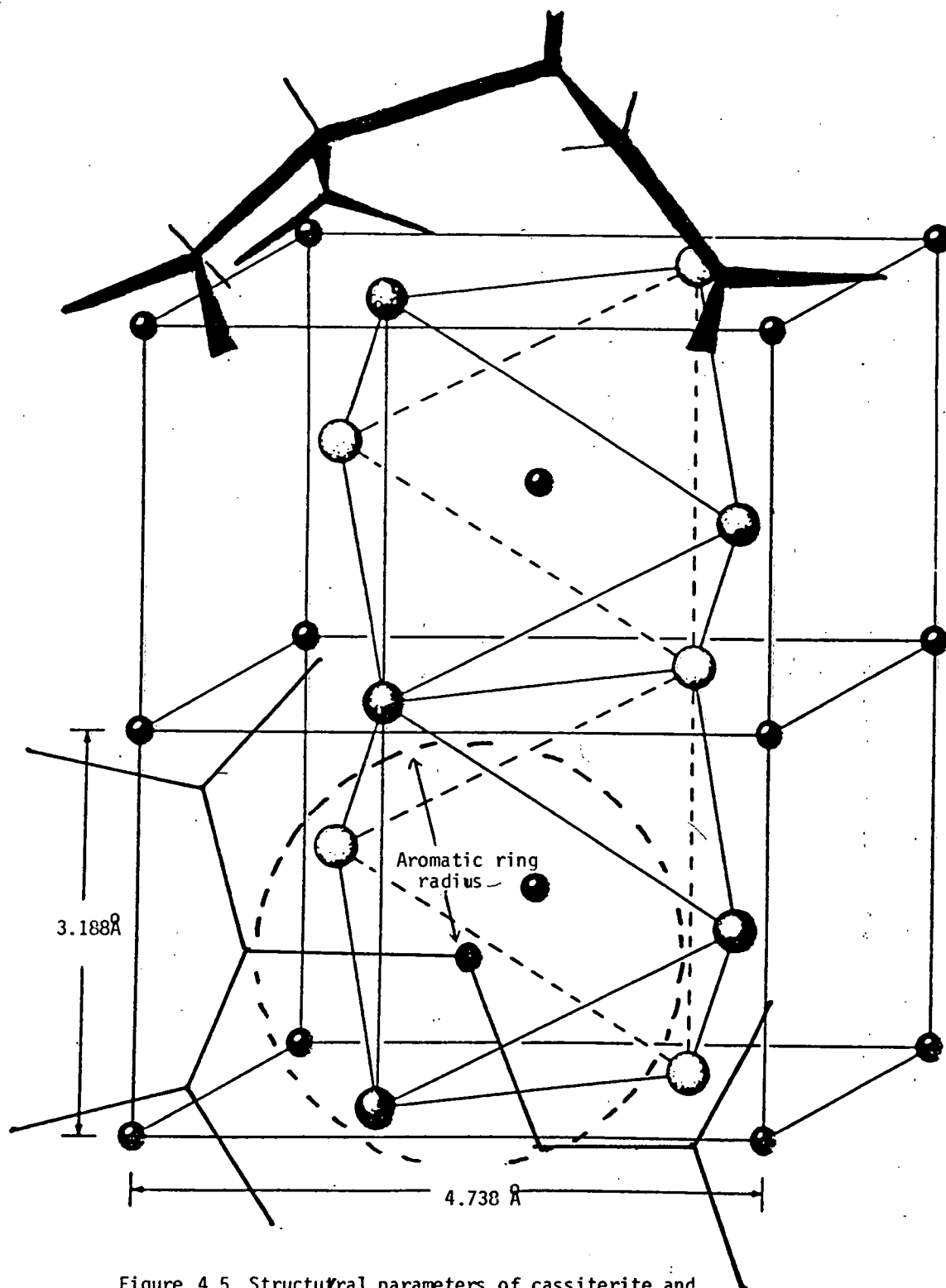


Figure 4.5 Structural parameters of cassiterite and the superimposition of a 2-phenylpropane-1,1,3-tricarboxylic acid structure.

It can be seen that the results above are intermediate between the expected unidentate and bidentate values proposed by Deacon and Phillips. The spectra are, in fact, similar to those obtained for tin tetraacetate, a compound known to contain bidentate acetate ligands ( $\nu_{\text{C-O}}^{40}$  of  $153\text{-}175\text{ cm}^{-1}$ ). With the exception of Cr28, the collectors displayed values in the range  $162\text{ to }176\text{ cm}^{-1}$  indicating the complexes or salts are most likely bidentate (unsymmetrical, symmetrical or bridged). The formation of bridging carboxylate ligands seems doubtful due to a  $3.2\text{ \AA}$  metal - metal distance in the cassiterite lattice. Similarly formal unidentate bonding can be eliminated as a major form of bonding to the cassiterite surface on the basis of current literature on tin carboxylate structures (see Deacon and Phillips and references therein).

It is instructive to superimpose a model of one of the polycarboxylic acids on a model of a cassiterite lattice (see Figure 4.5). This suggests that the proposed collectors may be capable of adsorption in the manner illustrated, although the model is in no way intended to be definitive for the adsorption of these compounds.

## CHAPTER 5. Assessment of the Flotation Activity of Aryl-substituted Polycarboxylic Acids and Aryl-substituted Phosphonocarboxylic Acids, and Correlation of Structural Features with Collector Activity.

### 5.1 Introduction and Flotation Results.

Assessment of the flotation activity of the collectors described in the previous chapters was carried out by Aberfoyle Ltd., Burnie, using the procedure outlined in Appendix A. Cassiterite from the Cleveland Tin Mine was predominantly used, along with some testing on cassiterite from the Ardlethan Tin Mine (N.S.W.), and some other oxide ores. It should be noted that 79% tin is equivalent to 100% cassiterite and thus the maximum grade obtainable on flotation.

The Cleveland cassiterite ore was approximately 50 to 58% silica ( $\text{SiO}_2$ ) after sulfide flotation, as outlined in Appendix C. The feed ore used for testing purposes was approximately 1.10% tin (see Table 5.1 for exact feed grades) except where a coarse feed (6.00% tin) was used for examination of the flotation characteristics of Cr28 on coarse ores.

The Ardlethan ore was approximately 0.85% tin containing 75-80%  $\text{SiO}_2$ . This ore also contained 0.36%  $\text{TiO}_2$ .

The results of the numerous tests carried out are presented in Tables 5.1 and 5.2, and, in part, in Graphs 1 to 20 at the end of this Chapter. Styrenephosphonic acid (SPA) was used as a standard for comparison of the collector efficiency (tin grade and recovery in the concentrate). A commercial collector CA540 was also assessed under the standard conditions used for comparison between the different structural types of collectors. These conditions were the optimum conditions for the use of SPA but not necessarily for the Cr series collectors. However, time did not permit optimisation of all flotation parameters for each Cr collector.

Table 2.1 Correlation table of aryl-substituted polycarboxylic acids.

R	1	2	3	5	11	17	19	21	22	23	32	33	36	37
H														
Me			4	6	12	18	20			24	32	34		
Et				7	13					25		35		
i-Pr										26				
MeO				8	14					27				
di MeO				9										
EtO				10	15					28				
n-PrO					16					29				
i-PrO										30				
n-BuO										31				

Table 3.1 Correlation table for aryl-substituted phosphono-carboxylic acids.

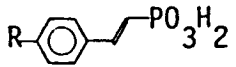
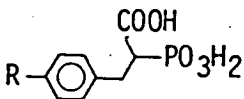
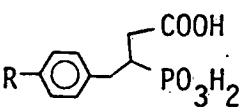
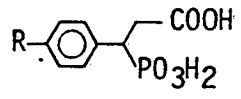
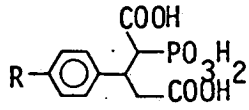
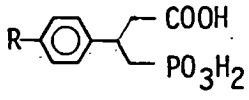
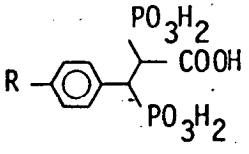
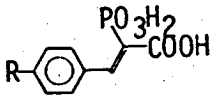
	R	
	H	Me
	S.P.A.	38
	39	
	40	
		41
	42	46
	43	
	44	
	45	



Table 5.1 Cassiterite Flotation Results, OC 1-4.

TEST No.	Cr No.	Cr Kg/t	SSF Kg/t	Grade %Sn	Rec. %Sn	Flot. Time (min.)	Feed %Sn	Graph No.	Coll. Crit. K
LW									
189	SPA	0.30	0.35	13.0	94.0	10	1.08	1	1037
233	SPA	0.30	0.32	10.6	93.4	10	0.85 *		1082
145	SPA	0.35	0.30	4.7	91.0	12	0.38 *	9	1034
191	CA540	0.30	0.35	8.5	85.0	10	1.02	1	623
240	1	0.50	0.32	1.2	1.5	10	1.09	2	-
215	2	0.35	0.33	1.9	3.9	10	1.11	2	3
216	3	0.35	0.33	22.4	92.3	10	1.00	2	1975
275	3	0.30	0.42	11.0	78.1	10	1.02		764
248	4	0.30	0.35	8.9	88.2	10	1.05	3	641
256	4	0.30	0.20	4.8	97.2	10	1.10		62
226	5	0.40	0.33	17.6	85.6	10	1.05	2	1350
276	5	0.30	0.42	10.8	79.7	10	1.04		748
200	6	0.30	0.35	18.0	94.7	10	1.07	3	1587
224	6	0.25	0.60	28.3	90.4	13	1.14	20	2154
210	7	0.25	0.35	6.6	97.4	10	0.99	4	552
271	7	0.27	0.65	4.2	97.0	10	0.80 *		412
237	8	0.27	0.34	21.6	90.4	10	1.09	6	1701
273	9	0.30	0.35	12.1	69.1	10	0.98	6	784
236	10	0.25	0.34	9.1	96.7	10	1.08	6	718
227	11	0.40	0.33	9.5	22.0	10	1.10	2	168
Ref19	11	2.00		10.1	48.1		0.38		1230
139	12	0.40	0.38	26.0	92.2	12	1.00	3	2305
143	12	0.42	0.38	14.5	93.6	12	1.10		1140
167	12	0.57	0.38	4.8	79.6	12	0.41 *		852
165	12	0.40	0.48	16.2	89.6	12	1.06		1280
166	12	0.40	0.36	14.3	92.2	12	1.12		1085
185	12	0.35	0.36	13.7	93.4	10	1.12		1049

TEST	Cr	Cr	SSF	Grade	Rec.	Flot.	Feed	Graph Coll.
No.	No.	Kg/t	Kg/t	%Sn	%Sn	Time	%Sn	No. Crit.
						(min.)		K
LW								
199	13	0.30	0.35	8.3	94.0	10	1.03	9 663
170	14	0.40	0.36	14.6	95.6	12	1.08	1197
218	14	0.35	nil	19.8	69.3	10	1.14	1134
219	14	0.20	0.35	15.6	42.7	10	1.04	598
222	14	0.55	0.39	27.9	79.7	10	1.00	9 2120
175	14	0.33	0.36	6.5	10.2	12	1.04 #	54
208	15	0.31	0.31	14.5	95.0	10	1.10	9 1157
187	16	0.35	0.36	9.5	92.9	10	1.13	9 688
228	17	0.40	0.33	18.8	92.0	10	0.94	2 1758
262	18	0.30	0.35	7.4	96.6	10	1.01	3 611
239	19	0.40	0.33	22.2	73.0	10	0.95	2 1633
252	20	0.30	0.35	13.9	92.4	10	0.98	3 1218
259	20	0.30	0.20	5.6	96.4	10	0.93	484
263	21	0.30	0.35	0.8	1.9	10	0.98	11 -
264	22	0.30	0.35	20.1	55.5	10	1.05	2 1007
242	23	0.40	0.33	20.4	61.8	10	1.10	2 1084
249	24	0.30	0.35	15.7	91.2	10	1.07	3 1247
257	24	0.30	0.20	13.8	96.5	7	1.07	1148
246	25	0.30	0.35	7.4	95.5	10	0.97	10 633
254	25	0.30	0.60	13.6	96.3	10	1.00	1213
269	25	0.30	0.35	6.2	97.6	10	1.06	10 473
270	25	0.30	0.90	10.3	97.7	10	1.15	777
247	26	0.30	0.35	5.1	96.0	10	1.01	10 389
255	26	0.30	0.60	7.0	93.7	10	1.09	508
243	27	0.30	0.35	22.6	81.7	10	1.45	10 1192

TEST No.	Cr No.	Cr Kg/t	SSF Kg/t	Grade %Sn	Rec. %Sn	Flot. Time (min.)	Feed %Sn	Graph No.	Coll. Crit. K
-------------	-----------	------------	-------------	--------------	-------------	-------------------------	-------------	--------------	---------------------

LW

174	28	0.40	0.38	8.1	96.7	12	1.10		615
197	28	0.30	0.35	13.9	97.2	10	1.00	10	1254
220	28	0.15	0.35	25.8	91.8	13	1.07	19	2122
221	28	0.25	0.70	36.5	92.9	10	1.09		3018
223	28	0.25	0.60	33.1	96.0	12	1.10	19	2793
230	28	0.62	0.76	55.0	87.3	10	6.11 +	18	698
231	28	0.45	0.55	51.5	84.0	10	5.92 +		647
232	28	0.40	0.35	15.7	88.2	10	0.96 ^		1354
229	28	0.27	0.62	14.6	83.9	12	0.77 *	19	1507
246A	28	0.23	0.31	13.6	93.4	10	0.72 *	19	1670
196	28	0.30	0.20	22.1	95.4	10	1.02 #		1972
186	29	0.30	0.37	4.9	96.4	10	1.08		341
244	29	0.20	0.35	12.9	96.4	10	1.03	10	1111
245	29	0.22	0.80	23.5	94.0	10	1.11	20	1896
250	30	0.30	0.35	7.8	96.1	10	1.10	10	585
258	30	0.30	0.60	13.3	96.5	10	1.04		1137
217	31	0.15	0.35	10.0	91.5	10	1.06	10	771
238	32	0.30	0.34	13.4	44.6	10	1.05	3	524
169	33	0.82	0.36	0.7	1.0	6	1.05		-
168	34	0.50	0.36	0.8	1.5	6	1.19		-
241	36	0.60	0.32	0.9	3.0	9	1.01		-
261	37	0.30	0.35	0.9	3.0	10	1.03		-
251	38	0.30	0.35	4.9	93.1	10	1.06	13	337
266	39	0.30	0.35	9.9	97.3	10	0.98	12	886
268	40	0.30	0.35	7.6	97.3	10	0.98	12	657
253	41	0.30	0.35	9.9	94.7	10	1.02	13	824
260	41	0.30	0.60	13.8	96.4	10	1.03		1195
267	42	0.30	0.35	2.5	8.0	10	1.10	12	10
272	43	0.30	0.35	11.9	97.5	10	1.08	12	976
265	44	0.30	0.35	0.9	2.6	10	0.95	12	-
277	45	0.30	0.35	6.4	97.0	10	0.98	12	536
274	46	0.30	0.35	8.1	97.7	10	1.12	13	609

# Pretreated  
+ Coarse feed (FTT Feed)  
\* Ardlethan Feed, Ardlethan Tin Mine, N.S.W.  
^ Coarse grind feed, no deslime.

Table 5.2 Cassiterite Flotation Results, OC 1.

TEST No.	Cr No.	Grade %Sn	Rec. %Sn	Flot. time (min.)	Collins' Criterion.
LW					K
189	SPA	27.6	66.5	2	1633
233	SPA	18.9	61.9	2	1314
191	CA540	15.7	41.6	2	599
240	1	1.0	0.6	2	-
215	2	1.3	0.8	2	-
216	3	26.6	35.2	2	901
248	4	18.8	53.3	2	901
256	4	17.9	83.6	2	1254
276	5	10.7	19.1	2	181
226	5	19.3	19.6	2	340
200	6	43.9	81.1	2	3246
224	6	46.3	55.2	2	2186
210	7	20.6	88.8	2	1759
271	7	13.5	89.4	2	1419
237	8	37.4	57.1	2	1902
273	9	12.3	19.7	2	278
236	10	24.2	77.1	2	1657
227	11	2.2	1.4	2	1
139	12	37.6	58.0	3	2122
143	12	31.5	70.8	3	1957
167	12	9.1	65.6	3	1390
165	12	32.9	49.3	3	1480
166	12	33.5	70.6	2	2041
185	12	31.8	57.5	2	1575
199	13	26.9	72.2	2	1813

TEST No.	Cr No.	Grade %Sn	Rec. %Sn	Flot time (min.)	Collins' Criterion
-------------	-----------	--------------	-------------	---------------------	-----------------------

LW

K

170	14	30.8	67.5	3	1857
218	14	21.5	21.9	2	391
219	14	7.9	7.6	2	50
222	14	32.1	39.2	2	1219
175	14	3.1	2.4	3	5
208	15	28.7	49.5	2	1242
187	16	38.1	80.0	2	2617
228	17	26.2	41.0	2	1102
262	18	25.2	87.3	2	2090
239	19	7.7	1.4	2	10
252	20	25.6	52.2	2	1311
259	20	15.7	72.1	2	1145
263	21	0.8	0.9	2	-
264	22	11.3	7.2	2	70
242	23	4.7	2.9	2	9
249	24	27.1	43.1	2	1048
257	24	29.3	76.5	2	2018
246	25	22.1	87.1	2	1897
254	25	36.9	85.2	2	3059
269	25	20.0	89.3	2	1596
270	25	31.3	89.7	2	2352
247	26	15.7	91.9	2	1337
255	26	25.1	88.6	2	1952
243	27	22.8	17.1	2	252

TEST No.	Cr No.	Grade %Sn	Rec. %Sn	Flot. time (min.)	Collins Criterion
LW				K	
174	28	21.9	89.1	3	1685
197	28	37.2	89.5	2	3239
220	28	41.6	53.0	2	2008
221	28	48.4	68.7	2	2982
223	28	51.8	80.6	2	3715
230	28	62.4	50.0	2	461
231	28	62.9	28.0	2	270
232	28	35.2	63.4	2	2261
229	28	30.4	64.6	2	2486
246A	28	29.5	80.1	2	3202
196	28	44.2	81.0	2	3429
186	29	9.5	86.0	2	670
244	29	37.4	86.9	2	3069
245	29	42.4	82.4	2	3065
250	30	25.4	83.3	2	1840
258	30	37.0	87.9	2	3039
217	31	26.3	82.3	2	1950
238	32	10.0	7.9	2	67
169	33	0.6	0.5	3	-
241	36	1.0	1.4	2	-
261	37	0.9	0.8	2	-
251	38	17.5	86.4	2	1340
266	39	33.2	66.1	2	2173
268	40	20.1	87.6	2	1709
253	41	23.6	80.8	2	1789
260	41	31.1	79.0	2	2306
267	42	1.9	0.5	2	-
272	43	26.0	48.1	2	1110
265	44	0.9	0.9	2	-
277	45	21.0	69.8	2	1426
274	46	25.3	79.4	2	1714

The flotation conditions (amount of collector and sodium fluoro-silicate (SSF)) were varied for a number of the proposed collectors and optimum conditions, usually slightly different than the standard conditions, were obtained.

For the purposes of the discussion of the results and the correlation of structural features with collector efficiency, a number of the results are presented graphically within this Chapter. Interpretation of these graphs in a simplified form, may be carried out by assuming that the better the recovery and grade the further the curve will tend to the upper right hand corner of the graph. The initial point on the graph, closest to the horizontal axis, represents the recovery and grade found for the first oxide concentrate (OC 1) after two or three minutes of flotation time (see Table 5.2 for complete listing). The terminal point on the curve (usually closest to the upper lefthand corner) is the cumulative result for OC 1 to OC 4 at the completion of the flotation trial. Intermediate points on the curve are obtained from the intermediate cumulative results obtained.

Using the commercial collectors in Graph 1 as an example, information of the following type may be deduced from these graphs. The collector CA540 showed limited selectivity for the cassiterite over gangue material. A final grade of 8.5% tin with a 85.0% recovery does not compare favourably with the results obtained for SPA. SPA was much more selective, the OC 1 grade being 27% with 66% recovery. The following concentrates, OC 2 to OC 4, for both collectors saw a drop in the grade of tin recovered due to the tendency of the collector to float an increasing amount of gangue material, as well as cassiterite, with the diminishing concentration of cassiterite in the float. The lower selectivity of CA540 is illustrated by the lower OC 1 tin grade leading to a lower final grade and poorer recovery.

Another method for comparison between flotation data is by the use of the Collins' criterion (K). This gives a numerical assessment of the collector performance according to the



equation below.

$$K = E (b-a) / a$$

where E is the tin recovery (%)

b is the tin grade in the concentrate (%)

and a is the tin content of the feed ore (%)

Comparing the performances of S.P.A. and CA540 in this manner, SPA has a K value of 1017 while for CA540 K is 623. However, these numerical comparisons do not give an overview of the behaviour of the collector during the course of the flotation trial, unless calculated for each concentrate during the trial, that is OC 1 to OC 4.

As previously mentioned some initial work on the synthesis of flotation collectors was carried out by Barlow<sup>19</sup>. A number of proposed collectors were synthesised and preliminary assessments of their collector potential made. A summary of the results of that work is presented in Table 5.3.

Table 5.3. Collectors Investigated by Barlow (1983).

Collector	Flotation Activity
Pyridine-2,3-dicarboxylic acid <sup>#</sup>	no activity
Triethyl 2-phenylpropane-1,1,3-tricarboxylate	no activity
Triethyl 2-(2-thienyl)propane-1,1,3-tricarboxylate	no activity
3-(2-Thienyl)pentanedioic acid	weak activity, achieved <sup>*</sup> 5% grade, 31% recovery
3-Phenylpentanedioic acid	weak collector, achieved <sup>*</sup> 10% grade, 48% recovery

<sup>#</sup> Obtained commercially.

<sup>\*</sup> Collector addition 2Kg/tonne feed ore (0.6% tin).

The failure of pyridine-2,3-dicarboxylic acid to act as a collector is not surprising as similar compounds such as gallic and salicylic acid have been used as modifiers and depressants in oxide flotation<sup>51</sup>. The results obtained for the esters are also those expected, since these compounds are nonionic with no available sites for strong cassiterite-collector interaction (which occurs with established metal oxide collectors and the collectors developed during the course of this work). The last two results in Table 5.3, concerning the substituted pentanedioic acids, formed the starting point for the investigations carried out in this study. Although the collectors are essentially very weak (requiring large additions of collector to obtain reasonable results), the upgrading effect of 3-phenylpentanedioic acid in particular, was approaching that of styrenephosphonic acid (SPA). The former collector was reassessed using standard conditions during the course of this study (see results for Cr11). Further work on thiophene containing structures was not carried out.

The results above indicated that aryl-substituted polycarboxylic acids of similar structure to Cr11, possessed some selectivity for cassiterite. There was a need for an investigation to establish which structural features enhanced collector activity and thus institute a systematic element to flotation collector design. The polycarboxylic acids in the previous chapters were developed to this end, and their assessment as collectors enabled the identification of structural features essential for increased collector activity. The replacement of a carboxylic acid functionality by a phosphonic acid moiety was investigated to compare their selectivities for metal oxides. Phosphonic acid containing collectors had, in the past, been found to be more efficient collectors for cassiterite.

Although economic factors, such as the cost of commercial production of these collectors, were not considered in the initial stages of this study, the results obtained for some of the collectors has raised the possibility of their commercial application. Further comment will be made on this at a later stage.

## 5.2 An Overview of the Flotation Potential of Aryl-substituted Polycarboxylic Acids.

To obtain an overview of the structure / activity relationships of aryl-substituted polycarboxylic acids without para-substituents, flotation tests were carried out under standard conditions. These conditions entailed the use of approximately 0.30g/t of collector and 0.35g/t of SSF.

The results of these tests are represented in Graph 2. The most obvious result of this work was the inability of the nitrogen containing acids to collect cassiterite. The compounds Cr33 to 37 inclusive showed virtually no capacity to concentrate or recover the cassiterite during the flotation trials. These potential collectors were found to be unstable and this may partially explain their failure. However, Cr36 and Cr37 were also equally dismal in their collecting ability. N-Benzyliminodiacetic acid (Cr36), as previously mentioned (Chapter 4), has very different proton dissociation properties compared with similar non-nitrogen containing acids. It was thought that this variation may have adversely affected the collector properties of the general collector type. To lessen the effect of the incorporated nitrogen, N-benzoyliminodiacetic acid (Cr37) was assessed. However, no marked increase in efficiency was found. It must therefore be assumed that incorporation of a nitrogen in the structure has an adverse effect on the hydrophobicity of the molecule by allowing water to associate at this point via hydrogen bonding. This would reduce the adherence of the collector to the froth and possibly the metal oxide and result in low upgrading effects and reduced recovery during oxide flotation. This could be further studied by the method of Kuys<sup>74</sup> using infrared spectroscopy.

It is interesting to contrast the above behaviour with that of the established collectors trisodium N-(3-carboxyacryloyl)-N-octadecylaspartate (S 3903) (see Figure 1.2), and N-alkyliminodi(methylphosphonic acid) (Briquest reagents) (see

Figure 1.8). The former contains an amide linkage and has collector ability approaching that of CA540. The long C<sub>18</sub> chain provides the hydrophobicity required for collector activity which also negates any hydrophilic nature of the amide grouping.<sup>68</sup> The Briquest reagents, and their aryl-substituted analogs<sup>68</sup> are more closely related to the nitrogen-containing carboxylic acids assessed in this work. They display reasonable selectivity and are used commercially at pH 4.5 to 5.5 (see Chapter 1). The use of phosphonic acid functionalities in collectors of this structural type is therefore far more beneficial than the use of carboxylic acid groups.

Apart from the nitrogen containing acids, Cr33 to 37, two other acids were also noted to be very poor collectors. Cinnamic acid (Cr1) was not expected to be an efficient collector and the results obtained confirmed this expectation. This reagent was included for comparison, as an aryl-substituted monocarboxylic acid of similar structure to the polycarboxylic acids investigated. Reasons for its lack of effectiveness may be associated with the high pKa of the single carboxylic acid group, and its low solubility in acidic solution.

Another compound that showed virtually no tendency to collect cassiterite was phenylmalonic acid (Cr2). Although the collector upgraded tin concentrate by a factor of two, the recovery was very poor (4%). Given the excellent results achieved by some of the other 1,1-dicarboxylic acids (discussed later), the result was seemingly anomalous. Solubility of this collector was not a problem and the lack of effectiveness was apparently related to its structural and/or chemical properties. The proximity of the aromatic ring would not have a great effect on the dissociation constants of the carboxylic acid entities. The most likely cause of the poor collector properties of Cr2 is the structural geometry of the collector molecule. The aromatic ring of phenylmalonic acid, adsorbed on the cassiterite surface, would not be far removed from the oxide surface. It is possible that this type of structure does not provide sufficient hydrophobicity to facilitate adherence of the collector to the

froth or hinders adsorption at the oxide surface. If this is the case the effect of the interposition of one methylene group, to give 2-phenylethane-1,1-dicarboxylic acid (Cr3) is quite astounding.

The collector, Cr3, provided one of the best results for the set of non-para-substituted collectors, giving nearly twice the grade at similar recovery to that obtained with SPA (see Graph 2). It is also of interest that the unsaturated version of Cr3, Cr5, was markedly different in collecting ability. The latter collector was weaker than the former, although the final grade and recovery was still better than that obtained for SPA.

It should be emphasised at this point that all the non-para substituted acids were slow collectors giving rise to the flotation curve shapes shown in graph 2. The grade of the tin increases with the recovery, in most cases, as the flotation experiment proceeds. With a stronger collector like SPA the grade decreases with increasing recovery as most of the cassiterite is floated in the initial two minutes and only scavenging of residual cassiterite and flotation of gangue materials proceeds after that point.

The potential collector 3-phenylpentanedioic acid (Cr11) may now be compared with other aryl-substituted polycarboxylic acids under standard flotation conditions (Graph 2). It is clear that the collector is weak, and a slow collector of cassiterite, as the overall recovery is low. However, the flotation curve

froth or hinders adsorption at the oxide surface. If this is the case the effect of the interposition of one methylene group, to give 2-phenylethane-1,1-dicarboxylic acid (Cr3) is quite astounding.

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The potential collector 3-phenylpentanedioic acid (Cr11) may now be compared with other aryl-substituted polycarboxylic acids under standard flotation conditions (Graph 2). It is clear that the collector is weak, and a slow collector of cassiterite, as the overall recovery is low. However, the flotation curve increased in recovery with increased grade, suggesting that a good grade and recovery may have been achievable if the strength of the collector was increased. The unsaturated analogue of this collector, Cr17, was stronger and returned a good end grade of 18.8% tin with 92% tin recovery.

Thus, two seemingly conflicting results were obtained for the effects of the inclusion of unsaturation on collector performance. Firstly, Cr3 (saturated) is a stronger collector than Cr5 (unsaturated), while Cr11 (saturated) is weaker than

Cr17 (unsaturated). The explanation of these results must lie in the individual structural characteristics of each molecular skeleton, rather than a uniform effect arising from the introduction of an unsaturated bond into a general collector structure. The introduction of a double bond to give Cr17 would be expected to reduce the pKa of the adjacent carboxylic acid (a similar effect was noted when comparing maleic acids and succinic acids : Chapter 4). This may have the effect of increasing the rate of adsorption of the collector at the cassiterite surface. It has been reported by Bochnia and Serrano<sup>24</sup> that reduction of the pKa of an alkanecarboxylic acid increased collector adsorption. A similar effect would be expected when comparing Cr23 (3-phenylbutenedioic acid) with Cr19 (3-phenylbutanedioic acid), however this is not the case as the collecting ability of these compounds are comparable. This case is further complicated as one of the carboxylic acid functionalities is substituted alpha to the aromatic ring, similar to the acid units in phenylmalonic acid, Cr2. If carboxylic acid units in this position are not well suited to adsorption on the cassiterite surface, as it would seem with Cr2, then this would influence the adsorption and the collecting ability of the Cr19 and Cr23 molecules.

In the case of Cr5, the inclusion of an unsaturated bond alters the geometry of the molecule yielding a planar dicarboxylic acid where the angle between acid groups is slightly decreased when compared with the saturated collector, Cr3. The double bond would also reduce the region of influence of the rotating aromatic ring, thus reducing the influence of the hydrophobic ring on any neighbouring water structure, making the collector weaker than its saturated counterpart. With Cr17 there is no such decrease in the region of influence of the aromatic ring, when compared with Cr11, providing both acid units of these collectors are adsorbed at the the surface in the same manner. The aromatic rings in the adsorbed acids are held in fixed positions, normal to the cassiterite surface.

Another consideration is raised on comparison between the



flotation characteristics of the acids Cr21 and Cr22, the E- and Z-isomers of 3-phenylbutenedioic acid (see Graph 11). The trans-form, Cr21, is not adsorbed at the surface of the cassiterite due to the inappropriate configuration of the carboxylic acids. Figure 5.1 illustrates this effect and a comparison is given with the adsorption of Cr22, the cis-isomer.

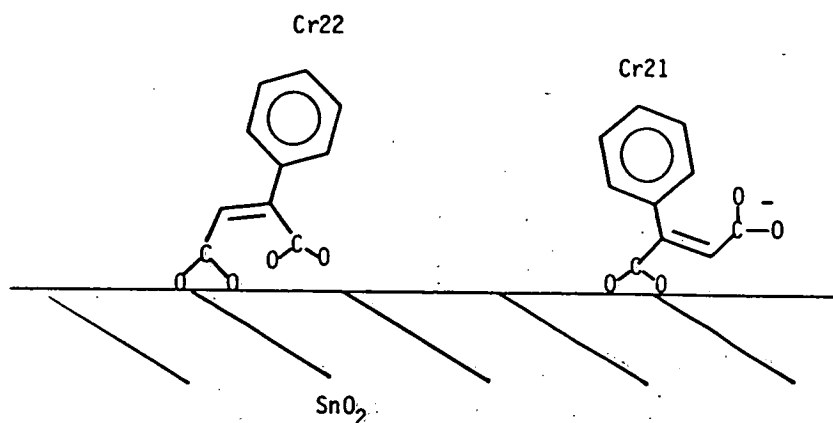


Figure 5.1 Adsorption of Cr21 and Cr22 at the cassiterite surface.

The cis-form shows reasonable collector efficiency for a non-para substituted acid due to the relative ease of adsorption of both carboxylic acid groups.

The collector Cr23, 2-phenylpropane-1,1,3-tricarboxylic acid, gives a flotation curve characteristic of a slow and weak collector, similar to the other non-para-substituted acids (Graph2). This collector shows an improvement over the efficiency of Cr11 which may be explained in terms of the presence of the 1,1-dicarboxylic acid structure in Cr23. This structural characteristic was found to be advantageous in general.

In summary, several important aspects of collector design are evident from a study of the collectors shown in Graph 2. Firstly, the inclusion of a nitrogen in the alkane skeleton of

the molecule (originally considered due to their ease of preparation) had a detrimental effect on collector activity. Secondly, the introduction of further unsaturation into the skeleton had varying effects depending on both the rigidity of their saturated analogs when adsorbed at the cassiterite interface, and the proximity and effect of the unsaturation on the pKa values of the adjacent carboxylic acid units. Thirdly, the inclusion of a 1,1-dicarboxylic acid unit was seen to be advantageous. A similar observation for alkane-1,1-dicarboxylic acids has been reported by Bochnia and Serrano<sup>24</sup>, who suggested that this effect was due to the lowering of the pKa of one of the carboxylic acid units. Finally, the acids generally showed a tendency to float cassiterite slowly, thus indicating a lack of hydrophobicity at the aromatic end of the molecule.

Comparison of these collectors with styrenephosphonic acid indicated that although they were frequently slower collectors of cassiterite, a number gave end grades and recoveries superior to those obtained by SPA (see Cr3, Cr5, and Cr17).

### 5.3 Effect of Para Substitution on the Collector Ability of Aryl-substituted Polycarboxylic Acids.

To increase the power of the collectors discussed in Chapter 5.2 the effects of para-substitution on collector efficiency were investigated. The general effects caused by such substitution are illustrated in Graphs 3 and 4.

General improvements in collector activity were observed on inclusion of a para-methyl substituent on the aromatic ring, however a decline in the performance of Cr4 with respect to 2-phenylethane-1,1-dicarboxylic acid (Cr3) was noted (see Graph 5). The latter collector had given good end grade and recovery prior to para-substitution. This substitution considerably reduced the grade of tin obtained. The optimum hydrophobicity of the hydrophobic tail of the molecule had obviously been exceeded by this substitution suggesting that a delicate balance exists so that optimum performance for any one structural class of collector may be achieved.

The unsaturated analogues of the above acids, Cr5 and Cr6, showed the expected behaviour. The para-methyl derivative, Cr6, showed a distinct increase in collector efficiency over Cr5. The difference in the effect of substitution on the unsaturated and saturated molecules, is caused by hindered rotation of the acid groups about the double bond. As stated previously, this hindered rotation reduces the effect and influence of the hydrophobic tail of the molecule on neighbouring water structure (see Figure 5.1). Thus, substitution on the aromatic ring of the saturated analogue Cr3, which already has a large field of influence, has a more dramatic effect, possibly to the extent of interfering with neighbouring adsorption sites.

Another para-methyl derivative also of interest due to its low activity was 2-(4-methylphenyl)propane-1,1,3,3-tetracarboxylic acid (Cr32). This collector contains two 1,1-dicarboxylic acid units, but gave a low grade (13%) and recovery (44%). Due to the

large number of hydrophilic carboxylic acid groups present in this molecule, it is possible that an appropriate balance between the hydrophobic property of the substituted aromatic ring and the hydrophilic acids had not been reached. That is the larger the number of carboxylic acids incorporated the larger the para-substituent must be to provide the hydrophobicity needed for attachment of the collector to the froth. This is supported by the form of the curve for Cr32 in Graph 3, characteristic of a weak acid. However, the curve was not indicative of a collector type that would provide better flotation results on substitution of larger groups. The inclination of the curve and the low grade, when compared to Cr23 (Graph 2), were not indicative of a good collector structure. For this reason it is possible that the collector possesses structural features that are not ideal for high collector efficiency. A model of the collector, similar to that in Figure 4.3 shows that one of the carboxylic acid units has no opportunity to adsorb at a tin atom site due to the geometry of the collector molecule. This would undoubtedly adversely effect collector adsorption at the cassiterite surface and possibly at the air bubble.

Generally, the substitution of a methyl group in the para-position of the aromatic ring had a beneficial effect on the collector ability of the polycarboxylic acids. Reference to Graph 13 shows that this is not true for substitution of styrenephosphonic acid. The para-methyl derivative (Cr38) floated predominately gangue material after the OC 1 concentrate due to excessive collecting power. However there is a clear increase in the general effectiveness of the aryl-substituted polycarboxylic acids which may be seen by comparing Graph 2 with Graph 3.

Graph 4 illustrates the effect of substitution of an ethyl group in the para-position. The overall power of the collector was once again increased, generally to the detriment of performance. Lower final grades were obtained as gangue material was collected along with the cassiterite in the flotation cell.

A comparison between the effects of the different para-substitutents on the collecting ability of the 2-phenylethene-1,1-dicarboxylic acid structural type (Cr5 to 10) is made in Graph 6. The unsubstituted acid, as already discussed, gave good grade and recovery although being reasonably slow in its flotation of cassiterite. Substitution of a methyl group (Cr6) greatly increased the power to give optimum performance for this group of collectors. Substitution of an ethyl group (Cr7) only served to increase the power to the detriment of selectivity. Substitution of a methoxy group (Cr8) gave increased power, when compared with Cr5, but not to the degree seen with Cr6, the methyl derivative. Extending the chain length of the alkoxy group to give an ethoxy derivative (Cr10) served to decrease selectivity of the collector, apparently exceeding the point of optimum performance. The substitution of two methoxy groups in the para- and meta-positions, as with Cr9, caused a decrease in selectivity. To explain the nature of this behaviour it is necessary to examine the effect of the substitution of alkoxy groups on collector action. The effect of alkoxy group substitution is markedly different to that of the substitution of an alkyl group on the aromatic ring. The incorporated oxygen atom in the former is able to associate via hydrogen bonding with water molecules in the surrounding solution. Although this association may be weak in comparison with the adsorption of the collector on both the oxide surface and the air bubble, it would have the effect of lowering the hydrophobicity of the tail unit of the collector when compared with the alkyl substituted analogue. The substitution of two methoxy groups in the 3- and 4-positions on the aromatic ring may result in a cumulative loss of hydrophobicity by further hydrogen-bonding to water. Preliminary further investigations also showed that 3-methoxy-4-ethoxy substitution gives greater collecting power than 3,4-dimethoxy substitution, thus supporting this conclusion.

The effect of para-alkyl substitution on 2-phenylbutanedioic acid (Cr19) is illustrated in Graph 7. Again, an increase in power was achieved, but with no significant increase in

selectivity. The methyl substituted derivative (Cr20) was of comparable performance to the commercial collector, SPA.

The effect of methyl substitution on 3-phenylpentenedioic acid (Cr17), to give Cr18, was similar. The collecting power was dramatically increased so much so that the first concentrate (OC 1) had a grade of 25% tin and a recovery of 87% under standard conditions. Alterations in the flotation trial conditions (amount of SSF and collector added) could have reduced the excessive flotation of gangue material in OC 2 to 4 and thus further improved collector ability. Substitution by larger alkyl groups was not studied for this group of collectors, as close to optimum balance seemed to have been achieved using the above substitution. Alkoxy substitution may have provided interesting results, as it did with the next few structural groups of collectors to be discussed.

The effect on collector ability of para-substitution of 3-phenylpentanedioic acid, the unsaturated analogue of the former collector, is shown in Graph 9. The substituted acid (Cr11) was a very weak collector, as demonstrated by Barlow<sup>19</sup>. Substitution of a methyl group in the para-position had a dramatic effect, greatly increasing the power of the collector. Ethyl substitution in the aromatic ring once again proved to provide excessive collector power to the detriment of selectivity. The effect of the substitution of alkoxy groups emphasises the "fine tuning" effect that may be achieved with this type of substitution giving increased grade and recovery. The para-methoxy derivative (Cr14) showed increases in selectivity and power over the non-substituted acid. Varying results were obtained for this collector, indicating a sensitivity to flotation conditions. Some of these results were comparable to those obtained for Cr12, the methyl derivative. Substitution of ethoxy (Cr15) or propoxy (Cr16) groups successively increased the collecting power in each case. Cr16 gave an OC 1 grade of 38% tin and a recovery of 80% tin.

Similar tendencies were noted with the 4-substituted-2-phenylpropane-1,1,3-tricarboxylic acids (Graph 10). The alkyl substituted collectors were very powerful in the cases of the ethyl and iso-propyl cases, while the alkoxy substituted acids gradually increased in selectivity and collecting power. Optimum performance was obtained with para-ethoxy substitution (Cr28). The propoxy derivative showed good self-frothing power and was able to be used without further addition of frother (Cyanamid AF65) after sulfide scavenging. The para-butoxy derivative (Cr31) showed high surface activity, being soap-like in its properties with very strong frothing power and cleansing action. The Critical Micelle Concentration (C.M.C.) of this derivative was found to be approximately 30 mmol/l at 18 °C. The C.M.C. of the other triacids of this class were found to be greater than 100 mmol/l, thus indicating low surface activity. Such properties are not required by flotation collectors and are in general detrimental as the froth becomes difficult to control and the selectivity for the metal oxide is diminished.

In summary, it is evident that collecting power varies greatly with differing alkyl substituents. Alkoxy substitution provides a more sensitive adjustment, but these acids are not always the most efficient of any given structural class of collector, as in the case of the substituted 2-phenylethene-1,1-dicarboxylic acids.

Collectors Cr6, 2-(4-methylphenyl)ethene-1,1-dicarboxylic acid, and Cr28, 2-(4-ethoxyphenyl)propane-1,1,3-tricarboxylic acid, were the most promising aryl-substituted polycarboxylic acids investigated. Both incorporated a 1,1-dicarboxylic acid structural feature.

#### 5.4 Collector Efficiency of Aryl-substituted Phosphonocarboxylic Acids.

The aryl-substituted phosphonocarboxylic acids were investigated to compare the effect of carboxylic acids with phosphonic acids, as hydrophilic units for collectors in the flotation of cassiterite. The majority of these collectors may be regarded as structural derivatives of styrenephosphonic acid, and thus provide a basis on which to examine features that enhance or detract from collector performance.

Graph 12 illustrates the collector activity of the non-para-substituted aryl-substituted phosphonocarboxylic acids investigated. With the exception of Cr44 and Cr 42, these collectors showed selectivity and collecting power similar to that observed for styrenephosphonic acid. The best result was obtained for 3-phenyl-2-phosphonopropanoic acid (Cr39) which was more selective than SPA and gave greater recovery, apparently due to both the incorporation of a carboxylic acid and saturation in the alkyl section of the molecule.

The poor results obtained for the collectors Cr44 and Cr42 are most likely due to the bulk of the hydrophilic units, especially in the case of Cr42 where the upgrading effect was negligible. The latter acid contained two phosphonic acid and one carboxylic acid unit in close proximity. It is possible that one of these acid units may not be able to find an appropriate adsorption site due to conformational restriction.

Cr43 was found to be comparable in efficiency to SPA since the final recovery for the former was slightly better than that for SPA. However, due to the added hydrophilicity of the carboxylic acid group the OC1 grade and recovery were lower indicating a slightly weaker collector. Para-substitution would undoubtedly improve the performance of this collector.



Cr40 proved to be a strong collector giving a high OCl recovery (88%) with reasonable grade (20%). This is apparently due to the added hydrophobicity imparted to the collector molecule by the methylene group adjacent to the carboxylic acid. Removal of this methylene group gives Cr39, a more selective but less powerful collector.

A comparison between Cr39 and Cr45, the saturated and unsaturated analogues of the same basic structure, reveals the same trend noted with their dicarboxylic acid analogs. Thus, the saturated acid is more selective and of similar collecting power, the OCl recoveries being comparable but the grades being 33% and 21% tin, respectively. The reasons for this trend are similar to those mooted for the dicarboxylic acids, that is, the effect of the double bond on the aromatic ring and / or the geometry of the acid units with respect to each other.

The para-methyl substituted derivatives of two phosphonocarboxylic acids and styrenephosphonic acid were also investigated (Graph 13). The compound Cr38, 4-methylstyrenephosphonic acid, was found to be a stronger collector than SPA but had less selectivity and thus showed no beneficial characteristics over the latter. The most dramatic effect of para-methyl substitution was observed with Cr46 (Graph 14). The non-substituted analogue, Cr42, as earlier discussed, was found to be a very weak collector; Cr46, however, was both more selective and more powerful than SPA (Graph 13). The extra hydrophobicity imparted to the molecule by para-substitution thus provided a better balance between the hydrophilic and hydrophobic portions of the collector molecule. This again reinforced the hypothesis that when a large number of hydrophilic groups are incorporated, more hydrophobicity (larger alkyl or alkoxy aromatic substitution) is required to optimise collector behaviour. It may have been possible to increase the efficiency of this collector further with the addition of more SSF and / or lowering the amount of collector added.

The comparison between Cr40 and Cr41 is interesting since they are of comparable collecting power, although the former is para-methyl substituted. The hydrophilic groups of these acids are in the same configuration since both are 3-phosphonopropanoic acids, although in the case of Cr40 the aromatic group is one methylene group removed. This alteration may have the effect of increasing the hydrophobicity of the aromatic ring since it is further removed from the tin surface on adsorption. Such a structural feature was not included elsewhere in this work but it may prove to be advantageous with some other collector types, for example, derivatives of Cr19, the dicarboxylic acid analogue.

In general, the phosphonocarboxylic acids were of comparable collecting ability to SPA. However, it should be emphasised that most of the results cited in this section were not optimised due to the limited time available for assessment and evaluation. It would be expected that investigation of other substitution types and variation of flotation conditions would provide improvements on many of the results obtained. However, use of standard conditions allows direct correlation of the effect of interchanging phosphonic acid and carboxylic acid groups.

### 5.5 Comparison between the Flotation Activity of the Polycarboxylic Acids and the Phosphonocarboxylic Acids.

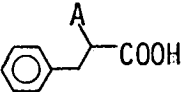
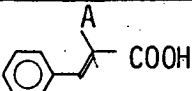
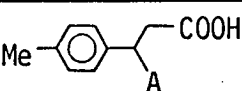
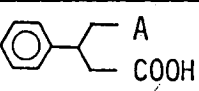
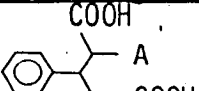
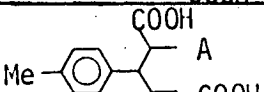
A number of the phosphonocarboxylic acids were structurally similar to the polycarboxylic acids discussed in Chapters 5.2 and 5.3. This allows direct comparison between the effect of substitution and interconversion between carboxylic and phosphonic acids on the flotation collector properties. Table 5.4 contains a correlation table of these acid types.

In general, the phosphonocarboxylic acids in Table 5.4 are more powerful collectors than their polycarboxylic acid analogues. An exceptional case, Cr42, can best be rationalised in terms of an imbalance in the hydrophilic / hydrophobic nature of the collector as previously discussed. The overall trend must be related to the rate of adsorption of the collector at the cassiterite interface. Kuys<sup>75</sup>, in preliminary trials using FTIR / ATR techniques, found that the rate of adsorption of SPA was greater than that of the polycarboxylic acid collectors. This faster rate of adsorption points to either a different adsorption mechanism or a slower reaction rate for the polycarboxylic acids. This faster adsorption rate of phosphonic acid may be the cause of their reduced selectivity and this phenomenon is illustrated in Graph 15.

The collector Cr3 (a dicarboxylic acid) is less powerful than Cr39, its phosphonocarboxylic acid counterpart. However, the end grade for Cr3 is superior to that of Cr39, both collectors giving equivalent recoveries. Similarly, with Cr5 and Cr45, the former is less powerful but more selective.

A comparison between Cr43 and Cr11 is illustrated in Graph 16 and exemplifies the collecting power imparted to the collector by the inclusion of a phosphonic acid group. The collector characteristics (Graphs 13 and 3) in this case are more similar, due to the incorporation of a para-methyl group, thus increasing the collector power of the dicarboxylic acid. This effect is

Table 5.4 Correlation of polycarboxylic and phosphonocarboxylic acids.

STRUCTURE (A = COOH or PO <sub>3</sub> H <sub>2</sub> )	Phosphono- carboxylic acids	Polycarboxylic acids
	Cr39	Cr3
	Cr45	Cr5
	Cr41	Cr20
	Cr43	Cr11
	Cr42	Cr23
	Cr46	Cr24

also seen with Cr24, 2-(4-methylphenyl)propane-1,1,3-tricarboxylic acid (Graph 3), where the flotation curve, although exhibiting characteristics of a weaker collector, approaches that for Cr46. As mentioned in Chapter 5.4 the increase in collector power from Cr42 to Cr46 was dramatic. However, a correspondingly large increase was not observed for the tricarboxylic acid derivatives Cr23 and Cr24 (Graph 10).

In general, comparison between these structural types allows determination of the comparative flotation characteristics of carboxylic acids and phosphonic acids as hydrophilic entities. The phosphonic acids were found to be more powerful, correlating<sup>75</sup> with their faster rate of adsorption on the collector surface. However, polycarboxylic acids were found to have greater inherent selectivity for cassiterite.

### 5.6 Optimum Conditions for the Cr Series Collectors.

A number of collectors, particularly the aryl-substituted polycarboxylic acids, were investigated under varying flotation conditions. (Refer to Tables 1 and 2).

The collector Cr28 was found to perform best at concentrations of approximately 0.25Kg collector and 0.7Kg of SSF per tonne (tests LW221 and LW222). Increasing collector concentration served to decrease the final grade by allowing greater entrainment of gangue materials in the flotation concentrates. A similar pattern was observed for a number of the powerful collectors, for example Cr6 (LW224), Cr29 (LW245), Cr30 (LW258) and Cr26 (LW255).

However, collectors such as Cr3 (LW216) and Cr5 (LW226) were found to perform better with lower concentrations of SSF (0.33Kg/t) and greater concentrations of collector (0.40Kg/t). These conditions gave better grades and recoveries than the standard conditions and lowering the SSF concentration may have further improved their performance <sup>162</sup>.

Table 5.5 Effect of flotation conditions on the efficiency of Cr3.

Test No. LW	Collector Kg/t	SSF Kg/t	OC1 (%Sn)		OC1-4 (%Sn)	
			Grade	Rec.	Grade	Rec.
216	0.40	0.33	26.6	35.2	22.4	92.3
275	0.30	0.40	10.7	19.1	11.0	78.1

To understand the trends of selectivity and power of the collector the molecular structure of the collector must be considered. Compound Cr3, 2-phenylethane-1,1-dicarboxylic acid and Cr5, 2-phenylethene-1,1-dicarboxylic acid, are reasonably

selective collectors although not very powerful, being slow to float cassiterite. The use of larger amounts of collector is beneficial, as the selectivity and slow rate of collection did not allow the excess collector to float increased quantities of gangue. Addition of large amounts of SSF served to reduce the rate of flotation of tin and therefore the collector power.

The collectors Cr6, Cr28 and Cr29 were found to be reasonably selective under standard conditions. The addition of further SSF and decreasing the collector concentration enhanced the overall grade, but slightly reduced the OC1 recovery. Results for Cr28 demonstrate the trends observed for these collectors (see Table 5.6).

Table 5.6 Effect of flotation conditions on the efficiency of Cr28

Test No.	Collector	SSF	OC1 (%Sn)		OC1-4 (%Sn)	
LW	Kg/t	Kg/t	Grade	Rec.	Grade	Rec.
197	0.35	0.35	37.2	89.5	13.9	97.2
220	0.15	0.35	41.6	53.0	25.8	91.8
223	0.26	0.60	51.8	80.6	31.0	96.0

Reduction of the amount of collector (as in LW220) increased the final grade by 12% tin with a small increase in the OC1 grade, the recovery for the latter being lower due to the lower concentration of collector. This indicated that considerable gangue entrainment resulted from the higher collector concentration, contrary to the results observed for the weaker collector Cr3. The addition of SSF (as in LW223) further increased both the OC1 and final grades by 10.2 and 5.2% tin respectively and also resulted in increased OC1 recovery.

It is therefore apparent that the need for the addition of SSF and optimum collector concentration are dependent upon the power

and thus the structure of the collector. The stronger collectors containing para-alkoxy or -alkyl substitution benefit from the depression of gangue materials resultant on higher concentrations of SSF. These collectors do not require as high a collector concentration as the unsubstituted collectors. High concentrations of the more powerful collectors only served to increase flotation of the gangue.

The weaker unsubstituted collectors benefited from higher collector concentrations, simply due to their slow collecting action. That is, the more collector available for adsorption at the cassiterite interface, the faster the rate of flotation. These collectors are inherently more selective for cassiterite particles than the stronger collectors. Thus more collecting power is needed to float gangue materials than to float cassiterite. However, the use of SSF negates any advantage of the weaker collectors such as Cr3 over the powerful collectors such as Cr6 and Cr28.

Graph 20 illustrates the optimum conditions obtained for Cr6, Cr28 and Cr29 in comparison with the commercial collector SPA. The illustrated Cr series collectors are clearly of superior collecting ability.



### 5.7 Comparison of Gangue Material Assays using Cr Series Collectors and Commercial Collectors.

The superior selectivity shown by a number of the collectors investigated in this study over current commercially used collectors was of considerable interest. As the cassiterite ore has a high percentage of silicates as gangue, analysis of the concentrates obtained from the flotation tests was carried out to determine whether silicates were preferentially suppressed or floated by these collectors. Any difference in the gangue composition would give some assistance in determining why the Cr series collectors, particularly the polycarboxylic acids, were more selective. The commercial collectors CA540 and SPA and three collectors developed during this work, Cr6, Cr14 and Cr28, were assessed in this manner.

The results of the silica analyses are given in Table 5.7. It is apparent that the Cr series collectors float less than 2% of the available silica while SPA and CA540 float 3.4% and 6.6%  $\text{SiO}_2$ , respectively. The Cr series collectors are therefore considerably more selective for cassiterite over silicate gangue materials than the above two commercial collectors. Table 5.8 gives a comparison between the non-silicate gangue materials floated.

It is apparent from Table 5.8 that both silicate and non-silicate gangue entrainment during flotation decreases with increasing selectivity. The most interesting observation is that for Cr28, the best collector, the ratio of recoveries of silicate to non-silicate gangue has increased over that for SPA and Cr6. Thus, the significant improvement in tin grade found for Cr28 over Cr6 is due, in part, to the lower entrainment of non-silicate gangue materials.

Table 5.7 Silicate recoveries for selected collectors.

Collector (test No.)		Grade		Recovery	Grade		Recovery
		%Sn	(cum.)	%Sn	%SiO <sub>2</sub>	(cum.)	%SiO <sub>2</sub>
Cr6	OC1	43.9		81.1	12		0.45
LW200	OC2	8.6	29.5	92.0	18	14.4	0.92
	OC3	1.75	21.8	94.1	21	16.3	1.43
	OC4	0.65	18.0	94.7	25	17.9	1.93
Cr28	OC1	41.6		53.0	18		0.46
LW220	OC2	28.7	36.2	79.4	24	20.5	0.87
	OC3	11.3	29.4	88.7	32	23.6	1.38
	OC4	5.7	25.8	91.8	36	25.5	1.78
Cr14	OC1	32.1		39.2	21		0.56
LW222	OC2	31.5	31.9	55.3	25	22.2	0.84
	OC3	22.5	29.4	69.3	28	23.8	1.22
	OC4	20.9	27.9	79.7	34	25.0	1.56
SPA	OC1	27.6		66.5	18		0.90
LW189	OC2	11.5	21.8	81.9	22	19.0	1.50
	OC3	5.10	16.2	91.6	25	21.0	2.50
	OC4	1.55	13.0	94.0	28	23.0	3.40
CA540	OC1	15.7		41.6	33		1.50
LW204	OC2	10.2	13.5	59.4	33	33.0	2.50
	OC3	5.05	9.20	82.3	41	37.0	5.70
	OC4	2.45	8.50	85.0	48	38.0	6.60

TABLE 5.8 Percentage silicate and non-silicate recoveries.

Collector	RECOVERY (Final)		
	Total gangue (%)	%SiO <sub>2</sub> gangue	%non-SiO <sub>2</sub> gangue
CA540	9.48	6.60	12.6
SPA	6.57	3.40	10.1
Cr6	4.43	1.93	7.24
Cr28	2.61	1.78	3.66

### 5.8 Use of Cr Series Collectors on other types of Cassiterite Ore.

The superiority of the aryl-substituted polycarboxylic acids over the commercial collector SPA was established in tests on feed ore (ca. 0.85% tin) from the Ardlethan Tin Mine (N.S.W.). This ore contained 75-90%  $\text{SiO}_2$  and is considerably more difficult to float than the Cleveland ore using SPA or CA540 as collectors.

The results obtained for SPA on this Ardlethan feed and comparable results using the collector Cr28 under varying conditions are illustrated in Graph 19. Results for the flotation of Cleveland ore are also presented for comparison. Table 5.9 shows the feed types and grades of tin used.

Table 5.9 Feed grades and ore types for Graph 19.

Test	Feed grade (%Sn)	Ore Type
SPA <sup>1</sup>	0.85	Ardlethan
Cr28 LW229	0.77	Ardlethan
LW246A	0.72	Ardlethan
LW223	1.10	Cleveland
LW220	1.07	Cleveland

The effect of varying feed grade must be taken into account when analysing the results obtained. SPA gave an overall grade of 10.3% tin at 93.5% tin recovery using a 0.85% tin feed. The best result for Cr28, using low amounts of collector and SSF, gave an overall grade of 13.6% tin with 93.4% recovery using a 0.73% tin feed. The OC1 for Cr28 was 30% tin with 80.1% recovery, significantly greater than that for SPA (18.9% tin grade, 62% tin recovery). Thus Cr28 was found to be more selective than SPA

on this ore type, particularly so when the feed grade is taken into account.

The use of larger quantities of SSF (to depress silicate entrainment in the float) only served to depress the recovery of tin when Cr28 was used as a collector, as in test LW229. This is in direct contrast to the results obtained for the Cleveland ore. In the latter case, the best result was obtained using 0.60g of SSF, while for the Ardlethan ore the use of 0.31g SSF was found to be more advantageous. Thus, the optimum addition of SSF is dependent on ore type.

Table 5.10 Collins' criteria for SPA and Cr28 for Cleveland and Ardlethan ore types.

Test	Ore type	OC No.	Collins' Criterion
SPA	Ard.	1-4	1040
		1	1315
SPA (LW189)	Clev.	1-4	1037
		1	1632
Cr28 (LW246A)	Ard.	1-4	1647
		1	3256
Cr28 (LW223)	Clev.	1-4	2792
		1	3715

The results in Table 5.10 again demonstrate the superiority of Cr28 as a collector over SPA. The Collins' criterion for SPA on the two ore types do not vary significantly. However, for Cr28 the results for the Ardlethan ore, particularly for final grade and recovery, are somewhat lower. This may be due to the lack of optimization of the flotation conditions or to the high percentage of silicates in the Ardlethan ore. Unfortunately, analysis of the float concentrate was not carried out on test LW246A. However, for test LW229 the results are given in Table 5.11.

Table 5.11 Flotation data for Test LW229.

Con. No.	Grade %Sn	Recovery (cum.) %Sn(cum.)	Grade %SiO <sub>2</sub> (Cum.)	Recovery %SiO <sub>2</sub> (Cum.)
OC1	30.4	64.6	29	0.64
OC2	11.8 (23.7)	78.6	44 (34.4)	1.19
OC3	4.20 (18.7)	83.5	52 (39.0)	1.82
OC4	0.98 (14.6)	83.9	54 (42.3)	2.53

Although the grades of SiO<sub>2</sub> in the various concentrates are higher than that seen for the Cleveland ore, the recovery of SiO<sub>2</sub> is comparable, given that the test was not undertaken at optimum conditions, and that the OC4 concentrate did not increase the recovery of cassiterite.

The Ardlethan ore also contained 0.36% titanium dioxide (TiO<sub>2</sub>). To assess whether the collector Cr28 was selective against TiO<sub>2</sub>, analysis of the concentrates was carried out.

Table 5.12 Flotation of TiO<sub>2</sub> from Ardlethan ore using Cr28 (LW229).

Test	TiO <sub>2</sub> Grade (%) (Cum.)	TiO <sub>2</sub> Recoveries.
LW229 OC1	4.15	18.9
OC2	5.55 (4.65)	33.0
OC3	3.90 (4.46)	42.8
OC4	3.00 (4.14)	51.0

From the above data it is apparent that Cr28 floated cassiterite at a faster rate than rutile and possessed some selectivity for the former over the latter.

Analysis of the gangue floated in the flotation test above shows that, for OC 1 to 3, the recoveries of the various components of the ore were 1.82%  $\text{SiO}_2$ , 83.5% tin, 51.0%  $\text{TiO}_2$  and 5.15% of other materials. The most notable difference between these recoveries and those found for the Cleveland ore (Chapter 5.6) is the higher percentage of non-silicate gangue recovered, due to the different ore composition.

### 5.9 Flotation of Coarse Cassiterite (greater than 0.040 mm) using Cr28.

Another interesting aspect of the use of the aryl-substituted polycarboxylic acids is their performance in the flotation of coarse cassiterite feeds. The oxide ore sample used in this trial was obtained from the gravity cleaning section of the Cleveland Tin Ltd. Mine (Tasmania). This sample was 19.9% coarser than 0.150mm and 13.4% finer than 0.038mm. The size by size recovery data (Table 5.13) shows the successful flotation of tin at sizes greater than 0.150mm using the collector Cr28 (as per test LW230). The results are also presented in Graph 17 (recovery against particle size) and Graph 18 (recovery against grade).

Work has been carried out on the flotation of coarse cassiterite using alkane-1,1-dicarboxylic acids by Baldauf and coworkers<sup>18</sup>. They concluded that these acids floated a maximum particle size of about 0.10 mm. This was a considerable increase in size compared with the 0.050 mm maximum particle size floated using SPA<sup>18</sup>. Figure 5.2 illustrates the recovery of size fractions for the Altenberg tin processing plant (G.D.R.)<sup>90</sup>. Comparison of these results with those obtained in this study shows that the aryl-substituted polycarboxylic acid collectors, such as Cr28, are far more efficient than either of the aforementioned collectors. Cr28 recovered 86.7% of available tin in the 0.106 to 0.150 mm size range at a grade of 56.5% tin, and 63.2% of tin in the 0.212 to 0.150 mm range in 51.3% tin grade.

The results illustrated in Graph 17 (recovery against particle size) indicated that the smaller particle size ranges, for example < 0.075mm, are floated preferentially with a higher percentage of larger size particles being floated in the later concentrates (OC 3 and OC 4). This is to be expected since the < 0.075 mm size particles require less collector per particle to be adsorbed (the surface area per mass is greater) and are more easily attached to the froth due to their small size.



Table 5.13 Size By Size Recovery Data For Coarse Tin Flotation.

Size (mm)	Feed			Concentrates		
	%Wt.	%Sn	Sn Dist.	%Wt	%Sn	Sn Recovery
+0.212	7.4	4.87	5.6	0.4	8.8	9.1
0.212-0.150	12.5	5.25	10.2	0.8	51.3	63.2
0.150-0.106	16.3	4.77	12.1	1.2	56.5	86.7
0.106-0.075	20.8	4.29	13.9	1.4	59.3	93.3
0.075-0.053	19.6	4.38	13.4	1.4	59.3	96.3
0.053-0.038	10.0	7.94	12.4	1.1	64.6	98.3
-0.038	13.4	15.54	32.4	3.4	60.8	99.3
TOTAL	100.0	(6.42)	100.0	9.7	(58.1)	87.7

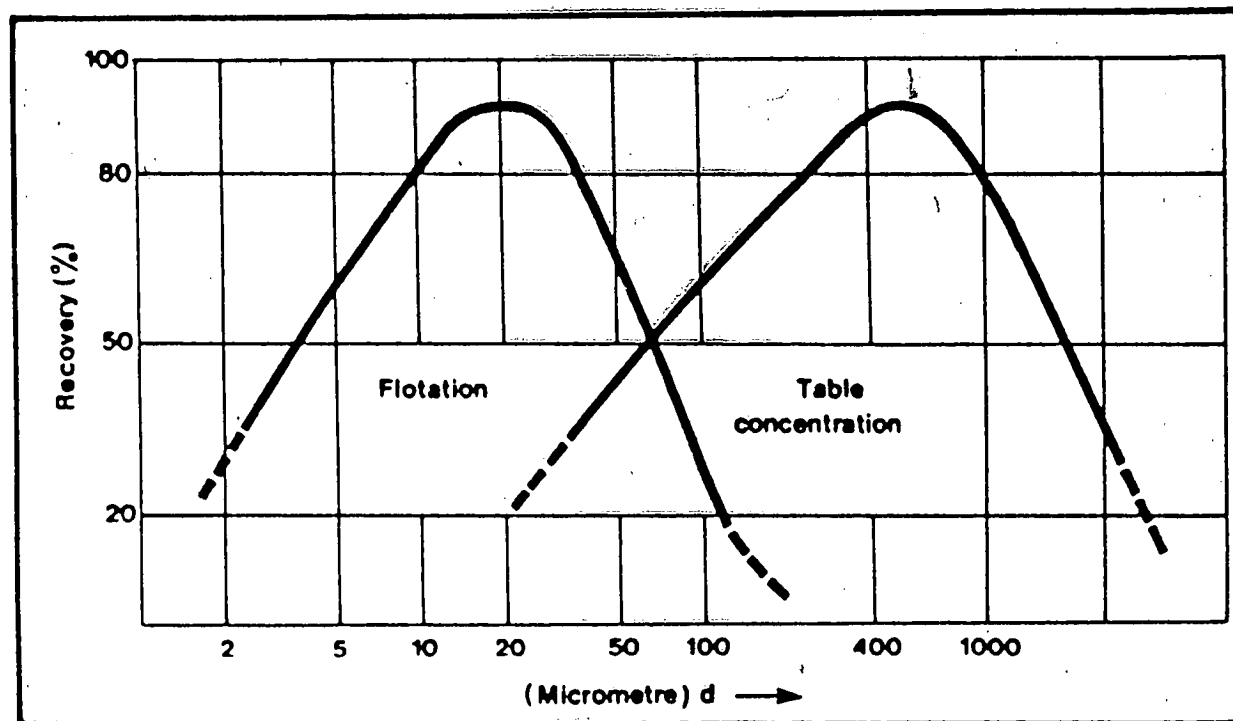


Figure 5.2 Recovery of cassiterite by flotation and table concentration at Altenburg.<sup>90</sup>

Graph 18 indicates that the peak grade of tin (62% tin or 80% cassiterite) is achieved for the OC 1, the grade decreasing only marginally to 55% tin as the recovery increases. This is an excellent result since a 72% cassiterite final grade with 88% recovery is a unique result in oxide flotation over any size range, in particular on coarse cassiterite feed where 6% of the tin is over 0.212 mm and therefore not recoverable.

The reason for the increased ability of Cr 28 over previously reported collectors to collect coarse cassiterite is open to conjecture. This compound is, in general, a more selective collector giving better grades and recoveries than SPA or alkane-1,1-dicarboxylic acids<sup>24</sup>. This is obviously important in the flotation of the coarser particle sizes where the energy of adsorption of the collector to the cassiterite surface, and the froth, is sufficient to float the larger particle sizes. Thus, collectors such as Cr28 must be more strongly adsorbed on the cassiterite surface, or more able to attach themselves to the froth than any previously reported collector systems.

In a commercial setting such results would reduce processing times and plant circuit size. Coarser grinding of ores would reduce the percentage of slimes (<0.005mm) obtained in the treatment of ores, as well as reducing grinding time. The beneficiation of particles to 0.200mm by flotation would complement the results illustrated in Figure 5.2. The Altenberg plant experiences considerable loss of recovery due to particles in the range 0.04 to 0.3mm using SPA and a table concentrator. This loss would be greatly reduced by the use of Cr28, or a similar reagent, as a collector.

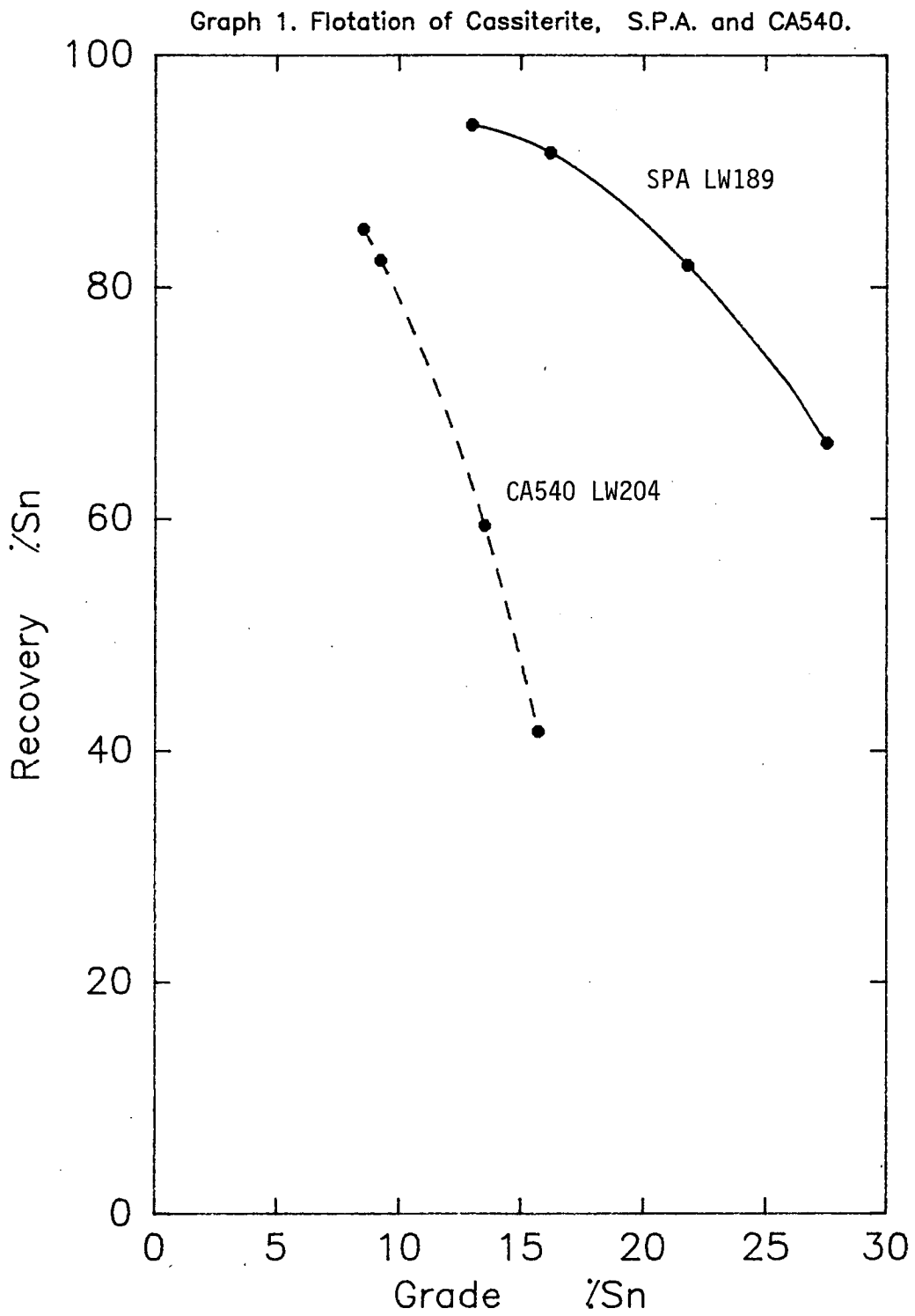
### 5.10 Flotation of Other Oxides Using Cr Series Collectors.

A preliminary assessment of the Cr series collectors on metal oxides other than cassiterite ores is currently underway at Aberfoyle Ltd.. Initial indications from the flotation of tantalum, niobium, titanium and tungsten oxides are promising. An example of these results is given below for wolframite ( $\text{FeMnWO}_3$ )<sup>1</sup>

Table 5.14 Flotation of wolframite using collector Cr12.

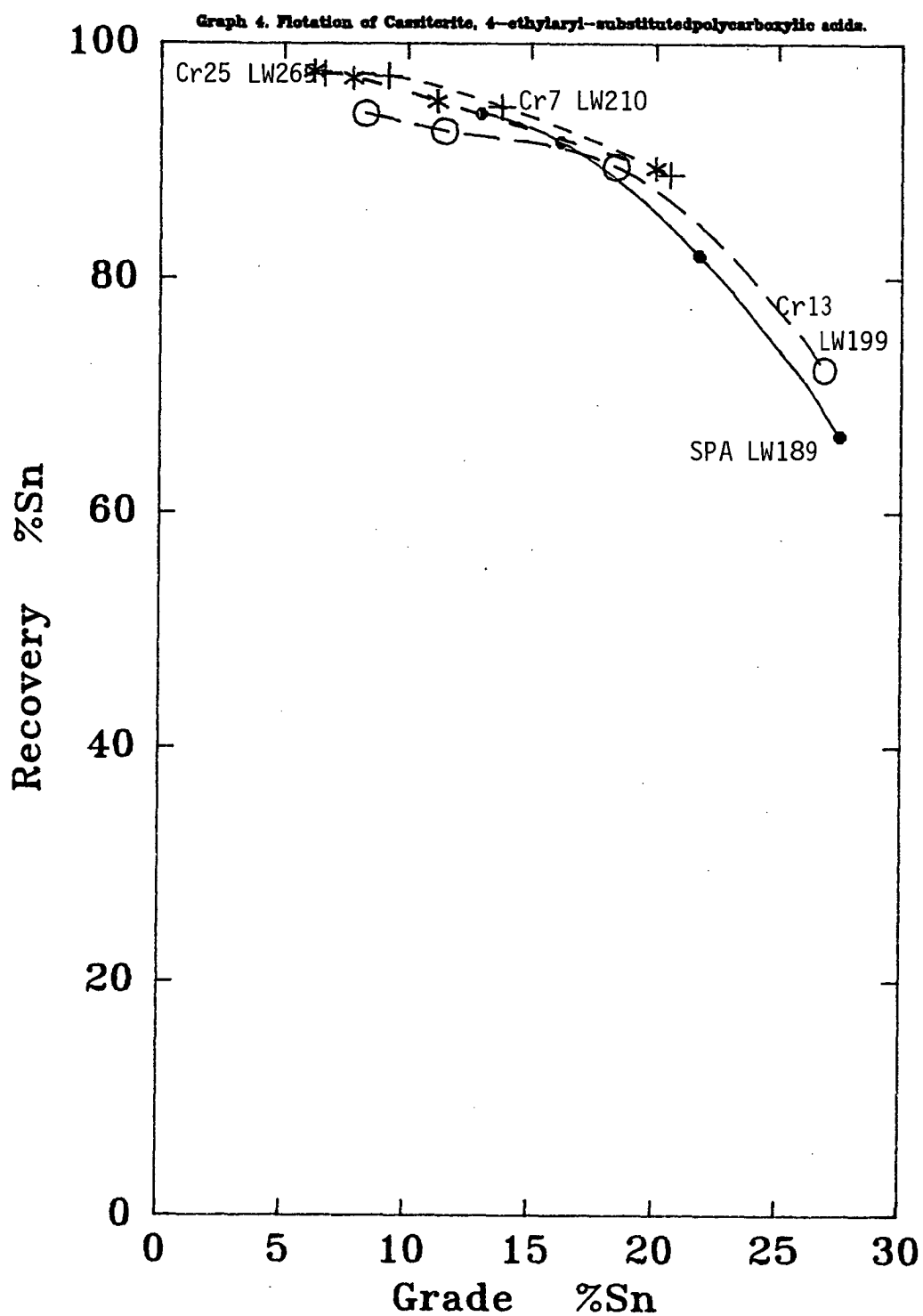
Collector	%Wt	%WO <sub>3</sub>		%WO <sub>3</sub> Distribution
		GRADE	(Cum.)	
Cr12	OC1	0.8	32.8	50.5
	OC2	0.6	20.6	27.6
	OC3	0.3	13.9	25.2
	OC4	0.2	6.5	23.2
				85.0

These results illustrate the versatility of the Cr series collectors giving a final grade of 23.2% WO<sub>3</sub> with 85% recovery from a 0.52% feed grade.

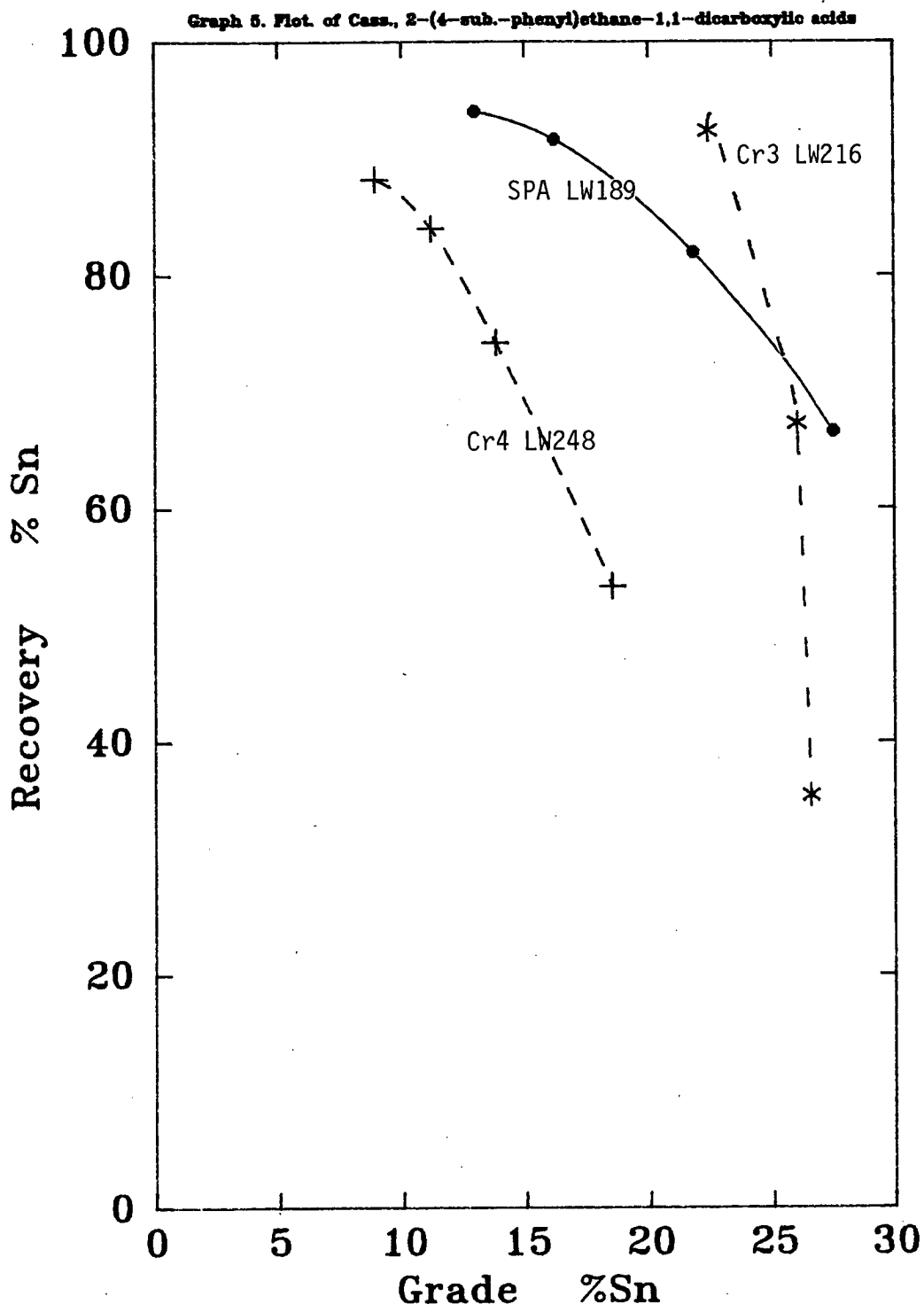


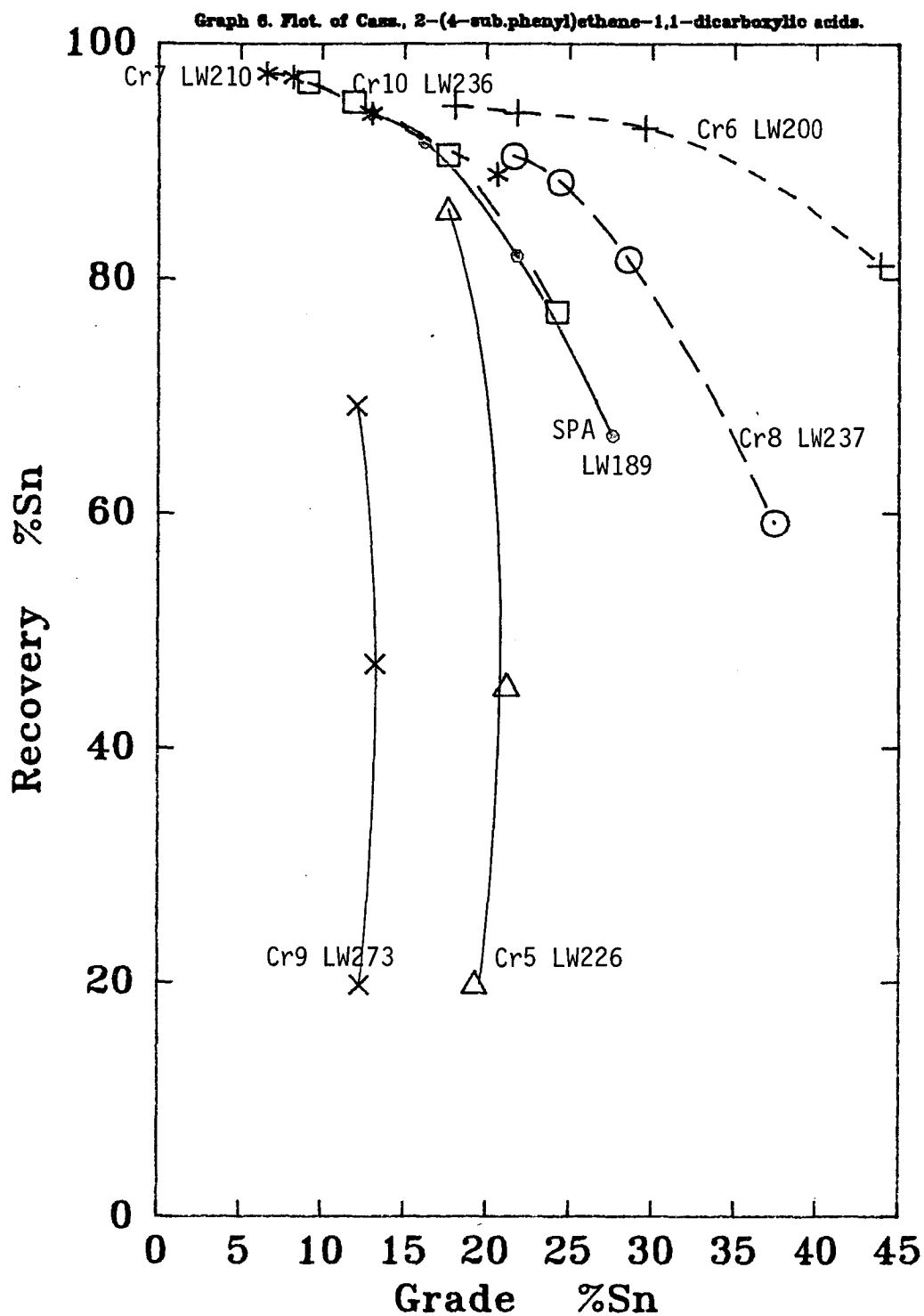


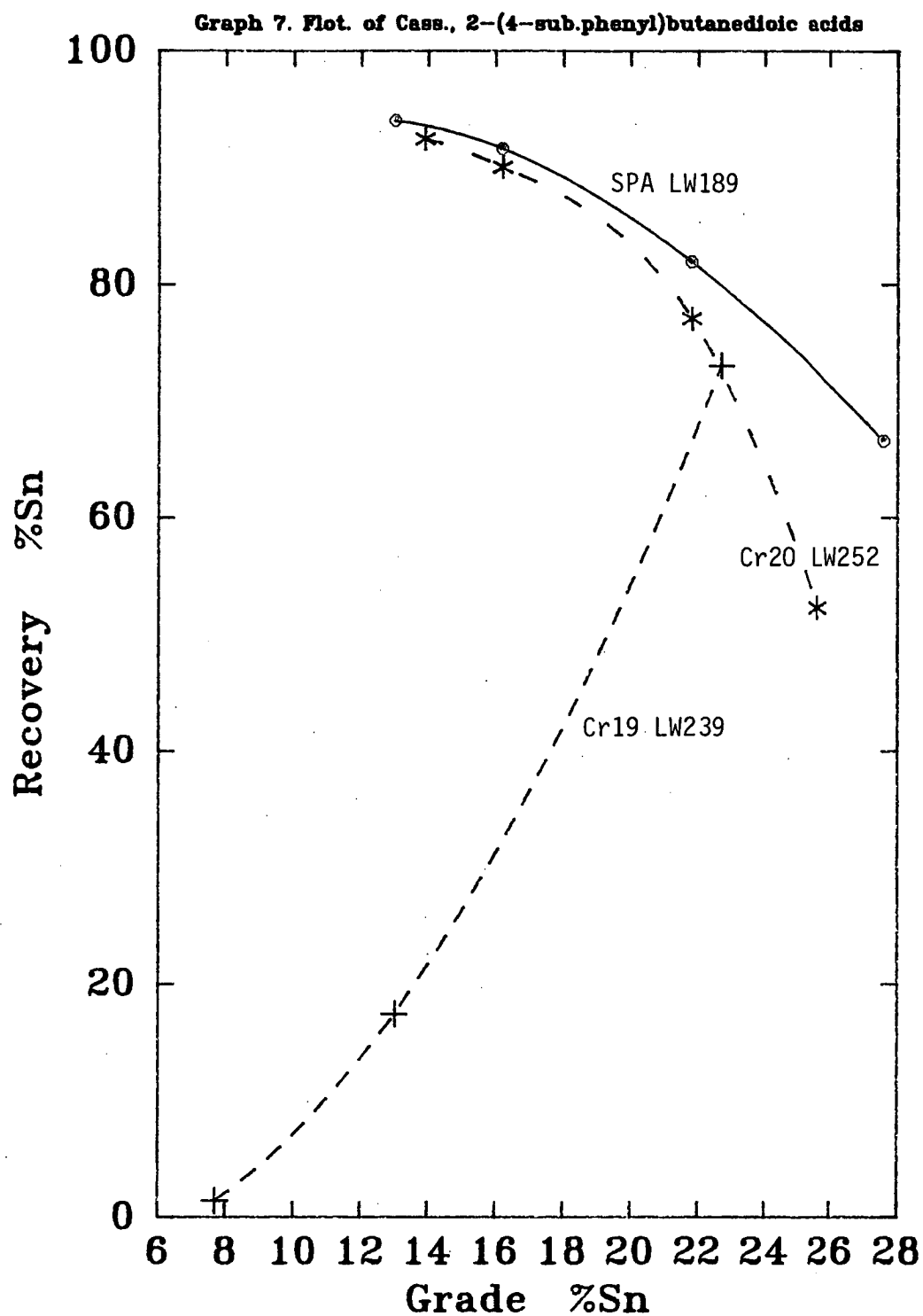


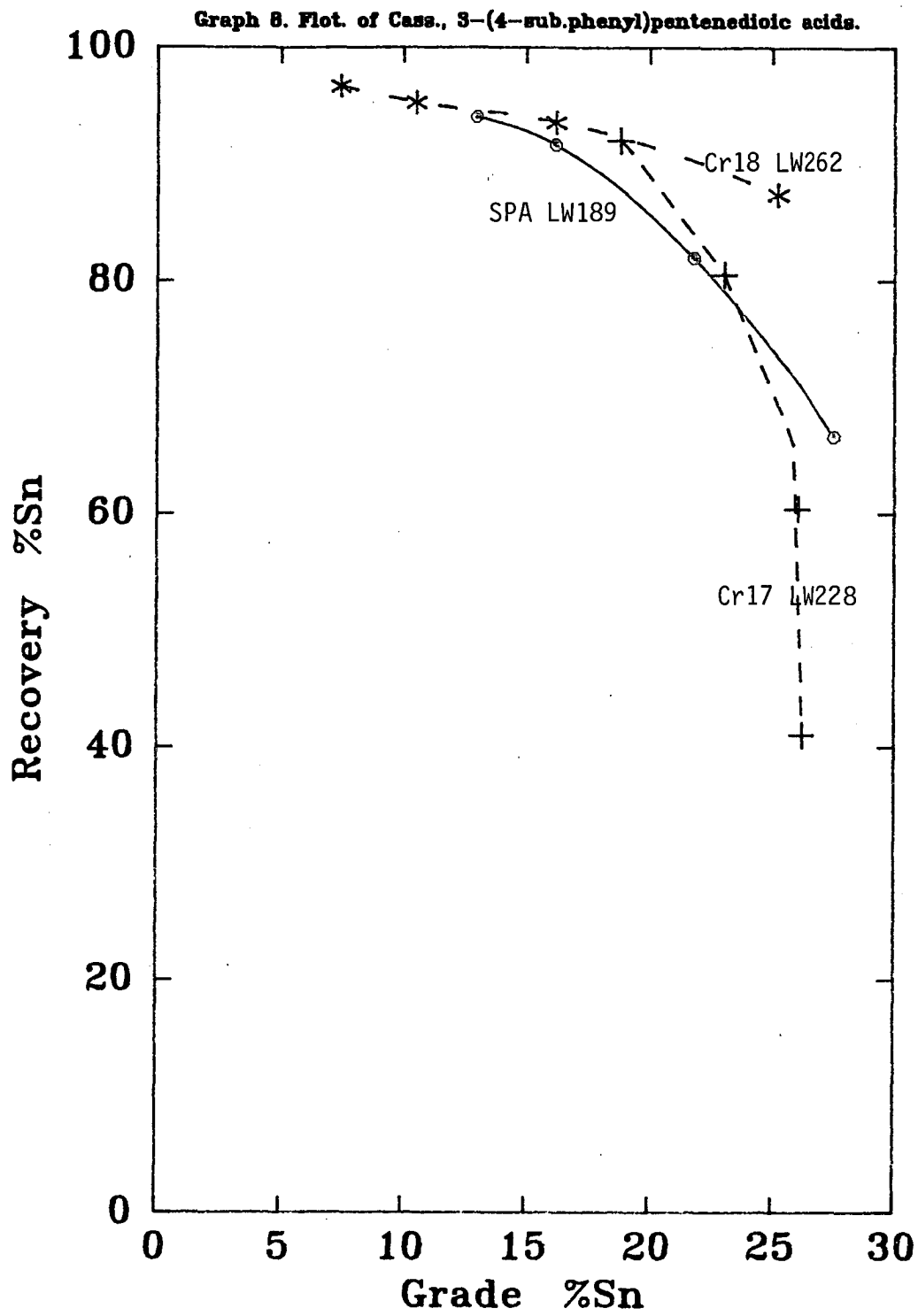


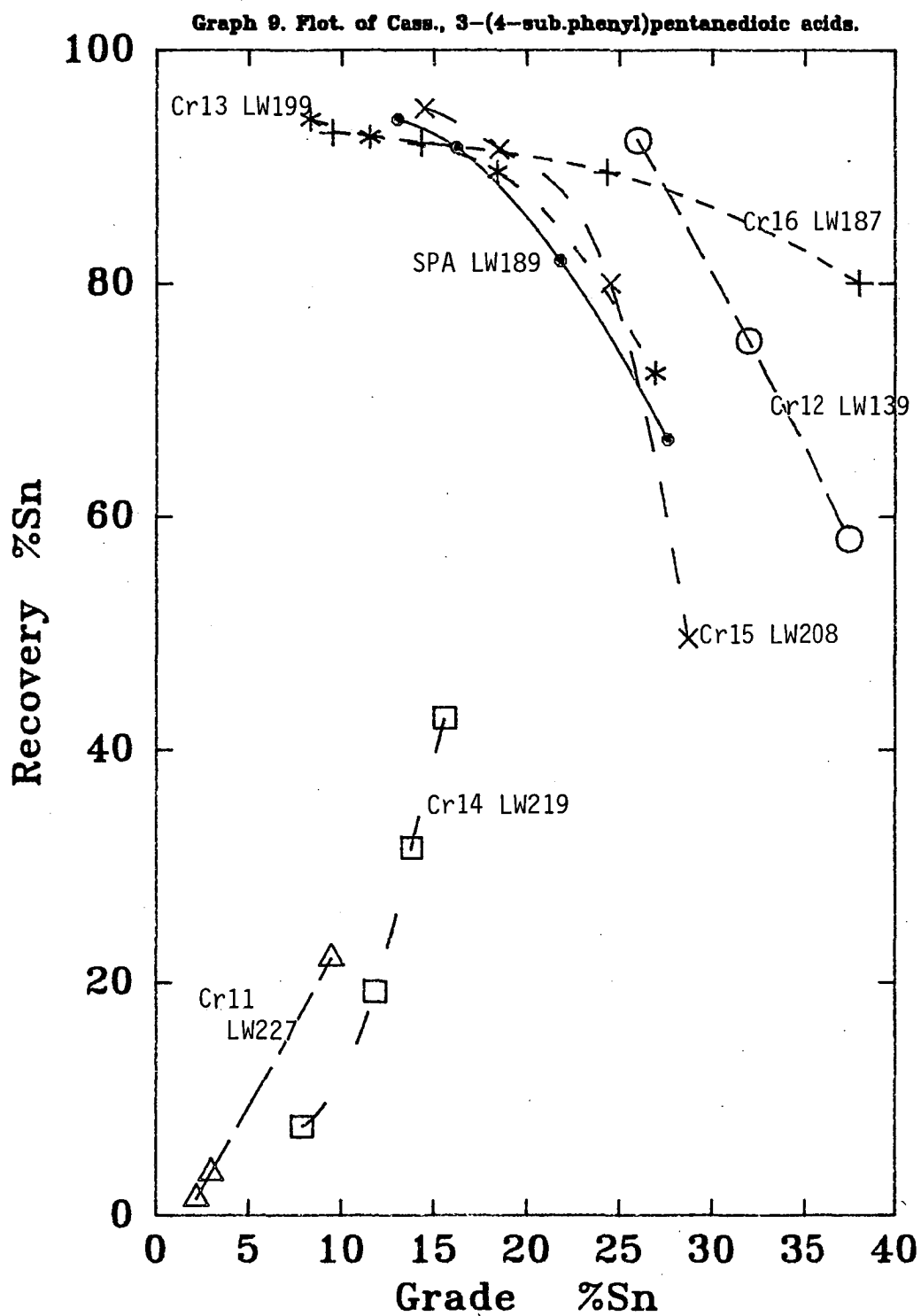


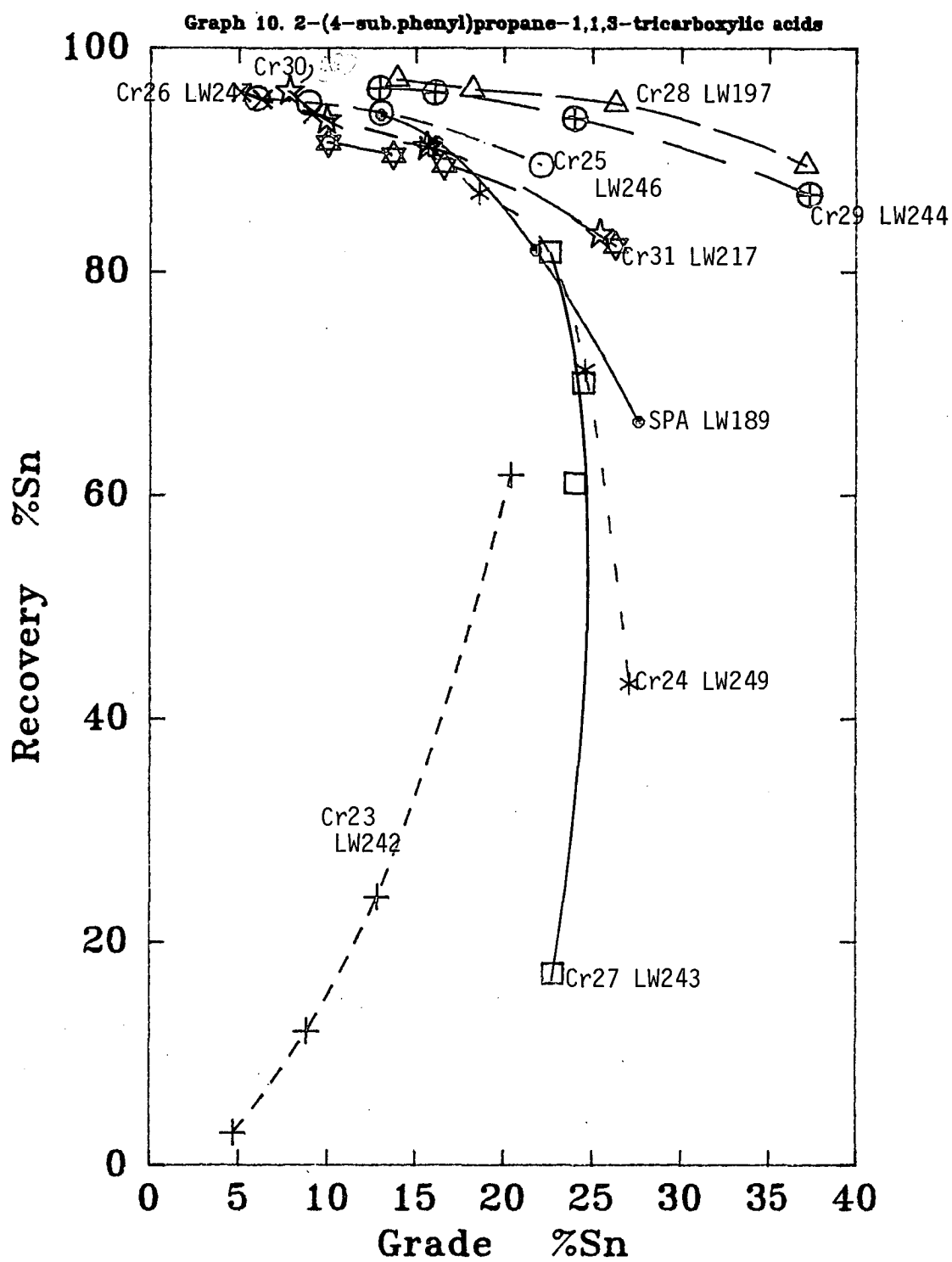


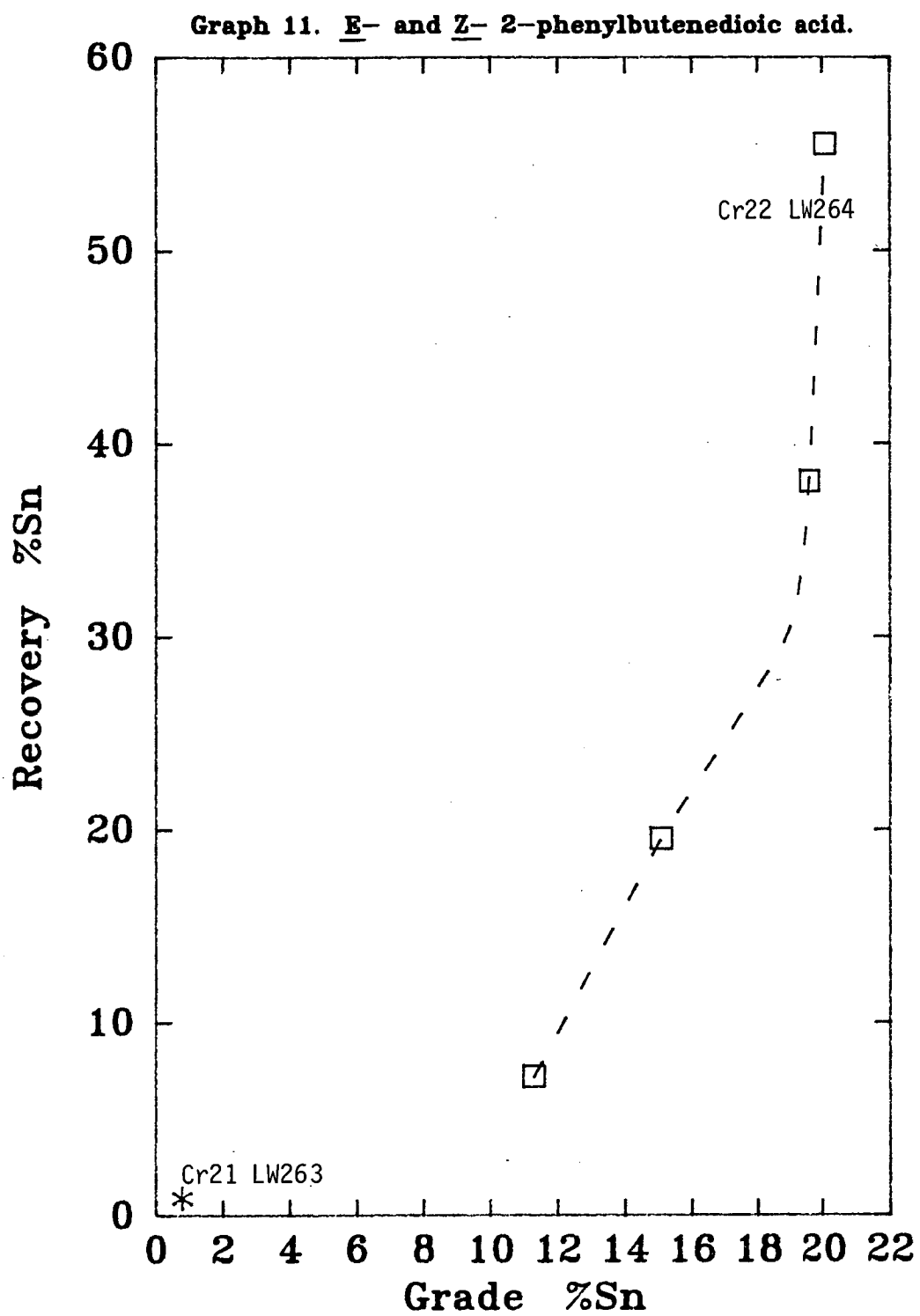




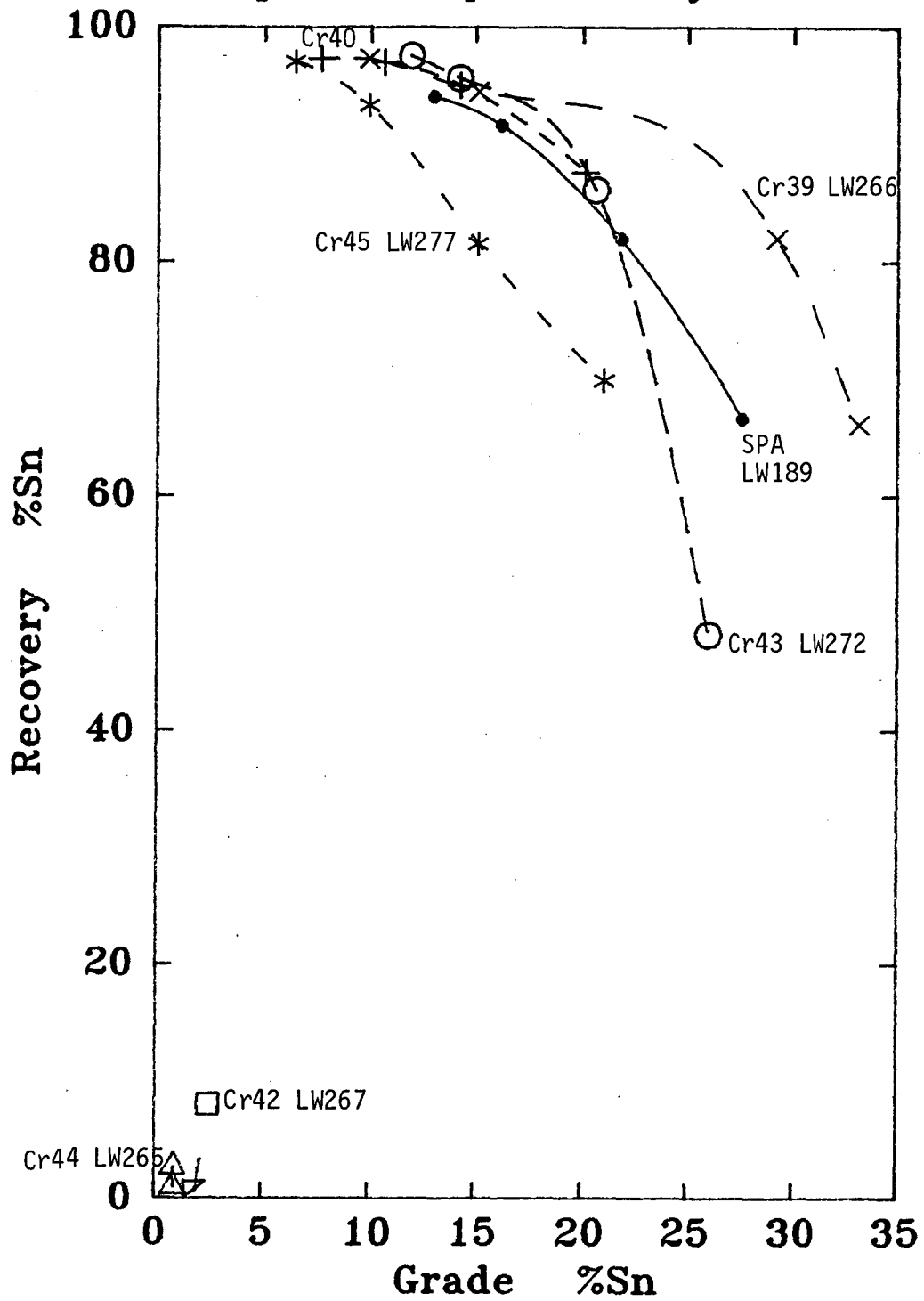




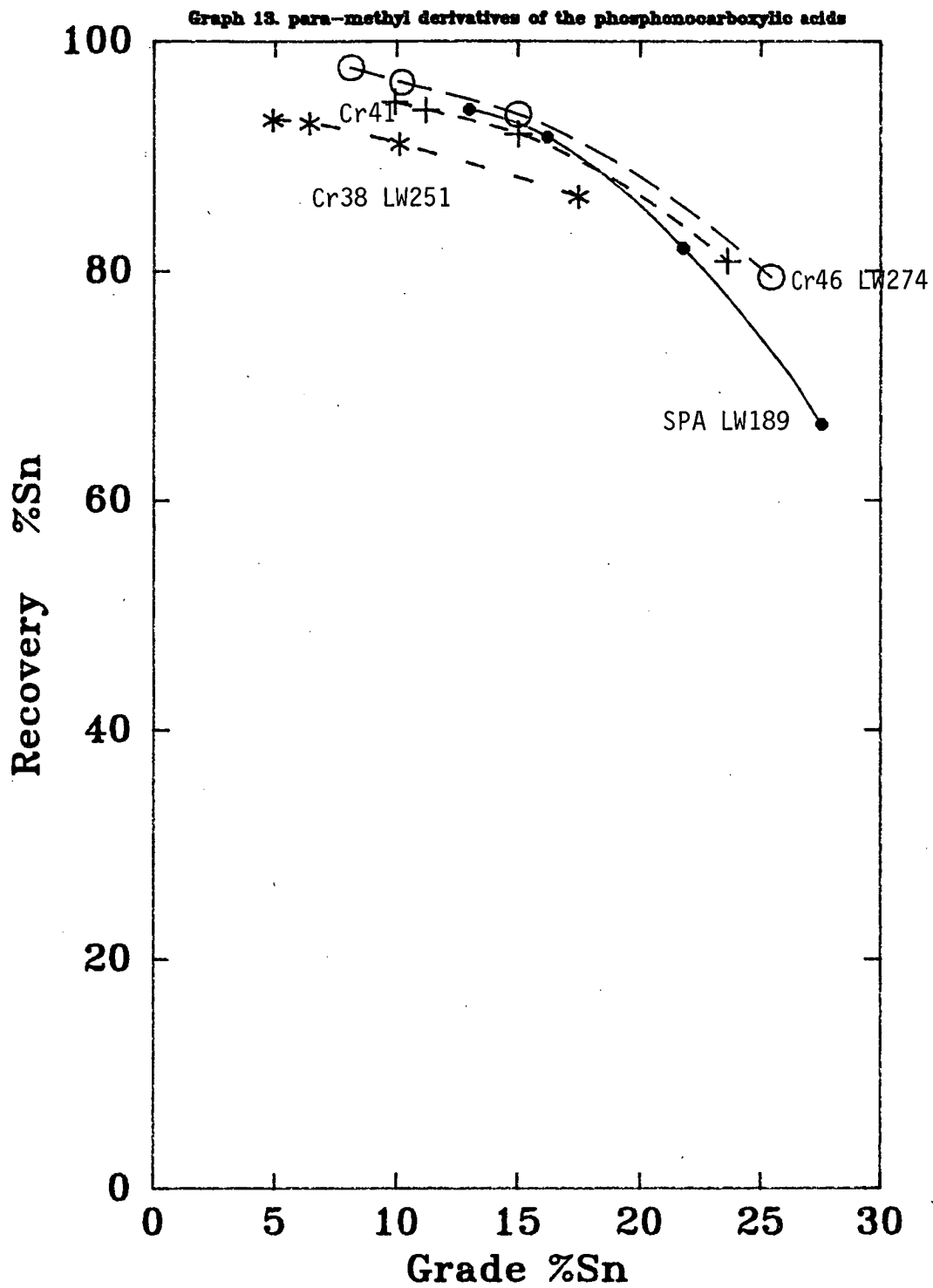


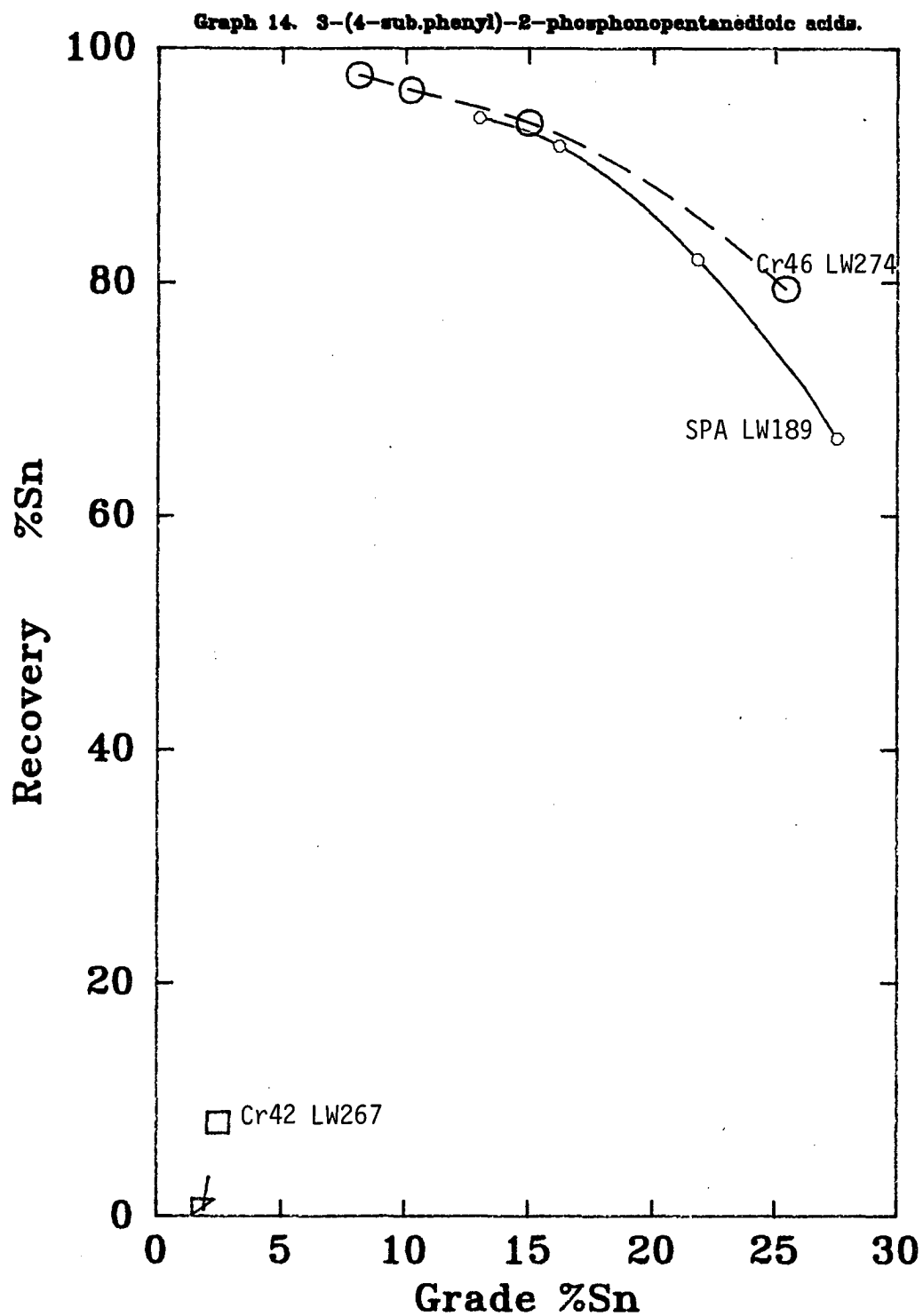


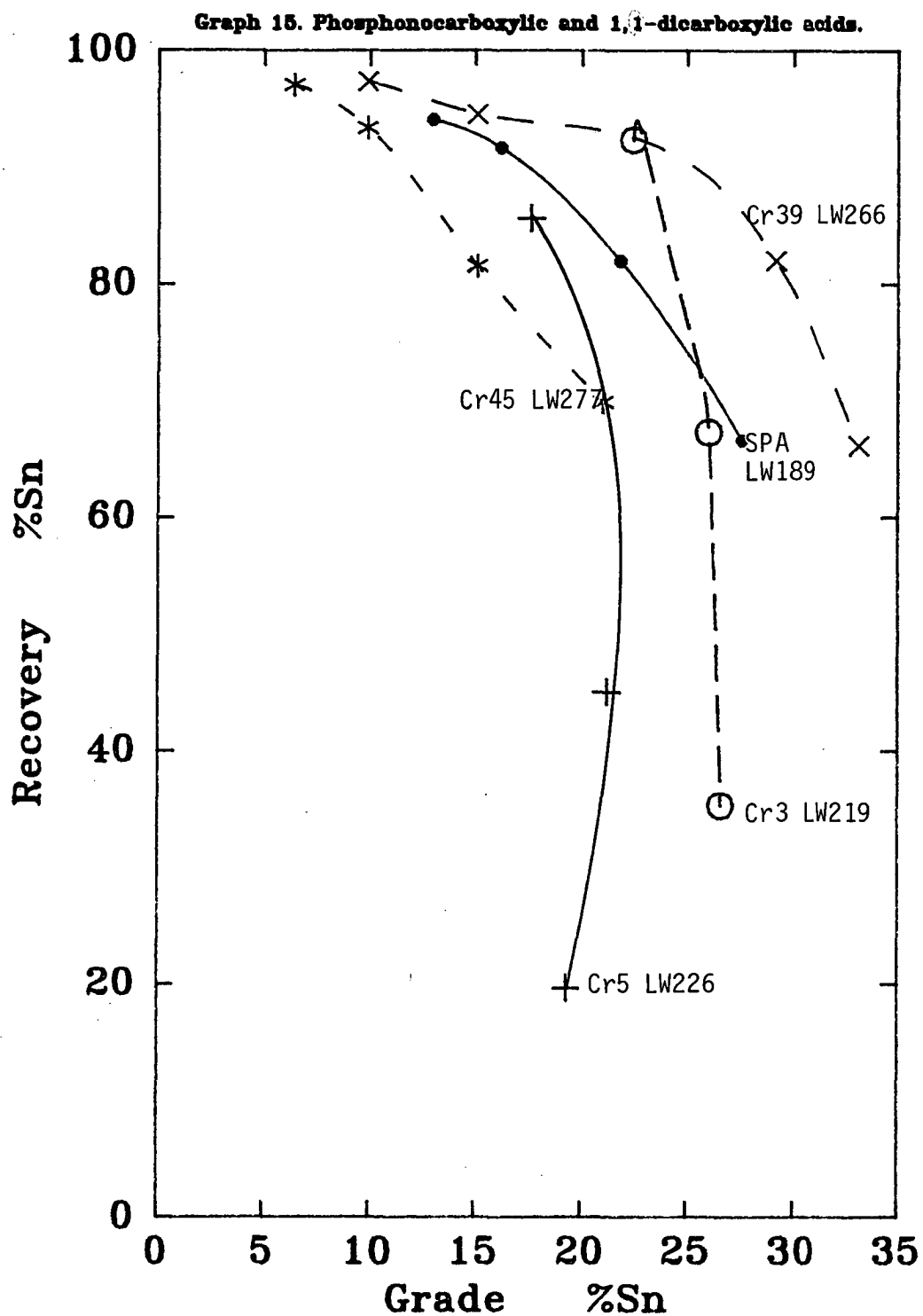
Graph 12. Phosphonocarboxylic acids.

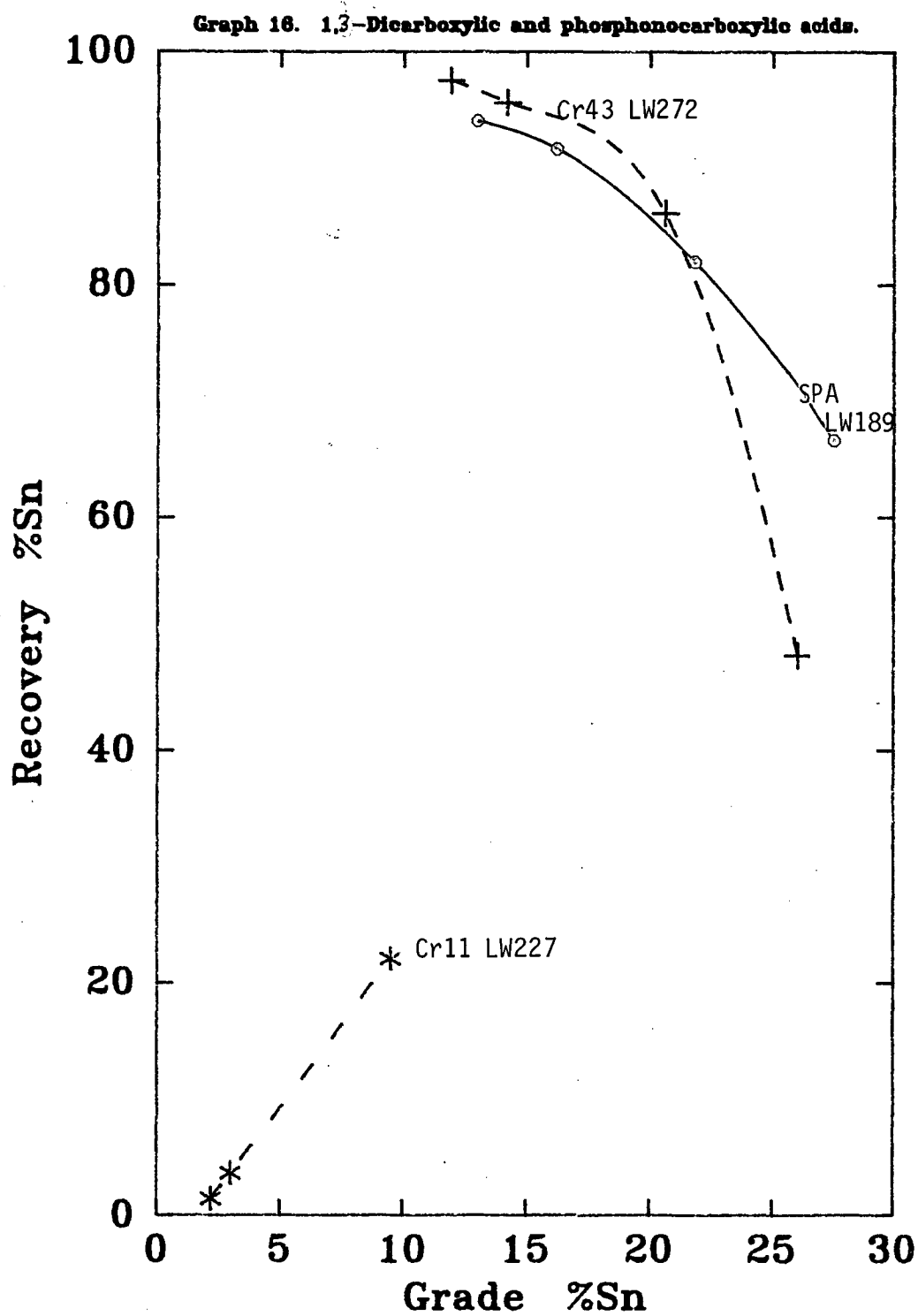


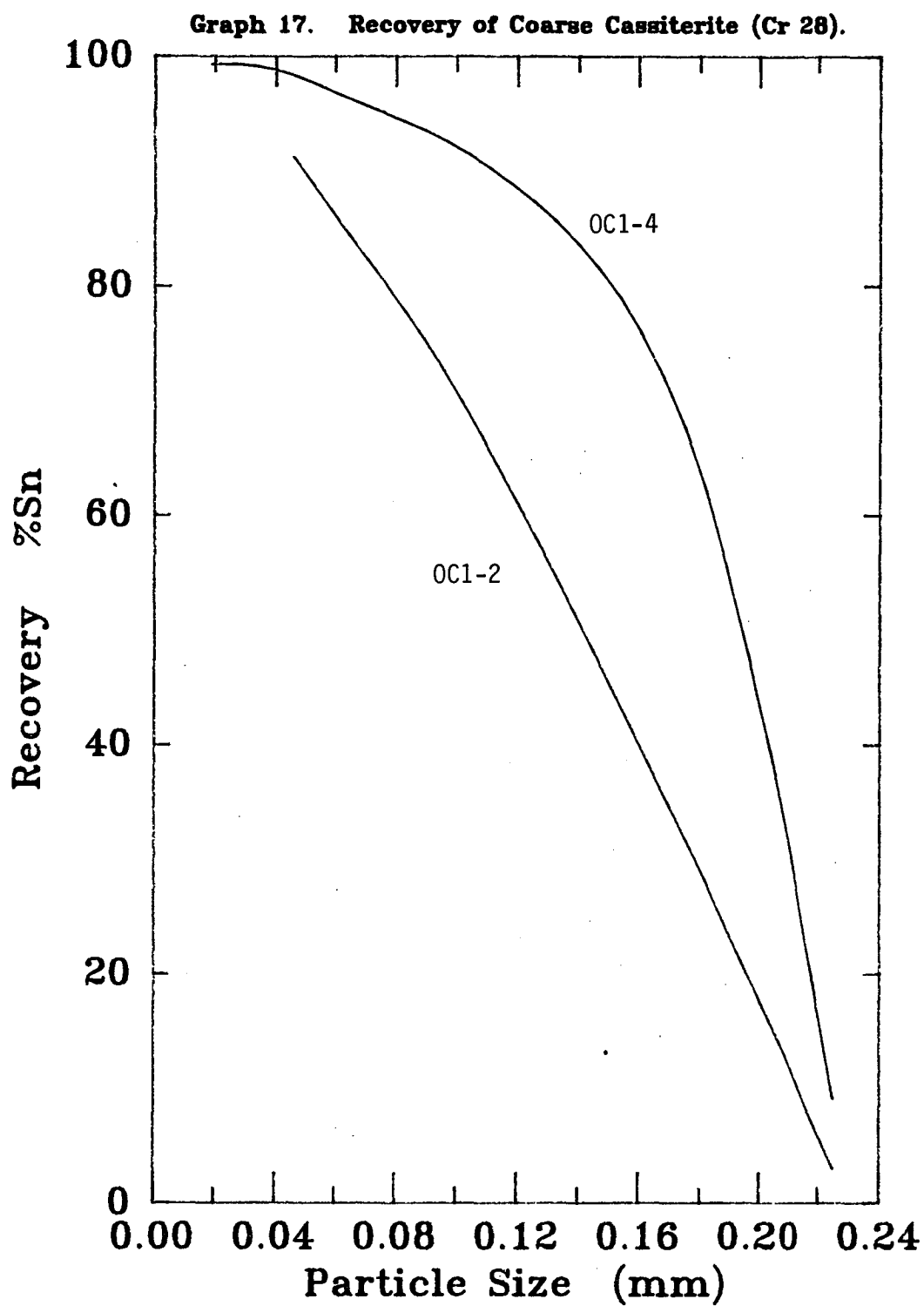




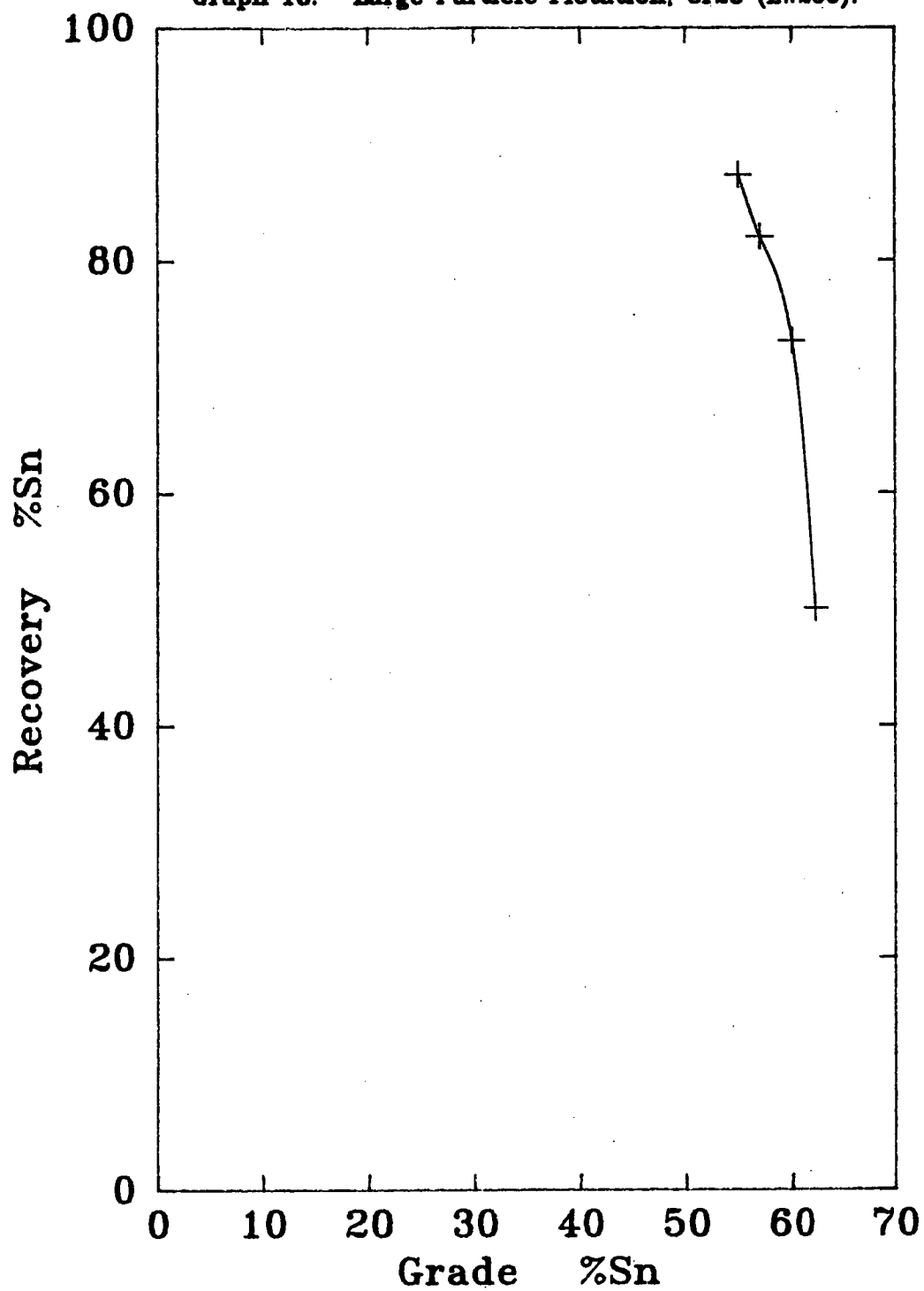


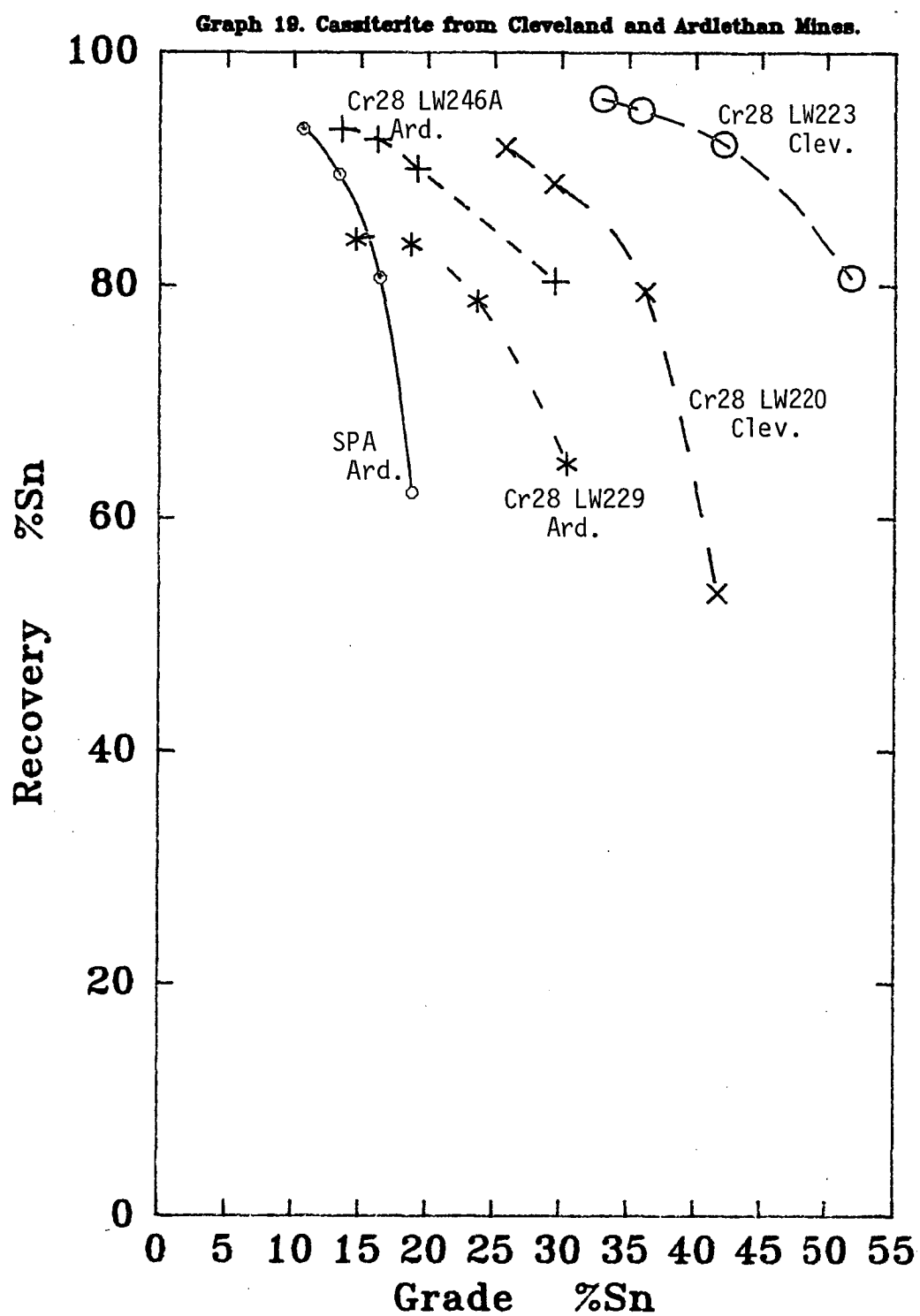


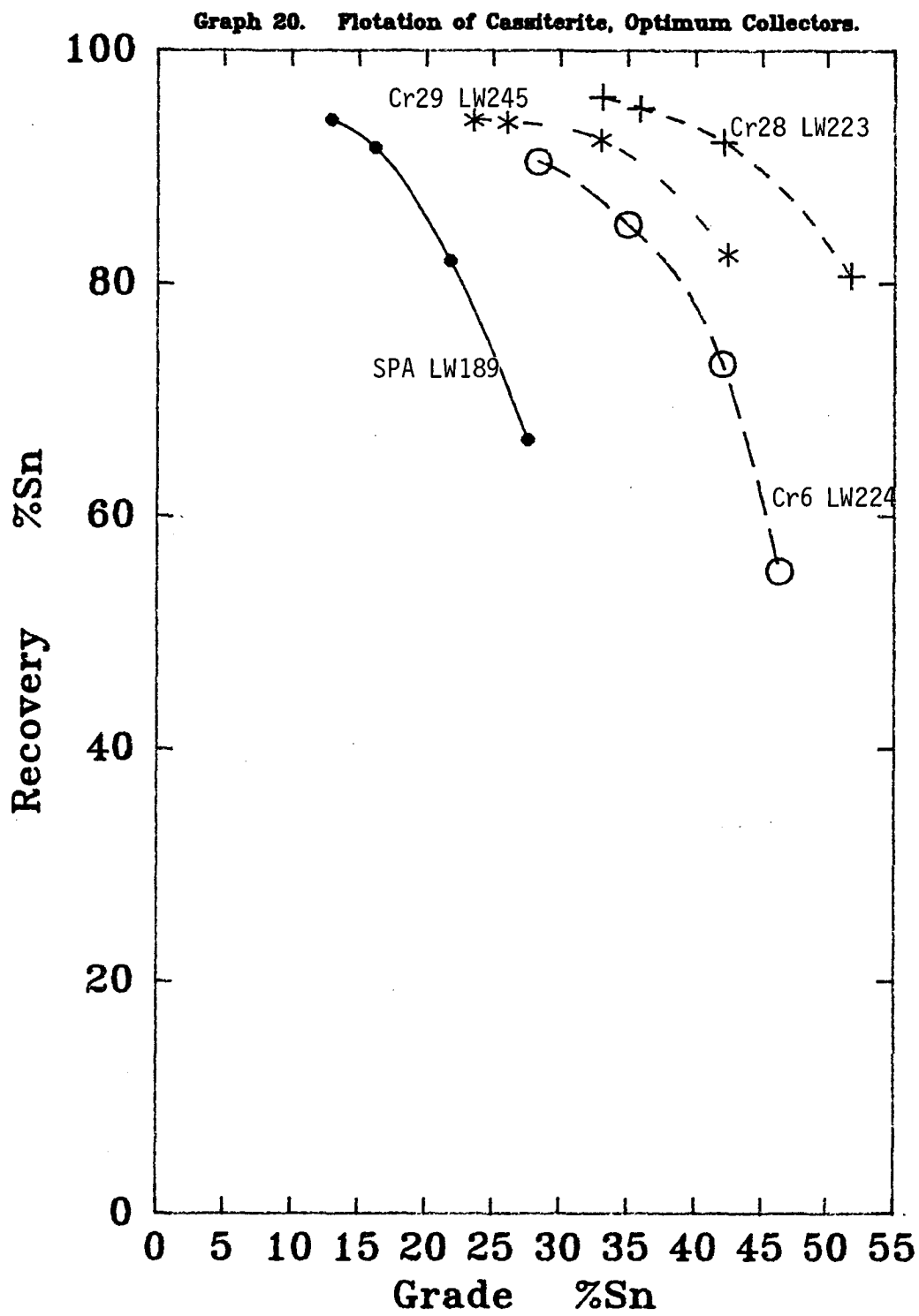




Graph 18. Large Particle Flotation, Cr28 (LW230).









## Chapter 6. Conclusion.

This study on the collecting ability of aryl-substituted polycarboxylic acids and aryl-substituted phosphonocarboxylic acids has identified new classes of collector compounds for use in the flotation of cassiterite and other metal oxides and silicates. Many salient features contributing to collector design and giving increased collector activity have been ascertained, culminating in the identification of specific collectors of vastly improved performance compared with those in current commercial use.

Methods have been developed for the synthesis of some of the Cr series collectors, notably 3-phenyl-4-phosphonobutanoic acid and 3-phenyl-2-phosphonopropenoic acid. Also, methods for the synthesis of a number of other collectors have been improved and these collectors fully characterised using N.M.R. techniques.

A number of specific characteristics necessary for high collector activity have been identified. These include the use of polyacidic functionalities associated with an arylalkyl skeleton, which may involve para-alkyl or alkoxy substitution of the aromatic ring. The presence of the aromatic ring was thought to be fundamental to high collector activity. The increase in activity of the aryl-substituted polycarboxylic acids over their alkane analogues is dramatic. This indicates an ability of adjacent aromatic groups to associate through Van der Waals forces to a greater extent than with the alkane groups in other collector types.

The two types of acid functionality investigated, phosphonic and carboxylic acids, demonstrated different collector characteristics. The use of a phosphonic acid gave stronger collecting power, that is they collected cassiterite ore at a faster rate due to faster adsorption on the oxide surface. However, the phosphonic acid lacked the inherent selectivity of the polycarboxylic acid collector for cassiterite. The weaker

polycarboxylic acid collectors were strengthened by para-substitution in the aromatic ring. This increased the power of the collector by increasing hydrophobicity.

Nitrogen containing analogues of the polycarboxylic acid collectors were found to be poor collectors. This was in direct contrast to the performance of analogous phosphonic acid collectors. The reason for this is unclear but may be associated with the lower collecting power of the carboxylic acid and the tendency for the nitrogen to be involved in hydrogen bonding to water. No studies have been carried out to investigate the adsorption of these collector types on cassiterite.

In general the inclusion of unsaturated bonds in the collector molecule was found to be advantageous effecting an increase in the dissociation of adjacent acid entities, and generation of increased rigidity in the collector. This rigidity decreases the free rotation of the aromatic ring and /or the acid units facilitating better adsorption of the acid entities. A static orientation of the aromatic ring may also facilitate better association between the collector molecules via Van der Waals interactions between aromatic rings.

Incorporation of a 1,1-dicarboxylic acid entity, as seen with Cr6, Cr28, and associated collectors, was found to instil increased collector activity and collectors containing this functionality were the most active of the Cr series.

Inclusion of an alkyl or alkoxy substituent in the para-position of the aromatic ring gave interesting results. Alkyl substitution induced a larger change in the hydrophobicity of the collector than did alkoxy substitution. The ether linkage of the alkoxy substituent was prone to association with water molecules thus reducing its hydrophobicity. This was further demonstrated by the flotation results for 2-(3,4-dimethoxyphenyl)ethene-1,1-dicarboxylic acid (Cr9), which showed reduced collector power, although more highly substituted, when compared with the para-methoxy analogue.

Preliminary work with 2-(4-ethoxy-3-methoxyphenyl)ethene-1,1-dicarboxylic acid underlines this effect as this compound demonstrates increased power approaching that of Cr6, the para-methyl analogue.

The optimum choice of substituents was dependent on the collector skeleton. For collectors based on the tricarboxylic acid series, Cr23 to Cr31, para ethoxy substitution (Cr28) was the most beneficial. This provided a powerful collector with a good response to the addition of sodium silicafluoride depressant and gave excellent selectivity in its presence. For the series Cr5 to Cr10, optimum results were obtained with para-methyl substitution (Cr6). Some correlation between the number of acidic groups and the nature of the para-substituent, required for reasonable collecting power, has been recognised. A balance between the hydrophilic character of the acid units and the hydrophobic character of the aromatic ring and its substituents was necessary to obtain good selectivity and collector strength. The larger hydrophobic group the more adsorption is induced at surfaces, thus, if the hydrophobic group becomes too large then adsorption, and thus flotation, becomes less selective and gangue entrainment increases.

Preliminary investigations currently in progress indicate that the need for para substitution can be replaced by interposing an extra methylene unit in the alkane section of the molecule. For example, the activity of 2-phenylbutanoic acid (Cr19) is less than 3-phenylprop-2-ene-1,2-dicarboxylic acid (phenylitaconic acid).

One of the unique characteristics of the aryl-substituted polycarboxylic acids was their ability to float large particle size cassiterite (to 0.2mm), compared with the maximum of 0.04mm by the use of currently available collectors. The economic implications of this result carried out on a commercial scale would be substantial.

Investigations are currently being undertaken into the flotation

of zircon, rutile, monazite and other non-sulfide based ores. The selectivity for these ore types will hopefully provide further insight into the mode of action of the Cr series collectors. There is scope in both metallurgy and chemistry for further research in areas related to the work carried out in this thesis. Preliminary work on the adsorption of some of the collectors has been carried out by Kuys in a related study, and there is undoubtedly scope for extending this to ascertain correlations between collector adsorption and flotation activity. An associated area, the modelling of the collector-oxide interaction on a molecular scale using theoretical methods, may quantify the efficiency of a particular collector type. Due to the success of the Cr series as

collectors for the flotation of cassiterite, and the promising results obtained in preliminary investigations on a number of other oxide ores, commercial application of these collectors has been investigated. Consequently, a provisional patent<sup>1</sup> has been applied for and the full patent is currently in preparation. The commercial application of these collectors may well be viable with high cost metal oxides, such as rare earth oxides, as well as with cassiterite if the current economic difficulties in the tin industry are overcome. Regardless of this, a new range of collectors for oxide ores has been established and the effects on cassiterite flotation of structural variations in collector design have been established.

## CHAPTER 7. Experimental.

### 7.1 General

Microanalyses were carried out by the Australian Microanalytical Service, Melbourne, or the Canadian Microanalytical Service, Vancouver, on samples which had been dried in vacuo over phosphorus pentoxide at greater than 60 °C.

Melting points were determined on Yanagimoto Seisakusho Micromelting Point apparatus and were uncorrected.

Refractive Indices were obtained on a Carl-Zeiss Jena Refractometer at 20 °C.

The 100MHz proton magnetic resonance (P.M.R.) spectra were recorded with a Jeol JNM-4H-100 analytical spectrometer, and the 300MHz P.M.R. spectra with a Bruker AM 300 or CXP 300 spectrometer. Tetramethylsilane or 3-(trimethylsilyl)propanoic acid, sodium salt (for spectra in D<sub>2</sub>O), was used as an internal standard. Chemical shifts are given in ppm ( $\delta$ ), coupling constants are in Hertz (Hz). Peaks are described as a singlet (s), doublet (d), triplet (t), quartet (q) or as a multiplet (m).

The carbon-13 nuclear magnetic resonance (<sup>13</sup>C N.M.R.) spectra were determined with a Bruker AM 300 or CXP 300 spectrometer operating at 75.469MHz. Chemical shifts ( $\delta$ ) are in ppm from internal tetramethylsilane or 3-(trimethylsilyl)propanoic acid, sodium salt. Carbon-hydrogen coupling constants are not given.

The phosphorus-31 nuclear magnetic resonance (<sup>31</sup>P N.M.R.) spectra were determined on a Bruker AM 300 spectrometer at 121.496MHz. Chemical shifts were measured in ppm using phosphoric acid as an external standard.

Infrared (I.R.) spectra were recorded on a Hitachi 270-30 Infrared Spectrophotometer in wavenumbers ( $\text{cm}^{-1}$ ). Absorption bands are described as either strong (s), medium (m), or weak (w) in intensity.

Low and High resolution mass spectra (M.S.) were run on a Vacuum General Micromass 7070F Spectrometer using the direct insertion technique. The source temperature was  $200^{\circ}\text{C}$  and the electron beam energy maintained at 70eV. Peaks are listed in descending order of m/e ratio. Gas chromatography / mass spectrometry was carried out on a HP 5890A Gas Chromatograph coupled to a HP 5970 series Mass Selective Detector or a Pye Unicam 204 series Chromatograph coupled to the aforementioned Vacuum General Spectrometer. Both systems utilized on-column injection to a multipurpose capillary column.

Dissociation constants were determined using the equipment described in Chapter 7.9.

#### General Preparative Methods.

Preparative thin layer (P.T.L.C.) and medium pressure column chromatography were carried out using Merck Silica gel GF<sub>254</sub> or Camag DSF-5 using the solvents indicated in v/v ratio.

The light petroleum used was of boiling point range  $60-80^{\circ}\text{C}$ . Solvents were purified and / or dried by standard procedures. Pressures for boiling points (Bp) are expressed as subscripts in mm Hg.

All solvents were evaporated under reduced pressure on a rotary evaporator.

Three types of general aqueous workup procedure were used. For the workup of esters (procedure A), the reaction solvents were evaporated, dichloromethane (D.C.M.) (ten times by volume of residue) was then added to the residue, and this was washed with acid solution (type specified) (one half by volume of D.C.M.), saturated sodium bicarbonate (one half by volume of D.C.M.) and then twice with water. All washings were again re-extracted with D.C.M.. The combined D.C.M. fractions were dried over sodium

sulfate. The solvents were then evaporated. The workup of the carboxylic acids (procedure B) from hydrolysis was by acidification to pH 1 (where necessary) with concentrated hydrochloric acid, followed by extraction with diethyl ether (one half by volume of aqueous phase) three times and drying the combined extracts with sodium sulfate. The solvents were then evaporated. Workup of the phosphonocarboxylic acids generally involved only evaporation of the hydrochloric acid and drying under vacuum.

The following polycarboxylic acids were obtained from the Aldrich Chemical Co., U.S.A..

3-Phenylpropenoic acid (cinnamic acid) (Cr1).

2-Phenylpropanedioic acid (phenylmalonic acid) (Cr2).

2-Phenylethane-1,1-dicarboxylic acid (benzylmalonic acid) (Cr3).

N-Phenylmethyliminodiacetic acid (benzyliminodiacetic acid) (Cr33).

3-Phenylpentanedioic acid (phenylglutaric acid) (Cr11).

3-Phenylbutanedioic acid (phenylsuccinic acid) (Cr19) was obtained from Tokyo Kasei Kogyo Co., Japan.

## 7.2 Experimental For Chapter 2.2.

### 7.2.1 Preparation of the 2-(4-substitutedphenyl)ethene-1,1-dicarboxylic acids (Cr5 to Cr10).

The diethyl esters of the title compounds were prepared from their respective aldehydes (0.042 mole) by condensation with diethyl malonate (0.042 mole) using pyridine (1g) / piperidine (0.25g) as catalyst and heating on a water bath for 12 hours. The general workup procedure A, using 2M sulfuric acid, followed by distillation gave the diesters as below.

Table 7.1 Yields for the synthesis of the diethyl 2-(4-substitutedphenyl)ethene-1,1-dicarboxylates.

R	Yield	b.p.(°C)(0.5 mm Hg)
H	77%	125-128 (lit. <sup>6</sup> b.p. <sub>4</sub> 140-142°C)
Me	84%	142-144, m.p. 45°C (lit. <sup>33</sup> m.p. 46-47°C)
Et	80%	147-149
MeO	78%	150-152, m.p. 40°C (lit. <sup>33</sup> m.p. 38-40°C)
EtO	81%	152-154 (lit. <sup>14</sup> Bp <sub>1</sub> 185-190°C)

The diethyl esters, above, were hydrolysed with aqueous potassium hydroxide (40% w/w) by refluxing for approximately 1 hour or until homogeneous. General workup procedure B and recrystallization (water) gave the following dicarboxylic acids.



2-phenylethene-1,1-dicarboxylic acid (Cr5) (92%, m.p. 194-195°C, lit. <sup>62</sup> 195°C), colorless needles.

2-(4-methylphenyl)ethene-1,1-dicarboxylic acid (Cr6) (59%, m.p. 182-186°C, lit. <sup>155</sup> 191-193°C), colorless needles.

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 9.8 (exchangeable peak, -COOH); 7.58 (s, 1H, Ar-CH=); 7.45 (d, 2H, J=8Hz, Ar-H); 7.16 (d, 2H, J=8Hz, Ar-H); 2.35 (s, 3H, Ar-CH<sub>3</sub>).

2-(4-ethylphenyl)ethene-1,1-dicarboxylic acid (Cr7) (78%, m.p. 162-164°C, lit. <sup>155</sup> 155°C), colorless needles.

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 9.5 (exchangeable peak, -COOH); 7.60 (s, 1H, Ar-CH=); 7.40 (d, 2H, J=8Hz, Ar-H); 7.08 (d, 2H, J=8Hz, Ar-H); 2.62 (q, 2H, J=7Hz, -CH<sub>2</sub>-); 1.21 (t, 3H, J=7Hz, -CH<sub>3</sub>).

2-(4-methoxyphenyl)ethene-1,1-dicarboxylic acid (Cr8) (66%, m.p. 164°C, lit. <sup>62</sup> 185-190°C), colorless needles.

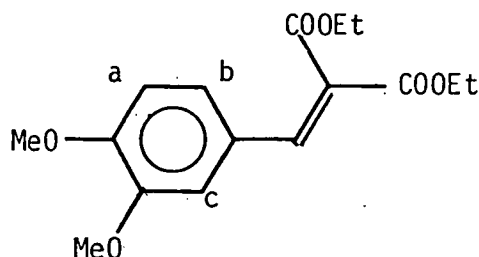
P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 9.4 (exchangeable peak, -COOH); 7.58 (s, 1H, Ar-CH=); 7.52 (d, 2H, J=8Hz, Ar-H); 6.80 (d, 2H, J=8Hz, Ar-H); 3.8 (s, 3H, -O-CH<sub>3</sub>).

2-(4-ethoxyphenyl)ethene-1,1-dicarboxylic acid (Cr10) (76%, m.p. 178-181°C), colorless needles.

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 10.1 (exchangeable peak, -COOH); 7.58 (s, 1H, Ar-CH=); 7.50 (d, 2H, J=8Hz, Ar-H); 6.80 (d, 2H, J=8Hz, Ar-H); 3.84 (q, 2H, J=7Hz, O-CH<sub>2</sub>-); 1.12 (t, 3H, J=7Hz, -CH<sub>3</sub>),

7.2.2 Synthesis of 2-(3,4-dimethoxyphenyl)-  
ethene-1,1-dicarboxylic acid (Cr9).

The diethyl ester of the title compound was prepared by the method of Allen and Spangler<sup>6</sup> (for diethyl phenylethene-1,1-dicarboxylate) using 3,4-dimethoxybenzaldehyde (5.1g) and diethyl malonate (5g). The general workup procedure A, using 2M sulfuric acid, gave diethyl 2-(3,4-dimethoxyphenyl)ethene-1,1-dicarboxylate (5.1g, 54%) as a yellow viscous oil.



P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 7.66 (s, 1H, Ar-CH=); 7.09 (dd, 1H, J=2.0Hz, F=8.4Hz, Ar-H<sup>b</sup>); 7.03 (d, 1H, J=2.0Hz, Ar-H<sup>c</sup>); 6.66 (d, 1H, J=8.4Hz, Ar-H<sup>a</sup>); 4.35, 4.25 (q, 2H, J=7.2Hz, O-CH<sub>2</sub>-); 3.94, 3.91 (s, 3H, O-CH<sub>3</sub>).

The above ester was hydrolysed with 10% sodium hydroxide (50ml) by refluxing for 7 hours. The general workup procedure B gave, upon recrystallization (EtOH /H<sub>2</sub>O) 2-(3,4-dimethoxyphenyl)ethene-1,1-dicarboxylic acid (Cr9) (1.93g, 45%) as yellow prisms, m.p. 190-192°C (lit<sup>58</sup> m.p. 208°C).

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 7.58 (s, 1H, Ar-CH=); 7.23 (d, 1H, J=2.0Hz, Ar-H<sup>c</sup>); 7.17 (dd, 1H, J=2.0Hz, J=8.4Hz, Ar-H<sup>b</sup>); 6.89 (d, 1H, J=8.4Hz, Ar-H<sup>a</sup>); 3.91, 3.87 (s, 3H, O-CH<sub>3</sub>).

7.2.3 Synthesis 2-(4-methylphenyl)ethane-1,1-dicarboxylic acid (Cr4).

Diethyl 3-(4-methylphenyl)ethene-1,1-dicarboxylate was hydrogenated by a method similar to that of Wojcik and Adkins<sup>149</sup>. The ester (10g) was placed in a bomb at 1700 p.s.i. with Raney nickel (1.1g) in ethanol (2ml) and ether (10ml) for 24 hours. The solution was filtered and the filtrate distilled to give diethyl 2-(4-methylphenyl)ethane-1,1-dicarboxylate, (9.80g, 91%, b.p.<sub>0.3</sub> 125°C, lit.<sup>39</sup> b.p.<sub>20</sub> 179-180°C). The above diester (9.80g) was hydrolysed with 10% sodium hydroxide (65ml) by refluxing until homogeneous. General workup procedure B and recrystallization from water, gave colorless needles, of 2-(4-methylphenyl)ethane-1,1-dicarboxylic acid (Cr4), (7.50g, 84%, m.p. 161-164°C lit.<sup>147</sup> 162.5-163.5°C). P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 9.8 (exchangeable peak, -COOH); 7.1 (s, 4H, Ar-H); 3.56 (t, 1H, J=7.5Hz, -C-H); 3.12 (d, 2H, J=7.5Hz, Ar-CH<sub>2</sub>-); 2.26 (s, 3H, Ar-H).

7.2.4 Synthesis of 2-(4-methylphenyl)butanedioic acid (Cr20).

2-(4-Methylphenyl)butanedioic acid was prepared by a method based on that of Allen and Johnson<sup>5</sup> for 2-phenylbutanedioic acid. Diethyl 2-(4-methylphenyl)ethene-1,1-dicarboxylate (12.7g) was dissolved in ethanol (120ml) and potassium cyanide (3.4g), in water (6ml), was added rapidly. The solution was placed on an oil bath at 70°C for 18 hours. General workup procedure B and distillation gave ethyl 3-cyano-3-(4-methylphenyl)propanoate (12.2g, 84%, b.p.<sub>0.5</sub> 134-138°C). This ester (7g) was hydrolysed using concentrated hydrochloric acid (25ml) and refluxing for 18 hours. General workup procedure B and recrystallization (water) gave 2-(4-methylphenyl)butanedioic acid (Cr20), (6.1g, 88%, m.p. 206-207°C) (lit.<sup>33</sup> 192°C).

P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 8.5 (exchangeable,  $-\text{COOH}$ ); 7.0-7.25 (m, 4H, Ar-H); 3.20 (dd, 1H,  $J=10\text{Hz}$ ,  $J=17\text{Hz}$ ), Ar-CH-); 2.35-2.8 (m, 2H,  $-\text{CH}_2-$ ); 2.25 (s, 3H, Ar- $\text{CH}_3$ ).

7.2.5 Synthesis of (E)- and (Z)-2-phenylbutenedioic acid (Cr21 and Cr22).

2-Phenylbutanedioic anhydride (b.p.<sub>16</sub> 196-198°C) was obtained from 2-phenylbutanedioic acid by the method of Verkade and Hartman<sup>141</sup>. This anhydride (10g) gave 2-phenylbutenedioic anhydride (5.9g, 59%, m.p. 119-121°C) by the method of Miller et al.<sup>84</sup>.

Photolysis (corex filter) and hydrolysis of the latter (1.7g) in water (500ml) at 65°C for 24 hours. General workup procedure B and recrystallization (water) gave (E)-2-phenylbutenedioic acid (Cr21), (1.43g, 76%, m.p. 206-206.5°C, lit.<sup>136</sup> 206.5-207.5°C).

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 8.9-9.4 (exchangeable,  $-\text{COOH}$ ); 7.2-7.4 (m, 5H, Ar-H); 7.02 (s, 1H,  $=\text{C-H}$ ).

Hydrolysis of the unsaturated anhydride (2g), by the method of Taylor and Strojny<sup>136</sup>, with 10% aqueous sodium hydroxide (70ml) by heating to 80 °C for 20 minutes and general workup procedure B, gave (Z)-2-phenylbutenedioic acid (Cr22), (1.99g, 90%, m.p. 135-136°C, lit.<sup>136</sup> 129-131°C).

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 7.5-7.6 (m, 2H, Ar-H); 7.3-7.4 (m, 3H, Ar-H); 6.0-6.7 (exchangeable,  $-\text{COOH}$ ); 6.25 (s, 1H,  $=\text{C-H}$ ).

7.2.6 Synthesis of 2-(4-methylphenyl)propane-1,1,3,3-tetracarboxylic acid (Cr32).

The title compound was prepared by the method of Zalukaev and coworkers<sup>155</sup> from tolualdehyde (2.4g) and 2,2-dimethyl-1,3-dioxane-4,6-dione (5.76g) by refluxing in ethanol (10ml) for 10 minutes and cooling in ice to give crystals of the adduct (5.1g, 65%). This ester was hydrolysed by refluxing in 30% sulfuric acid (30ml). General workup procedure B gave 2-(4-methylphenyl)propane-1,1,3,3-tetracarboxylic acid

(Cr32) (3.60g, 89%, m.p. 152°C, lit. <sup>155</sup> 161-163°C), as colorless needles.

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 8.5-9.0 (exchangeable, -COOH); 7.18-7.33 (m, 3H, Ar-H); 6.90-7.10 (m, 2H, Ar-H); 4.08 (s, 3H, Ar-C-H, 2x-C-H); 2.25 (s, 3H, Ar-CH<sub>3</sub>).

The above method was also used with 4-methoxybenzaldehyde (2.72g). This gave only isopropylidene 2-(4-methoxyphenyl)ethene-1,1-dicarboxylate, (3.47g, 70%), as yellow transparent platelets, m.p. 115-116°C.

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>) 8.33 (s, 1H, Ar-C-H); 8.30 (d, 2H, J=7.5Hz, Ar-H); 6.93 (d, 2H, J=7.5Hz, Ar-H); 3.86 (s, 3H, O-CH<sub>3</sub>); 1.76 (s, 6H, -CH<sub>3</sub>).

### 7.3 Experimental for Chapter 2.3

#### 7.3.1 Synthesis of 2-(4-substitutedphenyl)propane-1,1,3-tricarboxylic acids (Cr23 to Cr31).

Alkyl-substituted benzaldehydes were obtained commercially from the Aldrich Co. (U.S.A.) (for R=Me, Et) and from Tokyo Kasei Kogyo Co. (Japan) (for R= iPr). Alkoxybenzaldehydes were prepared from 4-hydroxybenzaldehyde and the respective alkylbromides. 4-Methoxybenzaldehyde was obtained commercially from the Aldrich Co.

The method of Kostanecki<sup>67</sup> (for R=Et, Pr, Bu) and Baddir and coworkers<sup>15</sup> (for R=iPrO) was used in the preparation of the alkoxybenzaldehydes. Their structures were confirmed by P.M.R. spectroscopy.

Table 7.2 Yields in the synthesis of 4-alkoxybenzaldehydes.

R	Yield	Bp
Et	93%	Bp <sub>15</sub> 125-128°C (lit. <sup>67</sup> Bp. 255°C)
Pr	76%	Bp <sub>15</sub> 142-145°C (lit. <sup>14</sup> Bp. <sub>1</sub> 130-133°C)
iPr	62%	Bp <sub>15</sub> 135-137°C (lit. <sup>148</sup> Bp <sub>16</sub> 135-136°C)
Bu	83%	Bp <sub>1</sub> 120-123°C (lit. <sup>14</sup> Bp <sub>3</sub> 119°C)

The para-substituted cinnamic acids were prepared by condensation of the respective aldehyde (1 eq.\* ) with malonic acid (1 eq.) using piperidine (0.1eq.) and pyridine (0.1eq.) as catalysts. Work up was as per general procedure B. Recrystallization from ethanol/water gave there required acid as below. Structure was confirmed by P.M.R. spectroscopy

\* Molar equivalent.

Table 7.3 Yields in the synthesis of para-substituted cinnamic acids.

R	Yield	Ref.
Me	91%	129
Et	90%	15
iPr	41%	15 128
MeO	85%	73 102
EtO	90%	102
PrO	82%	102
iPrO	50%	52 73
BuO	57%	102 135

Esterification of the substituted cinnamic acids above, was carried out by reflux in ethanol (eight times by volume) for six hours using dimethylsulfate (0.1 eq.) as catalyst. Workup was by procedure A, using a 2M sulfuric acid wash. Distillation yielded the esters in the yields given below. ( Identified by P.M.R.).

Table 7.4 Yields in the preparation of ethyl 4-substitutedcinnamates.

R	Yield	
H	80%	Bp <sub>0.5</sub> 90-92°C
Me	90%	Bp <sub>0.5</sub> 112-115°C
Et	88%	Bp <sub>0.5</sub> 125-127°C
iPr	91%	Bp <sub>0.5</sub> 122-124°C
MeO	94%	Bp <sub>0.4</sub> 142-144°C
EtO	95%	Bp <sub>0.1</sub> 136-138°C
PrO	91%	Bp <sub>0.1</sub> 138-141°C
iPrO	93%	Bp <sub>0.2</sub> 135-137°C
BuO	93%	Bp <sub>0.15</sub> 140-142°C

The method of Michael<sup>81,82</sup> was used to synthesise the triethyl 2-(4-substitutedphenyl)propane-1,1,3-tricarboxylates. Typically, an ester (from Table 7.4) was combined with diethyl malonate (0.95eq.) and sodium (0.3eq.) in ethanol (10 eq.) and this mixture refluxed for 12 hours. Workup was by procedure A, using 10% v/v aqueous sulfuric acid. On distillation, the triesters shown in Table 7.5 were obtained in the stated yields. (Identified by P.M.R.).



Table 7.5 Yields in the synthesis of triethyl  
2-(4-substitutedphenyl)propane-1,1,3-tricarboxylate.

R	Yield	
H	75%	Bp <sub>3</sub> 184-187°C (lit. <sup>97</sup> Bp <sub>5</sub> 186-187°C)
Me	81%	Bp <sub>0.3</sub> 161-163°C
Et	79%	Bp <sub>0.25</sub> 175-180°C
iPr	56%	Bp <sub>0.25</sub> 164-165°C
MeO	80%	Bp <sub>1.0</sub> 203-205°C (lit. <sup>97</sup> Bp <sub>2</sub> 194-198°C)
EtO	70%	Bp <sub>0.13</sub> 192-195°C
PrO	79%	Bp <sub>0.15</sub> 198-199°C
iPrO	62%	Bp <sub>0.15</sub> 173-175°C
BuO	80%	Bp <sub>0.15</sub> 200-202°C

The tricarboxylic acid was obtained by reflux in 10% aqueous sodium hydroxide (5 eq.) until homogenous (2-10 hours). Workup was by procedure B followed by recrystallization from dry ethyl acetate and light petroleum. The following acids were obtained:

2-phenylpropane-1,1,3-tricarboxylic acid (Cr23) (83% yield, m.p. 142-143°C) (lit.<sup>81 82</sup> m.p. 137°C), colorless needles.

2-(4-methylphenyl)propane-1,1,3-tricarboxylic acid (Cr24) (92% ,m.p. 168-170°C), colorless needles.

Found: C, 58.58%; H, 5.41%. C<sub>13</sub>H<sub>14</sub>O<sub>6</sub> requires C, 58.65%; H, 5.30%.

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 6.8-7.8 (exchangeable broad peak, -COOH); 7.04 (d, 2H, J=8Hz, Ar-H); 6.68 (d, 2H, J=8Hz, Ar-H); 3.71 (ddd, 1H, J=9.8Hz, J=4.3Hz, J=10.1Hz, C-H); 3.53 (d, 1H, J=9.8Hz, C-H); 2.76 (dd, 1H, J=4.3Hz, J=15.5Hz, -CH<sub>2</sub>); 2.51 (dd, 1H, J=10.1, J=15.5Hz, -CH<sub>2</sub>); 2.14 (s, 3H, CH<sub>3</sub>-Ar).

2-(4-ethylphenyl)propane-1,1,3-tricarboxylic acid (Cr25) (83%, m.p. 150-151.5°C), colorless needles.

Found : C, 60.05%; H, 5.83%.  $C_{14}H_{16}O_6$  requires C, 60.00%; H, 5.75%.

P.M.R. (300MHz)  $\delta$  ( $CDCl_3$ /DMSO) 7.7-8.7 (exchangeable broad peak, -COOH); 7.12 (d, 2H,  $J=8$ Hz, Ar-H); 6.94 (d, 2H,  $J=8$ Hz, Ar-H); 3.76 (ddd, 1H,  $J=9.8$ Hz,  $J=4.4$ Hz,  $J=10.2$ Hz, -C-H); 3.58 (d, 1H,  $J=9.8$ Hz, -C-H); 2.81 (dd, 1H,  $J=4.4$ Hz,  $J=15.6$ Hz,  $-CH_2-$ ); 2.62 (dd, 1H,  $J=10.2$ Hz,  $J=15.6$ Hz,  $-CH_2-$ ); 2.48 (q, 2H,  $J=13$ Hz, Ar- $CH_2-$ ); 1.10 (t, 3H,  $J=13$ Hz,  $-CH_3$ ).

2-(4-(1-methylethyl)phenyl)propane-1,1,3-tricarboxylic acid (Cr26) (75%, m.p. 167-167°C), colorless needles.

Found: C, 60.72%; H, 6.42%.  $C_{15}H_{18}O_6$  requires C, 61.22%; H, 6.16%.

P.M.R. (300MHz)  $\delta$  ( $CDCl_3$ /DMSO) 7.7-9.0 (exchangeable broad band, -COOH); 7.06 (d, 2H,  $J=8.1$ Hz, Ar-H); 6.93 (d, 2H,  $J=8.1$ Hz, Ar-H); 3.71 (ddd, 1H,  $J=15.6$ Hz,  $J=10.2$ Hz,  $J=9.8$ Hz, Ar-C-H); 3.54 (d, 1H,  $J=9.8$ Hz, -C-H); 2.76 (dd, 1H,  $J=15.6$ Hz,  $J=4.3$ Hz,  $-CH_2-$ ); 2.71 (q, 1H,  $J=7$ Hz, Ar-C-H); 2.58 (dd, 1H,  $J=15.6$ Hz,  $J=10.2$ Hz,  $-CH_2-$ ); 1.08 (d, 6H,  $J=6.9$ Hz,  $=CH_3$ ).

2-(4-methoxyphenyl)propane-1,1,3-tricarboxylic acid (Cr27) (58%, m.p. 138-141°C (lit.<sup>97</sup> m.p. 90-120°C)), colorless needles.

Found: C, 55.58%; H, 4.96%.  $C_{13}H_{14}O_7$  requires C, 55.32%; H, 5.00%.

P.M.R. (300MHz)  $\delta$  ( $CDCl_3$ /DMSO) 10.46 (s, exchangeable, -COOH); 7.13 (d, 2H,  $J=9$ Hz, Ar-H); 6.72 (d, 2H,  $J=9$ Hz, Ar-H); 3.78 (ddd, 1H,  $J=9.7$ Hz,  $J=9.5$ Hz,  $J=4.9$ Hz, Ar-C-H); 3.68 (s, 3H, O- $CH_3$ ); 3.62 (d, 1H,  $J=9.4$ Hz, -C-H); 2.87 (dd, 1H,  $J=16.0$ Hz,  $J=4.9$ Hz,  $-CH_2$ ); 2.67 (dd, 1H,  $J=16.0$ Hz,  $J=9.7$ Hz,  $-CH_2$ ).

$^{13}C$  N.M.R.  $\delta$  ( $CDCl_3$ /DMSO) 174.74 ( $n^\#$ ), 171.24 (l), 171.08 (m), 158.62 (e), 132.18 (h), 129.24 (g), 113.84 (f), 56.77 (k), 55.15 ( $d^*$ ), 40.85 (i), 38.45 (j).

\*  $CH_3-O-$

# All C atom assignments as per Figure 2.10.

2-(4-ethoxyphenyl)propane-1,1,3-tricarboxylic acid (Cr28) (75%, m.p. 169.5-170°C), colorless needles.

Found: C, 56.31%; H, 5.60%.  $C_{14}H_{16}O_7$  requires C, 56.76%; H, 5.44%.

P.M.R. (300MHz)  $\delta$  ( $CDCl_3$ /DMSO) 9.85 (s, exchangeable, -COOH); 7.11 (d, 2H,  $J=8.7$ Hz, Ar-H); 6.69 (d, 2H,  $J=8.7$ Hz, Ar-H); 3.89 (q, 2H,  $J=7$ Hz, -CH<sub>2</sub>-O-); 3.76 (ddd, 1H,  $J=9.5$ Hz,  $J=4.9$ Hz,  $J=9.8$ Hz, Ar-CH-); 3.59 (d, 1H,  $J=9.5$ Hz, -C-H); 2.84 (dd, 1H,  $J=15.9$ Hz,  $J=4.9$ Hz, -CH<sub>2</sub>-); 2.64 (dd, 1H,  $J=15.9$ Hz,  $J=9.9$ Hz, -CH<sub>2</sub>-); 1.30 (t, 3H,  $J=7.0$ Hz, -CH<sub>3</sub>).

$^{13}C$  N.M.R. (300MHz)  $\delta$  ( $CDCl_3$ /DMSO) 173.80 (n), 170.68 (l), 170.10 (m), 157.83 (e), 132.41 (h), 129.10 (g), 114.25 (f), 63.30 (d), 57.19 (k), 40.79 (i), 38.55 (j), 14.80 (h).

2-(4-propoxyphenyl)propane-1,1,3-tricarboxylic acid (Cr29) (70%, m.p. 146-147°C), colorless needles.

Found: C, 58.36%; H, 6.06%.  $C_{15}H_{18}O_7$  requires C, 58.06%; H, 5.85%.

P.M.R. (300MHz)  $\delta$  ( $CDCl_3$ /DMSO) 11.00 (s, exchangeable, -COOH); 7.11 (d, 2H,  $J=8.7$ Hz, Ar-H); 6.71 (d, 2H,  $J=8.7$ Hz, Ar-H); 3.80 (t, 2H,  $J=6.5$ Hz, O-CH<sub>2</sub>-); 3.77 (ddd, 1H,  $J=4.9$ Hz,  $J=9.4$ Hz,  $J=9.4$ Hz, Ar-C-H); 3.63 (d, 1H,  $J=9.4$ Hz, -C-H); 2.88 (dd, 1H,  $J=4.9$ Hz,  $J=16.0$ Hz, -CH<sub>2</sub>-); 2.68 (dd, 1H,  $J=16.1$ Hz,  $J=9.4$ Hz, -CH<sub>2</sub>-); 1.70 (tq, 2H,  $J=7.2$ Hz,  $J=7.2$ Hz, -CH<sub>2</sub>-); 0.95 (t, 3H,  $J=7.2$ Hz, -CH<sub>3</sub>).

$^{13}C$  N.M.R.  $\delta$  ( $CDCl_3$ /DMSO) 174.05 (n), 170.62 (l,m), 157.84 (e), 132.05 (h), 129.14 (g), 114.06 (f), 69.16 (d), 57.09 (k), 40.53 (i), 38.42 (j), 22.37 (b), 10.37 (a).

2-(4-(1-methylethoxy)phenyl)propane-1,1,3-tricarboxylic acid (Cr30) (76%, m.p. 158-159°C), colorless needles.

Found: C, 57.95%; H, 5.96%.  $C_{15}H_{18}O_7$  requires C, 58.06%; H, 5.85%.

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 7.5-8.6 (broad exchangeable, -COOH); 7.04 (d, 2H,  $J=8.7\text{Hz}$ , Ar-H); 6.59 (d, 2H,  $J=8.7\text{Hz}$ , Ar-H); 4.33 (q, 1H,  $J=6.0\text{Hz}$ , O-C-H); 3.68 (ddd, 1H,  $J=10.0\text{Hz}$ ,  $J=4.2\text{Hz}$ ,  $J=10.3\text{Hz}$ , Ar-C-H); 3.49 (d, 1H,  $J=9.8\text{Hz}$ , -C-H); 2.75 (dd, 1H,  $J=15.6\text{Hz}$ ,  $J=4.3\text{Hz}$ ,  $-\text{CH}_2-$ ); 2.54 (dd, 1H,  $J=15.6\text{Hz}$ ,  $J=10.3\text{Hz}$ ,  $-\text{CH}_2-$ ); 1.17 (t, 6H,  $J=6\text{Hz}$ ,  $-\text{CH}_3$ ).

2-(4-butoxyphenyl)propane-1,1,3-tricarboxylic acid (Cr31) (72%, m.p.  $140-141^\circ\text{C}$ ), colorless needles.

Found: C, 59.16%; H, 6.18%.  $\text{C}_{16}\text{H}_{20}\text{O}_7$  requires C, 59.25%; H, 6.22%.

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 9.96 (s, exchangeable, -COOH); 7.11 (d, 2H,  $J=8.7\text{Hz}$ , Ar-H); 6.71 (d, 2H,  $J=8.7\text{Hz}$ , Ar-H); 3.84 (t, 2H,  $J=6.8\text{Hz}$ , O- $\text{CH}_2-$ ); 3.77 (ddd, 1H,  $J=9.4\text{Hz}$ ,  $J=9.4\text{Hz}$ ,  $J=5.1\text{Hz}$ , Ar-C-H-); 3.63 (d, 1H,  $J=9.4\text{Hz}$ , -C-H); 2.87 (dd, 1H,  $J=16.0\text{Hz}$ ,  $J=9.4\text{Hz}$ ,  $-\text{CH}_2-$ ); 2.67 (dd, 1H,  $J=16.0\text{Hz}$ ,  $-\text{CH}_2-$ ); 1.68 (tt, 2H,  $J=6.4\text{Hz}$ ,  $J=6.8\text{Hz}$ ,  $-\text{CH}_2-$ ); 1.40 (tq, 2H,  $J=6.8\text{Hz}$ ,  $J=7.3\text{Hz}$ ,  $-\text{CH}_2-$ ); 0.91 (t, 3H,  $J=7.3\text{Hz}$ ,  $-\text{CH}_3$ )

$^{13}\text{C}$  N.M.R. ( $\text{CDCl}_3/\text{DMSO}$ ) 173.82 (n), 170.71 (l), 170.10 (m), 158.00 (e), 132.24 (h), 129.21 (g), 114.20 (f), 67.51 (d), 57.04 (k), 40.78 (i), 38.48 (i), 31.26 (c), 19.11 (b), 13.68 (a).

### 7.3.2 Syntheses of 3-(4-substitutedphenyl)pentanedioic acids (Cr11 to Cr16).

3-Phenylpentanedioic acid (Cr11) was commercially available from the Aldrich Co. Preparation was also from triethyl 2-phenylpropane-1,1,3-tricarboxylate by hydrolysis with concentrated hydrobromic acid / water (2:1) (ten times volume of ester) and refluxing for 10 hours. The cooled reaction mixture was worked up as per procedure B and recrystallization from dilute hydrochloric acid gave 3-phenylpentanedioic acid (68%, m.p.  $137-138^\circ\text{C}$ , lit.<sup>81 132</sup>  $137-138^\circ\text{C}$ ), as colorless platelets.

P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 8.5 (broad exchangeable peak, -COOH); 7.2 (s, 5H, Ar-H); 3.35-3.65 (m, 1H, Ar-C-H); 2.35-2.70 (m, 4H,  $-\text{CH}_2-$ ).

The preparation of 3-(4-methylphenyl)pentanedioic acid (Cr12) was by the method above from triethyl 2-(4-methylphenyl)propane-1,1,3-tricarboxylate. (68%, m.p. 156-158.5°C, lit.<sup>155</sup> 161°C).

P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 9.2 (exchangeable broad peak, -COOH); 7.06 (s, 4H, Ar-H); 3.35-3.65 (m, 1H, Ar-C-H); 2.40-2.75 (m, 4H,  $-\text{CH}_2-$ ); 2.27 (s, 3H, Ar- $\text{CH}_3$ ).

3-(4-Ethylphenyl)pentanedioic acid (Cr13) was prepared by the above method from the respective triethyl ester to give Cr13 as colorless platelets (74%, m.p. 119°C, lit.<sup>155</sup> 121-122°C)

P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 9.0 (exchangeable broad band, -COOH); 7.1 (s, 4H, Ar-H); 3.35-3.65 (m, 1H, Ar-C-H); 2.45-2.75 (m, 6H, Ar- $\text{CH}_2-$ , 2x  $-\text{CH}_2-$ ); 1.15 (t, 3H, J=7Hz,  $-\text{CH}_3$ ).

3-(4-Methoxyphenyl)pentanedioic acid (Cr14) was prepared by the method of Michael<sup>81</sup>, by refluxing triethyl 2-(4-methoxyphenyl)propane-1,1,3-tricarboxylate with aqueous barium hydroxide (4 eq.) for 3 hours. Acidification and filtration of the precipitated barium sulfate, followed by workup as per procedure B. The oil obtained was placed in an oven (120°C) for 4 days ( $\text{CO}_2$  evolved). The resultant crystals were recrystallized from the minimum quantity of water to give colorless platelets. (62%, m.p. 159°C, lit.<sup>148</sup> 165°C, lit.<sup>85</sup> 160-161°C)

P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 9.8 (exchangeable, -COOH); 7.15 (d, 2H, J=8Hz, Ar-H); 6.75 (d, 2H, J=8Hz, Ar-H); 3.70 (s, 3H,  $-\text{O}-\text{CH}_3$ ); 3.55-3.70 (m, 1H, Ar-C-H); 2.35-2.80 (m, 4H,  $-\text{CH}_2$ ).

3-(4-Propoxyphenyl)pentanedioic acid (Cr16) was obtained by the method above from triethyl 2-(4-propoxyphenyl)propane-1,1,3-tricarboxylate, to give colorless platelets (72%, m.p. 118°C, lit.<sup>85</sup> 98-100°C).

P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 9.0 (exchangeable broad peak,  $-\text{COOH}$ ); 7.10 (d, 2H,  $J=8\text{Hz}$ , Ar-H); 6.72 (d, 2H,  $J=8\text{Hz}$ , Ar-H); 3.80 (t, 2H,  $J=8\text{Hz}$ ,  $\text{O}-\text{CH}_2-$ ); 3.30-3.70 (m, 1H, Ar-C-H); 2.20-2.72 (m, 4H,  $-\text{CH}_2-$ ); 1.50-1.88 (m, 2H,  $-\text{CH}_2-$ ); 1.0 (t, 3H,  $J=8\text{Hz}$ ,  $-\text{CH}_3$ ).

3-(4-Ethoxyphenyl)pentanedioic acid (Cr15) was obtained by the method of Smith and Kort<sup>132</sup> (for the 4-methoxy derivative). 4-Ethoxybenzaldehyde (5g) and ethyl acetoacetate (8.8g) were placed in a dry flask with piperidine (0.68ml) and ethanol (1.7ml) and left to stand for 19 hours at room temperature. Workup was as per procedure A, using 5M hydrochloric acid and recrystallization from ethanol to give diethyl 2,4-dimethoxy-3-(4-ethoxyphenyl)pentanedioate, (7.3g, 59%, m.p.  $148-150^\circ\text{C}$ ), colorless needles.

The latter was hydrolysed by refluxing in ethanol (100ml) and 50% aqueous sodium hydroxide (125ml) for 3 hours. Ethanol was evaporated and workup was as per procedure B, and recrystallized from water, to give 3-(4-ethoxyphenyl)pentanedioic acid (Cr15) (67%, m.p.  $122^\circ\text{C}$ , lit.<sup>85</sup>  $132-133^\circ\text{C}$ ), as colorless platelets.

P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 10.1 (exchangeable peak,  $-\text{COOH}$ ); 6.90 (d, 2H,  $J=8\text{Hz}$ , Ar-H); 6.50 (d, 2H,  $J=8\text{Hz}$ , Ar-H); 3.73 (q, 2H,  $J=7.5\text{Hz}$ ,  $\text{O}-\text{CH}_2-$ ); 3.15-3.45 (m, 1H, Ar-C-H); 2.20-2.50 (m, 4H,  $-\text{CH}_2-$ ); 1.10 (t, 3H,  $J=7.5\text{Hz}$ ,  $-\text{CH}_3$ ).

### 7.3.3 Synthesis of 3-(4-substitutedphenyl)pentenedioic acids (Cr17 and Cr18).

A method similar to that for the preparation of triethyl 2-phenylpropane-1,1,3-tricarboxylate was used, using ethyl phenylpropiolate (15g) as the Michael acceptor and diethyl malonate (0.95 eq.) to give triethyl 2-phenylpropene-1,1,3-tricarboxylate (20.5g, 75%, b.p.<sub>0.5</sub>  $163-165^\circ\text{C}$ , (lit.<sup>120</sup> b.p.<sub>11</sub>  $215-220^\circ\text{C}$ ).

Hydrolysis of the above ester (15g) with 10% sodium hydroxide (150ml) by refluxing until homogeneous, followed by workup as per procedure B, and recrystallization (ethyl acetate/ petroleum ether) gave 3-phenylpentenedioic acid (Cr17) (11.2g, 82%), small colorless crystals, m.p. 155-156.5°C, (lit.<sup>101</sup> m.p. 154-155°C).  
P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 8.8 (exchangeable, -COOH); 7.35-7.50 (m, 5H, Ar-H); 6.34 (s, 1H, =C-H); 4.18 (s, 2H, -CH<sub>2</sub>-).

Ethyl 4-methylcinnamate was brominated and dehydrobrominated<sup>164</sup> to give 3-(4-methylphenyl)propionate (50%, b.p.<sub>0.3</sub> 90-92°C). The Michael reaction as previously described was carried out on the latter ester (10.1g) using diethyl malonate (9.53g) as a donor to give triethyl 2-(4-methylphenyl)propene-1,1,3-tricarboxylate (13.2g, 71%), b.p.<sub>0.3</sub> 163-165°C.

This ester (4.7g) was hydrolysed with 10% sodium hydroxide (40ml) by refluxing until homogeneous. Workup as per procedure B and recrystallization (ethyl acetate/ petroleum ether) gave 3-(4-methylphenyl)pentenedioic acid (Cr18) (2.23g, 77%), m.p. 180-182°C, as colorless platelets.

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 9.1 (exchangeable, -COOH); 7.38 (d, 2H, J=8Hz, Ar-H); 7.15 (d, 2H, J=8Hz, Ar-H); 6.25 (s, 1H, =C-H); 4.14 (s, 2H, -CH<sub>2</sub>-); 2.35 (s, 3H, Ar-CH<sub>3</sub>).

Attempts to prepare 2-(4-methylphenyl)propane-1,1,3-tricarboxylic acid were unsuccessful. The sodium salt of this acid was obtained but this decarboxylated (the vigorous reaction resulting in appreciable foaming) on acidification to pH 6.

## 7.4 Experimental for Chapter 2.4.

### 7.4.1 Syntheses of N-(4-substitutedphenyl)iminodiacetic acids (Cr33 to Cr35).

N-Phenyliminodiacetic acid (Cr33) was prepared by the method of Pettit and Irving<sup>100</sup>, (4.54g, 61%), m.p. 149°C, lit.<sup>100</sup> 154°C.

P.M.R. (100MHz)  $\delta$  ( $D_2O$ ) 7.2-7.45 (m, 2H, Ar-H); 6.55-6.95 (m, 3H, Ar-H); 4.15 (s, 4H,  $-CH_2-$ ).

A similar method was used with toluidine (3.6g) to give N-(4-methylphenyl)iminodiacetic acid (Cr34), (2.15g, 30%), m.p. 120°C (decomposed), lit.<sup>53</sup> 120°C.

P.M.R. (100MHz)  $\delta$  ( $D_2O$ ) 7.12 (d, 2H,  $J=7.5\text{Hz}$ , Ar-H); 6.54 (d, 2H,  $J=7.5\text{Hz}$ , Ar-H); 4.15 (s, 4H,  $-CH_2-$ ); 2.19 (s, 3H, Ar-H).

A similar method was used with anisidine (4.11g) to give N-(4-methoxyphenyl)iminodiacetic acid (Cr35), (2.9g, 36%), m.p. 89°C, lit.<sup>53</sup> 95-96°C. This compound decomposed on standing over a period of time.

P.M.R. (100MHz)  $\delta$  ( $CDCl_3/DMSO$ ) 7.6 (s, exchangeable,  $-COOH$ ); 6.75 (d, 2H,  $J=9\text{Hz}$ , Ar-H); 6.51 (d, 2H,  $J=9\text{Hz}$ , Ar-H); 4.10 (s, 4H,  $-CH_2-$ ); 3.68 (s, 3H,  $-O-CH_3$ ).

### 7.4.2 Synthesis of N-benzyliminodiacetic acid (Cr37).

The title compound was prepared by the method of Cherkosov<sup>31</sup>. Iminodiacetic acid (1.7g) was dissolved in 10% sodium hydroxide (10ml) and benzoylchloride (2g) added over 4 hours. Acidification to pH 3 gave benzoic acid (150mg). Extraction of the aqueous portion with ethyl acetate (30ml) three times, drying with sodium sulfate, evaporation of solvent and recrystallization (ethyl acetate/ light petroleum) gave the title compound (2.2g, 65%), m.p. 118°C, (lit.<sup>31</sup> 121-122°C).



P.M.R. (100MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 7.75 (exchangeable broad peak, -COOH); 7.38 (s, 5H, Ar-H); 4.23 (s, 2H,  $-\text{CH}_2-$ ); 4.03 (s, 2H,  $-\text{CH}_3$ )

## 7.5 Experimental for Chapter 3.1.

### 7.5.1 Synthesis of 4-methylstyrenephosphonic acid (Cr38).

The title compound was prepared by a similar method to that of Anisimov<sup>8</sup> for the preparation of non-substituted styrenephosphonic acid. 4-Methylstyrene (5g), phosphorus pentachloride (17.5g) and toluene (100ml) were stirred for 24 hours under nitrogen. Sulfur dioxide was then bubbled through the solution until clear. Solvent was evaporated and water (100ml) added. The solid was filtered off and 4-methylstyrene (1.8g) was recovered from the filtrate on evaporation. The solid gave 4-methylstyrenephosphonic acid (Cr38) (3.5g, 65%), m.p. 172-172.5°C.

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 8.0 (broad exchangeable, -COOH); 7.15-7.5 (m, 3H, Ar-CH=, 2xAr-H); 6.93-7.15 (d, 2H, J=8Hz, Ar-H); 6.27 (dd, 1H, <sup>3</sup>J<sub>P-H</sub>=17Hz, J<sub>H-H</sub>=16.5Hz, =C-H-); 2.28 (s, 3H, Ar-CH<sub>3</sub>).

## 7.6 Experimental for Chapter 3.2.

### 7.6.1 The hydrolysis of diethyl 2-phenylethene-1,1-dicarboxylate using trimethylsilyl iodide.

Diethyl 2-phenylethene-1,1-dicarboxylate (1g), acetonitrile (4ml) and trimethylsilyl iodide (1.8ml) were placed in a sealed tube and heated at 70°C for 12 hours. This was then quenched with water (4 ml) and extracted with ether (3x20ml). The combined extracts were washed with saturated sodium sulfite solution (15ml), dried with sodium sulfate, and evaporated giving on recrystallization from water, 2-phenyl-ethene-1,1-dicarboxylic acid (Cr5) (0.68g, 88%), as colorless needles, m.p. 195-196°C (lit.<sup>62</sup> 195°C).

### 7.6.2 Synthesis of 3-phenyl-2-phosphonopropanoic acid (Cr39).

The triethyl ester of the title acid was prepared by two methods. Firstly the method of Robinson<sup>115</sup> <sup>116</sup> using benzaldehyde (5.30g), triethyl phosphonoacetate (12g), piperidine (0.5ml), benzoic acid (0.5g), benzene (100ml) and refluxing for 6 days using a Dean-Stark trap. Workup by procedure A, using 5M hydrochloric acid, followed by distillation gave triethyl 3-phenyl-2-phosphonopropenoate (9.80g, 64%), b.p. <sub>0.5</sub> 162.-168°C, (lit.<sup>10</sup> b.p.<sub>0.35</sub> 154-158°C). The latter ester was hydrogenated using sodiumborohydride (1.33g) in ethanol (20ml), added dropwise over 20 minutes. Workup by procedure A, using 5M hydrochloric acid gave triethyl 3-phenyl-2-phosphonopropanoate (7.05g, 72%), b.p.<sub>0.5</sub> 148°C, (lit.<sup>116</sup> b.p.<sub>5</sub> 189-191°C).

Secondly, the method of Kosolapoff and Powell<sup>66</sup>, triethylphosphonoacetate (28g) was added dropwise to potassium (6g) and xylene (200ml), benzylchloride (40g) was added dropwise and refluxed for 8 hours. Workup by procedure A, using 5M hydrochloric acid, gave triethyl 3-phenyl-2-phosphonopropanoate (20.1g, 20.5%), b.p.<sub>0.5</sub> 148-150°.

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) 7.16-7.32 (m, 5H, Ar-H); 4.18 (dq, 4H,  $^2J_{\text{P-H}} = 7.0\text{Hz}$ ,  $J = 7.0\text{Hz}$ , P-O-CH<sub>2</sub>-); 4.08 (q, 2H,  $J = 7.5\text{z}$ , C-O-CH<sub>2</sub>-); 3.13-3.35 (m, 3H, Ar-CH<sub>2</sub>-, -C-H); 1.35 (t, 6H,  $J = 7.0\text{Hz}$ , P...CH<sub>3</sub>); 1.05 (t, 3H, 7.1Hz, C..CH<sub>3</sub>)

Hydrolysis of the above ester (2.45g), from either method, by the method of Kosolapoff and Powell<sup>66</sup> with refluxing concentrated hydrochloric acid (20ml) for 7 hours gave 3-phenyl-2-phosphonopropanoic acid (Cr39) (1.60g, 89%), m.p. 150-151°C, (lit.<sup>66</sup> 150-152°C), as colorless needles.

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 7.10-7.28 (m, 5H, Ar-H); 6.86 (exchangeable, -COOH, -PO<sub>3</sub>H<sub>2</sub>); 3.1-3.32 (m, 3H, -CH<sub>2</sub>-, -C-H)

I.R. (Nujol) (Ba salt) 3617 (m, -OH); 1560 (s, C-O); 1071 (s, P-O)  $\text{cm}^{-1}$ .

<sup>31</sup>P N.M.R.  $\delta$  ( $\text{D}_2\text{O}$ ) 19.93

The above acid was also prepared from the triethyl ester via the formation of the tri(trimethylsilyl) ester. Triethyl 3-phenyl-2-phosphonopropanoate (1g) (previously distilled twice from calcium hydride) acetonitrile (4ml) and trimethylsilyl iodide<sup>122</sup> (2.88g) were placed in a teflon sealed glass tube under nitrogen and heated to 85°C for 12 hours. On cooling a further amount of trimethylsilyl iodide (1.44g) was added and the resealed reaction tube heated for a further 12 hours. On cooling the solvent and excess trimethylsilyl iodide were evaporated under a stream of nitrogen to give a brown oil. This oil was dissolved in water (15ml) and extracted with dichloromethane (3x30ml). The aqueous layer was then evaporated and put under vacuum for 24 hours to give 3-phenyl-2-phosphonopropanoic acid (Cr39), as a yellow oil (0.68g, 93%).

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3/\text{DMSO}$ ) 7.10-7.30 (m, 5H, Ar-H); 5.32 (exchangeable, -COOH, -PO<sub>3</sub>H<sub>2</sub>); 3.1-3.32 (m, 3H, -CH<sub>2</sub>-, -C-H).

To the above acid (0.65g) was added a saturated solution of barium hydroxide (40ml) and the precipitate filtered off and washed thoroughly with warm water. The resultant white powder was dried under vacuum for 24 hours at 60°C to give the hydrated

barium salt.

I.R. (nujol) 3616 (-OH); 1560 (s, C-O); 1069 (s, P-O)  $\text{cm}^{-1}$ .

### 7.6.3 Synthesis of 3-phenyl-2-phosphonopropenoic acid (Cr45).

Triethyl 3-phenyl-2-phosphonopropenoate (1g) (previously distilled from a small amount of calcium hydride), dry acetonitrile (3ml) and trimethylsilyl iodide (2ml) were added, via a syringe, to a dry glass tube fitted with a teflon screw tap, that had been previously been flushed with nitrogen. The tube was sealed and heated at 85-90°C overnight, cooled and further trimethylsilyl iodide (1ml) added. The tube was resealed and heated for a further 12 hours.

Upon cooling the solvent and volatile components were evaporated under a stream of nitrogen to give a viscous brown oil, crude tri(trimethylsilyl) 3-phenyl-2-phosphonopropenoate. This ester was dissolved in dichloromethane (10ml) and then transferred to a separating funnel where the ester was hydrolysed with deuterium oxide (5ml) and the acid extracted into the aqueous phase. Washing the deuterium oxide with dichloromethane (3x10ml), to extract coloration, gave a light brown solution of the acid in deuterium oxide. This was analysed by N.M.R. techniques as described below.

The barium salt (a hydrated dimer) was obtained by addition of a saturated solution of barium hydroxide (30ml) to the above solution, leaving for 4 weeks, and washing the crystals adhered to the flask with copious quantities of warm water. All other precipitate was discarded.

For the barium salt, Found: C, 23.45%; H, 2.13%; P, 6.00%.  $\text{C}_{18}\text{H}_{12}\text{O}_{10}\text{P}_2\text{Ba}_3 \cdot 4\text{H}_2\text{O}$  requires C, 23.10%; H, 2.16%; P, 6.6%.

Tris(trimethylsilyl) 3-phenyl-2-phosphonopropenoate, brown oil (crude).

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) 7.13-7.65 (m, 6H, Ar-H, =C-H); 0.35 (s, 27H,  $\text{CH}_3$ -Si-).

3-phenyl-2-phosphonopropenoic acid, (Cr45) (in solution).(Z)- form, 8%P.M.R. (300MHz) ( $D_2O$ ) 8.28 (d, 1H,  $^3J_{P-H}=41\text{Hz}$ , =C-H);  
7.35-7.52 (m, 5H, Ar-H). $^{31}P$  N.M.R.  $\delta$  ( $D_2O$ ) 9.3(E)-form, 92%P.M.R. (300MHz)  $\delta$  ( $D_2O$ ) 7.55 (d, 1H,  $^3J_{P-H}=25\text{Hz}$ , =C-H);  
7.35-7.52 (m, 5H, Ar-H). $^{13}C$  N.M.R. ( $D_2O$ ) 173.5 ( $^2J_{P-C}=13.6\text{Hz}$ , -COO); 148.7 (Ar-C=);  
136.2 ( $^3J_{P-C}=18\text{Hz}$ , Ar(quaternary)); 133.5 (Ar); 131.8 (Ar);  
131.2 (Ar); 128.9 ( $J_{P-C}=178\text{Hz}$ , =C-). $^{31}P$  N.M.R.  $\delta$  ( $D_2$ ) 10.4I.R. (E- and Z- forms) (barium salt) (nujol) 3380 (b,  $H_2O$ ); 1544 (s, C-O<sub>asy</sub>); 1403 (m, C-O<sub>sym</sub>); 1091, 1049 (s, P-O).7.6.4. Synthesis of ethyl (E)-3-phenyl-2-phosphonopropenoate.

The method for the synthesis of 3-phenyl-2-phosphonopropenoic acid was used except that the second addition of trimethylsilyl iodide was not made and the reaction worked up at this point. Workup consisted of dissolving the crude product in water (15ml) and washing with light petroleum (50ml) until the aqueous phase was colorless. The aqueous phase was then extracted with dichloromethane (3x30ml) and the combined organic extracts dried with sodium sulfate. Evaporation, and recrystallization from acetone / petroleum ether gave the monoester. From triethyl 3-phenyl-2-phosphonopropenoate (lg) was obtained ethyl (E)-3-phenyl-2-phosphonopropenoate (610mg, 74%), as transparent needles, m.p. 140-142°C.

Found: C, 51.51%; H, 5.22%; P, 11.9%.  $C_{11}H_{13}O_5P$  requires C, 51.57%; H, 5.11%; P, 12.09%.

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) 7.51 (d, 1H,  $^3J_{\text{P-H}}=26\text{Hz}$ , =C-H); 7.25-7.38 (m, 5H, Ar-H); 4.43 (broad exchangeable,  $\text{PO}_3\text{H}_2$ ); 4.23 (q, 2H,  $J=7.4\text{Hz}$ , O- $\text{CH}_2$ -); 1.21 (t, 3H,  $J=7.3\text{Hz}$ , - $\text{CH}_3$ ).

$^{13}\text{C}$  N.M.R.  $\delta$  ( $\text{CDCl}_3$ ) 166.6 ( $^2J_{\text{P-C}}=12\text{Hz}$ , a); 144.8 (c); 134.0 ( $^3J_{\text{P-C}}=20\text{Hz}$ , d); 129.4 (e); 128.7 (f); 128.1 (g) 127.9 ( $J_{\text{P-C}}=180\text{Hz}$ , b); 61.2 (h); 13.6 (i). For assignments see Figure 3.3.

M.S. (low res.) m/e 256 (7%); 254 (46%); 211 (49%); 183 (92%); 147 (72%); 131 (100%); 103 (100%).

I.R. (nujol) 1716 (s, C=O); 1596 (w, C=C); 1236 (P=O); 1185, 1158, 1104, 1023 (P-O)  $\text{cm}^{-1}$ .

## 7.7 Experimental for Chapter 3.3.

### 7.7.1 Preparation of 3-(4-methylphenyl)-3-phosphonopropanoic acid (Cr41).

The title compound was prepared by the method of Pudovik<sup>105</sup> (for 3-phenyl-3-phosphonopropanoic acid). Ethyl 3-(4-methylphenyl)propenoate (11.0g) and diethyl phosphite (6.7g) were stirred whilst saturated sodium ethoxide/ethanol was slowly added until the reaction started. A small excess was then added and the reaction let stand for 1 hour. The reaction was worked up as per procedure A, using glacial acetic acid, followed by distillation to give triethyl 3-(4-methylphenyl)-phosphonopropanoate (12.82g, 68%), b.p.<sub>0.25</sub> 144-148°C.

The above ester was hydrolysed with 250ml of 1:1 hydrochloric acid by refluxing for 6 hours. Evaporation of the aqueous phase and recrystallization (ethyl acetate/light petroleum) gave 3-(4-methylphenyl)-3-phosphonopropanoic acid (Cr41) (8.52g, 89%), m.p. 221-223°C

P.M.R. (100MHz)  $\delta$  (CDCl<sub>3</sub>/DMSO) 8.85 (exchangeable, -COOH, -PO<sub>3</sub>H<sub>2</sub>); 7.21 (d, 2H, J=8Hz, Ar-H); 7.04 (d, 2H, J=8Hz, Ar-H); 3.20-3.70 (m, 1H, -C-H); 2.65-3.20 (m, 2H, -CH<sub>2</sub>-); 2.26 (s, 3H, -CH<sub>3</sub>).

Attempts to synthesise 2-(4-methylphenyl)-2-phosphonoethane-1,1-dicarboxylic acid by hydrolysis of the respective tetraethyl ester (1.2g) (prepared by the method of Pudovik<sup>106</sup>) gave only 3-(4-methylphenyl)-3-phosphonopropanoic acid, (0.69g, 82%).



### 7.7.2 Preparation of 3-phenyl-2,3-diphosphonopropanoic acid (Cr44).

Diethyl phosphite (10g) and ethyl phenylpropynoate (5.5g) were treated as in the preparation of triethyl 3-(4-methylphenyl)-3-phosphonopropanoate and refluxed for 2 hours. This gave after workup pentaethyl 3-phenyl-2,3-diphosphonopropanoate (10.73g, 75%), as two diastereomers, b.p.<sub>0.1</sub> 172-180°C, (lit.<sup>110</sup> b.p.<sub>2</sub> 208°C).

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 7.20-7.48 (m, 5H, Ar-H); 3.68-4.35 (m, 10H, O-CH<sub>2</sub>-); 3.35-3.68 (m, 2H, -C-H); 0.92-1.42 (m, 15H, -CH<sub>3</sub>).

The above ester (3.2g) was hydrolysed with 1:1 aqueous hydrochloric acid (50ml) in a sealed flask by heating to 140°C for 8 hours. After cooling, the aqueous mixture was washed with dichloromethane and the aqueous phase was then evaporated under reduced pressure to give 3-phenyl-2,3-diphosphonopropanoic acid (Cr44), as a crystalline hygroscopic solid (1.943g, 88%), m.p. 209-215°C, (lit.<sup>110</sup> 113-115°C).

P.M.R. (300MHz)  $\delta$  (D<sub>2</sub>O) 7.05-7.27 (m, 5H, Ar-H); 3.35-3.75 (m, 2H, -C-H).

<sup>31</sup>P N.M.R.  $\delta$  (D<sub>2</sub>O) diastereomer A, 25.6 (d, <sup>3</sup>J<sub>P-P</sub> = 71Hz, b); 18.4 (d, <sup>3</sup>J<sub>P-P</sub> = 71Hz, a). diastereomer B 25.8 (s, b); 18.4 (s, a).

### 7.7.3 Syntheses of 3-(4-alkylphenyl)-4-phosphonopentanedioic acids (Cr42 and Cr46).

The unsubstituted analogue of the title compound was prepared by the method of Pudovik and Lebedeva<sup>107</sup> using ethyl cinnamate (4g), triethyl phosphonoacetate (6g) and ethanol/ sodium ethoxide (0.2 eq.) to give tetraethyl 3-phenyl-4-phosphonopentanedioate (2.19g, 23%), yellow oil, b.p.<sub>0.3</sub> 171-174°C (lit.<sup>107</sup> b.p.<sub>2</sub> 190-192°C, <sup>44</sup> b.p.<sub>0.02</sub> 138°C) as a diastereomeric mixture (62% A and 38% B, from P.M.R.).

A - P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) 7.15-7.26 (m, 5H, Ar-H); 4.15-4.27 (m, 4H,  $\text{O-CH}_2$ -); 3.81-3.96 (m, 4H,  $\text{O-CH}_2$ -); 3.71-3.85 (m, 1H, Ar-C-H); 3.24 (dd, 1H,  $J=15.6\text{Hz}$ ,  $J=11.1\text{Hz}$ ,  $-\text{CH}_2$ -); 2.82 (d, 1H,  $J=9.7\text{Hz}$ , -C-H); 2.67 (dd, 1H,  $J=15.6\text{Hz}$ ,  $J=3.8\text{Hz}$ ,  $-\text{CH}_2$ -); 1.38, 1.35 (t, 3H,  $J=6.8\text{Hz}$ ,  $-\text{CH}_3$ ); 1.04, 0.92 (t, 3H,  $J=7.2\text{Hz}$ ,  $-\text{CH}_3$ ).

B - P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) 7.15-7.326 (m, 5H, Ar-H); 4.15-4.25 (m, 4H,  $-\text{O-CH}_2$ -); 3.81-3.85 (m, 4H,  $\text{O-CH}_2$ -); 3.71-3.85 (m, 1H, Ar-C-H); 3.43 (dd, 1H,  $J=11.7\text{Hz}$ ,  $J=20.2\text{Hz}$ ,  $-\text{CH}_2$ -); 3.33 (dd, 1H,  $J=9.5\text{Hz}$ ,  $J=20.2\text{Hz}$ ,  $-\text{CH}_2$ -); 2.83 (d, 1H,  $J=5.6\text{Hz}$ , -C-H); 1.29, 1.16, 1.15, 1.04 (t, 3H,  $J=7.1\text{Hz}$ ,  $-\text{CH}_3$ ).

The above diastereomeric mixture (2.00g) was hydrolysed with 1:1 aqueous hydrochloric acid (50ml) by reflux for 8 hours and washing the cooled solution with dichloromethane (50ml). The aqueous solution was evaporated to give a hygroscopic solid foam of 3-phenyl-4-phosphonopentanedioic acid (Cr42) (1.37g, 95%) as a diastereomeric mixture.

A - P.M.R. (300MHz)  $\delta$  ( $\text{D}_2\text{O}$ ) 7.28-7.34 (m, 5H, Ar-H); 3.60-3.80 (m, 1H, Ar-C-H); 3.30 (dd, 1H,  $J=15.7\text{Hz}$ ,  $J=3.8\text{Hz}$ ,  $-\text{CH}_2$ -); 2.94 (d, 1H,  $J=11.6\text{Hz}$ , -C-H); 2.75 (dd, 1H,  $J=15.7\text{Hz}$ ,  $J=11.8\text{Hz}$ ,  $-\text{CH}_2$ -).

B - P.M.R. (300MHz)  $\delta$  ( $\text{D}_2\text{O}$ ) 7.28-7.34 (m, 5H, Ar-H); 3.60-3.80 (m, 1H, Ar-C-H); 3.33 (d, 1H,  $J=11.5\text{Hz}$ ,  $-\text{CH}_2$ -); 3.27 (d, 1H,  $J=11.5\text{Hz}$ ,  $-\text{CH}_2$ -); 2.97 (d, 1H,  $J=4.6\text{Hz}$ , -C-H).

$^{31}\text{P}$  N.M.R.  $\delta$  ( $\text{D}_2\text{O}$ ) 15.41, 14.64.

The barium salt was obtained on addition of a saturated solution of barium hydroxide to a solution of the above acid, and filtration to give a white powder which was dried under vacuum.

I.R. (Barium salt) (nujol) 3420 (b,  $\text{H}_2\text{O}$ ); 1562, 1538 (s, C-O); 1086, 1050, 1038 (s, P-O),  $\text{cm}^{-1}$ .

Tetraethyl 3-(4-methylphenyl)-2-phosphonopentanedioate was synthesised by the same method as the former unsubstituted acid from ethyl 4-methylcinnamate (6g) and triethyl phosphonoacetate (8g). The same workup gave tetraethyl 3-(4-methylphenyl)-2-phosphonopentanedioate (2.60g, 20%), yellow

viscous oil, B.p.<sub>0.3</sub> 185-190°C.

This ester was hydrolysed similarly to the unsubstituted derivative to give a hygroscopic gum (1.79g), found to be a mixture of the following:

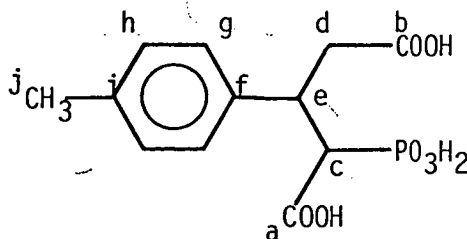
A. 3-(4-methylphenyl)-2-phosphonopentanedioic acid (Cr46) , as a diastereomeric mixture (60:40 ratio of a:b) approximately 80% of total product.

a) P.M.R. (300MHz)  $\delta$  ( $D_2O$ ) 7.15-7.28 (m, 4H, Ar-H); 3.6-3.8 (m, 1H, Ar-C-H); 3.30 (dd, 1H,  $J=15.2\text{Hz}$ ,  $J=3.4\text{Hz}$ ),  $-\text{CH}_2-$ ); 2.97 (d,  $J=11.6\text{Hz}$ , -C-H); 2.73 (dd, 1H,  $J=11.6\text{Hz}$ ,  $J=15.5\text{Hz}$ ,  $-\text{CH}_2-$ ); 2.27 (s, 3H, Ar- $\text{CH}_3$ )

b) P.M.R. (300MHz)  $\delta$  ( $D_2O$ ) 7.15-7.28 (m, 4H, Ar-H); 3.6-3.8 (m, 1H, Ar-C-H); 3.30 (d, 1H,  $J=9.4\text{Hz}$ ,  $-\text{CH}_2-$ ); 3.25 (d, 1H,  $J=9.4\text{Hz}$ ,  $-\text{CH}_2-$ ); 2.99 (d, 1H,  $J=$  Hz, -C-H); 2.29 (s, 3H, Ar- $\text{CH}_3$ ).

a)  $^{13}\text{C}$  P.M.R.  $\delta$  ( $D_2O$ ) 176.9 (a); 173.9 (b); 138.3 (f); 137.7 (i); 129.9 (g); 128.6 (h); 53.5 ( $J_{\text{P-C}}=121\text{Hz}$ , c); 42.5 ( $^3J_{\text{P-C}}=12\text{Hz}$ , d); 41.6 (e); 20.6 (j)

b)  $^{13}\text{C}$  P.M.R.  $\delta$  ( $D_2O$ ) 176.6 (a); 173.7 (b); 138.2 (f); 137.7 (i); 128.6 (f); 128.0 (h); 53.4 ( $J_{\text{P-C}}=127\text{Hz}$ , c); 41.0 (e); 39.4 ( $^3J_{\text{P-C}}=12\text{Hz}$ , d); 20.6 (j).



$^{31}\text{P}$  N.M.R.  $\delta$  ( $D_2O$ ) (diastereomers) 16.9, 16.4

B. 3-(4-methylphenyl)pentanedioic acid approximately 20% of the total product.

The required phosphonocarboxylic acid was partially purified using the preferential solubility of this acid, over the dicarboxylic acid, in water. The resultant 3-(4-methylphenyl)pentanedioic acid was estimated to be 95 % pure.

## 7.8 Experimental for Chapter 3.4.

### 7.8.1 Synthesis of diethyl styrenephosphonate.

Styrenephosphonylchloride was prepared from styrene and phosphorus pentachloride by the method of Anisimov et al.<sup>7</sup> or Woodstock<sup>150</sup>, the former being the preferred method due to the ease of using sulfur dioxide rather than phosphorus pentoxide in the oxidation of the styrene-phosphorus pentachloride adduct. The styrenephosphonylchloride was esterified by the method of Anisimov and Nesmeyanov<sup>8</sup> to give the title compound.

### 7.8.2 Attempted Michael reactions on diethyl styrenephosphonate.

The following procedures gave only starting materials (by N.M.R.) on work up using procedure A (2M sulfuric acid).

A. To the above ester (2g) and diethyl malonate (1.19g) was added sodium (0.06g) in ethanol (2ml) and refluxed for 10 hours.

B. To the ester (1g) was added isopropylidene malonate (0.53g) and acetonitrile (5ml). This was refluxed for 45 minutes.

C. Above method was used with dimethylsulfoxide as a solvent.

D. Dry cesium fluoride (0.6g) in methanol (2ml), ethyl nitroacetate (0.49g) and diethyl styrenephosphonate (1g) were combined. The mixture was refluxed for 6 hours.

Workup of the above was as per procedure A, using 2M sulfuric acid.

7.8.3 Attempted Michael reaction on diethyl  $\alpha$ -chlorostyrenephosphonate.

$\alpha$ -Chlorostyrenephosphonate was prepared by the method of Anisimov above, using phenylacetylene as a precursor.

Sodium (0.09g) in ethanol (4ml) was added to malononitrile (0.12g) and diethyl  $\alpha$ -chlorostyrenephosphonate (0.5g) at less than 10°C. This was stirred for 4 hours and then refluxed for 24 hours. Workup as per procedure A, using 2M sulfuric acid, gave diethyl phenylacetylenephosphonate (0.38g, 88%).

7.8.4 Attempted Michael reaction of tetraethyl methylenediphosphonate and ethyl cinnamate.

Ethyl cinnamate (1g) and tetramethylenediphosphonate (1.75g) were added to dry benzene (30ml) and refluxed under nitrogen. Sodium (0.13g) in ethanol (0.13g) in ethanol (6ml) was added and the mixture refluxed for 14 hours. Workup as per procedure A, using 2M sulfuric acid, gave only unreacted material (by P.M.R.).

7.8.5 Synthesis of triethyl 3-phenyl-4-phosphonobutanoate from 3-phenyl-2-butenolide.

3-Phenyl-2-butenolide was prepared by the method of Epstein and Sonntag<sup>42</sup> in comparable yield (mp. 93-94.5°C, lit.<sup>42</sup> 93-94°C).

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 7.25-7.55 (m, 5H, Ar-H); 6.39 (s, 1H, =C-H); 5.23 (s, 2H, -CH<sub>2</sub>-O).

The butenolide (3.3g) was then hydrogenated using Raney nickel (100mg) in ether (15ml) at 1500 psi for 24 hours to give 3-phenylbutyrolactone (3.3g, quant.) as an oil.

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 7.12-7.48 (m, 5H, Ar-H); 4.68, 4.28 (t, 1H, J=9.5Hz, -CH<sub>2</sub>-O); 3.58-3.82 (m, 1H, Ar-C-H); 2.92, 2.66 (dd, 1H, J=18.0Hz, J=9.5Hz).

The butyrolactone (2.66g) was then placed in a sealable tube with a teflon screw-seal top and trimethylsilyl bromide (3.51g,

1.4eq.) added and the sealed tube heated at 100°C for 38 hours. The resultant mixture was flushed with nitrogen until the excess trimethylsilylbromide was removed and then ethanol (3ml) was added and the tube resealed and left overnight. Evaporation of the volatile material gave crude ethyl 4-bromo-3-phenylbutanoate (79%, by P.M.R.). This was distilled using microdistillation apparatus to give 90-95% pure ethyl 4-bromo-3-phenylbutanoate.

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 7.20-7.35 (m, 5H, Ar-H); 4.05 (dd, 2H, J=7.1Hz, -CH<sub>2</sub>-O); 3.53-3.65 (m, 1H, -CH<sub>2</sub>-Br, Ar-C-H); 2.99 (dd, 1H, J=5.9Hz, J=15.9Hz, -CH<sub>2</sub>-); 2.68 (dd, 1H, J=8.4Hz, J=15.9Hz, -CH<sub>2</sub>-); 1.15 (t, 3H, J=7.1Hz).

M.S. (m/e) (low res.) 191 (47%); 185 (13%); 162 (11%); 145 (58%); 117 (66%); 104 (100%); 91 (46%).

The above ester (580mg) and triethylphosphite (280mg) were reacted at 160°C for 4 hours using a Dean-Stark trap to collect the ethyl bromide produced. The crude product (435mg) was resolved using P.T.L.C. (25% ethyl acetate/ light petroleum) (multiple development) to give 3-phenylbutyrolactone (280mg, 80%), diethyl ethanephosphonate (79mg) and triethyl 3-phenyl-4-phosphonobutanoate (74.7mg, 10.6%)

Triethyl 3-phenyl-4-phosphonobutanoate.

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 7.11-7.25 (m, 5H, Ar-H); 3.80-4.11 (m, 6H, -CH<sub>2</sub>-O); 3.40-3.56 (m, 1H, Ar-C-H); 2.72 (dd, 1H, J=6.2Hz, J=15.5Hz, -CH<sub>2</sub>-CO); 2.58 (dd, 1H, J=8.5Hz, J=15.6Hz, -CH<sub>2</sub>-CO); 2.14 (ddd, 1H, J=7.1Hz, J=15.5Hz, <sup>2</sup>J<sub>P-H</sub>=18.5Hz, -CH<sub>2</sub>-P); 2.05 (ddd, 1H, J=7.7Hz, J=15.5Hz, <sup>2</sup>J<sub>P-H</sub>=18.5Hz, -CH<sub>2</sub>-P); 1.02-1.32 (m, 9H, -CH<sub>3</sub>).

<sup>13</sup>C N.M.R.  $\delta$  (CDCl<sub>3</sub>) 171.3 (c); 143.0 (<sup>4</sup>J<sub>P-C</sub>=9Hz, i); 128.4 (j); 127.2 (k); 126.8 (l); 61.5, 61.2 (g<sup>-</sup>, g); 60.2 (b); 41.8 (<sup>4</sup>J<sub>P-H</sub>=12Hz, d); 36.6 (e); 32.1 (<sup>2</sup>J<sub>P-H</sub>=140Hz, f); 16.2, 16.1 (h<sup>-</sup>, h); 13.9 (a). Assignments as per Figure 3.14.

<sup>31</sup>P N.M.R.  $\delta$  (CDCl<sub>3</sub>) 35.4

M.S. (m/e) 328 ( $M^{+}$ , accurate mass 328.1441,  $C_{16}H_{25}O_5P$  requires 328.1439. 328 (30%), 283 (24%), 254 (45%), 227 (20%), 199 (19%), 193 (72%), 165 (84%), 152 (32%), 137 (67%), 118 (100%), 104 (48%).

I.R. 1734 (s, C=O); 1247 (s, P=O); 1030 (s, P-O)  $cm^{-1}$ .

7.8.6 Michael reactions on, and the preparation of, tetracarbonyl(dimethyl styrenephosphonate)iron.

Dimethyl styrenephosphonate was prepared by the method of Anisimov and Nesmeyanov<sup>8</sup> in yields of 69%. The improvement on Anisimov's yield was obtained by not refluxing during the esterification procedure. Standing of the reaction mixture at room temperature for 12 hours was sufficient to obtain the above yield.

The iron carbonyl complex was obtained by placing  $Fe_2(CO)_9$ <sup>119</sup> (11.3g) in a roundbottom flask (500ml) which had been dried under vacuum and flushed with carbon monoxide. Dimethyl styrenephosphonate (6.57g) was dissolved in tetrahydrofuran (200ml) and added to the  $Fe_2(CO)_9$ . Carbon monoxide was passed through the solution for 10 minutes and a static head of carbon monoxide maintained throughout the reaction period (5 hours). The tetrahydrofuran was then evaporated on a rotary evaporator at less than 40° and light petroleum (bp. 40-60°C) (40ml) added. This solution was filtered through celite and placed in a freezer overnight (with precaution being taken to exclude moisture). Filtration of the precipitated solid yielded the compound below. The complex was found to be light sensitive and unstable in solution in a number of solvents. However, the complex was stable for a number of months at 4°C away from the light.

Tetracarbonyl(dimethyl styrenephosphonate)iron, (9.45g, 80%), yellow needles, mp. 81-81.5°C, decomposition.

Found: C, 43.95%; H, 3.49%.  $C_{14}H_{13}O_7FeP$  requires C, 44.24%; H, 3.45%.

P.M.R. (300MHz) 4mg/ml.  $\delta$  ( $\text{CDCl}_3$ ) 7.14-7.28 (m, 5H, Ar-H); 4.79 (dd, 1H,  $^3J_{\text{P-H}}=15.4\text{Hz}$ ,  $J_{\text{trans}}=13.0\text{Hz}$ , =CH-); 3.85 (d, 3H,  $^2J_{\text{P-H}}=10.7\text{Hz}$ ,  $-\text{CH}_3$ ); 3.74 (d, 3H,  $^2J_{\text{P-H}}=10.8\text{Hz}$ ,  $-\text{CH}_3$ ); 3.18-3.28 (m, 1H, =CH-, undefined).

P.M.R. (100MHz) 40mg/ml.  $\delta$  ( $\text{CDCl}_3$ ) 7.05-7.45 (m, 5H, Ar-H); 4.75 (dd, 1H,  $J_{\text{trans}}=13\text{Hz}$ ,  $^3J_{\text{P-H}}=17\text{Hz}$ , =CH-); 3.81, 3.70 (d, 3H,  $^2J_{\text{P-H}}=10\text{Hz}$ ,  $-\text{CH}_3$ ); 3.17 (dd, 1H,  $J_{\text{trans}}=13\text{Hz}$ ,  $^1J_{\text{P-H}}=4.5\text{Hz}$ , =CH-).

$^{31}\text{P}$  N.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) ( $^1\text{H}$  decoupled) 34.5.

I.R. (nujol mull) 2096 (s, C-O); 2020 (s, C-O); 1990 (s, C-O); 1232 (s, P=O), 1024 (s, P-O) ( $\text{cm}^{-1}$ ).

Attempts to carry out the analogous reaction to that carried out on tetracarbonyl(methyl cinnamate)iron by Ross<sup>119</sup>, on tetracarbonyl(dimethyl styrylphosphonate)iron were unsuccessful in all cases.

In a typical reaction for either complex potassium hydride (4.6mM) was suspended in dry hexamethylphosphoramide (7ml) and dry ethyl cyanoacetate (5.41mM) added slowly with stirring under nitrogen. After 15 minutes from the cessation of the initial reaction, the carbonyl complex (1.92mM) was added and the reaction left for 24 hours at  $0^\circ\text{C}$  with stirring. The reaction was then quenched with trifluoroacetic acid (5.1mM) and ceric ammonium nitrate (2g) added slowly. This was washed with saturated sodium chloride solution (50ml) after addition of diethyl ether (100ml) and then with saturated sodium bicarbonate (2x40ml).

A red oil was recovered, after evaporation of the dried ether solution, which was found to contain only starting materials (P.M.R., t.l.c.).



### 7.8.7 Syntheses of diethyl 4-nitrostyrenephosphonate and derivatives thereof.

Diethyl 4-nitrostyrenephosphonate was prepared using a modification of the procedure of Wadsworth and Emmons<sup>143</sup> for diethyl styrenephosphonate. Dry tetrahydrofuran or dry dioxan were found to be suitable solvents, the former being desirable due to its low boiling point and the relative ease of purification and drying. Typically, 56% sodium hydride (2.85g) (in oil) was suspended in tetrahydrofuran (250ml) and tetraethyl methylenediphosphonate (19g) added slowly over 30 minutes. The suspension was then stirred for a further 15 minutes under dry nitrogen. 4-Nitobenzaldehyde (10g) in tetrahydrofuran (50ml) was then added slowly from a dropping funnel over 20 minutes and the resultant solution stirred overnight at room temperature. An orange-red gum formed during the course of the reaction. The solvent was then partially evaporated and the residue dissolved in dichloromethane and washed with water. Evaporation of the solvent and subsequent recrystallization from toluene resulted in slightly yellowish platelets (88%) mp. 92-95°C.

This compound had been previously reported<sup>142</sup> in 17% yield from 4-nitrobenzenediazonium chloride and diethyl vinylphosphonate to have a  $bp_{2.5}$  182-188°C. Distillation was not warranted in the former preparation. If poor yields were encountered the product Rf 0.25 and the starting material Rf 0.8 (dichloromethane) were separated on silica gel (plate or column).

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 8.25 (m, 2H, ArH); 7.63 (m, 2H, ArH); 7.54 (dd, <sup>3</sup>J=17.5Hz, J<sub>P-H</sub>=22Hz, 1H, Ar-C-CH=); 6.45 (dd, J=17.3Hz, <sup>2</sup>J<sub>P-H</sub>=16.3Hz, 1H, =C-CH-P); 4.10-4.26 (m, 4H, P-O-C-CH<sub>2</sub>-); 1.30-1.45 (m, 6H, 2x -CH<sub>3</sub>)

I.R. (thin film) 1598 (s, C=C); 1520, 1346 (s, -NO<sub>2</sub>); 1238 (s, P=O); 1056, 1022 (s, P-O-C) (cm<sup>-1</sup>).

M.S. m/e 285 (M<sup>+</sup>, accurate mass 285.0765 C<sub>12</sub>H<sub>16</sub>NO<sub>5</sub>P requires 285.0762) 285 (30%); 257 (13%); 240 (10%); 229 (17%); 212 (26%); 176 (45%); 166 (20%); 149 (17%); 130 (100%).

Michael Reaction on diethyl 4-nitrostyrenephosphonate using ethyl cyanoacetate as a donor.

Diethyl 4-nitrostyrenephosphonate (1g) was dissolved in dry ethanol (8ml), containing Na (0.08g) and (1.1eq.) of ethyl cyanoacetate (0.44g). The solution was stirred at 25°C for 72 hours forming a deep red colour. TLC in 25% ethyl acetate/chloroform showed a product at Rf 0.5 and the starting material at Rf 0.3. The solution was then quenched with glacial acetic acid (3ml) and extracted into dichloromethane. This was washed with saturated sodium bicarbonate solution (20ml) and then with water (20ml) and dried with sodium sulfate. Multiple development of the evaporated solution on silica gel in 10% v/v ethyl acetate/chloroform gave three fractions.

Fraction 1, Adduct A, triethyl 2-cyano-3-(4-nitrophenyl)-4-phosphonobutanoate (210mg, 15%) as an oil - (boiling point greater than 450°C) (Rf 0.3 20% - ethyl acetate/chloroform).

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 8.10-8.20 (m, 2H, Ar-H); 7.61-7.64 (m, 2H, Ar-H); 3.8-4.5 (m, 10H, 2xC-H, 3x -O-CH<sub>2</sub>-); 2.1-2.7 (m, 2H, -CH<sub>2</sub>-); 1.1-1.4 (m, 9H, 4x-CH<sub>3</sub>).

<sup>31</sup>P N.M.R. (<sup>1</sup>H decoupled)  $\delta$  26.45.

I.R. (thin film) 2252 (w, -C≡N); 1744 (s, -C=O); 1605 (s, -NO<sub>2</sub>); 1242 (s, -P=O); 1022 (, -P-O-) (cm<sup>-1</sup>).

M.S. m/e 398 (M<sup>+</sup> accurate mass 398.1244, C<sub>19</sub>H<sub>28</sub>NO<sub>9</sub>P requires 398.1240.) 398 (14%); 353 (12%); 325 (96%); 297 (27%); 269 (50%); 152 (100%).

Refractive index (20°C) 1.5149

Fraction 2, Adduct B, triethyl 2-cyano-4-(4-nitrophenyl)-3-phosphonobutanoate (515mg, 37%) as an oil - (boiling point greater than 450°C) (Rf 0.52 - 20% ethyl acetate/chloroform) ; two diastereomers.

P.M.R. (300MHz)  $\delta$  (CDCl<sub>3</sub>) 8.1-8.2 (m, 2H, Ar-H); 7.42-7.47 (m, 2H, Ar-H); 4.06-4.25 (m, 8H, 4x-O-CH<sub>2</sub>-); 3.85-4.00 (m, 1H, -CH(COOEt)(CN)); 3.28-3.60 (m, 1H, -CH(PO<sub>3</sub>Et<sub>2</sub>)-); 2.85-3.20 (m, 2, -CH<sub>2</sub>-); 1.16-1.41 (m, 12H, 4x-CH<sub>3</sub>).

$^{31}\text{P}$  N.M.R. ( $^1\text{H}$  decoupled)  $\delta$  25.846, 24.381 (two diastereomers)  
I.R. (thin film) 2260 (w,  $\text{C}\equiv\text{N}$ ); 1747 (s,  $\text{C}=\text{O}$ ); 1605 (s,  $-\text{NO}_2$ );  
 1244 (s,  $-\text{P}=\text{O}$ ); 1026 (s,  $-\text{P}-\text{O}-$ ) ( $\text{cm}^{-1}$ ).

M.S. m/e 398 ( $\text{M}^{+}$ , accurate mass 398.1248,  $\text{C}_{19}\text{H}_{28}\text{NO}_9\text{P}$  requires 398.1240). 398 (0.5%); 353 (2%); 286 (100%); 230 (37%); 157 (10%); 138 (16%).

Refractive index ( $20^\circ\text{C}$ ) 1.5182

Fraction 3-starting material (403mg, 40%)(Rf 0.3 20% ethyl acetate/chloroform)

Michael reaction on diethyl 4-nitrostyrenephosphonate using diethyl malonate.

Diethyl 4-nitrostyrenephosphonate (10g) and diethyl malonate (5.65g, 1.1eq.) and sodium (0.28g, 0.35eq.) in ethanol (5ml) was heated in an oil bath at  $50^\circ\text{C}$  for 8 hours. Sodium (0.53g, 0.65eq.) was added during the course of the reaction. The reaction was quenched with glacial acetic acid (15ml) and worked up as per procedure A. An attempt to resolve this oil into its components was made using 25% ethyl acetate in toluene and medium pressure column chromatography. A pure fraction was obtained, the residual being a mixture. Other attempts to resolve this mixture proved unsatisfactory using a number of solvent systems. The residue (12.52g) was carried through to the next reduction step.

Fraction 1, Adduct C, tetraethyl 3-(4-nitrophenyl)-2-phosphonopropane  
-1,1-dicarboxylate (1.96g, 12.5%)oil (high bp.) Rf 0.55 25% ethyl acetate/chloroform.

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) 8.15 (d, 2H,  $J=8.5\text{Hz}$ , Ar-H); 7.51 (d,  $J=8.5\text{Hz}$ , 2H, Ar-H); 3.87-4.30 (m, 8H,  $4\times\text{OCH}_2-$ ); 3.75-3.87 (m 1H,  $-\text{C}-\text{H}$ ); 2.98-3.26 (m, 3H,  $\text{CH}_2$ ,  $-\text{C}-\text{H}$ ); 1.10-1.40 (m, 12H,  $4\times\text{CH}_3$ )

$^{31}\text{P}$  N.M.R.  $\delta$  ( $\text{CDCl}_3$ ) 27.952.

I.R. (thin film) 1734 (s, C=O); 1606 (s, NO<sub>2</sub>); 1248 (s, P=O); 1026 (s, P-O) (cm<sup>-1</sup>).

M.S. (m/e) 445 (M<sup>+</sup> accurate mass 445.1450 (very weak) C<sub>19</sub>H<sub>28</sub>NO<sub>9</sub>P requires 445.1498). 445 (1.5%); 400 (15%); 286 (100%); 230 (38%).

Refractive Index (20°C) 1.5003.

#### Hydrogenation and deamination of Michael adducts.

Triethyl 2-cyano-4-(4-nitrophenyl)-3-phosphonobutanoate (adduct B) (1.82g) was dissolved in ethanol (45ml) and 5% Pd on charcoal (80mg) added. This was shaken under hydrogen at atmospheric pressure until the reaction was complete (approximately 1 1/2 hour). The charcoal was filtered off and the solvent evaporated. This gave a crude material (1.55g) which was then dissolved in 5M hydrochloric acid (5ml) and ethanol (4ml) and cooled to 5°C. Sodium sulfite (0.35g) in water (5ml) was added over 20 minutes and a precipitate formed. Aqueous 30% hypophosphorus acid (15ml) was added and the solution kept at 10°C for 2 days and then at room temperature for 30 hours. The mixture containing an oily precipitate was extracted with dichloromethane (30ml) and dried over sodium sulfate and the solvent evaporated. Medium pressure column chromatography (silica gel, 0.75% v/v methanol/dichloromethane) yielded the following product.

Triethyl 2-cyano-4-phenyl-3-phosphonobutanoate (700mg, 51%).

Yellow oil, (Rf 0.6, 3% methanol/dichloromethane).

P.M.R. (300MHz) δ (CDCl<sub>3</sub>) 7.26-7.30 (m, 5H, Ar-H); 4.00-4.35 (m, 6H, -OCH<sub>2</sub>-); 3.70-3.93 (m, 1H, -C-H); 3.25-3.50 (m, 1H, -C-H); 2.75-3.15 (m, 2H, -CH<sub>2</sub>); 1.05-1.45 (m, 9H, -CH<sub>3</sub>).

<sup>31</sup>P N.M.R. (CDCl<sub>3</sub>) δ 25.0, 26.3 diastereomers.

I.R. (thin film) 2250 (w, -C≡N); 1746 (s, -C=O); 1252 (s, -P=O); 1052 (s, -P-O-) (cm<sup>-1</sup>).

M.S. (m/e) 354 ((M+1)<sup>+</sup> accurate mass 354.149 (autochemical ionization), C<sub>17</sub>H<sub>26</sub>N<sub>5</sub>P requires 354.1467), 354 (73%); 241 (100%); 213 (17%); 185 (3%); 143 (25%); 115 (45%).

Refractive Index (20°C) 1.4919 .

The residue (12.52g) from the Michael reaction of diethyl 4-nitrostyrenephosphonate and diethyl malonate was reduced following the forementioned procedure. The crude amine was dissolved in aqueous 32% hypophosphorus acid (120ml) and cooled to 5°C. Sodium nitrite (2.6g) in water (10ml) was added keeping the temperature below 5°C. The resultant solution was kept at 5°C for 2 hours then warmed to room temperature and left overnight. The mixture was extracted with dichloromethane. The solvent was evaporated to give 10.5g of crude material.

Column chromatography (1% methanol/dichloromethane) of this crude material gave a clear yellowish oil. The residual being colored baseline material.

The clear oil was distilled to give three fractions.

1. Bp<sub>0.06</sub> 110-138°C diethyl phenylethanephosphonate, 2.67g
2. Bp<sub>0.06</sub> 142-155°C mixture, 1.79g
3. Bp<sub>0.06</sub> 155-160°C mixture of products D and E below, 3.44g.

(Analysis of distillates by GC/MS).

Fractions 2 and 3 were resolved using P.T.L.C. (20% ethyl acetate/petroleum ether) (six developments).

Fraction 2 gave 1.212g of product D, 202mg of product E and 208mg of diethyl phenylphosphonate. Fraction 3 gave 2.264g of product D and 605mg of product E.

Product D, tetraethyl 3-phenyl-2-phosphonopropane-1,1-dicarboxylate, (3.48g, 24.8%). Yellow oil.

P.M.R. (300MHz) (CDCl<sub>3</sub>) 7.12-7.35 (m, 5H, Ar-H); 3.80-4.20 (m, 8H, -OCH<sub>2</sub>-); 3.70-3.80 (m, 1H, -C-H); 2.94-3.18 (m, 3H, Ar-CH<sub>2</sub>-); 1.10-1.34 (m, 12H, -CH<sub>3</sub>).

<sup>13</sup>C N.M.R. δ (CDCl<sub>3</sub>) 167.8 (c); 138.95 (i); 29.34 (l); 128.18 (j); 126.46 (k); 61.43-61.97 (J<sub>P-C</sub>=4.4Hz, f,b); 51.01 (d); 38.44 (J<sub>P-C</sub>= 142Hz, e); 32.52 (h); 16.01-16.23 (g); 13.87 (a). (See Figure 3.24 for structure and correlation).

I.R. (thin film) 1740 (s, -C=O); 1248 (s, -P=O); 1032 (s, -P-O-), ( $\text{cm}^{-1}$ ).

M.S. (m/e) 400 ( $\text{M}^{+}$ , accurate mass 400.165,  $\text{C}_{19}\text{H}_{29}\text{O}_7\text{P}$  requires 400.1648) 400 (16%); 355 (40%); 327 (7%); 309 (28%); 241 (100%).

Refractive index ( $20^\circ\text{C}$ ) 1.4847

Product E, tetraethyl 2-phenyl-3-phosphonopropane-1,1-dicarboxylate (807mg, 5.5%), colorless needles, m.p.  $62-64^\circ\text{C}$ .

Found: C, 57.05%; H, 7.37%; P, 7.85%.  $\text{C}_{19}\text{H}_{29}\text{O}_7\text{P}$  requires C, 56.99%; H, 7.30%; P, 7.74%.

P.M.R. (300MHz)  $\delta$  ( $\text{CDCl}_3$ ) 7.2-7.4 (m, 5H, Ar-H); 4.20 (q,  $\text{J}=7.1\text{Hz}$ , 2H, C-OCH<sub>2</sub>-); 3.65-3.90 (m, 6H, 2xP-O-CH<sub>2</sub>-, 2x-C-H) 2.15-2.40 (m, 2H, -CH<sub>2</sub>-P-); 1.26 (t, 3H,  $\text{J}=7.1\text{Hz}$ , -C-O-CH<sub>2</sub>-CH<sub>3</sub>); 1.14 (t, 3H,  $\text{J}=7.1\text{Hz}$ , -C-O-CH<sub>2</sub>-CH<sub>3</sub>); 1.06 (t, 3H,  $\text{J}=7.1\text{Hz}$ , -P-O-CH<sub>2</sub>-CH<sub>3</sub>); 0.99 (t, 3H,  $\text{J}=7.1\text{Hz}$ , -P-O-CH<sub>2</sub>-CH<sub>3</sub>).

$^{13}\text{C}$  N.M.R.  $\delta$  ( $\text{CDCl}_3$ ) 167.87 (c<sup>-</sup>); 167.30 (c); 139.67 (i); 128.57 (l); 128.20 (j); 127.3 (k); 61.27-61.67 (g,b,b<sup>-</sup>); 58.80 ( $^3\text{J}_{\text{P-H}}=4.4\text{Hz}$ , d); 40.24 (e); 30.13 ( $\text{J}_{\text{P-C}}=141\text{Hz}$ , f); 16.24 (h<sup>-</sup>); 15.96 (h); 14.02 (a<sup>-</sup>); 13.68 (a). (See Figure 3.25 for structure and correlation).

I.R. (thin film) 1732 (s, -C=O); 1246 (s, -P=O); 1030 (s, -P-O-) ( $\text{cm}^{-1}$ ).

M.S. (m/e) 400 ( $\text{M}^{+}$ , accurate mass 400.166,  $\text{C}_{19}\text{H}_{29}\text{O}_7\text{P}$  requires 400.1648), 400 (5%); 355 (5%); 327 (22%); 309 (9%); 281 (63%); 241 (100%); 225 (24%); 213 (28%); 185 (39%).

Refractive index ( $20^\circ\text{C}$ ) (prior to solidification) 1.4834

#### Hydrolysis of tetraethyl 3-phenyl-2-phosphonopropane-1,1-dicarboxylate.

Tetraethyl 3-phenyl-2-phosphonopropane-1,1-dicarboxylate (2.264g) was hydrolysed with 1:1 aqueous hydrochloric acid by refluxing for 8 hours to give, on evaporation of the aqueous phase, 4-phenyl-3-phosphonobutanoic acid (Cr40) (1.22g, 88%) as a foam.

P.M.R. (300MHz)  $\delta$  ( $D_2O$ ) 7.18-7.27 (m, 5H, Ar-H); 3.08-3.17 (m, 1H, -C-H); 2.49-2.63 (m, 2H, Ar-CH<sub>2</sub>-, 1H, -CH<sub>2</sub>-); 2.23-2.40 (m, 1H, -CH<sub>2</sub>-).

<sup>31</sup>P N.M.R.  $\delta$  ( $D_2O$ ) 32.5.

<sup>13</sup>C N.M.R.  $\delta$  ( $D_2O$ ) 176.4 (<sup>3</sup>J<sub>P-C</sub>=11.3Hz, a); 139.2 (<sup>3</sup>J<sub>P-C</sub>=12.6Hz, e); 130.0 (f); 129.3 (g); 127.5 (h); 36.1 (J<sub>P-C</sub>=138Hz, c); 35.0 (d); 33.6 (b). (See Figure 3.27 for correlation).

I.R. (Ba salt) (nujol) 1548 (s, C-O); 1065, 1041 (s, P-O) cm<sup>-1</sup>.

#### Hydrolysis of tetraethyl 3-phenyl-2-phosphonopentanedioate.

Tetraethyl 3-phenyl-2-phosphonopentanedioate (762mg) was hydrolysed for 8 hours with 1:1 aqueous hydrochloric acid (50ml) and the aqueous phase then evaporated under reduced pressure to give 3-phenyl-4-phosphonobutanoic acid (Cr43) (426mg, 97%) as a glass.

P.M.R. (300MHz)  $\delta$  ( $D_2O$ ) 7.15-7.25 (m, 5H, Ar-H); 3.32-3.43 (m, 1H, Ar-C-H); 2.80 (dd, 1H, J=9.5Hz, J=15.3Hz, -CH<sub>2</sub>-); 2.59 (dd, 1H, J=9.5Hz, J=15.3Hz, -CH<sub>2</sub>-); 2.13, 2.07 (dd, 2H, J=6.7Hz, <sup>2</sup>J<sub>P-H</sub>=18.07Hz, -CH<sub>2</sub>-P).

<sup>31</sup>P N.M.R.  $\delta$  ( $D_2O$ ) 28.3.

<sup>13</sup>C N.M.R.  $\delta$  ( $D_2O$ ) 178.2 (g); 145.5 (d); 131.4 (c); 130.0 (b); 129.8 (a); 44.3 (<sup>3</sup>J<sub>P-C</sub>=11Hz, e); 39.4 (g); 35.4 (J<sub>P-C</sub>=135Hz, f). (See Figure 3.26 for correlation).

### 7.9 Experimental for Chapter 4.

Determination of the dissociation constants of polycarboxylic acids and phosphonocarboxylic acids.

The dissociation constants of a number of potential collectors were obtained using the following equipment .

Lauda Mgw RC6 thermostat bath.

Radiometer PHM 84 Research pH meter.

Metrohm 655 Dosimat with 5.0000ml syringe.

IBM PC XT interfaced for data collection.

TITRATE<sup>13</sup> and ACBA<sup>12</sup> programs were used to collect and correlate data respectively.

Phillips GAT130 low resistance glass (0-14pH) and Phillips R44/2-SD/1 inverted glass sleeve, double junction calomel reference electrodes were used. The outer liquid junction was 1M sodium chloride. The electrodes were contained in a double wall thermostatable cell of 10-20ml capacity .

All solutions were made of doubly distilled deionized water and were 1.00M sodium chloride. The titrant was prepared from a standard ampoule containing 1 mole of sodium hydroxide and this diluted to 1.00 litre and then again to make a solution of 0.100M sodium hydroxide in 1.00M sodium chloride.

The pH meter was standardised using pH 6.865 buffer (0.025M potassium dihydrogenphosphate and 0.025M disodium hydrogen phosphate) and pH 4.008 buffer (0.05M potassium hydrogen phthalate).

The system was then calibrated against potassium hydrogen phthalate buffer to give the following  $pK_a$ 's.

$$pK_{a_1} = 5.061 \pm 0.009$$

$$pK_{a_2} = 3.245 \pm 0.028$$

The concentration of the dissociable protons was determined as  $0.1006 \pm 0.0002$  M.



The software used by the IBM PC enabled the simultaneous refinement of any parameter for acid-base titration. Initial estimates of acid proton concentration,  $pK_w$  and electrode  $E^0$  were simultaneously refined .

The determinations were carried out at  $25.00 \pm 0.03^\circ\text{C}$  using approximately 100 micromoles of Cr series acid in 10ml of 1.00M sodium chloride to make a 10mM solution of the collector. 0.05ml aliquots of 0.100M sodium hydroxide were added using TITRATE. The rate of change of pH with time was monitored with further aliquots being added when this was less than  $0.001 \text{ min}^{-1}$  (usually after about 20-30 seconds).

The titration was typically carried out between pH 2.0 and pH 8.0, the former depending on the natural pH of the 10mM solution.

Dissociation constants were determined using ACBA and the data collected by TITRATE.

The results are displayed in Table 4.1. Further information on the automated titrator is obtainable in the paper by Arnold, Daignault and Rabenstein<sup>13</sup>.

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162. Optimum conditions for the use of Cr<sup>3</sup> and some other weaker collectors were still under investigation at the time of completion of this thesis.

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APPENDIX A.    General Procedure for Flotation Testing.

The ore, obtained in general from the heavy medium concentrate sink, was first ground to a size finer than 0.075mm, followed by cyclone classification of the resulting pulp, thereby removing the majority of the slime particles (those less than 0.005mm in size) - a prerequisite of current technology for oxide flotation. Samples containing a significant proportion of sulfide minerals (greater than 1%) were then normally subjected to a preliminary froth flotation to remove the sulfide minerals. The ore pulp was then substantially sulfide free and sized 0.005 to 0.075mm.

The aqueous slurry prepared as above, usually 20-45% solids, was then subjected to flotation of the cassiterite. During the flotation the slurry was aerated to form a froth in which the metal oxide became concentrated leaving most of the gangue in the aqueous phase. The metal oxide was recovered by collecting the froth mechanically. Frothing agents were usually added, although in some cases they were not essential. Suitable frothers included AF65 (Cyanamid Aust. Pty. Ltd.).

This flotation process was generally carried out at a pH of 4.5, this being adjusted by the addition of aqueous sulfuric acid or sodium hydroxide.

The collectors were employed in varying amounts as specified in Tables 5.1 and 5.2 in Chapter 5

The frothing step during flotation was performed for approximately 10 minutes, and the collector added in varying numbers of portions, usually four, with the metal oxides being concentrated in the froth which was removed after each collector addition.

In order to improve the selectivity of the flotation process for cassiterite a pretreatment with sodiumfluorosilicate (SSF) was used. Varying quantities, usually 0.25-0.80g were added and the

float stirred for approximately 5 minutes prior to the addition of collector.

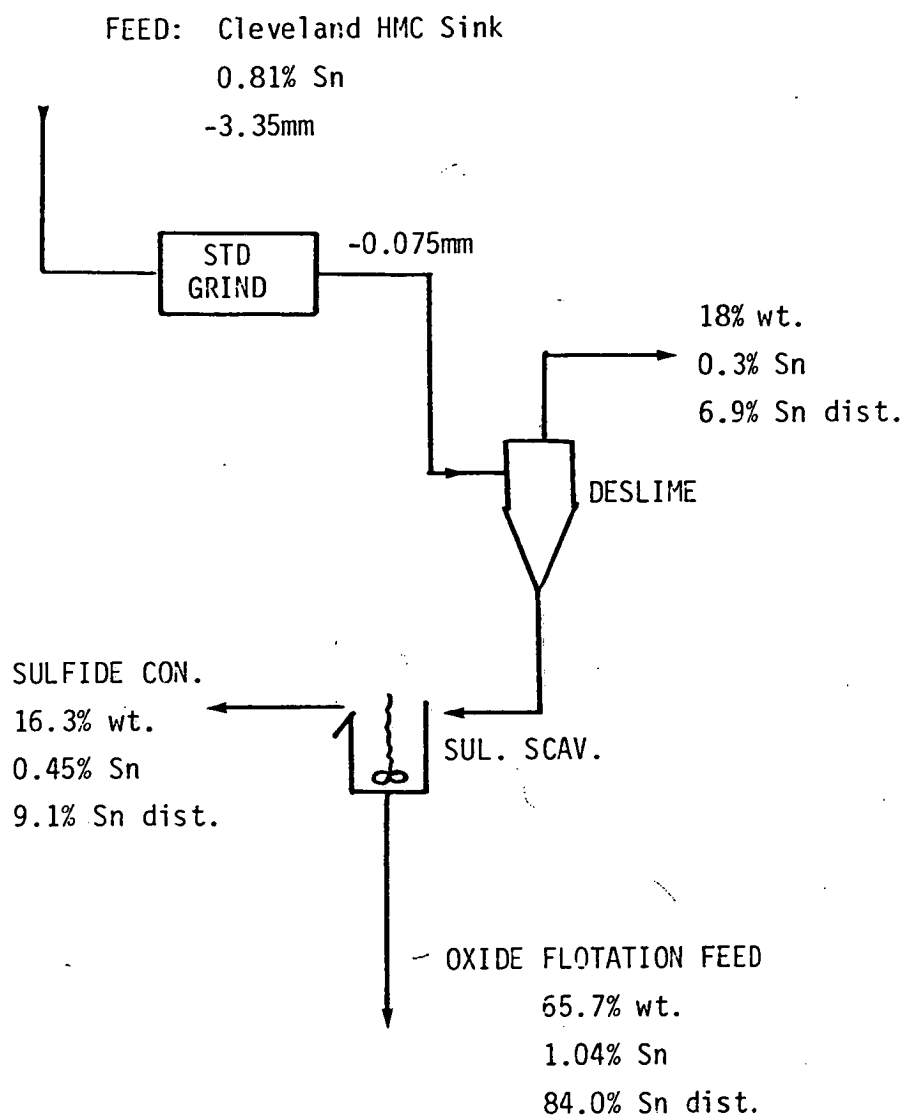
Thus for the standard tests the following procedure was followed:-

- A) The ore was ground in a laboratory ball mill to give a product which was 89% finer than 0.075mm and 53% finer than 0.038mm.
- B) The ground product was deslimed in two stages of cyclone classification to reject particles of 0.005mm and below.
- C) The sulfides present were removed from the deslimed feed by flotation after pH modification with sulfuric acid to pH 5.0, activation and 3 minutes conditioning with 100g/tonne copper sulfate, 23 minutes conditioning with potassium amylxanthate collector, and 0.5 minutes conditioning with 20 g /tonne of a frothing agent of trade name AF65.
- D) The remaining material ( deslimed with sulfides removed) was then prepared for tin flotation by five minutes conditioning with 300 g/tonne SSF after pH modification to 4.5 with sulfuric acid.
- E) The preconditioned material was then conditioned for ten minutes with 0.35 g/tonne of collector, 0.5 minutes conditioning with 10 g/tonne AF65 frother and 3 minutes flotation with air. The process of collector addition was repeated to obtain four upgraded tin concentrates in total being carried out for 2-3, 2-3, 3-6, 3-6 minutes of flotation time for each concentrate respectively. The material remaining was the tailing devoid of tin.

The concentrates were then dried, weighed and analysed for tin using X-ray fluorescence spectroscopy.



## Appendix B.



PREPARATION OF OXIDE FLOTATION FEED.

APPENDIX C.      Composition   of Cleveland Tin Mine Ore and Oxide  
Flotation Test Feed.

Mineral composition of Cleveland Ore.

- |              |                    |
|--------------|--------------------|
| 1. SULFIDES. | pyrrhotite         |
|              | pyrite             |
|              | chalcopyrite       |
|              | stannite (trace)   |
|              | sphalerite (trace) |
|              | galena (trace).    |

These sulfides are all removed by sulfide flotation prior to testing of collectors.

- |            |                |
|------------|----------------|
| 2. OXIDES. | cassiterite    |
|            | rutile (trace) |

- |               |          |
|---------------|----------|
| 3. CARBONATES | siderite |
|               | calcite  |

4. FLUORITE

- |              |                |
|--------------|----------------|
| 5. SILICATES | quartz / chert |
|              | tourmaline     |
|              | chlorite       |
|              | actinolite     |

Chemical composition of oxide flotation test feed after sulfide flotation.

ELEMENT	%
Sn	1
S	0.5
Fe	11
SiO <sub>2</sub>	58
CO <sub>2</sub>	5
CaF <sub>2</sub>	6
CaO	5
Al <sub>2</sub> O <sub>3</sub>	10
TiO <sub>2</sub>	0.5
MgO	2
MnO	0.5
K <sub>2</sub> O	1.4
Na <sub>2</sub> O	0.4
P <sub>2</sub> O <sub>5</sub>	0.2
Cu	0.02
Zn	0.02
Pb	0.005

## Appendix D.

List of Cr Series Collectors.

Cr	
1	Cinnamic acid #
2	Phenylmalonic acid #
3	2-Phenylethane-1,1-dicarboxylic acid #
4	2-(4-Methylphenyl)ethane-1,1-dicarboxylic acid 147
5	2-Phenylethene-1,1-dicarboxylic acid 62
6	2-(4-Methylphenyl)ethene-1,1-dicarboxylic acid 155
7	2-(4-Ethylphenyl)ethene-1,1-dicarboxylic acid 155
8	2-(4-Methoxyphenyl)ethene-1,1-dicarboxylic acid 62
9	2-(3,4-dimethoxyphenyl)ethene-1,1-dicarboxylic acid 58
10	2-(4-Ethoxyphenyl)ethene-1,1-dicarboxylic acid *
11	3-Phenylpentanedioic acid # 81
12	3-(4-Methylphenyl)pentanedioic acid 155
13	3-(4-Ethylphenyl)pentanedioic acid 155
14	3-(4-Methoxyphenyl)pentanedioic acid 85 148
15	3-(4-Ethoxyphenyl)pentanedioic acid 85
16	3-(4-Propoxyphenyl)pentanedioic acid 85
17	3-Phenylpentenedioic acid 101
18	3-(4-Methylphenyl)pentenedioic acid *
19	2-Phenylbutanedioic acid #
20	2-(4-Methylphenyl)butanedioic acid 33
21	(E)-2-Phenylbutenedioic acid 136
22	(Z)-2-Phenylbutenedioic acid 136
23	2-Phenylpropane-1,1,3-tricarboxylic acid 82
24	2-(4-Methylphenyl)propane-1,1,3-tricarboxylic acid *
25	2-(4-Ethylphenyl)propane-1,1,3-tricarboxylic acid *
26	2-(4-(1-Methylethyl)phenyl)propane-1,1,3-tricarboxylic acid *
27	2-(4-Methoxyphenyl)propane-1,1,3-tricarboxylic acid 97
28	2-(4-Ethoxyphenyl)propane-1,1,3-tricarboxylic acid *
29	2-(4-Propoxyphenyl)propane-1,1,3-tricarboxylic acid *
30	2-(4-(1-methylethoxy)phenyl)propane-1,1,3-tricarboxylic acid *

Cr

- 31 2-(4-Butoxyphenyl)propane-1,1,3-tricarboxylic acid \*
- 32 2-(4-Methylphenyl)propane-1,1,3,3-tetracarboxylic acid 155
- 33 N-Phenyliminodiacetic acid 100
- 34 N-(4-Methylphenyl)iminodiacetic acid 53
- 35 N-(4-Methoxyphenyl)iminodiacetic acid 53
- 36 N-Benzyliminodiacetic acid #
- 37 N-Benzyliminodiacetic acid 31
- 38 4-Methylstyrenephosphonic acid \*
- 39 3-Phenyl-2-phosphonopropanoic acid 66
- 40 4-Phenyl-3-phosphonobutanoic acid \*
- 41 3-(4-Methylphenyl)-3-phosphonopropanoic acid \*
- 42 3-Phenyl-4-phosphonopentanedioic acid \*
- 43 3-Phenyl-4-phosphonobutanoic acid \*
- 44 3-Phenyl-2,3-diphosphonopropanoic acid 110
- 45 3-Phenyl-2-phosphonopropenoic acid \*
- 46 3-(4-Methylphenyl)-4-phosphonopentanedioic acid \*

# Available from commercial sources (see text)

\* Not previously reported

All references are as per references for main text