KINETICS OF OXIDATION OF SOME DIOLS AND HYDROXY ACIDS BY QUINOLINIUM DICHROMATE

SUMMARY

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Hexavalent chromium compounds have been widely used as oxidizing agents reacting with diverse kinds of organic substrates. The mechanism of oxidation varies with the nature of chromium(VI) species and the solvent used. The development of newer chromium(VI) reagents for the oxidation of organic substrates continues to evince keen interest. Over the years, a large number of novel chromium(VI) oxidizing agents have been introduced especially for complex or highly sensitive substances where great selectivity and effectiveness, coupled with mildness of conditions, are prerequisites for success.

Some of the chromium(VI) reagents which have been used as efficient oxidizing agents have included:
Chromium trioxide; chromyl chloride; Jones reagent - a solution of chromium(VI) oxide in concentrated sulfuric acid(1); Collins reagent- dipyridinium chromium(VI) oxide in dichloromethane(2); chromium(VI) oxide adsorbed on solid supports such as graphite, silica, alumina, silica gel, and

celite(3,4); Corey's reagent - pyridinium chloro-chromate(PCC) in dichloromethane(5); pyridine oxodiperoxo chromium(VI) reagent - a complex of chromium pentoxide with pyridine(6); pyridinium dichromate(PDC) used either in solution in dimethylformamide or as a suspension in dichloromethane(7); bis-tetrabutyl ammonium dichromate (TBADC) in refluxing dichloromethane(8); Chaudhuri's reagent-pyridinium fluorochromate in dichloromethane(9); 4-(dimethylamino)pyridinium chlorochromate(1Ø); tetrabutyl ammonium chlorochromate (TBACC) in chloroform(11); bis-(trimethylsilyl) peroxide (BTSP) in dichloromethane, in the presence of pyridinium dichromate(PDC)(12); pyridinium chlorochromate(PCC) in conjunction with 3,5-dimethyl pyrazole(DMP) in dichloromethane(13,14); chromium(VI) oxide diperoxide(15); diverse chlorochromate reagents such as benzyltrimethyl ammonium chlorochromate (BTMACC), tetrabutyl ammonium chlorochromate(TMACC) in dichloroethane(16); some fluorochromates such as tetramethyl ammonium fluoro-chromate(TMAFC) and tetrabutyl ammonium fluoro chromate(TBAFC) also in dichloroethane(16); tetrakis

(pyridine) silver dichromate in refluxing benzene(17); peroxyacetic acid as the stoichiometric oxidant and a catalytic amount of 2,4-dimethylpentane-2,4-diol cyclic chromate in carbon tetrachloride-dichloromethane mixtures (18); chlorotrimethylsilanechromium trioxide(19); benzotriazole in conjunction with pyridinium chlorochromate(PCC) in dichloromethane(20); 2-cyanopyridinium chlorochromate and powdered molecular sieves in dichloromethane(21); 3-carboxy pyridinium dichromate and 4-carboxypyridinium dichromate in pyridine(22); a small quantity of anhydrous acetic acid added to pyridinium dichromate(PDC) and freshly activated molecular sieve powder in dichloromethane(23); chromium peroxide complexes(24); imidazolium dichromate(IDC) in dimethylformamide(25); pyridinium bromochromate(PBC) in chloroform(26); benzyltriethyl ammonium chlorochromate (BTACC) generated in situ under phase transfer conditions in refluxing chloroform(27); biphosphonium dichromate reagents(28); zinc-dichromate trihydrate in dichloromethane(29); catalytic amounts of chromium trioxide and an excess of aqueous

t-butylhydroperoxide(30); cyanopyridinium chlorochromate (CPCC) in dichloromethane(31); pyridinium chlorochromate in conjunction with silica gel and by the use of the ultrasound technique(32); pyridinium chlorochromate(PCC) in chloroform, using anhydrous acetic acid as a catalyst (33); 1-methyl imidazolium chlorochromate (MCC) and imidazolium chlorochromate (ICC) in chloroform (34); isoquinolinium chlorochromate in dichloromethane (35); ferric dichromate, polyvinylpyridine supported zinc dichromate, and polyvinylpyridine supported ferric dichromate, taken in acetonitrile(36), and chromium trioxide in the presence of wet aluminium oxide taken in hexane (37).

The most recent chromium (VI) reagent which has been introduced for the oxidation of organic substrates has been quinolinium fluorochromate (QFC), used in chloroform as solvent (38). This reagent has been used for the oxidation of alcohols, polycyclic arenes and diphenyl sulfide, and the yields reported have been excellent (38).

The reagent employed in the present investigation has been quinolinium dichromate (QDC), $(C_9H_7NH^+)_2Cr_2O_7^{2-}$.

This reagent was first reported to have been used for the oxidation of primary and secondary alcohols to aldehydes and ketones respectively, and for the oxidation of aldehydes to acids(39). This reagent has now emerged as a very useful and versatile oxidant, and has been used for the oxidation of a variety of organic substrates. When taken in dimethylformamide or in dimethylformamide-water mixtures, in the presence of an acid, quinolinium dichromate (QDC) was found to be very efficient for the oxidation of benzyl alcohols (40), arylalkanes (41), diphenylamines (42), polynuclear aromatic hydrocarbons(43,44), toluene and substituted toluenes(44,45), fluorene(46), amino acids(47), benzoin(48), styrenes(49), unsaturated acids(50), bicyclic alcohols(51), cyclic alcohols(52), and allylic alcohols(53).

The present investigation focuses attention on the kinetic features pertaining to the oxidation of various organic substrates by quinolinium dichromate (QDC) in acid medium, using water and water-acetic acid mixtures (in the case of diols), and dimethylformamide and dimethyl-formamide-water mixtures (in the case of α-hydroxy acids),

as the solvents, under a nitrogen atmosphere. The rationale governing the present kinetic investigation has been to enlarge the scope of this versatile oxidizing agent, quinolinium dichromate (QDC), in acidic medium, and to provide experimental evidence for the mechanistic pathways of reactions involving diverse organic substrates. The substrates which have been used for the purpose of oxidation by quinolinium dichromate (QDC), in acid medium, using water and water-acetic acid mixtures, (in the case of diols), and DMF and DMF-H_2O mixtures (in the case of α-hydroxy acids), have included the following :

1. Diols - Chapter 1

(a) Acyclic vicinal diols (1,2-ethanediol, 1,2-propanediol, 1,2-butanediol and pinacol).

(b) Cyclic vicinal diol (trans-1,2-cyclohexanediol).

(c) Acyclic non-vicinal diols (1,3-butanediol, 1,4-butanediol and 1,5-pentanediol).

2. α-Hydroxy acids - Chapter 2

(a) Aliphatic α-hydroxy acids (glycolic acid, lactic acid,

and tartaric acid).

(b) Aromatic α-hydroxy acids (mandelic acid and benzilic acid).

Chapter 1 - Kinetics of Oxidation of Diols

The kinetics of oxidation of diols (vicinal and non-vicinal) by quinolinium dichromate (QDC) has been studied in acid medium, using water and water-acetic acid mixtures as the solvent, under a nitrogen atmosphere. The progress of the reaction was followed spectrophotometrically, by observing the disappearance of chromium(VI) at 440 nm. For all the diols studied, stoichiometric ratios, Δ[QDC]/Δ[substrate], in the range 0.65 - 0.72 were obtained. The rate of the reaction was found to be dependent on the first powers of the concentration of each reactant (substrate, oxidant and acid). The linear increase in the rate of oxidation with acidity suggested the involvement of a protonated chromium(VI) species in the rate-determining step.

The reaction has been found to be slowest in those solvent mixtures that contained the largest proportions of water, and increasing proportions of acetic acid resulted in an increase in the rate of oxidation. Plots of log k_1 (the pseudo-first-order rate constant) against the inverse of the

dielectric constant were linear, with positive slopes. This suggested an interaction between a positive ion and a dipole (54), and was in consonance with the observation that, in the presence of an acid, the rate-determining step involved a protonated chromium (VI) species.

The reactions were studied over a range of temperatures, and it was observed that the Arrhenius equation was obeyed. Plots of log k_1 against the reciprocal of temperature were linear. The activation energies and the different activation parameters were evaluated. The reactions were characterized by negative entropies of activation. This suggested an ordered transition state, relative to the reactants. The isokinetic temperature, obtained from the plot of $\Delta H^{\neq}$ against $\Delta S^{\neq}$ was 250K. Although current views do not attach much physical significance to isokinetic temperature, a linear correlation between $\Delta H^{\neq}$ and $\Delta S^{\neq}$ is usually a necessary condition for the validity of the Hammett equation. It was further found that the values for the free energies of activation ($\Delta G^{\neq}$) were nearly constant, indicating that the same mechanism operated for the

oxidation of all the diols studied in this investigation.

There was no induced polymerization of acrylonitrile or the reduction of mercuric chloride. This indicated that a one-electron oxidation was unlikely.

It seemed pertinent to attempt a general correlation between the rate of oxidation of all these diols by QDC and the proximity of the hydroxyl groups. The observed order of reactivity for the oxidation of diols by QDC showed that :

(a) 1,4-butanediol > 1,2-ethanediol ;

(b) 1,3-butanediol > 1,2-propanediol ;

(c) trans-1,2-cyclohexanediol > 1,5-pentanediol ;

(d) pinacol was oxidized at a rate faster than any of the other diols under investigation.

The order of reactivity showed that compounds having vicinal hydroxyl groups reacted the slowest, which indicated that there was no cyclic mechanism operating in these oxidation reactions. Hence, the order of reactivity observed in (a) and (b) above could be justified.

For the diols listed in (c) above, the order of reactivity could be rationalized on the basis of a difference in the ease of ester decomposition.

For pinacol, the rapid rate of reaction was ascribed to steric crowding of the methyl groups and the absence of an α-hydrogen atom. Relief in the steric strain resulted in a rapid rate of decomposition of the cyclic chromate ester. The net result was the cleavage of the bond between the vicinal alcohol carbon atoms.

For the diols listed in (a), (b) and (c) above, the mechanistic pathway could also be confirmed by the nature of the products obtained. In the absence of products which would have resulted from carbon-carbon bond fission, it is suggested that an acyclic mechanism would be operating in these oxidation reactions. The major part of the diol was oxidized in a manner $\diagdown\!\diagup CHOH \longrightarrow \diagdown\!\diagup C{=}O$. It was further observed that the fission of these diols could not be brought about in the presence of added free acid. Hence, it would be justified to postulate that all these diols reacted with quinolinium dichromate (QDC) to give the corresponding

α-hydroxycarbonyl compounds. Such a pathway was established to be energetically more favourable than that yielding the fission product, to the extent of 15 kcal per mole or more (55). It was further observed that the rates of oxidation and the enthalpies of activation favoured the formation of the hydroxycarbonyl compounds, which suggested that the structure of the transition state was quite near to that of the products. Cyclic ester formation involving both the hydroxyl groups was thus unlikely. The mechanistic pathway would be an acyclic process via the chromate ester, which then underwent decomposition by a rate-determining carbon-hydrogen bond fission.

This mechanistic pathway was supported by the following correlations :

(a) Oxidizing agents such as periodic acid, lead tetraacetate and phenyliodoso acetate (used primarily to cleave 1,2-diols) do not readily oxidize diols to α-hydroxycarbonyl compounds (55), as do oxidizing agents such as chromic acid or permanganate.

(b) The Zimmerman treatment of electrocyclic reactions

showed that the oxidative cleavage of 1,2-diols by periodate was an allowed electrocyclic process. The corresponding reaction of 1,2-diols by Cr(VI) was shown to be a forbidden process (56). This excluded the operation of a cyclic mechanistic pathway and supported the view that the oxidation of diols by QDC involved the normal pathway, that is, the conversion of $\backslash / CHOH \longrightarrow \backslash / C=O$.

The rate of oxidation of pinacol was much higher than the rate of oxidation of any of the other vicinal or non-vicinal diols. Since, there was no hydrogen atom on the carbon atom bearing the hydroxyl groups, a change in mechanism with increasing methyl substitution was proposed. Here, the formation of a cyclic chromate ester became more probable. This intermediate underwent decomposition, resulting in the cleavage of the carbon-carbon bond. The major product obtained was acetone, which would be possible only if the oxidation process involved the formation of a cyclic chromate ester intermediate.

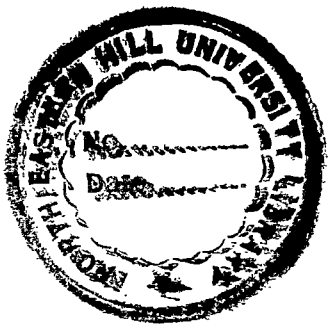
Under the experimental conditions employed in the

present investigation, all the vicinal and non-vicinal diols were oxidized by quinolininum dichromate (QDC), in acid medium, to the corresponding α-hydroxycarbonyl compound. The products obtained were characterized by the respective 2,4-dinitrophenylhydrazone derivatives and by ir analysis.

Under the present experimental conditions employed in the present investigation, pinacol was oxidized by QDC, in acid medium, to acetone, which was characterized by its 2,4-dinitrophenylhydrazone derivative.

In the present investigation, the kinetic data obtained showed that quinolinium dichromate could be used to oxidize diols (vicinal and non-vicinal) to give the corresponding α-hydroxycarbonyl compounds in good yields. It can be suggested that this efficient reaction could prove to be a very useful and general route for the synthesis of α-hydroxycarbonyl compounds. The oxidation of pinacol by quinolinium dichromate had resulted in the formation of acetone, due to the cleavage of the carbon-carbon bond. Such a mechanistic pathway indicated that this could be the general sequence for the oxidation of diols which do not

possess a hydrogen atom attached to the carbon atom bearing the hydroxyl groups.



Chapter 2 - Kinetics of Oxidation of α-Hydroxy acids

The oxidation of α-hydroxy acids by various oxidants is an important and well-known reaction. Earlier work on the oxidation of α-hydroxy acids have been reported, wherein oxidants such as manganic pyrophosphate(57), ceric sulfate(58,59), vanadium(V)(60), 1-chlorbenzotriazole(61), oxygen in the presence of copper(I) as catalyst(62), N-bromoacetamide(63), chloramine-T in alkaline medium(64), N-bromosuccinimide(65), pyridinium hydrobromide perbromide (66), potassium nitrosodisulfonate(67), copper (III) periodate and copper(III) tellurate(68), benzotrimethyl-ammonium tribromide(69) have been employed. Chromic acid and various other chromium(VI) oxidizing agents(70-81) have also been used for the oxidation of α-hydroxy acids.

The present work is a detailed kinetic investigation of the oxidation of α-hydroxy acids (glycolic acid, lactic acid, mandelic acid, benzilic acid and tartaric acid) by quinolinium dichromate (QDC), in acid medium, using dimethylformamide (DMF) and dimethylformamide - water (DMF-H_2O) mixtures as the solvent, under a nitrogen

atmosphere. The course of the reactions was monitored by observing the disappearance of chromium(VI) at 440 nm, spectrophotometrically. The stoichiometric ratios, Δ[QDC]/Δ[Substrate], were in the range 0.64 - 0.73. The rate of the reaction was observed to be dependent on the first powers of the concentrations of each reactant (substrate, oxidant and acid). The rate of oxidation showed a linear increase with acidity, which suggested the participation of a protonated chromium(VI) species in the rate-determining step.

The role of the solvent in these oxidation reactions was investigated. It was observed that the rate of oxidation decreased with decrease in the polarity of the medium, in going from 80% DMF to 100% DMF. Plots of log k_1 (pseudo-first-order rate constant) against the reciprocal of the dielectric constant were linear, with positive slopes, indicating an ion-dipole type of reaction.

The effect of changes in temperature on the rate of the reaction was studied, and the Arrhenius equation was found to be valid. The activation energies and the other

activation parameters were evaluated. The negative entropies of activation($\Delta S^{\neq}$) indicated that the transition state formed was considerably rigid, resulting in a reduction in the degrees of freedom of the molecule. The similarities in $\Delta G^{\neq}$ values for all the substrates arose due to changes in $\Delta H^{\neq}$ and $\Delta S^{\neq}$ values, and emphasized the probability that all these reactions involved similar rate-determining steps.

It was observed that there was no induced polymerization of acrylonitrile or the reduction of mercuric chloride. This indicated that a one-electron oxidation was quite unlikely.

It has been established that α-hydroxy acids could undergo a process of oxidation by different mechanistic pathways. Based on the nature of the oxidizing agent used, there was the possibility of variations in the kinds of products obtained, for the oxidation of α-hydroxy acids. It has been reported that the two pathways available for the oxidation of α-hydroxy acids, have been as follows :

(a) The oxidation pathway resulting in the formation of the corresponding aldo- or keto-acids.

(b) The oxidation process leading to the formation of the corresponding carbonyl compounds (due to carbon-carbon bond cleavage), and a process of oxidative decarboxylation.

In the present investigation, the experimental data indicated that quinolinium dichromate(QDC) was able to oxidize the α-hydroxy acids by both these pathways. The nature of the pathway for the oxidation process seemed to be dependent on the nature of the α-hydroxy acids.

The oxidation of glycolic acid and lactic acid by QDC, in acid medium, had resulted in the formation of the corresponding aldo- and keto-acids (glyoxylic acid and pyruvic acid respectively), which clearly indicated the absence of any oxidative decarboxylation. There was no cleavage of the carbon-carbon bond, as seen by the nature of the products obtained. Hence, the reaction pathway could be visualized as proceeding by way of a hydride ion transfer in the rate-determining step. The hydride ion transfer could involve the prior formation of a chromate ester (82), which

could then undergo decomposition to give the products. The products obtained (glyoxylic acid and pyruvic acid respectively), were characterized by spectral analysis and by the preparation of their corresponding 2,4-dinitrophenylhydrazone (DNP) derivatives.

The oxidation of mandelic acid and benzilic acid by QDC, in acid medium, yielded benzaldehyde and benzophenone respectively, as the major product, with the evolution of carbon dioxide. The formation of these products indicated that α-hydroxy acids containing phenyl group(s) would facilitate the process of decarboxylation, owing to the stabilization of the chromate ester by the phenyl group(s) through the resonance effect. The mechanistic pathway involved the formation of the intermediate chromate ester, which underwent decomposition with the cleavage of the carbon-carbon bond, and the evolution of carbon dioxide. The formation of the respective products (benzaldehyde and benzophenone) was confirmed by spectral analysis and by the preparation of the respective 2,4-dinitrophenylhydrazone (DNP) derivatives.

In the present investigation, the kinetic data obtained indicated that quinolinium dichromate, in acid medium, could oxidize aliphatic α-hydroxy acids having primary or secondary hydroxyl groups (glycolic and lactic acids), to the corresponding aldo- or keto-acids in good yields. In the case of aromatic α-hydroxy acids, quinolinium dichromate, in acid medium, could oxidize α-hydroxy acids having secondary or tertiary hydroxyl groups (mandelic acid and benzilic acid), by a process involving the cleavage of the carbon-carbon bond leading to oxidative decarboxylation. The reaction sequence, which involved the formation of the chromate ester intermediate, satisfactorily explained the observed kinetic data. The ester formed would be better stabilized in the presence of solvents of high polarity. Thus, an increase in the polarity of the solvent media accelerated the rate of oxidation. Further, variation in the reaction rate for the oxidation of α-hydroxy acids by QDC was in conformity with the ester mechanism, since the chromate ester formation was likely to be little influenced by structural changes.

In the present investigation, the oxidation of tartaric acid by QDC, in acid medium, had yielded glyoxylic acid, which was characterized by spectral analysis and by its 2,4-dinitrophenylhydrazone (DNP) derivative. Since, this product was obtained in trace amounts, it could be suggested that there was the possibility of glyoxylic acid undergoing a process of oxidative decarboxylation to yield formic acid. The formation of glyoxylic acid indicated that there was the cleavage of the carbon-carbon bond bearing the two hydroxyl groups in tartaric acid. The mechanistic pathway involved the formation of a cyclic chromate ester, which underwent symmetrical carbon-carbon bond cleavage to give glyoxylic acid. The presence of hydroxyl groups on adjacent carbon atoms would facilitate the formation of a cyclic chromate ester, involving some amount of steric strain in the transition state. There would be a relief of the steric strain when this cyclic intermediate underwent further oxidation. This would involve a process of bond cleavage, occurring between two carbon atoms containing the hydroxyl groups.

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KINETICS OF OXIDATION OF SOME DIOLS AND HYDROXY ACIDS BY QUINOLINIUM DICHROMATE

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CERTIFICATE

I certify that the Thesis entitled "KINETICS OF OXIDATION OF SOME DIOLS AND HYDROXY ACIDS BY QUINOLINIUM DICHROMATE" submitted by Mr. ABHIJIT DEBROY, for the degree of Doctor of Philosophy of the North-Eastern Hill University, Shillong, embodies the record of original investigation carried out by him under my supervision. He has been duly registered and the Thesis presented is worthy of being considered for the award of the Ph.D. degree. This work has not been submitted for any degree of any other university.

Mahendra K. Mahanti 28/5/97

Shillong
28 May 1997

(MAHENDRA K. MAHANTI)
Supervisor

COMPUTERISED

DEDICATED TO THE MEMORY OF MY

BELOVED FATHER

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CONTENTS

INTRODUCTION

INTRODUCTION

Oxidation is an essential operation in organic syntheses and several reagents have been developed for a wide variety of transformations (1-3). Hexavalent chromium compounds have been widely used as oxidizing agents reacting with diverse kinds of organic substrates. During the course of these reactions, the Cr(VI) compounds are reduced to the Cr (III) species.

The earliest known chromium (VI) oxidants were chromium trioxide and chromyl chloride. Chromyl chloride has generally been used in carbon tetrachloride or carbon disulfide media. Chromium trioxide has been used in various kinds of reaction media such as water, acetic acid, sulfuric acid, acetic anhydride, acetone, t-butyl alcohol and pyridine.

In recent years, a large number of novel chromium(VI) oxidizing agents have been introduced, mostly in response to the needs of mildness and selectivity. The "Jones reagent" was introduced for the oxidation of organic compounds (4-6). This reagent was a solution of

chromium (VI) oxide in concentrated sulfuric acid, which was added dropwise to the substrate dissolved in acetone. The usefulness of the "Jones reagent" has been established.

Several facile oxidations of secondary alcohols were achieved with chromic acid in a two-phase system of ether and water (7). This method proved particularly suitable for the synthesis of ketones, which were susceptible to epimerization under oxidizing conditions (7).

In order to protect acid-sensitive functional groups during the oxidation of alcohols with Cr(VI) oxide, polar aprotic solvents have been used. A solution of Cr(VI) oxide in dimethylformamide, containing a trace of concentrated sulfuric acid, was able to oxidize alcohols containing acid-sensitive protecting groups. The presence of catalytic amounts of sulfuric acid was essential, accompanied by low temperatures and an inert nitrogen atmosphere (8). When a solution of Cr(VI) oxide was added to an equal volume of the substrate (alcohol), dissolved in hexamethyl phosphoric triamide (HMPT),

simple axial and equatorial hydroxyl functions were oxidized, the latter at a much faster rate (9). Under the same experimental conditions, Cr(VI) oxide in HMPT was found to oxidize allylic hydroxyl functions in preference to other alcoholic groups (9). A series of primary and secondary alcohols were oxidized in 80-90% yields by a solution of sodium dichromate dihydrate, in concentrated sulfuric acid, in dimethyl sulfoxide (DMSO) at 70^{o}C(10). In these oxidations, DMSO acted as a solvent and not as an oxidant, as shown by the negligible oxidation of the substrates in the absence of dichromate (10).

One of the earliest and most widely employed chromium (VI) oxidants has been the "Collins reagent", dipyridinium-Cr(VI) oxide in dichloromethane(11). Collins reagent has been extensively used for the oxidation of primary and secondary alcohols (12-20).

The technique of using reagents intercalated in, or adsorbed on, a solid support has also been exploited in oxidations with chromium(VI) oxidizing agents. The solid

supports used have included graphite, silica, alumina, silica gel and celite. As in the case of many Cr(VI) reagents, attempts were made to achieve mild reaction conditions, better selectivity and convenient isolation of the oxidation products. On heating with graphite under reduced pressure, chromium(VI) oxide was claimed to be uniformly intercalated, and the resulting substance was found to oxidize primary alcohols to aldehydes in high yields (21). Later work showed that the oxidizing agent was a surface deposit of chromium(VI) oxide on graphite (22-23). Collins reagent(11), adsorbed on celite, has been used to oxidize allylic alcohols to the corresponding aldehydes (24).

Chromium(VI) oxide, in conjunction with 3,5-dimethyl pyrazole(25), has been used to oxidize primary and secondary alcohols. This reagent was presumed to form a cyclic chromate ester that generated the corresponding carbonyl compound through intramolecular elimination. Despite the high yields of some simple aldehydes and ketones from the corresponding alcohols and

near quantitative oxidation of geraniol(25), this reagent did not give satisfactory yields in a number of cases (16,26).

For oxidation purposes, the most widely used Cr(VI) complex with pyridine has been pyridinium chlorochromate (PCC), popularly known as "Corey's reagent"(27). Its principal advantage was that this reagent was not air- or moisture-sensitive, and oxidation with it did not involve handling a large volume of solvent. Studies on the kinetics of oxidation of primary alcohols by PCC have provided important information on the mechanism of the process (28). Involvement of protonated chromium species in the rate-determining step was indicated by the catalysis of the reaction by acid, the acid-catalyzed reaction being first order. PCC did not polymerize acrylonitrile, and a hydrogen transfer hypothesis was thus not tenable. A substantial kinetic isotope effect, k_H/k_D = 5.71, at 303K suggested a hydride tranfer in the rate-determining step. The transfer could occur directly between the alcohol and the protonated species or intramolecularly after the

initial formation of a chromate ester (28). A few representative examples of oxidation of primary and secondary alcohols by PCC have been given in Table 1.

Table 1. Oxidation of Primary and Secondary Alcohols by PCC, in dichloromethane at 25°C (ref 27).

Alcohol	Product	Yield (%)
1-Heptanol	Heptanal	78
1-Decanol	Decanal	92
1,6-Hexanediol	Hexanedial	68
Oct-2-yn-1-ol	Oct-2-ynal	84
Citronellol	Citronellal	82
Benzhydrol	Benzophenone	100
4-t-Butylcyclohexanol	4-t-Butylcyclohexanone	97
Presqualene alcohol	Presqualene aldehyde	78

Pyridine oxodiperoxychromium(VI), $C_5H_5N{:}CrØ_5$, a complex of chromium pentoxide with pyridine, has been used for the oxidation of primary and secondary alcohols(29).

This reagent was prepared by the addition of aqueous H_2O_2 to an aqueous solution of chromium (VI) oxide containing pyridine, maintained at low temperature.

Chromic acid supported on an ion-exchange resin has been used to oxidize primary and secondary alcohols (30). This polymer-supported reagent was prepared by the addition of the chloride form of the resin to an aqueous solution of chromium (VI) oxide under stirring. Chromyl chloride, adsorbed on silica-alumina, was found to be an effective oxidizing agent for primary and secondary alcohols, under neutral non-aqueous conditions (31). This reagent was prepared by the addition of chromyl chloride, in dichloromethane, to a slurry of the adsorbent, also taken in dichloromethane(31). The instantaneous oxidation of primary and secondary alcohols, in good yields, were obtained using chromic acid adsorbed on silica gel(32). This reagent was prepared by adding a weighed amount of silica gel to a solution of chromium(VI) oxide in water (32). Pyridinium chlorochromate(PCC), supported on a polymer, was found to

be an efficient system for the oxidation of alcohols to the corresponding carbonyl compounds(33). This reagent, poly[vinyl(pyridinium chlorochromate)], (PVPCC), was prepared by the addition of chromium(VI) oxide and concentrated hydrochloric acid to polyvinyl pyridine suspended in water(33). Pyridinium chlorochromate, adsorbed on alumina, has been claimed to be a better oxidizing agent than PCC taken in dichloromethane suspension(34). Thus, carveol was efficiently oxidized to carvone, and no cationic cyclization was observed during the the conversion of citronellol to citronellal (34).

The difficulties in handling Collins reagent and the problem arising out of the acidic nature of Corey's reagent were overcome by the use of pyridinium dichromate, $(PyH)_2Cr_2O_7$(PDC), which was recognized as a mild and selective oxidizing agent(35). This reagent was soluble in a number of solvents, though an aprotic medium was necessary for getting satisfactory results. PDC was generally used either in solution in dimethylformamide or as a suspension in dichloromethane. Anhydrous conditions

were used during oxidation with PDC, and when the oxidation was performed in dimethylformamide, the carbonyl compounds were isolated by ether extraction after pouring the reaction mixture in water. PDC showed remarkable selectivity as an oxidizing agent. When dissolved in dimethylformamide, it clearly oxidized allylic alcohols to the corresponding α,β-unsaturated aldehydes in excellent yields. PDC in dichloromethane oxidized primary and secondary alcohols efficiently. The aldehydes obtained as products from primary alcohols did not undergo further oxidation(35).

In the presence of a mixture of ether and dichloromethane, chromium(VI) oxide was used to oxidize several secondary alcohols, in the presence of celite(36). The best results were obtained by the addition of solid chromium(VI) oxide to an ice-cold solution of the substrate (alcohol) in ether-dichloromethane as the solvent mixture, with celite as a suspension(36).

There have been several reports on the oxidation of primary and secondary alcohols by various chromium(VI)

oxidants under phase-transfer catalysis(37-41). Some of the phase-transfer catalysts employed have included Adogen 464 (a commercially available mixture of methyltrialkyl-ammonium chloride, ref.37), tetrabutylammonium bisulfate (38,39), and tetra-n-butylammonium chloride (40,41).

Allylic and benzylic alcohols were efficiently oxidized to the corresponding aldehydes with bis-tetrabutylammonium dichromate (TBADC) in refluxing dichloromethane(42).

The 2,2′-bipyridine complex of chlorochromic acid was a useful oxidizing agent which had resulted in simplified procedures for the purification of the resulting carbonyl compounds(43). The 2,2′-bipyridinium chlorochromate and the 2,2′-bipyridine-chromium trioxide complex have both proved to be specially useful in oxidations of compounds with acid-sensitive protecting groups, due to the internal buffering of the 2,2′-bipyridyl system. These results indicated that synthetically useful changes in the properties and reactivity of Cr(VI) reagents could be brought about by varying the amine ligand associated with

chromium trioxides(43).

The pyridinium chlorochromate/H_2O_2 system has been used as an oxidative reagent for the conversion of oximes to parent carbonyl compounds in reasonably good yields(44). Pyridinium chlorochromate in dichloromethane containing 2% pyridine at 2-3^{o}C was reported to effect the high-yield selective oxidation of the allylic hydroxyl function of a number of steroidal alcohols(45).

The oxidation of complex allylic and benzylic alcohols to the corresponding carbonyl compounds was achieved using a mild selective reagent, 4-(dimethyl amino) pyridinium chlorochromate(46). Secondary alcohols proved to be more reactive towards this reagent than primary alcohols. The ready preparation of this oxidizing agent, its selectivity, and the ease of using this reagent indicated its effectiveness for the oxidation of complexed allylic and benzylic alcohols(46).

The pyridinium chlorochromate-iodine system was

found to be an efficient method for the conversion of enol silyl ethers to α-iodoketones in excellent yields(47). A highly selective oxidant, bis[benzyltriethyl ammonium] dichromate was prepared and used for the oxidation of active alcohols to the corresponding carbonyl compounds, and of mercaptans to disulfides in hexamethyl phosphoric triamide (HMPT) as solvent; the yields reported were almost quantitative(48).

Since the process of oxidation in organic chemistry is of great value as a fundamental process in a wide scope of chemical conversions, there has been considerable interest in the development of newer chromium(VI) reagents for oxidation reactions. Since the introduction of pyridinium chlorochromate(27), and its extensive use as a versatile oxidant in organic synthesis(49), several new oxidizing agents have been developed, varying the amine ligand associated with the chlorochromate anion.

A new Cr(VI) reagent, pyridinium fluorochromate (PFC), was found to have certain advantages over similar

oxidizing agents, in terms of the amounts of oxidant and solvent required, shorter reaction times, and high yields(50). In dichloromethane as solvent, PFC was found to oxidize primary and secondary alcohols to the corresponding aldehydes or ketones, respectively, and was also found to oxidize benzoin to benzil, as also anthracene and phenanthrene to their corresponding quinones(50).

At room temperature, tetrabutyl ammonium chlorochromate(TBACC), in chloroform, was used as a selective reagent for the oxidation of alcohols such as geraniol, which was converted to geranial in excellent yields (51).

Two new chlorochromate complexes were prepared and used as mild oxidizing agents. These were :
(a) 1,8-naphthyridinium chlorochromate ($C_8H_6N_2HCrO_3Cl$); and (b) pyrazinium chlorochromate ($C_4H_4N_2HCrO_3Cl$). These two reagents, taken in dichloromethane as solvent, were used to oxidize benzylic and cyclic alcohols to corresponding carbonyl products in good yields(52).

Bis-(trimethylsilyl) peroxide (BTSP), in the presence of Cr(VI), has been used to oxidize alcohols to the corresponding ketones. A solution of $Me_3SiOOSiMe_3$ (BTSP) in dichloromethane, in the presence of pyridinium dichromate, was used to oxidize borneol to camphor, as also for the conversion of cyclic alcohols to cyclic ketones in good yields (53,54).

Pyridinium chlorochromate(PCC), in conjunction with 3,5-dimethylpyrazole(DMP), in dichloromethane as solvent, was found to be a convenient and useful reagent for the rapid and selective oxidation of steroidal allylic alcohols (55,56). The selectivity of this reagent was such that primary and secondary alcohols did not undergo significant oxidation, relative to allylic alcohols (55,56).

Among many chromium (VI) reagents examined, pyridinium fluorochromate (PFC) was as reactive as pyridinium chlorochromate, and oxidation took place at $25^{o}C$(57). The reaction with benzyl-trimethylammonium chlorochromate (BTMACC) proceeded very slowly at $25^{o}C$, and the completion of the reaction in 1,2-dichloroethane

required heating at 80°C(57). However, BTMACC was able to convert alcohols to the corresponding carbonyl compounds in very good yields (57). Tetrabutylammonium chlorochromate (TBACC) was also able to carry out these oxidation reactions, though with yields which were much less than the yields obtained by oxidation with BTMACC (57). Other reagents which were prepared had included tetramethylammonium fluorochromate (TMAFC), tetramethylammonium chlorochromate (TMACC) and tetrabutylammonium fluorochromate (TBAFC), but all these reagents were found to be inert for the oxidation of alcohols(57).

A useful contribution to organic synthesis was the preparation of tetrakis(pyridine) silver dichromate, $Py_4Ag_2Cr_2O_7$, which was used for the oxidation of benzylic and allylic alcohols in refluxing benzene, giving high yields of the corresponding carbonyl compounds(58).

The oxidation of primary and secondary alcohols to the corresponding carbonyl compounds has been most frequently accomplished in synthetic practice by the use of Cr(VI) reagents in amounts ranging from stoichiometric

to large excess over stoichiometric(59). A new and highly effective reagent combination for the catalytic oxidation of secondary alcohols to ketones has been used(60). This reagent consisted of peroxyacetic acid as the stoichiometric oxidant and a catalytic amount of 2,4-dimethylpentane-2,4-diol cyclic chromate, using carbon tetrachloride-dichloromethane mixtures as solvent. A solution of the chromate ester was prepared from 2,4-dimethylpentane-2,4-diol and chromium trioxide in dry carbon tetrachloride. The yields of the corresponding ketones were almost quantitative, using this method(60).

A new class of Cr(VI) reagents derived from chromium trioxide and halosilanes has been developed(61). These reagents are highly efficient for the oxidation of alcohols to carbonyl compounds, for the oxidative coupling of mercaptans into disulfides, and for a mild cleavage of oximes to carbonyl compounds. Chlorotrimethylsilane-chromium trioxide has been shown to be an efficient oxidizing agent for the conversion of arylmethanes to benzaldehyde, and for the oxidative

cleavage of some benzyl esters(61).

The use of a triazole to mediate selective Cr(VI) oxidation has been described(62). Benzotriazole, when used in conjunction with pyridinium chlorochromate in dichloromethane, was found to be a mild and useful reagent system for the rapid and selective oxidation of steroidal allylic alcohols to the corresponding ketones(62). A new method for the 1,4-oxygenation of 1-alkylated cyclo-pentadienes had made use of 2-cyanopyridinium chlorochromate and powdered molecular sieves, in dichloromethane, to give the corresponding cyclopentenones in good yields(63).

Two new Cr(VI) reagents derived from nicotinic acid and isonicotinic acid were prepared(64). 3-Carboxypyridinium dichromate (nicotinium dichromate, NDC) and 4-carboxy-pyridinium dichromate(isonicotinium dichromate, INDC), were synthesized from chromium trioxide dissolved in a small amount of water, and nicotinic or isonicotinic acid respectively. These two reagents (NDC and INDC) have been used for the oxidations of allylic and benzylic alcohols to

aldehydes, thiols to disulfides, hydroquinones to benzoquinones, and for the oxidation of polynuclear aromatic hydrocarbons(64). This reagent, 3-carboxypyridinium dichromate(NDC), proved to be an efficient reagent for the oxidation of alcohols to carbonyl compounds, in the presence of pyridine. In order to ensure complete oxidation of the substrate, the optimum molar ratio of substrate: oxidant:pyridine was found to be 1:2.5:20, respectively(65).

The efficient oxidation of alcohols to carbonyl compounds under mild conditions has been a necessary theme in organic syntheses. An improved procedure was described for the extremely rapid and efficient oxidation of alcohols, by the addition of a small quantity of anhydrous acetic acid to pyridinium dichromate(PDC) and freshly activated molecular sieve powder, in dichloromethane, at room temperature(66).

Chromium peroxide complexes have been used as general oxidants in organic syntheses. 2,2´-Bipyridyl-chromium peroxide has been used to convert different classes of alcohols to the carbonyl compounds, for C-C bond

cleavages in 1,2-diols, the quantitative decarboxylation of α-hydroxy acids, the conversion of oximes to their carbonyl compounds, thiols to disulfides, dihydroxy phenolic compounds to quinones, benzylamine to benzaldehyde, aromatic amines to their azo compounds, and for the conversion of anthracene and phenanthrene to their quinones(67). Pyridine chromium peroxide has been used to convert different classes of alcohols to the carbonyl compounds, thiols to disulfides, anthracene to anthraquinone, and for the decarboxylation of mandelic and benzylic acids(67). Chromium peroxide etherate has also been used as an effective reagent for the oxidation of different classes of alcohols to their respective carbonyl compounds(67).

Under mild conditions, imidazolium dichromate (IDC), in dimethylformamide as solvent, was found to be a useful and selective reagent for the oxidation of allylic and benzylic alcohols to the corresponding carbonyl compounds, the yields being very good(68).

A phase-transfer catalysis(PTC) technique for the oxidation of benzylic primary and secondary alcohols was

reported(69). Benzyltriethylammonium chlorochromate, generated in situ under phase-transfer conditions, was used in refluxing chloroform to oxidize alcohols to the corresponding carbonyl compounds in good yields(69).

Pyridinium bromochromate(PBC), in chloroform, was found to be an efficient reagent for the oxidation of benzyl alcohols, fluorenols and benzoin, giving good yields of the respective products(70).

The suitable biphosphonium dichromate reagent, $(C_6H_5)_3P^+CH_2P^+(C_6H_5)_3Cr_2O_7^{2-}$, was a particularly mild and selective reagent for the oxidation of primary and secondary alcohols(71). The oxidation of primary alcohols to aldehydes occurred without further oxidation to acid, and without any isomerization or migration of the double bond(71).

Zinc dichromate trihydrate $[ZnCr_2O_7.3H_2O]$, in dichloromethane, was found to be a mild reagent for the oxidation of primary and secondary alcohols to the corresponding aldehydes and ketones in good yields(72).

Allyl alcohols and tricyclic allyl alcohols were observed to be resistant towards any reaction with this reagent(72).

Catalytic amounts of chromium trioxide and excess of aqueous t-butyl hydroperoxide, was found to be an effective reagent for the conversion of alcohols to carbonyl compounds, geraniol having been converted to geranial at room temperature in quantitative yields(73).

The pyridinium dichromate induced oxidative rearrangement of various enynols proceeded with complete regiospecificity giving good yields(74). In these rearrangements, it was observed that chromate ester formation and subsequent ring flip created severe 1,4-steric (flag pole) interaction(74).

The oxidation of alcohols by pyridinium fluorochromate (PFC) in dichloromethane had yielded the corresponding carbonyl compounds in good yields(75). This study indicated that PFC was an efficient two-election oxidant which was capable of participating in oxygen-transfer reactions(75).

The versatility of pyridinium fluorochromate as an oxidizing agent has been brought out by the various studies which have been carried out on the oxidation of some organic substrates such as aliphatic alcohols(76), sulfides(77), and aromatic alcohols(78).

Cyano-pyridinium chlorochromate (CPCC), in dichloromethane, was found to be the reagent of choice for the conversion of alkenes to α-chloroketones, and this procedure seemed to have broad applicability(79).

Pyridinium chlorochromate(PCC), in the presence of sodium azide or sodium cyanide, was used to transform aldehydes into carbamoyl azides or acyl azides in fairly good yields(80).

Cr(VI)-oxide diperoxide has been used for the oxidation of tertiary amines(81). These reactions were carried out in chloroform, and the products obtained were the corresponding N-oxides in good yields. The rate law observed suggested a mechanism involving a preliminary coordination of the amine to the metal. The oxidation rate of the amines and some organic sulfides

indicated a mechanism having some single-electron-transfer (SET) character(81).

By using the ultrasound technique(82), pyridinium chlorochromate in conjuntion with silica gel was developed as a heterogeneous process for the oxidation of alcohols to the corresponding carbonyl compounds(83). Using this process, borneol was converted to camphor, and geraniol was converted to geranial in excellent yields(83). The synthetic utility of pyridinium chlorochromate in chloroform was demonstrated for the oxidation of alcohols, using anhydrous acetic acid as a catalyst(84). Such anhydrous conditions have been used for the oxidation of primary and secondary alcohols by pyridinium chlorochromate(84).

With a view to provide further evidence so as to ascertain the mechanism of the oxidation of alcohols by Corey's reagent(PCC), two new Cr(VI) reagents were synthesized. These two reagents were 1-methyl imidazolium chlorochromate (MCC) and imidazolium chlorochromate(ICC). It was found that these two reagents were similar in

selectivity. The mechanism for the oxidation of alcohols by these reagents was similar to that for the oxidation of the alcohols by PCC(85).

The oxidation of alcohols by isoquinolinium chlorochromate, in dichloromethane solvent, yielded the corresponding carbonyl compounds in reasonably good yields(86).

Three new Cr(VI) reagents (ferric dichromate, polyvinylpyridine supported zinc dichromate, and polyvinylpyridine supported ferric dichromate), were prepared and found to be stable, mild and efficient reagents for the oxidation of different kinds of organic compounds(87). Of these three reagents, ferric dichromate seemed to be the most efficient. When taken in acetonitrile, ferric dichromate was able to oxidize styrene to benzaldehyde, and alcohols to their corresponding carbonyl compounds in good yields(87).

The oxidation of secondary alcohols with chromium trioxide, in the presence of wet aluminium oxide in hexane,

had yielded the corresponding ketones(88). This method was used for the oxidation of cyclic alcohols, giving good yields of the cyclic ketones(88). For the oxidation of geraniol by this reagent, it was observed that the reaction proceeded without any appreciable loss of double bond stereochemistry(88).

The most recent chromium(VI) reagent(89) which has been introduced for the oxidation of organic substrates has been quinolinium fluorochromate(QFC), $C_9H_7NH[CrO_3F]$. This reagent has been found to be as effective as pyridinium chlorochromate(PCC) and pyridinium fluorochromate(PFC). The major improvements have been the relatively higher solubility of QFC in non-aqueous solvents and much less pronounced acidic character, as compared to PCC and PFC. The versatile nature of QFC has been highlighted by the diverse types of organic substrates which have been oxidized by it. QFC in chloroform has been used to oxidize alcohols, polycyclic arenes, triphenylphosphine, trimethylsilyl ether and

diphenylsulfide, and the yields reported have been excellent(89).

Kinetic studies involving the use of various chromium(VI) reagents have been reported. Pyridinium bromochromate has been employeed for the kinetics of oxidation of phosphinic, phenylphosphinic and phosphorus acid(90). Pyridinium fluorochromate (PFC), in aqueous acetic acid medium, was found to be an efficient oxidant for the oxidation of secondary alcohols(91). Pyridinium chlorochromate(Corey's reagent) has been extensively employed for the oxidation of different organic substrates. In the oxidation of cinnamic acids by this reagent, kinetic data has been used to support the mechanistic pathway for this reaction, which was characterized by a non-linear Hammett plot(92). The reaction of hydromates and hydroxyacids with pyridinium chlorochromate(PCC), in acid medium, catalysed by ruthenium(III), yielded kinetic data which suggested a mechanism involving an electron transfer reaction(93). Kinetic studies on the oxidation of some thioacids by

2,2′-bipyridinium chlorochromate has been reported(94). Quinolinium bromochromate has been selectively used for the oxidation of different alcohols in anhydrous acetic acid(95). The oxidation of cyclopentanol by chromic acid in micellar medium has been reported, with a detailed study on the effect of sodium lauryl sulfate on this reaction(96). A new chromium(VI) reagent, tetra-ethylammonium chlorochromate (TEACC), has been introduced, and a kinetic study has been carried out on the oxidation of benzyl alcohol by this reagent in dimethylformamide solvent(97).

Quinolinium dichromate(QDC), having the structure $(C_9H_7NH^+)_2Cr_2O_7^{2-}$, has been used for the oxidation of primary and secondary alcohols to aldehydes and ketones respectively, and for the oxidation of aldehydes to acids(98). QDC is a stable orange solid, which was prepared by dissolving CrO_3 in water, adding quinoline, and collecting the product. Solutions of QDC, in dimethylformamide or suspensions in dichloromethane, have been used for the oxidation of alcohols and aldehydes,

giving good yields of the corresponding products(98). A few representative examples of the oxidation of alcohols and aldehydes by QDC are given in Table 2.

Table 2. Oxidation of alcohols and aldehydes by QDC(ref.90)

Compound	Product	Yields (%) In CH_2Cl_2	Yields (%) In DMF
n-Butanol	n-Butanal	69	74
n-Hexanol	n-Hexanal	70	44
Benzyl Alcohol	Benzaldehyde	45	45
Cinnamyl Alcohol	Cinnamaldehyde	70	52
Benzhydrol	Benzophenone	55	48
Benzaldehyde	Benzoic Acid		55
Cinnamaldehyde	Cinnamic Acid		52
Crotonaldehyde	Crotonic Acid		85

Quinolinium dichromate (QDC) has emerged as a very useful and versatile oxidant, which is clearly deserving of widespread application. QDC in dimethylformamide-water mixtures, in the presence of acid, has been used for the oxidation of a variety of organic substrates. Some of the

organic substrates which have been oxidized by QDC in acid medium, have included benzyl alcohols (99), arylalkanes(100), diphenylamines(101), polynuclear aromatic hydrocarbons(102,103), toluene and substituted toluenes(103,104), fluorene(105), amino acids(106), benzoin(107), styrenes(108), unsaturated acids(109), bicyclic alcohols(110), cyclic alcohols(111) and allylic alcohols(112).

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SCOPE OF THE PRESENT INVESTIGATION

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There has been a sustained interest in the development of new reagents for the effective and selective oxidation of organic substrates. The development of oxidizing agents based upon higher-valent transition metal oxo derivatives has resulted in the use of reagents derived from transition metals such as ruthenium, osmium, iron, manganese, molybdenum, chromium and vanadium. Of all such reagents, chromium (VI) oxidants seem to have proved to be the most versatile and efficient in bringing about various kinds of transformations.

The conversion of hydroxy groups to the corresponding carbonyl groups has been considered to be an important transformation in organic synthesis. Many procedures have been developed for these conversions. The use of oxochromium(VI) amine reagents in oxidative transformations have been quite extensive. These reagents have been used for the general oxidation of alcohols to carbonyl compounds, the selective oxidation of allylic and benzylic alcohols, the

oxidation of organometallics, oxidative transpositions and cleavages, and oxidative cyclizations. Since the introduction of pyridinium chlorochromate (PCC, Corey's reagent) as an oxidant for the purpose of carrying out the oxidation of alcohols to carbonyl compounds, several new oxochromium (VI)amine reagents have been developed with the purpose of achieving a desired selectivity, improvement in yield, or a modification of product outcome.

In the present investigation, the chromium(VI) reagent which has been employed is quinolinium dichromate (QDC), $(C_9H_7NH^+)_2Cr_2O_7^{2-}$. This reagent has emerged as a useful and versatile oxidant, capable of oxidizing diverse kinds of organic substrates.

The present investigation is a detailed kinetic probe into the oxidation of various organic substrates by quinolinium dichromate (QDC) in acid medium, using water (in the case of diols), and dimethylformamide (in the case of α-hydroxy acids), as the solvents, under a nitrogen atmosphere. The purpose of this investigation has been to attempt to extend the scope of this oxidizing

agent, QDC, in acid medium, and to explore and establish mechanistic pathways of reactions involving diverse organic substrates. The substrates chosen for the purpose of oxidation by quinolinium dichromate (QDC), have included the following :

1. Diols - Chapter 1

   (a) Acyclic vicinal diols (1,2-ethanediol, 1,2-propanediol, 1,2-butanediol and pinacol).

   (b) Cyclic vicinal diol (trans-1,2-cyclohexanediol).

   (c) Acyclic non-vicinal diols (1,3-butanediol, 1,4-butanediol and 1,5-pentanediol).

2. α-Hydroxy acids - Chapter 2

   (a) Aliphatic α-hydroxy acids (glycolic acid, lactic acid and tartaric acid).

   (b) Aromatic α-hydroxy acids (mandelic acid and benzilic acid).

For each oxidation reaction, the stoichiometry of the reaction has been determined. The concentrations of substrate, oxidant and acid have been varied, and the effects of these variations on the reaction rates have

been studied. The solvent composition has been varied (water and water-acetic acid mixtures, in the case of diols; and DMF and DMF-H_2O mixtures, in the case of α-hydroxy acids), in order to study the effects of changes in the dielectric constant of the medium on the rates of the reactions. Changes in the temperature of the reaction medium have been made, and the activation parameters have been evaluated. Based on the observed kinetic data, the nature of the transition states involved in these reactions has been rationalized. For each reaction, the products have been isolated, and characterised by analytical and spectral methods. Based on the observed experimental data, mechanistic pathways for the oxidation of these substrates by quinolinium dichromate (QDC), in acid medium, have been proposed.

EXPERIMENTAL

EXPERIMENTAL

Conductivity Water

Conductivity water was prepared by the following method : tap water was distilled first with alkaline potassium permanganate and then redistilled with sulfuric acid (Merck) from an all-glass vessel. This sample of double distilled water was further distilled from an all-quartz vessel. The conductivity water thus prepared was utilized for the preparation of all the solutions used in the kinetic determinations.

Sulfuric Acid

E. Merck sample was used.

Acetic acid

Acetic acid (E. Merck) was refluxed for 3 hours with chromic oxide, with the addition of a quantity of acetic anhydride corresponding to the water content of the acetic acid. The solids that separated out were filtered off, and the acid was distilled from an all-glass apparatus. Large head and tail fractions were rejected and

the fraction distilling at 116^{o}C was collected.

N,N-Dimethylformamide

Dimethylformamide was purified by the following method : Anhydrous copper sulfate was prepared by heating copper sulfate. ($CuSO_4.5H_2O$), until it turned white. The complete removal of water molecules was checked by its constant weight after repeated heating. Anhydrous copper sulfate was mixed with dimethylformamide (SD'S, AR grade), and the mixture was allowed to stand for 24 hours. The solution was filtered and the filtrate was distilled under reduced pressure.The distillate thus collected was used as the solvent(bp.153^{o}C).

Quinolinium dichromate (QDC), $(C_9H_7NH^+)_2Cr_2O_7^{2-}$

To a stirred solution of CrO_3 (100g) in water (100 ml) cooled in ice, quinoline (86 ml) was added in small portions. The solution was diluted with acetone (400 ml), cooled to -20^{o}C, and the orange solid which separated out was filtered, washed with acetone, dried in vacuo and recrystallized from water (mp.160^{o}C). The

purity of the compound was further checked by spectral analysis. Infrared spectrum (KBr) exhibited bands at 930, 875, 765 and 730 cm^{-1}, characteristic of the dichromate ion.

Substrates

The diols (1,2-ethanediol, 1,2-propanediol, 1,3-butanediol and 1,4-butanediol) were obtained from BDH and were purified by distillation, and their purity was checked from physical constants. Pure samples of other diols (1,2-butanediol, 1,5-pentanediol, pinacol and trans-1,2-cyclohexanediol) were obtained from Aldrich Chemical Company, and their purity was further checked from physical constants.

The hydroxyacids (glycolic acid and tartaric acid) were obtained from Aldrich Chemical Company, and their purity was checked from physical constants.

Lactic acid used was obtained from E.Merck. This was purified by distillation, and its purity was checked from physical constants.

Mandelic acid was obtained from Sigma Chemical Company, and its purity was checked from physical constants.

Benzilic acid was obtained from E.Merck. It was purified by recrystallization, and its purity was checked from physical constants.

All ir spectra were recorded on an IR 297 (Perkin Elmer) spectrophotometer.

The boiling points and melting points of the substrates used are summarized in Table 1.

Table 1

Substrate	Boiling points or Melting points (^{o}C)
1,2-Ethanediol	199
1,2-Propanediol	188
1,2-Butanediol	191-192
Trans-1,2-cyclohexanediol	104 mp.
Pinacol	40 mp.
1,3-Butanediol	203-204
1,4-Butanediol	230
1,5-Pentanediol	242
Glycolic acid	80 mp.
Lactic acid	122
L(+) Mandelic acid	133 mp.
DL-Tartaric acid	210 mp.
Benzilic acid	150 mp.

Acrylonitrile

The monomer (BDH) was washed with 5% sodium hydroxide solution to remove the inhibitor (hydroquinone),

and then with 3% orthophosphoric acid to remove any basic impurities. It was then washed with water, dried over anhydrous calcium chloride, and distilled under reduced pressure in an atmosphere of nitrogen. The middle fraction was collected (b.p. 77^{o}C) and used.

Other Reagents

All other reagents used were of AnalaR grade, and were purified before use, and their boiling points/melting points were checked, and found to agree with those given in the literature.

Kinetic Method

All the standard flasks and reaction vessels were of pyrex glass with well-ground stoppers. The reaction vessels used were stoppered conical flasks. All the glass apparatus used were tested for loss of solvent, and the loss was found to be negligible. The standard flasks, reaction vessels and the pipettes used were standardized, using conductivity water, and the correction was found out and applied.

An electrically operated thermostatic water bath

was used. It was provided with sufficient thermal lagging, suitable heaters and timers with proper cooling arrangements for continuous work. A xylene-filled regulator, working in conjunction with an electronic relay, was used to maintain the required temperature accurately, with fluctuations of not more than $\pm 0.1^{o}C$. The temperatures were recorded by means of an accurate sensitive thermometer, reading to tenths of a degree. The bath liquid was water, covered with a layer of liquid paraffin to minimize evaporation of water and loss of heat due to radiation.

Spectrophotometer

For absorption measurements, the spectrophotometer used was the Digital Spectrophotometer, Type 106 (Systronics model).

The Type 106 Digital Spectrophotometer was a single beam spectrophotometer having a grating of 600 lines/mm and a wave length range from 340 nm to 960 nm. The nominal spectral slit width was 20 nm, constant over the entire range. The full scale deflection could be

obtained over the wavelength range of 340 nm to 600 nm. By the addition of a red filter and inter-changing of the phototube, the range could be extended to 960 nm. In order to ensure maximum sensitivity of the instrument, and to minimize the errors in the measurements of optical density due to fluctuations in voltage, the spectrophotometer was connected to the mains through an external voltage stabilizer. This was in addition to the in-built voltage stabilizer within the instrument itself. The light source was a 15 watt tungsten lamp operated by a regulated power supply. The instrument was calibrated, as specified in the instruction manual, over the range of concentrations of K_2CrO_4 in KOH solutions, so as to verify Beer's law at 370 nm.

Absorption cells

The absorption cells were of 'Corning' glass and of 8 ml capacity. All the cells were thoroughly cleaned by aqueous ethanol and acetone, and dried before they were used for the spectral measurements. After the transfer of the solution to the cell, care was taken such that no

solution adhered to the outer surface of the cell. During the measurements, the cells were covered.

Rate measurements

A known amount of the substrate was weighed accurately in a 10ml standard flask, dissolved and the volume made up with the requisite quantities of water (in the case of diols), or with dimethylformamide (in the case of α-hydroxy acids), so as to make the solutions of the required molarity. Quinolinium dichromate (QDC) was accurately weighed out in a 10ml standard flask, dissolved and the volume was made up with water (or dimethylformamide). Sufficient time was allowed to compensate for any change of heat during dilution. A known volume of sulfuric acid was taken in a 10 ml standard flask, the volume was made up with distilled water so as to make the solution of required strength. The three solutions thus prepared (substrate,oxidant and acid), were separately thermostated at the required temperature for 1 h, under a nitrogen atmosphere. Equal volumes of the two solutions of oxidant and sulfuric acid were mixed. An equal volume of

the substrate solution was then introduced, and the reaction mixture was shaken well. The reaction mixture remained homogeneous throughout the duration of the reaction.

The progress of the reaction was followed by observing the disappearance of Cr(VI). Readings were taken at regular intervals of time, by noting the decrease in optical density at 440 nm, spectrophotometrically.

All the kinetic experiments were carried out in duplicate or triplicate, and the rate constants which were determined were found to be reproducible to within ±3%. All reactions were performed under a nitrogen atmosphere. Since the reactions were performed at high concentrations of acid, the ionic strength was not maintained constant.

Calculations

(a) Rate constants

For all the kinetic determinations, pseudo-first-order reaction conditions have been used, wherein the substrate was taken in large excess over that of the oxidant.

The pseudo-first-order rate constant, k_1, expressed in s^{-1}, was calculated from the equation (1) :

$$k_1 = \frac{2.303}{t} \log \frac{D_o}{D_t} \qquad (1)$$

where D_o was the initial optical density of the reaction mixture, and D_t was the optical density at time t. The logarithmic plots of optical density against time were linear, and extrapolation to zero time gave the value of D_o .

The values of the second order rate constant, k_2, expressed in $M^{-1}\ s^{-1}$, were computed by dividing the pseuo-first-order rate constant (k_1, s^{-1}) by the concentration of the substrate (M).

All values of rate constants were the average of two or more experiments, with agreement being within ±3%.

(b) Thermodynamic activation parameters

These parameters were determined from a study of the effect of temperature on the rate of the reaction.

The various parameters have been calculated as follows:-

(i) Activation energy (E)

From the linear plot of log k_1 against the reciprocal of temperature (T),

$$\text{Slope} = -\frac{E}{2.303R}$$

$$E = -\text{slope} \times 2.303R \ (\text{kJ mol}^{-1})$$

(ii) Enthalpy of activation ($\Delta H^{\neq}$)

$$\Delta H^{\neq} = E - RT$$

$$(\text{kJ mol}^{-1})$$

(iii) Entropy of activation ($\Delta S^{\neq}$)

$$k_1 = \frac{kT}{h} e^{\Delta S^{\neq}/R} e^{-\Delta H^{\neq}/RT}$$

$$\Delta S^{\neq} = 2.303R[\log k_1 + \frac{\Delta H^{\neq}}{2.303RT} - \log \frac{kT}{h}]$$

$$(\text{JK}^{-1} \text{ mol}^{-1})$$

where k is the Boltzmann constant, h is the Planck's constant, and R is the gas constant.

(iv) Free energy of activation ($\Delta G^{\neq}$)

$$\Delta G^{\neq} = \Delta H^{\neq} - T\Delta S^{\neq}$$

$$(\text{kJ mol}^{-1})$$

Stoichiometry

The stoichiometric experiments were carried out under nitrogen, at the particular temperature under the conditions of $[QDC]_o$ > $[Substrate]_o$, at varying acid concentrations. The disappearance of Cr(VI) was followed, until the absorbance values became constant. The $[QDC]_\infty$ was estimated. The stoichiometric ratio, $\Delta[QDC]/\Delta[Substrate]$, was obtained for each oxidation reaction studied. The individual stoichiometric equations have been shown along with the reactions of each of the substrates with the oxidant.

Test for Radical formation

Various tests were performed to determine whether radical intermediates were formed during the course of the oxidation reactions of the substrates by quinolinium dichromate (QDC), in acid medium, under nitrogen. The following tests were carried out:

(1) Reduction of mercuric chloride (2) :

It was observed that there was no reduction of

mercuric chloride, thus indicating the absence of radical intermediates during the process of oxidation of the substrates by QDC.

(2) Polymerization of an added olefinic monomer, such as acrylonitrile (2) :

1 ml of acrylonitrile (Ø.Ø2M) and 2 ml of substrate solution (Ø.2M) in water (in the case of diols) and DMF (for hydroxy acids) and H_2SO_4 (4.ØM), were taken in a 1Ø ml conical flask. In a separate test tube, 2 ml of QDC solution (Ø.Ø2M) was taken. The two reactant solutions were placed under nitrogen, and then mixed and allowed to stand at 4Ø^{o}C for 3Ø min. There was no formation of a white opalescence, indicating the absence of any polymer formation. The reaction mixture was warmed to 6Ø^{o}C in order to accelerate the oxidation. There was no formation of polymer. Each experiment was accompanied by a blank control.

Product Analysis

Using the same reaction conditions as those used for the kinetic determinations, the reactions were allowed to proceed to completion, at the requisite temperature. The

products obtained, from the reaction of the various substrates with the oxidant, were isolated as follows :

(A) Products obtained from the oxidation of 1,2-ethanediol, 1,2-propanediol, 1,2-butanediol, 1,3-butanediol, 1,4-butanediol and 1,5-pentanediol :

The products of oxidation were the corresponding hydroxyaldehydes.

At the end of the reaction, the reaction mixture was treated with an excess (250 ml) of a saturated solution of 2,4-dinitrophenylhydrazine in 2M HCl and kept in a refrigerator for about 8h. The precipitated 2,4-dinitrophenylhydrazone (DNP) was filtered off, dried, weighed, recrystallized from ethanol and weighed again (yield ~ 75-80%). The 2,4-DNP derivative, in each case was characterized by its melting point. (Table 2).

Table 2

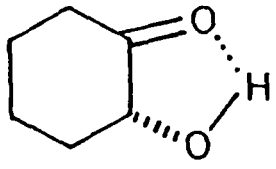
Substrate	Oxidation product	Melting point (^{o}C) of 2,4-DNP derivatives prepared
1,2-Ethanediol	2-hydroxyethanal	158
1,2-Propanediol	2-hydroxypropanal	92
1,2-Butanediol	2-hydroxybutanal	88
1,3-Butanediol	3-hydroxybutanal	96
1,4-Butanediol	4-hydroxybutanal	87
1,5-Pentanediol	5-hydroxypentanal	80

(B) Product obtained from the oxidation of trans-1,2-cyclohexanediol :

The product of oxidation of trans-1,2-cyclohexanediol was 2-hydroxycyclohexanone. The reaction product was extracted with ether and the solvent ether was removed carefully. The product was recrystallized from ethanol, and the melting point was determined. (mp 113^{o}C; yield ~90%).

IR spectrum of this product showed a sharp band at 1687cm^{-1}, suggesting the presence of a hydrogen-bonded

carbonyl group. The absorption band at 3050cm^{-1} was due to the presence of the hydroxyl group. The lowering in the wave number of the O-H absorption band was probably due to the presence of hydrogen bonding between the hydroxyl and the carbonyl group, thus,



The product was thus confirmed as 2-hydroxycyclohexanone. The phenylhydrazone derivative of the product was prepared, recrystallized from ethanol and dried (mp. 121^{o}C).

(C) Product obtained from the oxidation of pinacol:

The oxidation product was acetone. At the end of the reaction, the reaction mixture was treated with an excess of a saturated solution of 2,4-dinitrophenylhydrazine in 2M HCl. The 2,4-dinitrophenylhydrazone formed was filtered, dried, weighed, recrystallized and weighed again (yield ~ 80%, mp 128^{o}C). The 2,4-DNP derivative of the oxidation product was found

to be identical (mixed melting point) with the 2,4-DNP derivative of authentic acetone.

(D) Products obtained from the oxidation of glycolic acid and lactic acid :

The oxidation product from glycolic acid was glyoxylic acid, and that from lactic acid was pyruvic acid. At the end of the reaction, the reaction mixture was poured into excess water and then extracted with ether. The ether extract was washed, dried over anhydrous Na_2SO_4 and the extract was carefully concentrated to get the product. The product obtained from the oxidation of glycolic acid indicated it to be glyoxylic acid (mp. 98^{o}C; yield ~ 70%). The oxidation product obtained from lactic acid indicated it to be pyruvic acid (bp 165^{o}C, yield ~ 65%). The 2,4-dinitrophenylhydrazone (DNP) derivatives of these oxidation products (glyoxylic acid and pyruvic acid) were prepared (mp. 124-125^{o}C for the DNP derivative of glyoxylic acid ; mp. 186-187^{o}C for the DNP derivative of pyruvic acid). These mps agreed well with those reported in the literature.

(E) Product obtained from the oxidation of mandelic acid

The product of oxidation of mandelic acid was benzaldehyde. At the end of the reaction, the reaction mixture was extracted with chloroform, washed with water, dried over anhydrous Na_2SO_4 and then concentrated to get the oxidation product (yield ~ 80%). An IR spectrum of the compound exhibited a carbonyl band at 1700cm^{-1} and certain other bands below 900cm^{-1}, that were characteristic of benzaldehyde. The 2,4-DNP derivative of the oxidation product was also found to be identical with the 2,4-DNP derivative of the authentic sample of benzaldehyde (mp. 237^{o}C).

(F) Product obtained from the oxidation of tartaric acid

The major product of oxidation of tartaric acid was glyoxylic acid. At the end of the reaction, the reaction mixture was diluted with water and then extracted with ether. Two immiscible layers (aqueous layer and ether layer) were obtained.

(i) The ether layer was concentrated and the oxidation product obtained was recrystallized (mp.96^{o}C).

The ir spectrum of the compound showed bands at 1730 cm^{-1} (saturated aldehyde) and at 3450cm^{-1} (O-H stretching). The 2,4-DNP derivative of the oxidation product was also prepared (mp. 124-125^{o}C). The oxidation product was confirmed to be glyoxylic acid.

(ii) The aqueous layer was taken and the 2,4-DNP derivative of the product was prepared (mp 168^{o}C). Since this product was obtained in trace amounts, there was the possibility of the glyoxylic acid undergoing a process of oxidative decarboxylation to give formaldehyde.

(G) Product obtained from the oxidation of benzilic acid

The product of oxidation of benzilic acid was benzophenone. At the end of the reaction, the reaction mixture was extracted with ether. The ether extract was washed with water and dried over anhydrous Na_2SO_4, and then concentrated. The crude product obtained was recrystallized (yield ~ 85%; mp 48^{o}C). The ir spectra of the oxidation product and that of authentic benzophenone were identical in all respects.

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DISCUSSION

CHAPTER 1

KINETICS OF OXIDATION OF DIOLS

Chromic acid has been extensively used for the oxidation of diverse organic substrates. Some of the forms in which Cr(VI) has been used to carry out these oxidation reactions have included: chromic acid in water or in aqueous acetic acid catalysed by mineral acid; chromic acid in water-acetone mixtures catalysed by mineral acid; dichromate ion in acetic acid; the chromium trioxide-pyridine complex; and tert-butylchromate in a variety of solvents. Many procedures have been developed to carry out the conversions of various kinds of organic substrates to their respective products using Cr(VI) reagents. While developing these procedures, several newer reagents have been introduced which have been able to carry out these oxidation processes, giving high yields of the corresponding products, and also achieving a high degree of selectivity. The synthetic utility of these newer reagents have been highlighted for the oxidation of a variety of diols to their corresponding products. The literature has been reviewed with the purpose of

highlighting the various kinds of reagents which have been used for the oxidation of diols(vicinal and non-vicinal) to their corresponding reaction products.

The kinetics of oxidation of several vicinal and non-vicinal diols by pyridinium chlorochromate (Corey's reagent, PCC) was studied in dimethyl sulphoxide (DMSO) medium(1). These reactions showed a first order dependence on the concentration of each of the reactants-diols and PCC. The principal product of this oxidation process was the corresponding hydroxyaldehyde. The reaction involved the transfer of a hydride ion in the rate-determining step of the reaction.

The kinetics of oxidation of diols (vicinal and non-vicinal) by N-bromoacetamide in acid solution was studied(2). The products obtained were different for vicinal and non-vicinal diols. The oxidation of vicinal diols yielded products resulting from the cleavage of the carbon-carbon bond, while the oxidation of non-vicinal diols gave the corresponding hydroxyaldehydes. Trifluoro acetic anhydride "activated" dimethylsulfoxide has been

used for the oxidation of vicinal diols(3). The products obtained from this oxidation process were predominantly the corresponding α-dicarbonyl compounds.

The kinetics of oxidation of vicinal and non-vicinal diols by sodium N-bromobenzene sulphonamide (bromamine-B or BAB) have been reported(4). The oxidation of vicinal diols resulted in the formation of products arising out of glycol bond fission, while the oxidation of non-vicinal diols gave the corresponding hydroxycarbonyl compounds. For the vicinal diols, an acyclic mechanism involving glycol bond fission was suggested, whereas the non-vicinal diols were oxidized by a hydride transfer mechanism.

The oxidation of diols with alkali hypochlorites catalysed by oxammonium salts under two phase conditions, have been studied(5).

The selective conversion of optically active sec, sec-diols to the corresponding α-hydroxyketones, using dimethyl dioxirane or its trifluoromethyl analogue, has

been carried out(6). This method was directed towards the synthesis of homochiral α-hydroxyketones in high optical purity.

The kinetics of oxidation of diols (vicinal and non-vicinal) by ethyl N-chlorocarbamate(ECC), have been studied(7). The reaction was first order with respect to ECC, diol, and hydrogen ions. An acyclic mechanism involving glycol bond fission was proposed for the oxidation of vicinal diols. The non-vicinal diols were oxidized by a hydride transfer mechanism.

The kinetics of oxidation of diols by pyridinium hydrobromide perbromide (PHPB) in 1:1 acetic acid-water mixtures has been studied (8). The reactions were found to be first order with respect to PHPB. However, the order of the reaction with respect to diol was less than unity. Typical Michaelis-Menten kinetics were observed with respect to diols.

The oxidation of diols (vicinal and non-vicinal) by pyridinium fluorochromate (PFC) led to the formation of

the corresponding hydroxyaldehydes(9). The reactions were found to be first order with respect to PFC. Michaelis-Menten kinetics were observed with respect to the diols. The oxidation process involved a hydride transfer via a chromate ester intermediate.

The kinetics of oxidation of diols with pyridinium chlorochromate (PCC) showed a first order dependence on both, the diols and PCC(10). The major products of this oxidation reaction were the corresponding hydroxyaldehydes.

Kinetics of oxidation of diols(vicinal and non-vicinal, and one of their monoethers) by bis (2,2'-bipyridyl) copper (II) permanganate (BBCP) has been studied (11). Vicinal diols yielded the products arising out of the glycol bond fission, while other diols yielded the hydroxycarbonyl compounds. The reaction was first order with respect to BBCP. Typical Michaelis- Menten kinetics were observed. A mechanism involving glycol bond fission for vicinal diols, and a hydride transfer mechanism for non-vicinal diols has been proposed (11).

PRESENT WORK

The oxidation of diols is an important transformation in organic synthesis. The nature of products obtained was dependent on the structure of the diols. Among the many oxidizing agents which have been used for the oxidation of diols, chromium(VI) reagents have proved to be versatile and efficient in performing these oxidation reactions.

The present work is a detailed kinetic investigation of the oxidation of diols, using a newer chromium(VI) reagent. The chromium(VI) reagent which has been employed for the purpose of oxidation of diols, in the present study, has been quinolinium dichromate (QDC) in aqueous medium, using a mineral acid (H_2SO_4).

The diols which have been chosen for the purpose of oxidation by QDC have included :

(i) Acyclic vicinal diols (1,2-ethanediol,1,2-propanediol, 1,2-butanediol and pinacol).

(ii) Cyclic vicinal diol (trans-1,2-cyclohexanediol).

(iii) Acyclic non-vicinal diols (1,3-butanediol, 1,4-butanediol and 1,5-pentanediol).

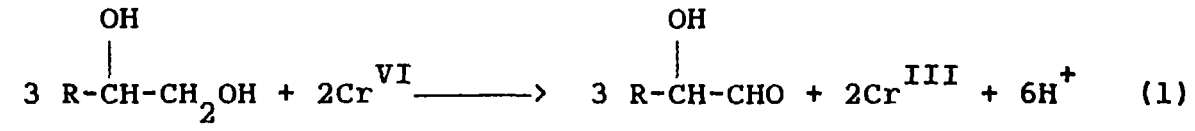
Stoichiometry (Vide "Experimental")

The stoichiometries of all the oxidation reactions were determined. The stoichiometric ratios, Δ[QDC]/Δ[Substrate], in the range 0.65-0.72, were obtained (Table 1).

Table 1: Stoichiometries of the Oxidation of the Substrates; [Substrate] = 0.005M, T = 323 K

$[H_2SO_4]$/M	0.10	0.25	0.50
10^2[QDC]/M	2.50	2.60	2.70
Δ[QDC]/Δ[1,2-Ethanediol]	0.72	0.68	0.65
Δ[QDC]/Δ[1,2-Propanediol]	0.70	0.69	0.72
Δ[QDC]/Δ[1,2-Butanediol]	0.66	0.71	0.68
Δ[QDC]/Δ[Trans-1,2-Cyclohexanediol]	0.72	0.68	0.66
Δ[QDC]/Δ[Pinacol]	0.68	0.69	0.72
Δ[QDC]/Δ[1,3-Butanediol]	0.67	0.72	0.65
Δ[QDC]/Δ[1,4-Butanediol]	0.69	0.70	0.67
Δ[QDC]/Δ[1,5-Pentanediol]	0.70	0.65	0.72

The observed stoichiometric ratios conformed to the overall equations :



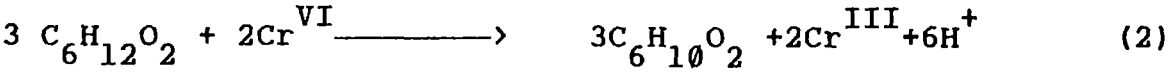
(1)

Vicinal diols

R=H; 1,2-ethanediol

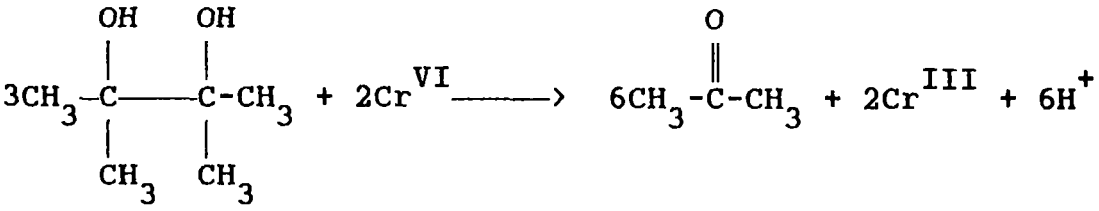
$R=CH_3$; 1,2-propanediol

$R=C_2H_5$; 1,2-butanediol



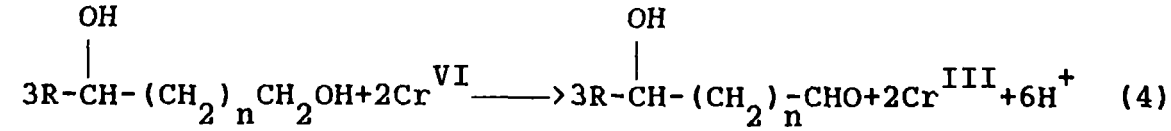
(2)

trans-1,2-cyclohexanediol



(3)

pinacol



(4)

R=H; n=2: 1,4-Butanediol

$R=CH_3$; n=1: 1,3-Butanediol

R=H; n=3: 1,5-Pentanediol

Effect of substrate

The rate of the reaction was observed to be dependent on the concentration of the substrates. The order of the reaction with respect to substrate concentration was obtained by changing the concentration of the substrate, and observing the effect on the rate of the reaction at constant [QDC] and $[H^+]$. The results have been recorded in Table 2.

Table 2: Dependence of Rate constants on the concentration of Diols in aqueous medium :
[QDC]=0.001M; [H_2SO_4]=1M; Temperature=323K

[Diols],M	0.01	0.025	0.05	0.075	0.10
$10^4 X k_1, s^{-1}$ for:					
1,2-Ethanediol	0.88	2.23	4.37	6.58	8.84
1,2-Propanediol	2.92	7.25	14.7	22.0	29.3
1,2-Butanediol	4.36	10.81	22.0	33.4	44.4
Trans-1,2-cyclohexanediol	7.67	19.2	38.5	58.0	77.1
1,3-Butanediol	6.26	15.8	31.3	46.8	63.0
1,4-Butanediol	4.51	11.2	22.6	34.5	46.0
1,5-Pentanediol	3.93	9.81	19.7	29.7	39.6
[Pinacol],M	0.01	0.015	0.025	0.035	0.05
10^4 X k_1, s^{-1}	24.7	39.4	57.9	88.1	124.00
10^2 X k_2, $M^{-1}s^{-1}$	24.7	26.3	23.2	25.2	25.0

$k_2 = k_1/[Substrate]$

Plots of k_1, the pseudo-first-order rate constant, against the concentrations of substrates, gave straight lines passing through the origin (Figures 1-3), indicating that the rate of oxidation was dependent on the first power of the concentration of the substrate. This was further confirmed by the constancy in the values of k_2, the second-order rate constant.

Effect of oxidant

Under pseudo-first-order conditions, individual kinetic runs were first order with respect to the concentration of the oxidant (QDC). When a constant concentration of substrate (large excess) was used, k_1 did not show any appreciable variation with the change in the concentration of the oxidant. This indicated a first order dependence of the rate of the reaction on the concentration of the oxidant (Table 3).

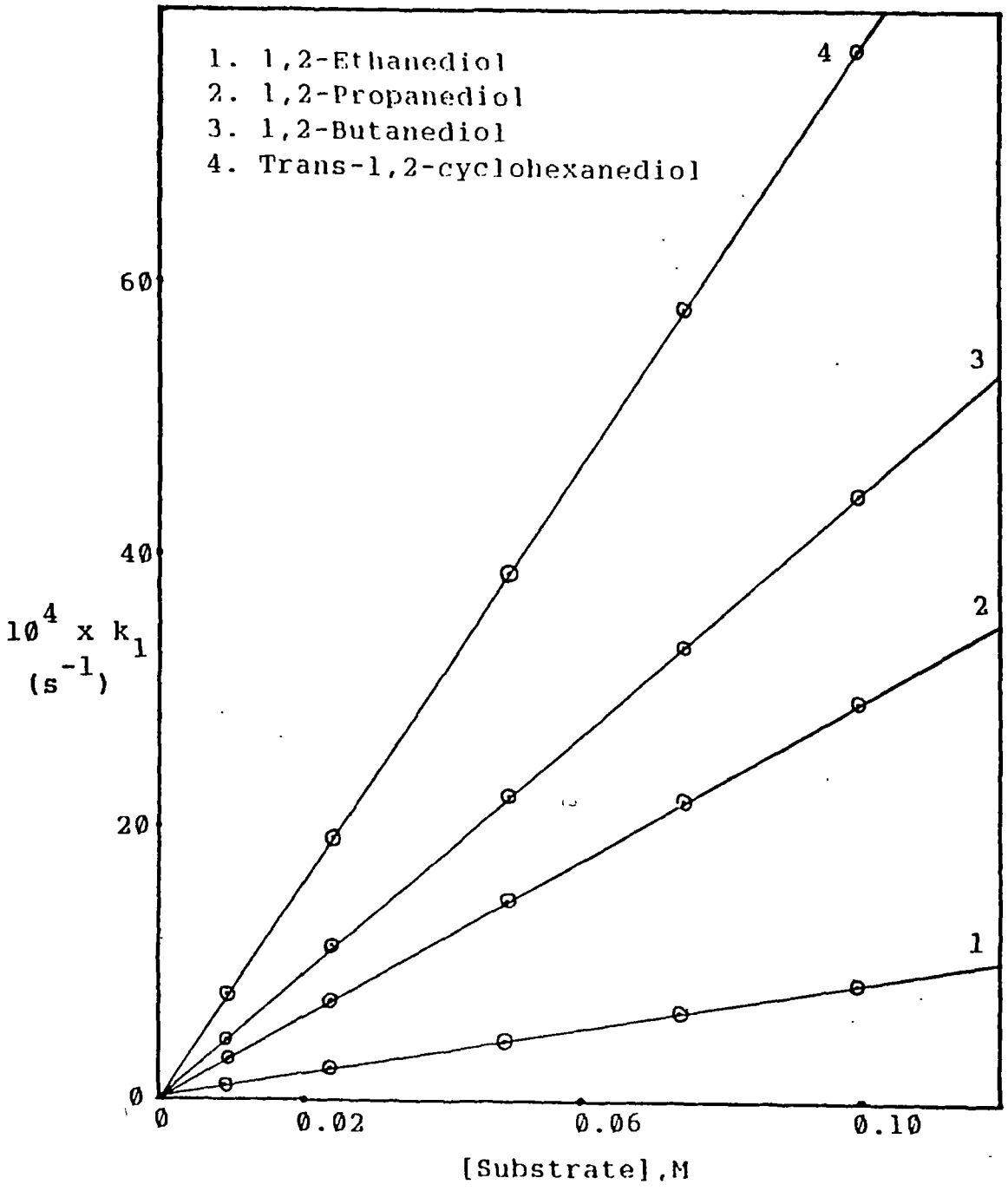


Fig.1. Plots of k_1 against the concentrations of substrates.

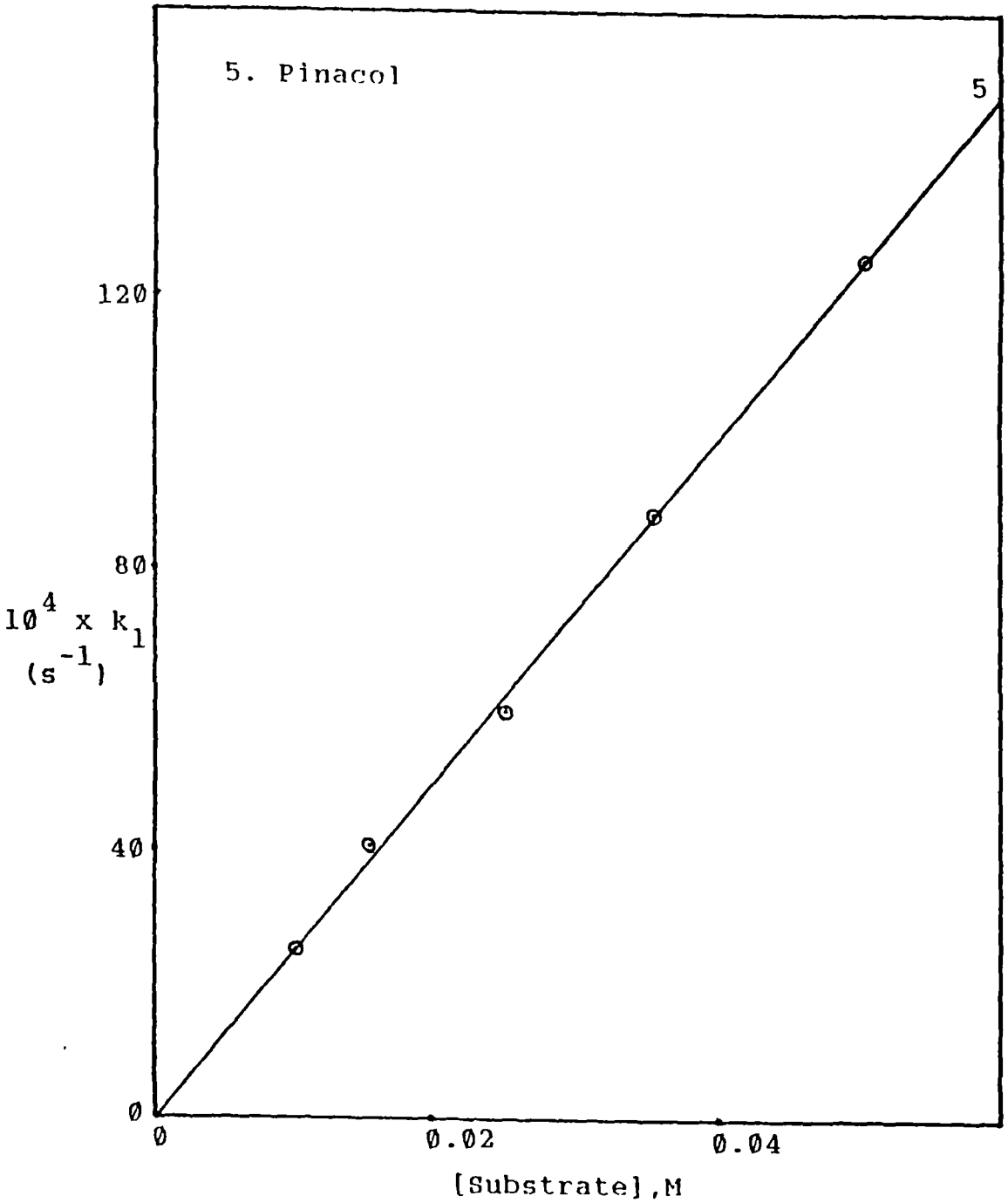


Fig.2. Plot of k_1 against the concentrations of substrate .

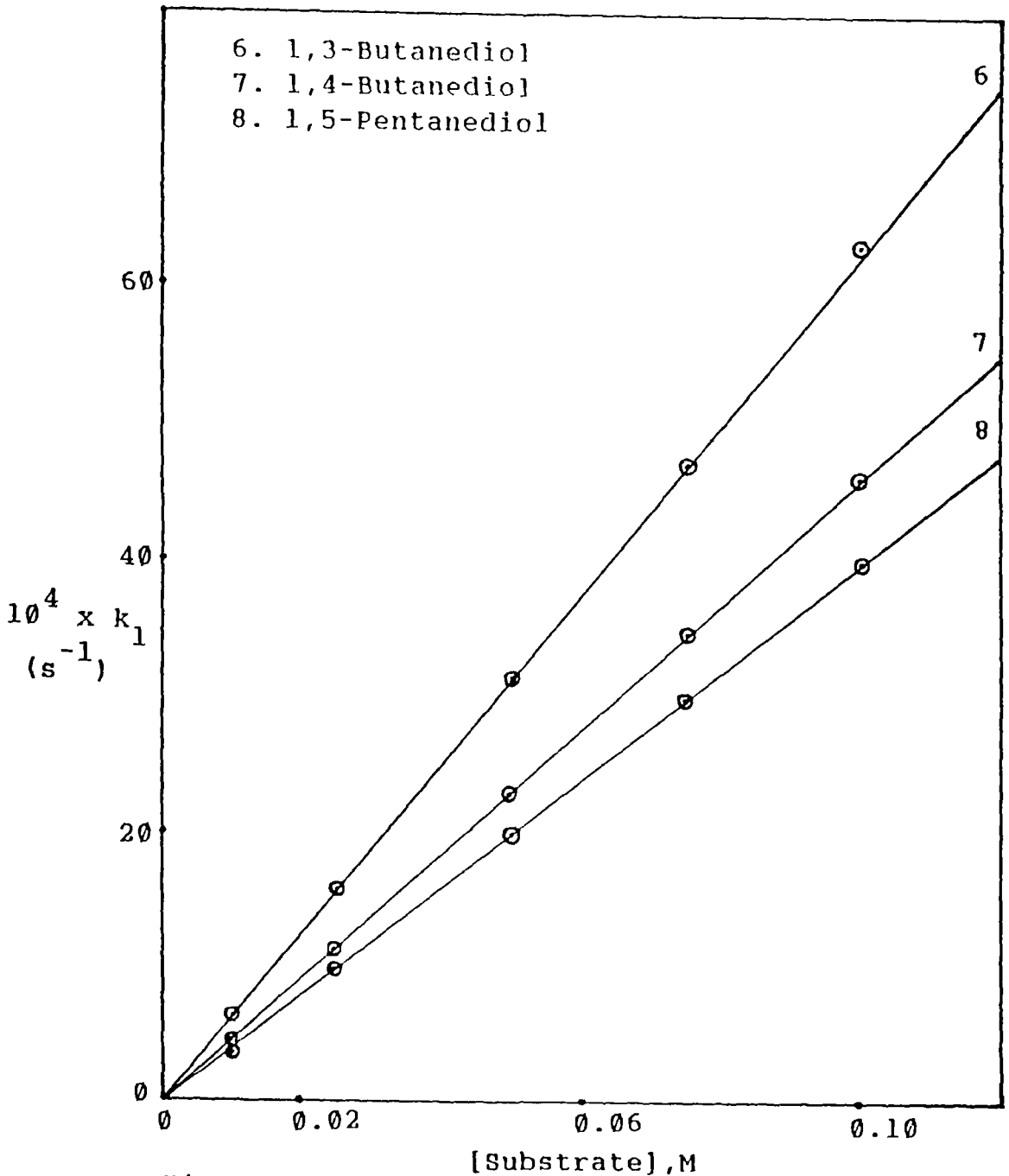


Fig.3. Plots of k_1 against the concentrations of substrates.

Table 3: Dependence of Rate constants on the concentration of oxidant [QDC] : [Diol]= 0.01M; [H_2SO_4]=1M; Temperature = 323K.

[QDC],M	0.0005	0.00075	0.001
$10^4 Xk_1, s^{-1}$ for:			
1,2-Ethanediol	0.89	0.82	0.88
1,2-Propanediol	2.87	2.96	2.92
1,2-Butanediol	4.29	4.33	4.36
Trans-1,2-cyclohexanediol	7.52	7.36	7.67
Pinacol	24.2	24.6	24.7
1,3-Butanediol	6.19	6.37	6.26
1,4-Butanediol	4.46	4.56	4.5
1,5-Pentanediol	3.79	3.86	3.93

Effect of acid

The reaction was observed to be susceptible to changes in the acid concentration, and the rate of the reaction was found to increase with an increase in the concentration of acid (Table 4).

Table 4: Dependence of Rate Constants on the Concentrations of Acid [H_2SO_4]; [Diol] = 0.01M; [QDC] = 0.001 M; Temperature=323K

$[H_2SO_4]$,M	0.50	0.75	1.00	1.25	1.50
$10^4 Xk_1, s^{-1}$ for:					
1,2-Ethanediol	0.42	0.63	0.88	1.07	1.30
1,2-Propanediol	1.43	2.15	2.92	3.60	4.32
1,2-Butanediol	1.68	3.07	4.36	5.79	7.49
Trans- 1,2-cyclohexanediol	3.70	5.75	7.67	9.50	11.6
Pinacol	20.8	22.7	24.7	27.1	29.5
1,3-Butanediol	3.10	4.70	6.26	7.81	9.34
1,4-Butanediol	2.24	3.40	4.51	5.6	6.75
1,5-Pentanediol	1.95	2.90	3.93	4.86	6.02

Plots of log k_1 against log $[H^+]$ were linear, with slopes equal to unity (Figures 4-6), indicating that the rate of the reaction was dependent on the first power of the concentration of the acid.

The linear increase in the rate of the reaction with acidity suggested the involvement of a protonated Cr(VI) species in the rate-determining step. There have been earlier reports of the involvement of protonated Cr(VI) species in chromic acid oxidations(12). Protonated Cr(VI) species have been observed in the presence of p-toluenesulfonic acid in nitrobenzene-dichloromethane mixtures(13). Since the concentrations of acids used were in the range of 0.5 M to 1.5 M, the dichromate ion (and its protonated form) would be the predominant species. Moreover, the protonated Cr(VI) species would be a more reactive electrophile capable of increasing its rate of coordination to the diol.

Rate law

Under the present experimental conditions, wherein

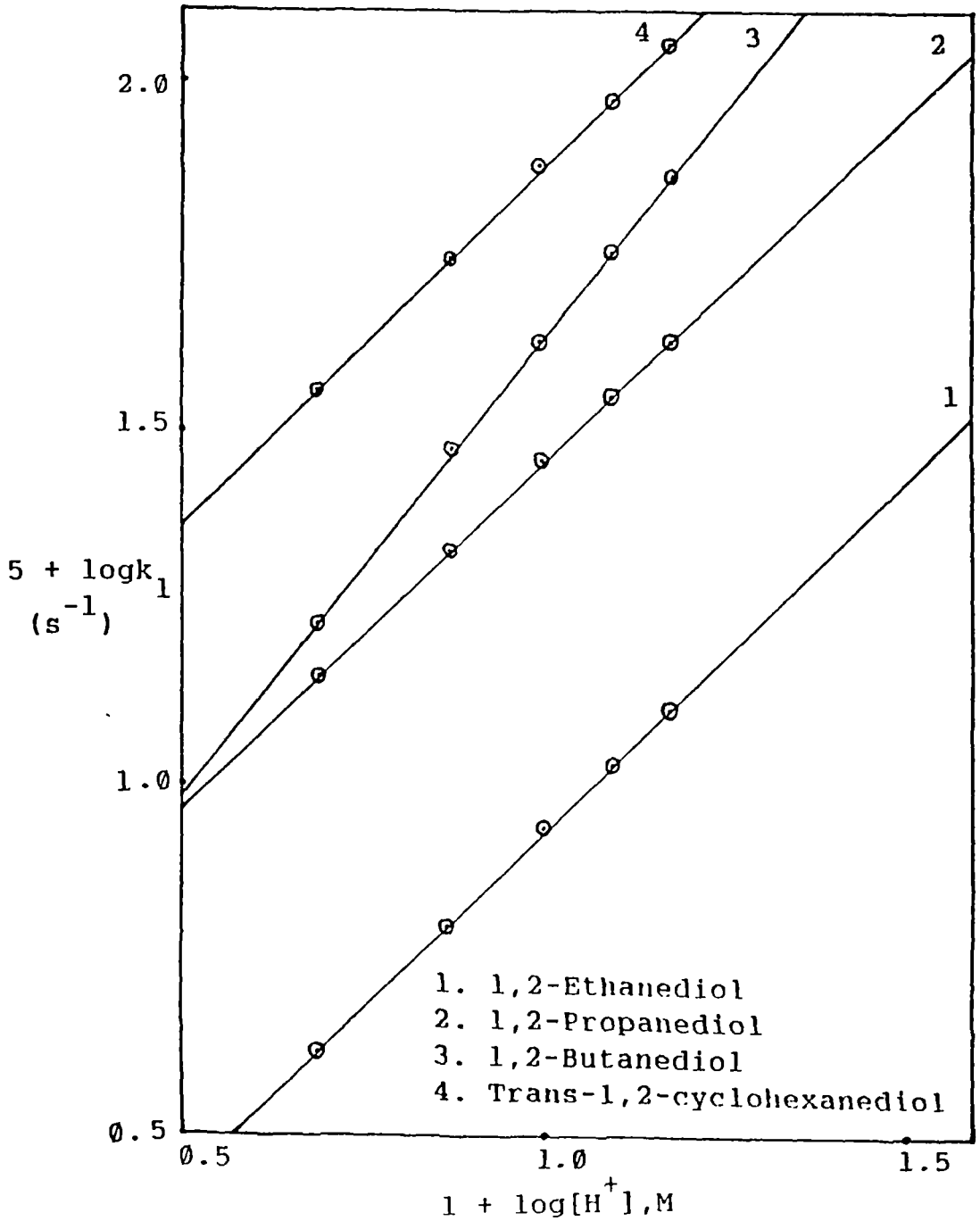


Fig.4. Plots of log k_1 against log[H^+]

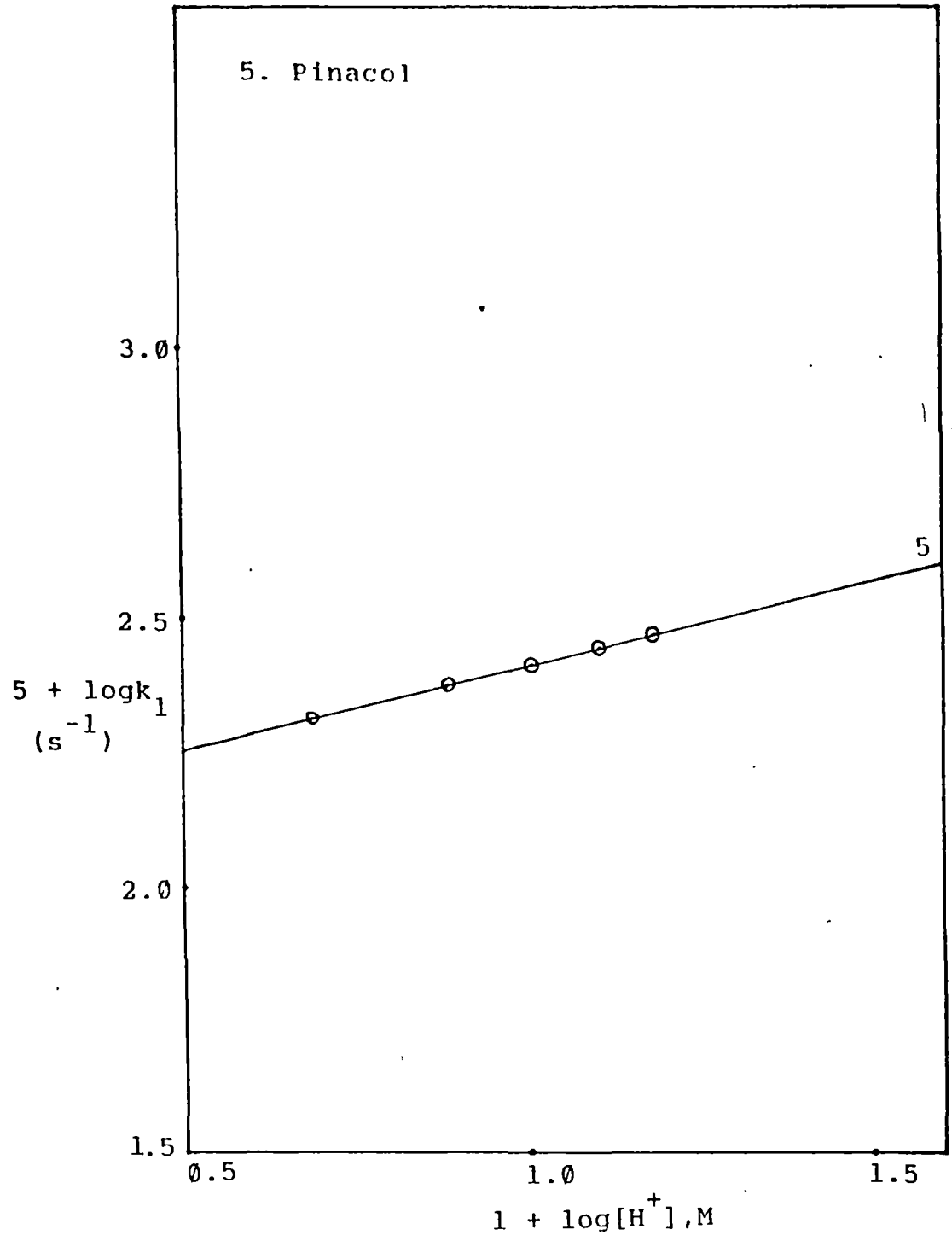


Fig.5. Plot of log k_1 against log[H^+]

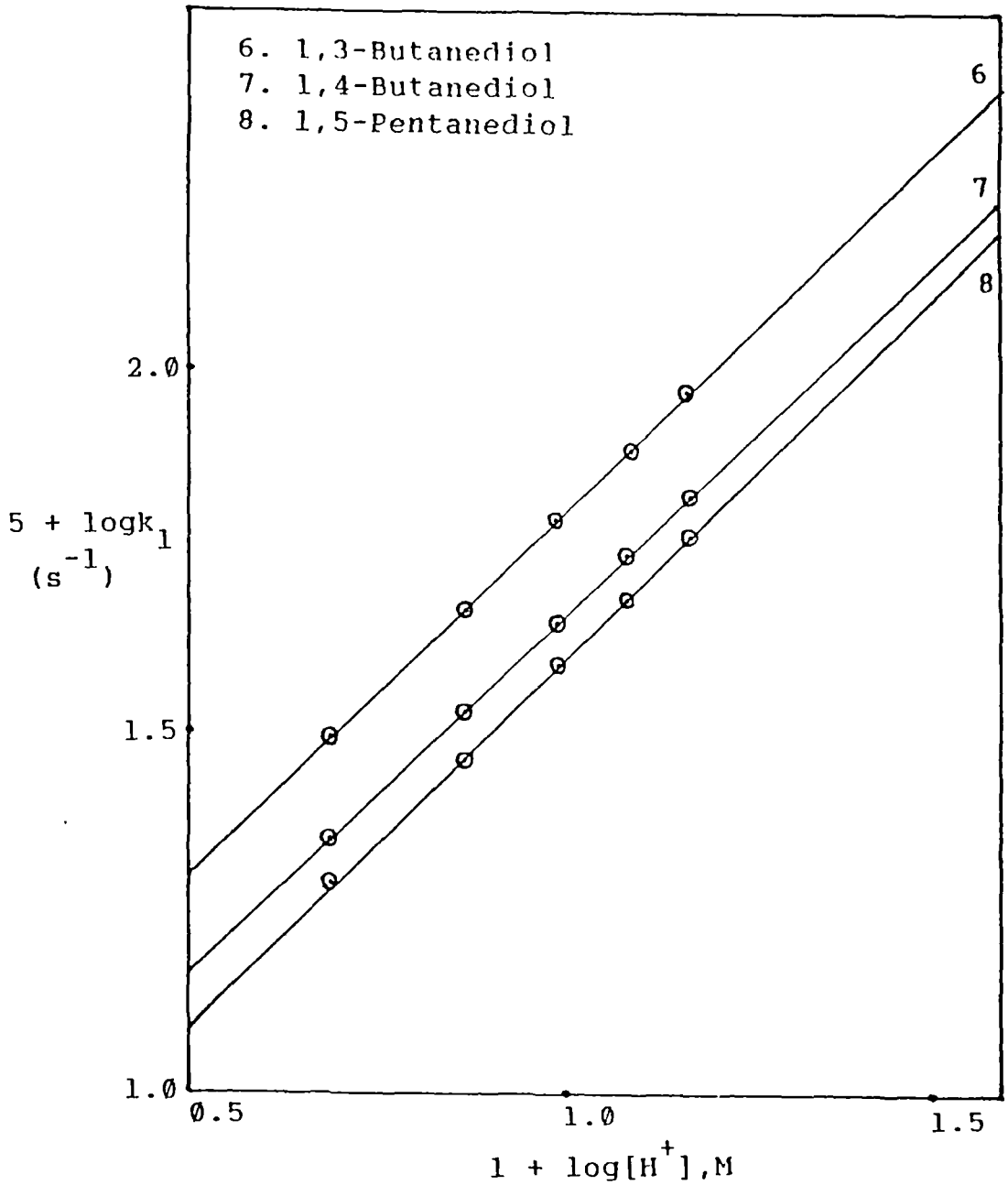


Fig.6. Plots of log k_1 against log[H^+]

pseudo-first-order conditions have been employed for all the kinetic runs, the observed rate law could be expressed as:

$$\text{Rate} = -\frac{d[Cr(VI)]}{dt} = k[\text{Substrate}]\ [QDC]\ [H^+] \qquad (5)$$

Effect of solvent

Reactions involving ionic reactants are generally susceptible to solvent influences. It is hence to be expected that, in the present investigation, the solvent should be playing an important role in all these reactions. The oxidation of diols by QDC was studied in solutions containing varying proportions of water and acetic acid. In the case of each of the substrates oxidized by QDC, the rate of oxidation was slowest in those solvent mixtures that contained the largest proportions of water, and increasing proportions of acetic acid resulted in an increase in the rate of oxidation (Table 5).

Table 5 : Dependence of Rate Constants on the solvent Composition; [Diol]= 0.01 M; [QDC] = 0.001 M; $[H_2SO_4]$=1M; T=323 K.

H_2O :HOAc (% V/V)	100:0	95:5	90:10	85:15	80:20
Dielectric Constants (D)	78.54	74.92	71.30	67.68	64.07
$10^4 Xk_1, s^{-1}$ for:					
1,2-Ethanediol	0.88	1.11	1.60	2.01	2.32
1,2-Propanediol	2.92	4.61	6.30	8.10	9.82
1,2-Butanediol	4.36	5.50	6.47	8.10	10.3
Trans- 1,2-cyclohexanediol	7.67	7.93	8.25	8.80	9.46
Pinacol	24.7	27.1	29.3	34.3	39.8
1,3-Butanediol	6.26	8.45	10.2	11.7	14.3
1,4-Butanediol	4.51	7.01	8.81	10.6	13.0
1,5-Pentanediol	3.93	4.06	4.22	4.50	4.84

The dielectric constants for water-acetic acid mixtures have been estimated approximately from the dielectric constants of the pure solvents.

In the present investigation, in proceeding from 80% to 100% water, the polarity increases. This increase in the polarity of the medium caused a decrease in the rate of the reaction (Table 5). Plots of log k_1 against the inverse of the dielectric constant were linear, with positive slopes (Figures 7-9). This suggested an interaction between a positive ion and a dipole (14), and was in conformity with the experimental observation that, in the presence of an acid, there was the involvement of a protonated Cr(VI) species. The data in Table 5 indicated that the dielectric constants for water-acetic acid mixtures were a linear function of the solvent composition used in this investigation. This relationship between log k_1 and 1/D was thus obeyed in the range of dielectric constants used.

Effect of temperature

The rates of the oxidation reactions were

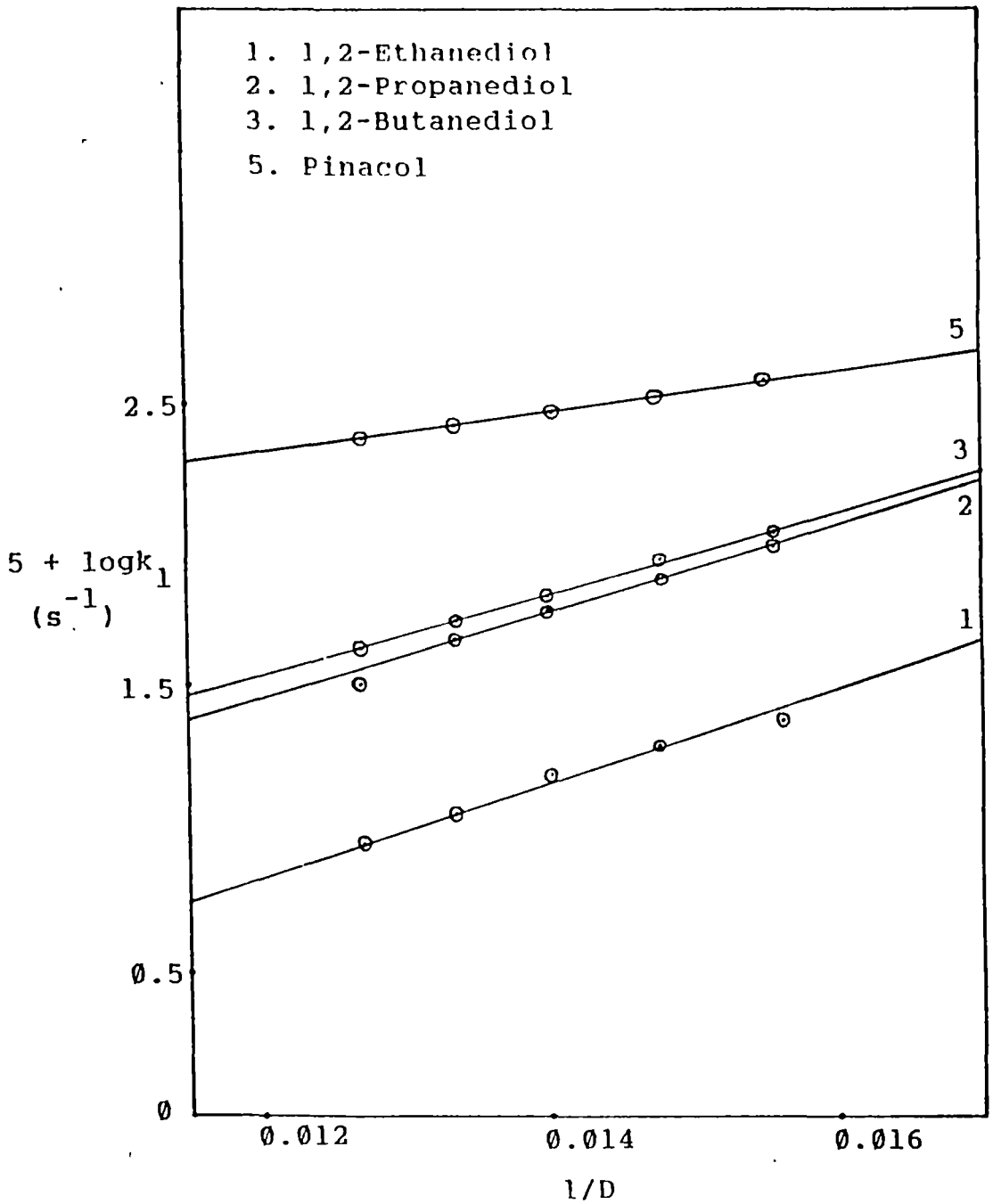


Fig.7. Plots of log k_1 against the reciprocal of dielectric constant.

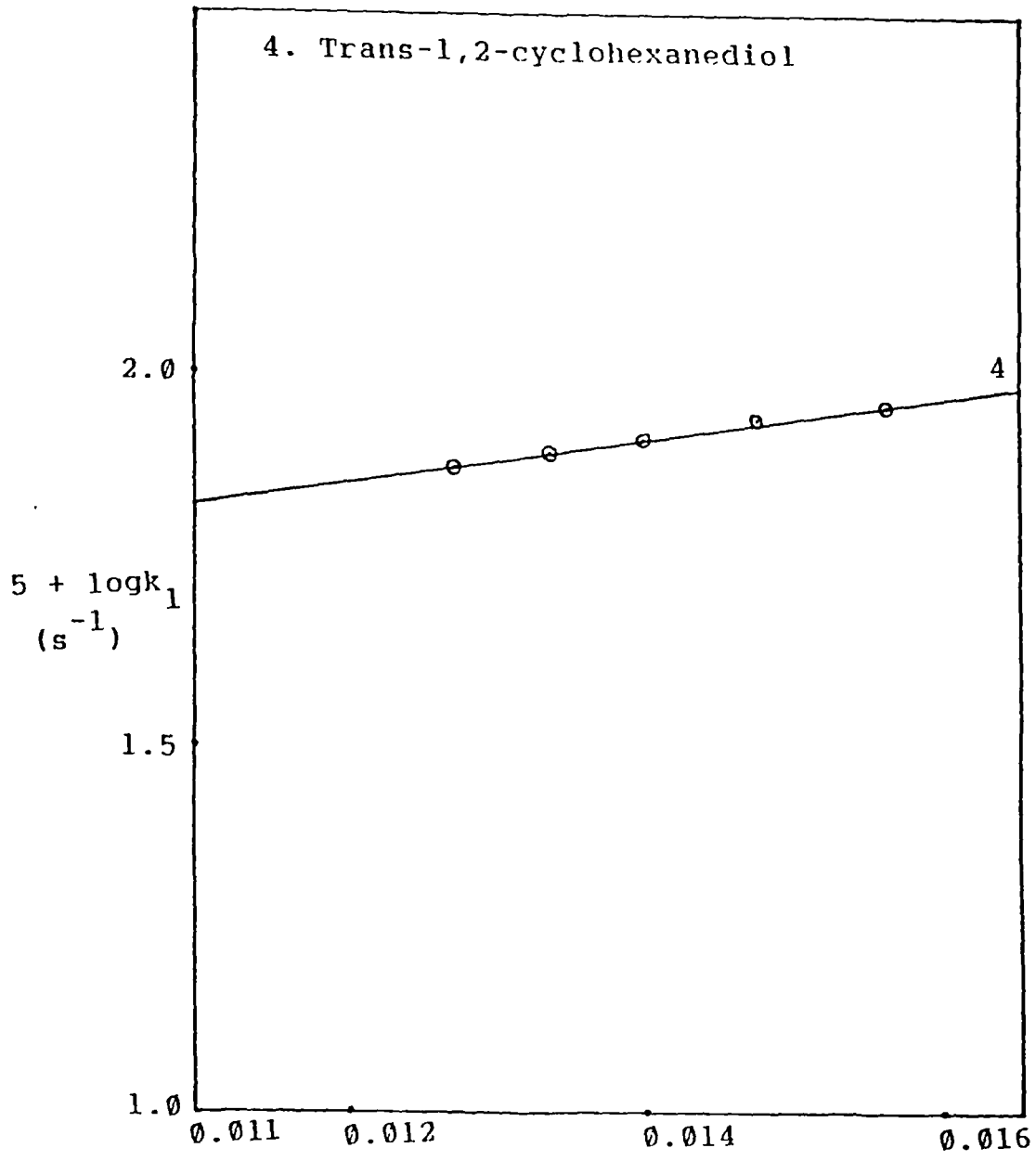


Fig.8. Plot of log k_1 against the reciprocal of dielectric constant.

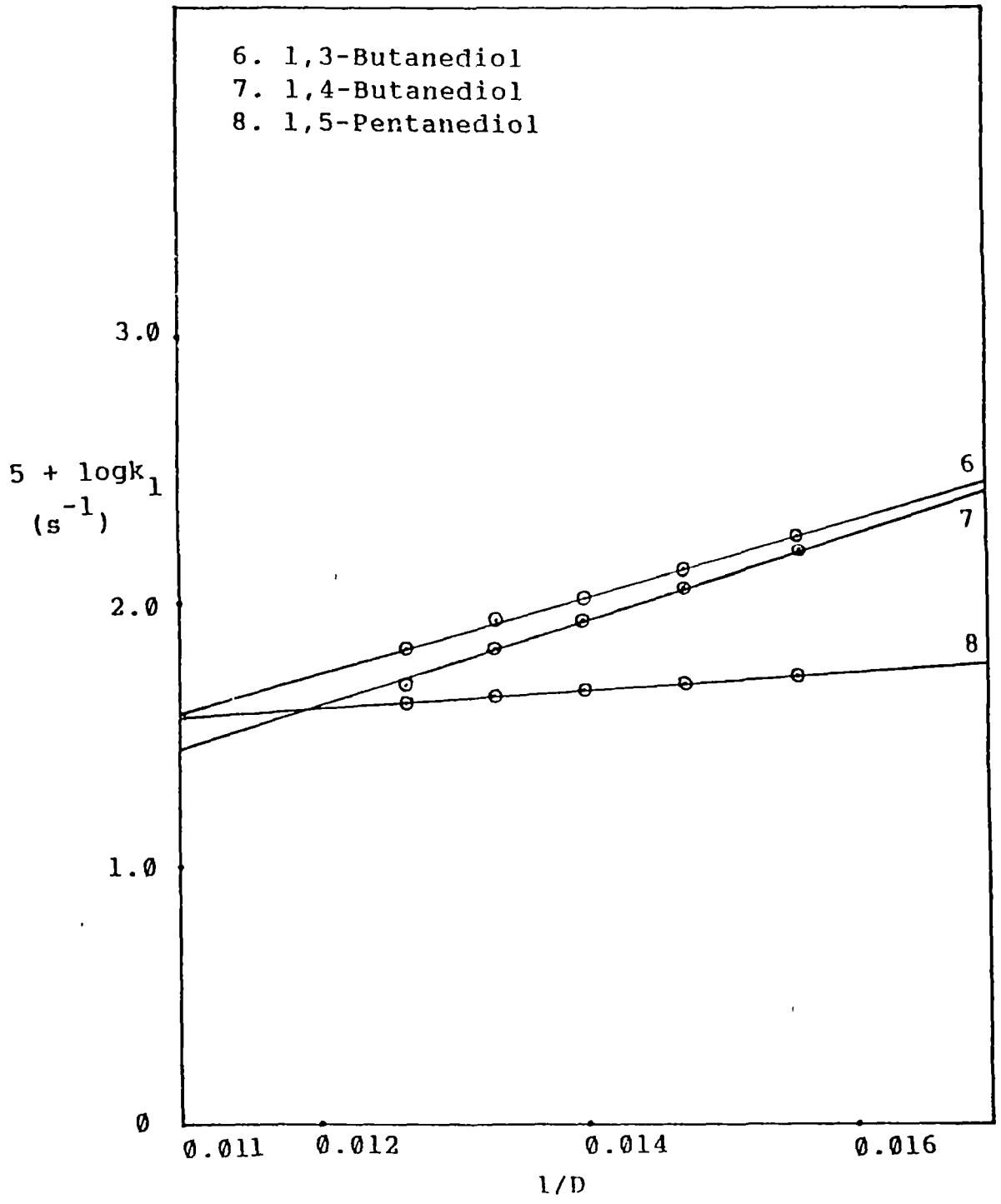


Fig.9. Plots of log k_1 against the reciprocal of dielectric constant.

influenced by changes in temperature. It was observed that an increase in temperature resulted in an increase in the rate of the reaction (Table 6).

Table 6: Dependence of Rate Constants on temperature :

[Diol] = 0.01 M; [QDC] = 0.001 M; $[H_2SO_4]$=1M.

Temperature(K)	313	318	323	328	333
1,2-Ethanediol	0.48	0.64	0.88	1.12	1.46
1,2-Propanediol	2.11	2.62	2.92	3.45	3.95
1,2-Butanediol	3.11	3.69	4.36	5.18	5.96
Trans-1,2-cyclohexanediol	3.81	5.75	7.67	11.4	15.5
Pinacol	13.8	18.0	24.7	34.2	42.6
1,3-Butanediol	3.89	5.01	6.26	8.01	10.4
1,4-Butanediol	2.69	3.55	4.51	6.03	8.32
1,5-Pentanediol	1.94	2.88	3.93	5.79	7.91

Plots of log k_1 against the reciprocal of temperature were linear (Figures 10-12), suggesting the validity of the Arrhenius equation. The slopes of the plots were used to calculate the activation energies of the reactions. The other activation parameters were evaluated (Vide "Experimental: Calculations") and have been shown in Table 7.

Table 7 : Activation Parameters :

Diols	E (kJ mol^{-1})	$\Delta H^{\neq}$ (kJ mol^{-1})	$\Delta S^{\neq}$ (JK^{-1} mol^{-1})	$\Delta G^{\neq}$ (kJ mol^{-1})
1,2-Ethanediol	49	46	-191	107
1,2-Propanediol	46	43	-196	107
1,2-Butanediol	29	26	-248	106
Trans-1,2-cyclohexanediol	60	57	-135	101
Pinacol	50	47	-169	101
1,3-Butanediol	43	40	-200	104
1,4-Butanediol	46	43	-198	106
1,5-Pentanediol	63	60	-129	102

Error limits: E ± 2 kJ mol^{-1}; $\Delta H^{\neq}$ ± 2 kJ mol^{-1}; $\Delta S^{\neq}$ ± 3 $JK^{-1}mol^{-1}$; $\Delta G^{\neq}$ ± 2 kJ mol^{-1}

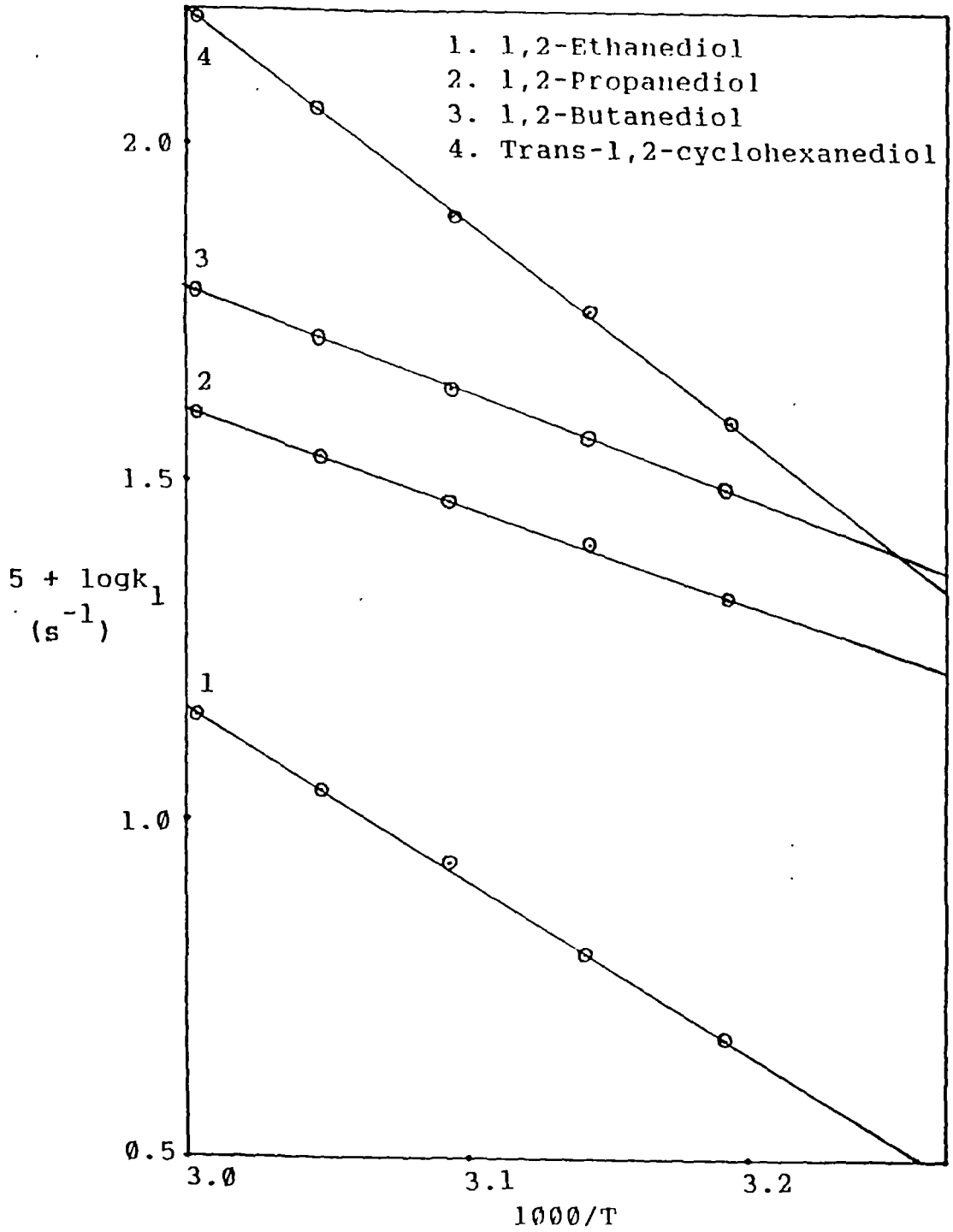


Fig.10. Plots of log k_1 against the reciprocal of temperature.

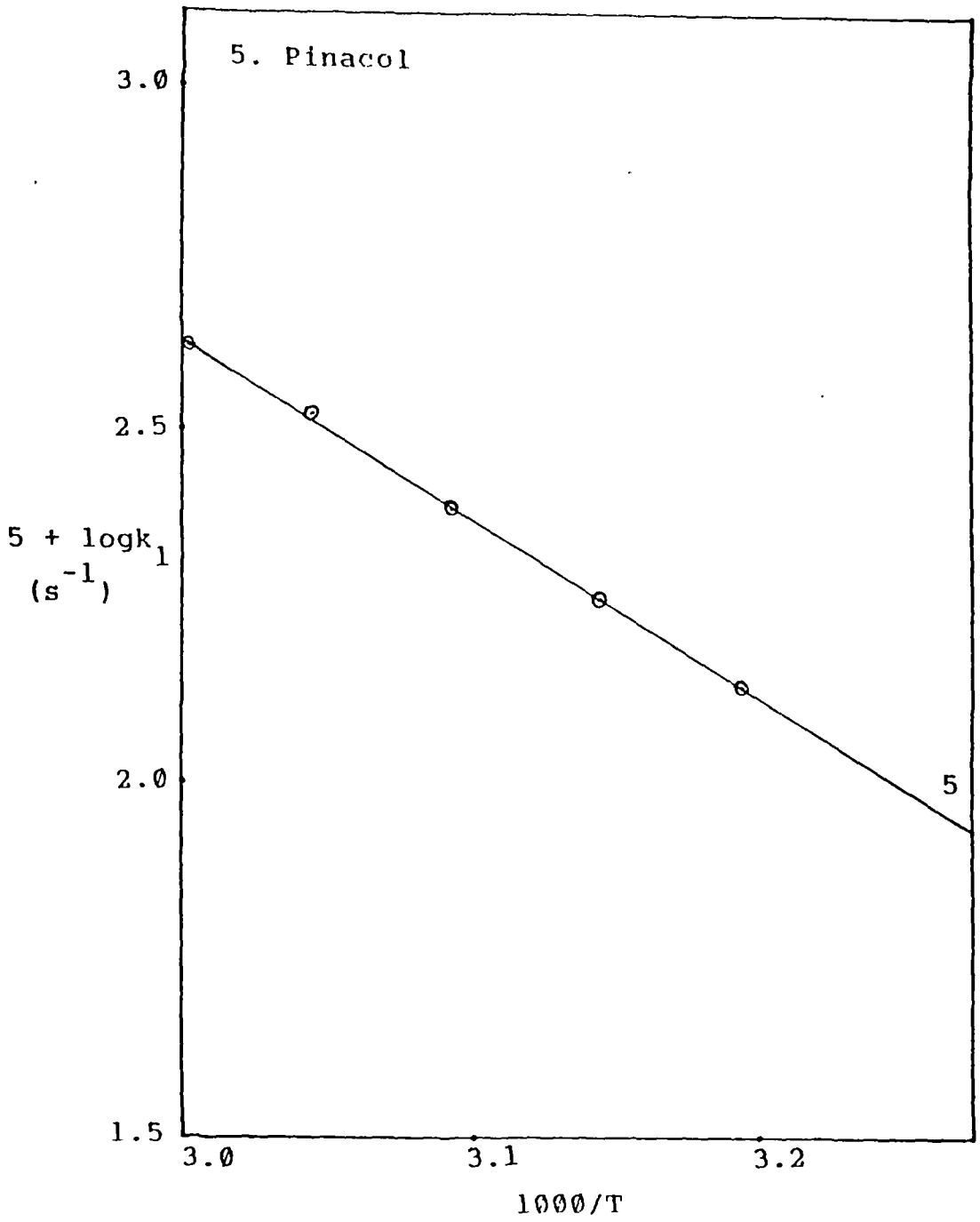


Fig.11. Plot of log k_1 against the reciprocal of temperature.

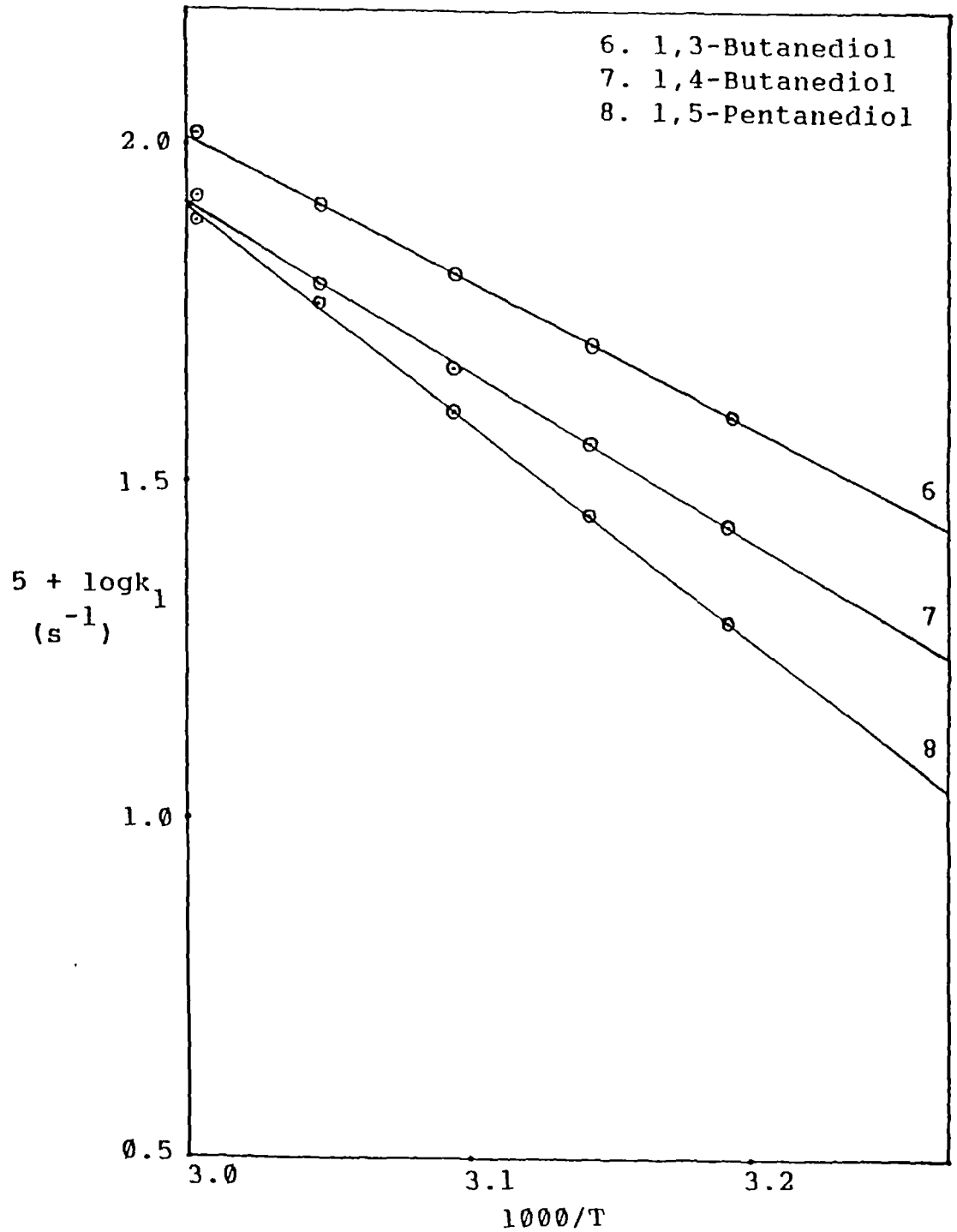


Fig.12. Plots of log k_1 against the reciprocal of temperature.

The oxidation of all the substrates were characterised by negative entropies of activation. This would suggest an ordered transition state, relative to the reactants(15). Differences in solvation of the substrate in the ground state and in the transition state might also contribute to the negative entropies of activation. The similarity of $\Delta G^{\neq}$ values for the oxidation of all the substrates arose due to the changes in $\Delta H^{\neq}$ and $\Delta S^{\neq}$ values, and stressed the probability that these oxidation reactions involved similar rate-determining steps.

Isokinetic relationship

The enthalpies and entropies of activation for a reaction are linearly related by the equation

$$\Delta H^{\neq} = \Delta H_{o}^{\neq} + \beta \Delta S^{\neq} \qquad (6)$$

where β is the isokinetic temperature. For the oxidation reactions studied in the present investigation, the activation enthalpies and entropies were linearly related. The correlation was tested and found to be valid by applying Exner's criterion (16). The isokinetic temperature, obtained from the plot of $\Delta H^{\neq}$ against $\Delta S^{\neq}$, was 250K (Figure 13).

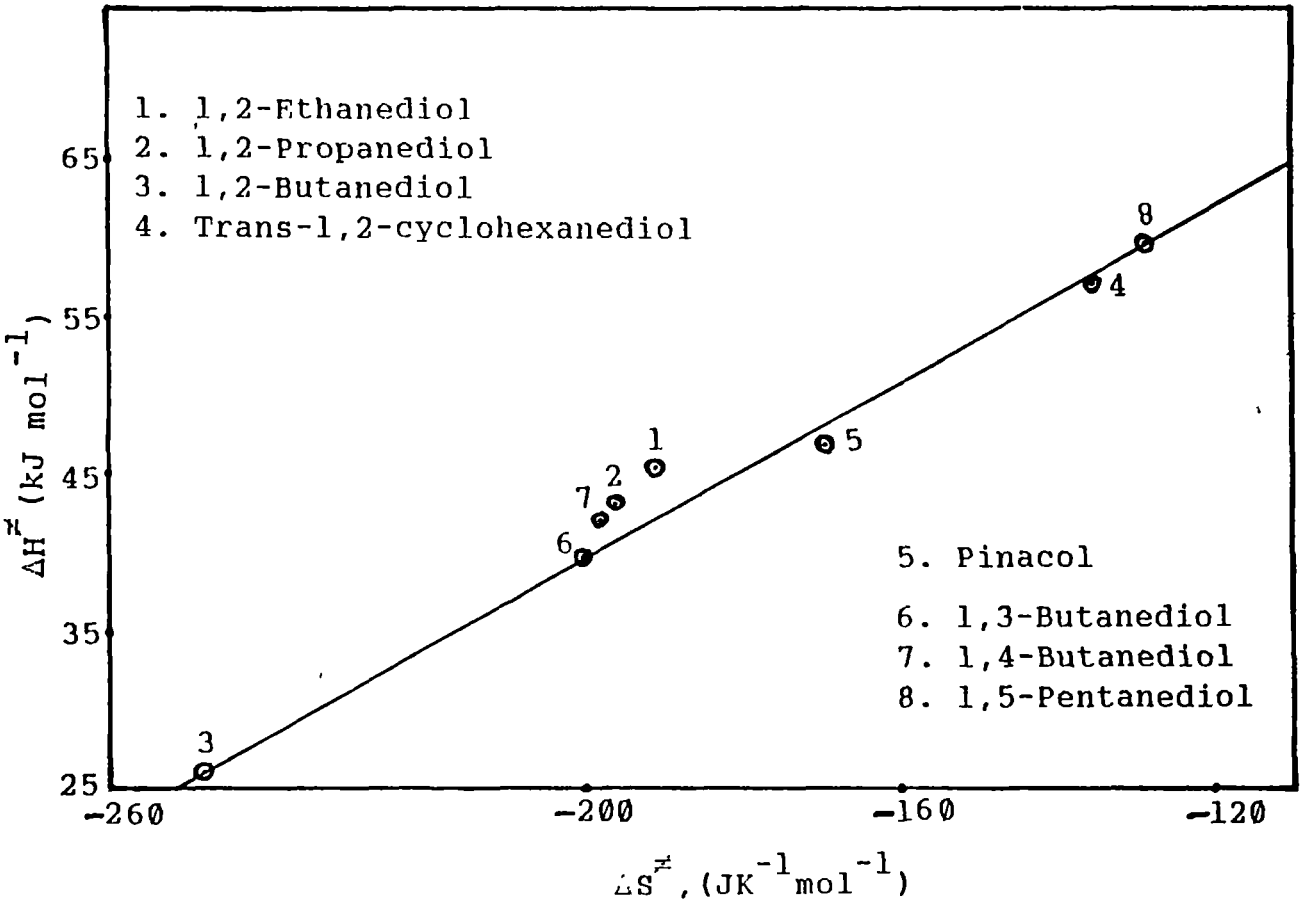


Fig.13. Plot of $\Delta H^{\neq}$ against $\Delta S^{\neq}$

Although current views do not attach much physical significance to isokinetic temperatures (17), a linear correlation between $\Delta H^{\neq}$ and $\Delta S^{\neq}$ is usually a necessary condition for the validity of the Hammett equation. Further, the values for the free energy of activation ($\Delta G^{\neq}$) were nearly constant, indicating that the same mechanism operated for the oxidation of all the diols studied in this investigation.

Induced polymerization

In the present investigation, since all the reactions were performed under nitrogen, the possibility of induced polymerization was tested. It was seen that there was no induced polymerization of acrylonitrile, or the reduction of mercuric chloride(18). This indicated that a one-electron oxidation was unlikely. Control experiments were performed in the absence of the respective substrates. The concentration of the oxidant (QDC) did not show any appreciable change.

Structural influences on the rates of oxidation

There was no kinetic evidence for the formation of a cyclic intermediate in any appreciable concentration between the diols and quinolinium dichromate (QDC). The rate of oxidation, for example, was first-order with respect to each reagent, for all the diols studied. The only evidence for the formation of a cyclic intermediate would depend upon the relation between the reaction rate and the configuration of the diol.

An attempt was made to decipher a general correlation between the rate of oxidation of all these diols by QDC and the proximity of the hydroxyl groups. Inspection of the kinetic data in Table 2 revealed that 1,4-butanediol reacted faster than 1,2-ethanediol; similarly, 1,3-butanediol reacted faster than 1,2-propanediol. This showed that compounds having vicinal hydroxyls reacted the slowest, indicating that there was no cyclic mechanism operating in these oxidation reactions. It may not seem very appropriate to compare the relative rates of oxidation for 1,3-butanediol and 1,4-butanediol,

since the site of attack may be different in the two oxidation processes. Increasing the alkylation resulted in an increase in the reactivity of the diol. The steric effect of the alkyl groups seemed to predominate over the electronic effect, because the more bulky the substituent, the more reactive would be the diol. In general, bulky groups would enhance the facile formation of the transition state for any reaction involving a change in the state of hybridization of the carbon atom from Sp^3 to Sp^2, as is evident in the decomposition of an ester chromium and a diol to form a carbonyl compound. Hence, electron release should facilitate the formation of an intermediate ester, envisaged by the attack of a hydroxyl group on the chromium atom, and thus help in the decomposition of this intermediate to give the carbonyl compound. The oxidation of diols by QDC would thus occur through an acyclic monoester of chromium, with assistance from the neighbouring hydroxyl group.

The kinetic data in Table 2 showed that trans-1,2-cyclohexanediol reacted faster than 1,5-pentane-

diol by a factor of 1.95. The geometry of trans-1,2-cyclohexanediol was such that the two hydroxyl groups were in equatorial positions. The chromate substituent group was quite strained. There would be a rate-enhancing relief of steric strain in the transition state, and hence the decomposition of the chromate ester would be facilitated. The factor of 1.95 would thus represent the difference in the ease of ester decomposition. In 1,5-pentanediol, the hydroxyl groups were quite far apart. Hence, there would not be any possibility of a cyclic mechanism operating in the oxidation reaction of the diols under investigation.

In the case of pinacol, the rate of the reaction was much faster than any of the other diols. Pinacol contains two tertiary carbon atoms, and does not possess a hydrogen atom α-to the hydroxyl group. Hence, it cannot undergo reaction by abstraction of hydrogen from the carbon atoms. The kinetic data can be interpreted on the assumption that the first step in the QDC oxidation of pinacol was the formation of an ester intermediate. The presence of four methyl groups would result in a great deal

of steric strain in the transition state. The fact that pinacol was oxidized much more rapidly than any of the other diols suggested that the next step was the formation of a cyclic ester, which than underwent cleavage as a result of a relief in the steric strain. Hence, the only mode of oxidation available for pinacol was the fission of the bond between the two vicinal alcohol carbon atoms.

Mechanism

Based on the stoichiometries of the oxidation reactions (Table 1), and the observed experimental data, the mechanistic pathways of the reactions have to be considered.

Some of the kinetic observations which must be taken into account are the following :

(1) The rate of oxidation of all the diols (vicinal and non-vicinal) were dependent on the first powers of the concentrations of each - substrate and oxidant (Table 2-3, Figures 1-3).

(2) The rates of reactions showed a first order dependence on the concentration of the acid (Table 4, Figures 4-6).

The acid catalysis of the oxidation reactions must be related to the structure of the oxidant (QDC). The oxidant was thus converted to a protonated Cr(VI) species.

3) An increase in the polarity of the solvent medium (using water-acetic acid mixtures) showed a decrease in the rate of the reaction (Table 5). Linear plots of log k_1 against the inverse of the dielectric constants (Figures 7-9) gave positive slopes, which indicated an ion-dipole type of interaction. This was in accordance with the involvement of a protonated Cr(VI) species.

(4) An increase in temperature resulted in an increase in the rates of the reactions (Table 6). The oxidation of diols was characterized by negative entropies of activation (Table 7), which suggested an ordered transition state, relative to the reactants. The similarity in $\Delta G^{\neq}$ values (Table 7) for all the substrates arose due to changes in $\Delta H^{\neq}$ and $\Delta S^{\neq}$ values, and emphasized the probability that all these

oxidation reactions involved similar rate-determining steps.

(5) There was no induced polymerization of acrylonitrile, or the reduction of mercuric chloride, indicating the absence of any radical formation.

(6) The observed order of reactivity for the oxidation of the diols was as follows :

(a) 1,4-butanediol reacted faster than 1,2-ethanediol (Table 2);

(b) 1,3-butanediol reacted faster than 1,2-propanediol (Table 2);

(c) trans-1,2-cyclohexanediol reacted faster than 1,5-pentanediol (Table 2);

(d) pinacol was oxidized at a rate faster than any of the other diols under investigation (Table 2).

For the diols listed in (a) and (b) above, the order of reactivity showed that compounds having vicinal

hydroxyl groups reacted the slowest, indicating that there was no cyclic mechanism operating in these oxidation reactions.

For the diols listed in (c) above, the order of reactivity represented the difference in the ease of ester decomposition.

For pinacol, the rapid rate of reaction was due to steric crowding of the methyl groups and lack of the α-hydrogen atom. The relief in the steric strain resulted in a very rapid rate of decomposition of the cyclic chromate ester, resulting in the cleavage of the bond between the vicinal alcohol carbon atoms.

The oxidation of diols by C-C bond fission, as for example, R.CH(OH)-CH R'(OH) —> R.CHO + R'CHO, was earlier thought to be a specific property of a few oxidants such as lead tetraacetate and periodic acid. However, the postulation of a free-radical mechanism for this process(19), and its confirmation by the observation that Fenton's reagent could also effect the fission of diols(20),

prompted a detailed analysis to determine whether other common oxidants could also act in a similar manner.

Initial experiments showed that acid dichromate and acid permanganate could react with :

(a) 1,2-ethanediol and glycerol, resulting in the production of small quantities of formaldehyde ;

(b) 2,3-butanediol, to give small amounts of acetaldehyde, and

(c) pinacol, to give acetone in very good yield.

These studies gave qualitative support for the view that homolytic bond fission may be possible in oxidations with chromic acid (21-22).

The oxidation of 1,2-ethanediol by chromic acid (23) revealed the following :

(i) The major portion of the diol was oxidized in the normal manner, that is, $\backslash / CHOH \longrightarrow \backslash / C=O$, to glyoxal and thence to oxalic acid. Only a small percentage of the diol underwent carbon-carbon bond fission, in either dilute

aqueous sulfuric acid or glacial acetic acid solutions, to give formaldehyde.

(ii)The fission of the diol could only be effected in the presence of added free acid; chromic acid itself was not effective.

However, when the oxidation of 1,2-ethanediol was carried out with chromyl chloride(24), both in carbon tetrachloride and in glacial acetic acid solutions, the pathway almost exclusively was via the cleavage of the carbon-carbon bond. The reaction proceeded by the initial formation of an addition complex at each hydroxyl group, followed by the breakdown of this complex to an organic diradical and a transient Cr(V) derivative. This diradical then underwent carbon-carbon bond fission, while the unstable Cr(V) fragment disproportionated to ultimately give Cr(III).

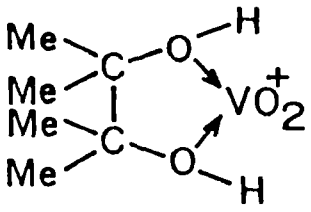
Kinetic measurements had shown that, in the oxidation of diols by vanadium(V), mono-and di-tertiary diols were oxidized by C-C bond fission, while primary and

secondary diols were oxidized in a manner similar to that of monohydric alcohols by $\diagdown\!\!\diagup$CH(OH)—> $\diagdown\!\!\diagup$C=O conversion (23). For example, diols such as 1,2-ethanediol were all converted by vanadium(V) to the corresponding carbonyl compounds, whereas pinacol was oxidized to acetone by a fission of the C-C bond (24).

It was shown that the oxidation of 2,3-dideuteriobutane-2,3-diol by vanadium(V) and chromium (VI) occured by $\diagdown\!\!\diagup$CH(OH)—> $\diagdown\!\!\diagup$C=O conversion, since a definite isotope effect was observed (k_H/k_D=2.7 for V(V); k_H/k_D=3.93) for Cr (VI) oxidations. Since there was an isotope effect with 2,3-butanediol when Cr(VI) was used, it was evident that this oxidant preferentially oxidized secondary alcohols at the $\diagdown\!\!\diagup$CH(OH) group, rather than by C-C fission (25).

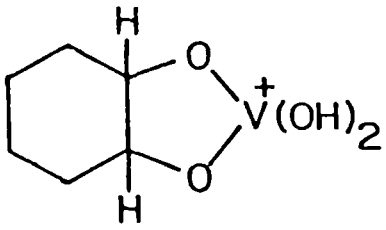
In the vanadium(V) oxidation of diols, it was observed that those diols containing a tertiary hydroxy group were oxidized to a detectable extent by VO_2^+. The difference in oxidation rates between pinacol and the isomeric 1,2-dimethyl cyclohexane-1,2-diol were due to stringent steric requirements in the transition state of the

reaction. The mechanism involved the formation of a nearly planar five-membered chelate ring (I),



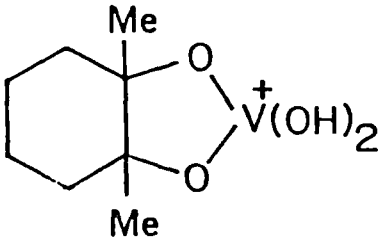
(I)

and would be greatly hindered if this ring was fused to a six-membered ring(II).



(II)

With the V-O distance taken as 1.86Å, structural models showed that while bicyclic structures such as II were nearly strainless in the case of cyclohexane-1,2-diol, yet structures(III)



(III)

for the dimethyl-diols were considerably strained, in comparison with both I and II. Hence, the oxidation rates would be lower for such bicyclic structures than for pinacol. Models of the di-tertiary diol complexes I, II and III showed that, if the five-membered chelate ring was to be strainless, then it must be planar. Hence, the methyl groups in the pinacol complex I must be considerably occluded. This proximity of groups would impose a considerable strain on the C-C bond which would be split in the ensuing oxidation, since the Me-Me interaction barrier has been estimated to be approximately 20kJ/mol(26). In this manner, the considerable ease of oxidation of pinacol, as compared with that of 2,3-butanediol (which was not oxidized by C-C bond fission) could be rationalized. Moreover, the inductive effect of the two methyl groups would operate so as to increase the stability constant of the more methylated diol complexes, resulting in the faster rate of oxidation of pinacol over 2,3-butanediol.

All the diols (1,2-ethanediol, 1,2-propane diol, 2,3-butanediol and trans-1,2-cyclohexanediol) were oxidized

by V(V) via the same mechanism as was cyclohexanol, that is $\backslash CH(OH) \longrightarrow \backslash C{=}O$(27). For trans-1,2-cyclohexanediol, the more stable conformation was that having the two hydroxyl groups oriented in an equatorial manner(28). In these circumstances, the environment of each hydroxyl group was very similar to that of the hydroxyl group in cyclohexanol itself. Therefore, with the diol, the oxidation rate should be twice that of cyclohexanol. Since each hydroxyl group may inductively affect the rate of oxidation of the other, the observed rate factor of 2.Ø5 was rational(27).

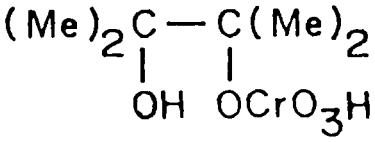
The relative oxidation rates of 1,2-ethanediol, 1,2-propanediol and butanediols could be ascribed to the +I inductive effect of the additional methyl groups.

The relative rates of oxidation of substituted cyclohexanediols have been used for structural assignments(29), using the chromate ester mechanism of Westheimer(3Ø).

In the oxidation of vicinal diols by chromic acid, the rate constants were computed(31) on the stoichiometric

assumption of only one carbinol group undergoing oxidation to the corresponding carbonyl compound(32). It was observed that even under preparative conditions (in relatively concentrated solution where the diol component was not always in large excess), the incidence of cleavage products from the chromic acid oxidation of primary and secondary vicinal diols was quite small(23, 25).

The kinetics of oxidation of pinacol by chromic acid were studied by two research groups (25,33). Pinacol does not contain a hydrogen atom alpha to the hydroxyl group, and cannot therefore undergo reaction by abstraction of hydrogen from the carbon-hydrogen bond. The reaction was first-order in pinacol, hydrogen ion and the acid chromate ion, $HCrO_4^-$ (33). The kinetic data was interpreted on the assumption that the first step was the formation of an ester,



The next step was the formation of a cyclic ester, which then underwent cleavage to give the product, acetone.

The oxidation of trans-1,2-dimethyl-1,2-

cyclopentanediol by chromic acid was first order in the diol and in chromic acid, and was dependent on H_o, the Hammett acidity constant (34). The pathway of this reaction involved an acyclic mechanism.

Information concerning the rate-controlling step can be obtained by considering the dependence of the rate of chromic acid cleavage on the structure of the diol. When diols containing primary or secondary hydroxyl groups reacted with chromic acid, they were predominantly oxidized to hydroxyketones or hydroxyaldehydes, without any cleavage. As the hydroxycarbonyl compounds cannot be considered to be intermediates in the fission of diols, the two processes :

(a) oxidation of a single hydroxyl group ; and

(b) fission of the diol to two carbonyl compounds must be concurrent.

The dependence of rate on structure, in the case of the chromic acid oxidation of diols, contrasted sharply with that for other reagents which could bring about the cleavage of diols. The rates for the cleavage of diols by

lead tetraacetate first increased with the introduction of methyl groups, reached a maximum with 2,3-butanediol, and then decreased. The rate for the oxidation of pinacol was only about twice as high as that for 1,2-propanediol(35). In the case of the oxidation of diols with periodic acid, the overall rates were separated into equilibrium and rate terms(36). It was observed that the rate of decomposition of the cyclic intermediate increased, with increasing substitution, to a maximum for 2-methyl-1,2-propanediol, and then decreased with each additional methyl group (36). Furthermore, cis-1,2-dimethyl-1,2-cyclopentanediol reacted with periodic acid only 1/3000 as fast as did the parent compound, cis-1,2-cyclopentanediol(37). It had been shown that the rate - controlling step, for the reaction with periodic acid of the more highly substituted diol, was the step involving esterification(36) rather than the second step (the cleavage of the cyclic ester). In chromic acid oxidation, since the introduction of alkyl groups accelerated, rather than retarded the cleavage, the mechanism presumably differed from those for oxidations by

periodic acid and lead tetracetate. A reasonable assumption ascribed the slow step to the actual cleavage, since alkyl groups could increase the rate by increasing the electron supply at the site of the oxidation. Additional support was obtained by comparing the reaction rates with the enthalpies for the fission of diols. The rates and the enthalpies increased with increasing stability of the carbonyl product formed (that is, in the order formaldehyde < acetaldehyde < acetone). This parallelism suggested that the structure of the transition state was quite near to that of the products, so that the rate-determining step was the decomposition of a cyclic ester, which was in rapid equilibrium with chromic acid and the glycol.

Diols of the structure $R_1R_2C(OH)CH(OH)R_3$ could react with an oxidant either to :

(a) produce a hydroxyaldehyde (or hydroxyketone); or

(b) cleave the central C-C bond.

Both processes have the same stoichiometry.

The data showed that oxidation to the

hydroxyaldehyde or hydroxyketone was energetically favoured by 15 kcal/mol or more (34).

When chromic acid oxidized a glycol which contained an α-hydrogen atom, the energetically favoured reaction predominated (38). Chromic acid was therefore the "normal oxidant". The question that arose was why oxidants such as periodic acid, lead tetracetate and iodosobenzene diacetate failed to oxidize appropriate diols to α-hydroxycarbonyl compounds. It is known that these oxidants(lead tetraacetate, periodic acid and iodosobenzene diacetate), where both the oxidant and its reduced product (lead diacetate, iodic acid and iodobenzene respectively) are diamagnetic, can specifically cleave diols. The effective oxidant for simple alcohols (chromic acid and permanganate) can function either as 1-electron or 2-electron acceptors. Furthermore, when they have accepted 2 electrons, the resulting ions are still paramagnetic. The reactions may be interpreted on the basis of a transition state which was postulated for the chromic acid oxidation of hydrocarbons(39). This transition state acquires its

stabilization from resonance between structures, each of which has 2 unpaired electrons :

(a) free-radical and Cr(V); and

(b) a carbonium ion and Cr(IV).

It was observed that the correlation of the rate with the acidity, in the oxidition of organic compounds by vanadium(V), could be used as a mechanistic tool to characterize the nature of the intermediate complex(40). The dependence of the oxidation rate on H_o, the Hammett acidity function (41), was considered to indicate the function of a chelate complex, and an acyclic complex was preferred when the rate of the reaction was dependent on the concentration of H_3O^+ (42). It was further observed that the oxidation of 1,3-propanediol and 1,4-butanediol gave the corresponding hydroxyaldehydes (42). The kinetics of oxidation of diols by CrO_3 in different solvent mixtures (acetone - water, acetonitrile - water, and acetic acid- water) at constant acidity, was reported (43). On the basis of the kinetic results, cyclic ester formation involving both the hydroxyl groups was unlikely. The mechanism proposed was an acyclic

process through chromate ester formation, followed by the loss of proton from the ester by a unimolecular pathway. Solvent changes did not affect the mechanism, which seemed to be the same in all the solvent mixtures studied(43). The kinetics of oxidation of diols by pyridinium chlorochromate(PCC) in dimethylsulfoxide (DMSO) have been reported(44). In each case, the principal products were the corresponding hydroxy aldehydes. The diols were oxidized by a hydride ion transfer mechanism, similar to the pathway observed for the oxidation of alcohols by PCC (45-46). The hydride transfer mechanism postulated an electron-deficient carbon centre in the transition state. The increase in the reaction rate with progressive substitution of the hydrogen atoms by methyl groups in 1,2-diols supported this postulation. The hydride ion transfer could take place either via an ester intermediate or by an acyclic mechanism(45-46). The kinetics of oxidation of diols by sodium-N-bromobenzene sulphonamide (bromamine-B or BAB) has been reported(4). The oxidation of vicinal diols by BAB proceeded via an acyclic mechanism and yielded products

arising from the rupture of the bond between the carbon atoms bearing the hydroxyl groups. The oxidation of non-vicinal diols gave products of simple oxidation of the hydroxyl group (hydroxycarbonyl compounds). The rate-determining step in the oxidation of non-vicinal diols involved the transfer of a hydride ion to protonated N-bromobenzenesulfonamide, a pathway which was similar to that suggested for the oxidation of alcohols by BAB (45-46).

Several studies have been directed towards the stereoselective synthesis of enantiomerically pure α-hydroxy ketones (47-48). These compounds have been used as important synthons in the asymmetric synthesis of natural products and fine chemicals (49-54). It has been shown that α-hydroxyketones, in high entantiomeric excess, could be obtained by the osmium-catalysed asymmetric dehydroxylation of the corresponding enol ethers or silyl enol ethers (55-60). The selective conversion of representative optically active sec-sec-diols to the corresponding α-hydroxyketones, using dimethyl dioxiranes and methyloxiranes, have been reported(6). Ethyl-N-

chlorocarbamate (ECC) has been used for the oxidation of diols in aqueous acetic acid solution (7). An acyclic mechanism, involving carbon-carbon bond fission, was reported for the oxidation of vicinal diols, while non-vicinal diols were oxidized by a hydride transfer mechanism(7).

The oxidative dehydrogenation of vicinal diols to α-hydroxyketones was difficult to achieve in good yields using common oxidation reagents (61-67). Quite frequently, such processes had resulted in over-oxidation to α-dicarbonyls and/or carbon-carbon bond cleavage to form carboxylic acids.

The unique feature of chromic acid was that it could effect both, normal oxidation and cleavage, in so far as its reactions with diols. For example, Waters had reported 1-2% cleavage in the case of oxidation of 1,2-ethanediol, and 20-30% cleavage in the case of the oxidation of 2,3-butanediol(22,23).

A more detailed investigation was reported by

Chatterjee and Mukherjee (25). The effect of methyl substitution on the degree of cleavage was confirmed, and it was found that pinacol was readily cleaved to give acetone(25). It was evident that two mechanistic pathways were thus available :

(1) a normal oxidation to yield an α-hydroxy carbonyl compound; or

(2) cleavage of the carbon-carbon bond.

Rocek and Westheimer had used energy considerations to ascertain the pathway of oxidation, and had established that the oxidation to a hydroxyaldehyde (or ketone) was energetically favoured by 15 kcal/mol or more (34). Moreover, reagents which were commonly used for the cleavage of diols (lead tetraacetate and periodic acid), did not satisfactorily effect secondary alcohol oxidation. The obvious conclusion was that when a mechanistic pathway was available, the oxidation of a primary or secondary alcohol group to a carbonyl would be preferred over cleavage of the diol.

The oxidation of diols by chromyl chloride had been investigated (22,23). Hydrobenzoin, benzpinacol and pinacol, all gave insoluble complexes which, on hydrolysis, gave cleavage products in good yield.

Diols were cleaved by permanganate, but this reaction was considerably slower than the corresponding reaction of alkenes (68). It was suggested that the carbon-carbon cleavage of alkenes (which always accompanied the dihydroxylation reaction) did not involve the diol which was formed. Instead, a manganese containing precursor was involved in this step (68).

Cerium(IV) has been used as an effective reagent for the cleavage of diols. For example, with ceric sulfate, pinacol was quantitatively cleaved to give acetone. A first-order dependence on the concentration of oxidant and substrate was observed, indicating the absence of complex formation(69). In the oxidation of diols by cerium(IV), the extent of complex formation appeared to be dependent on the anion associated with cerium and on the type of diol used (70-72). With ceric sulfate, 1,2-ethanediol was oxidized via

complex formation, whereas in the oxidation of diols such as pinacol and 2,3-butanediol, there was no evidence for any complex formation(70). With ceric nitrate, the oxidation of 2,3-butanediol proceeded through complex formation(71). With ceric perchlorate, kinetic evidence indicated that 2,3-butanediol was oxidized via complex formation (72). While considering the ceric sulfate oxidation of 2,3-butanediol and 1,2-ethanediol, complex formation was observed with the latter, but not with the former (72). It was suggested that, with increased substitution of the carbon atom bearing the hydroxyl groups, the stability of the incipient radical in the activated complex should increase (73). In addition, steric effects were also observed to decrease complex formation with 2,3-butanediol, as compared with 1,2-ethanediol. It was further observed that pinacol was oxidized faster than 2,3-butanediol, on the basis of radical stability (73).

Sodium bismuthate was found to cleave 1,2-diols to the carbonyl compounds (74). It was observed that both, cis-and trans-1,2-cyclohexanediols had similar reactivities

towards sodium bismuthate. It was sugggested that these reactions were probably occurring on the surface of the sparingly soluble sodium bismuthate, and its rate was not strongly dependent on the structure of the diol(74).

Xenic acid has been used to oxidize 1,2-diols (75). It was found that the initially formed products were further oxidized to carbon dioxide and carbonyl compounds(75).

Diols were oxidized at a rate independent of the acidity of the solution (24). The acid-catalysed reactions of diols were dependent on H_0, the Hammett acidity constant. This indicated that the diols formed chelate complexes with vanadium(V), and pinacol was oxidized at a rate much faster than 1,2-cyclohexanediols (24). In the case of vanadium(V) oxidations, chelate complexing was confirmed for pinacol by isotopic substitution (70). The rate of decomposition of the complex was increased by the increased stabilization of the incipient carbonyl group in acetone, as compared with acetaldehyde or formaldehyde(70). The observed order of reactivity of ditertiary diols toward one-equivalent oxidants was in contrast to the oxidation of diols by both,

lead tetraacetate and periodic acid. These reagents effect carbon-carbon bond fission of most 1,2-diols. Both types of reagents could form chelate complexes with 1,2-diols, but in order to facilitate the cyclic movement of electrons, the two-equivalent oxidations must involve a transition state having a planar chelate ring. With one-equivalent reagents, this ring planarity was not essential. Hence, steric interactions in the transition state would be more important in two-equivalent processes, and thus favour the oxidation of less substituted diols. Also, a concerted two-equivalent process need not require the development of any high degree of unsaturation, so that stabilization by hyperconjugation of the transition state was relatively unimportant. This results in the fission of diols by two-equivalent oxidants (as by chromic acid), at relative rates which could be correlated with the standard free energy of the process(34,76).

In the present investigation involving the oxidation of diols by quinolinium dichromate (QDC), there was no kinetic evidence for the formation of a cyclic

intermediate in any appreciable concentration between the diols and QDC. The rate of oxidation, for example, was first-order with respect to each reagent, for all the diols studied. The only evidence for the formation of a cyclic intermediate would depend upon the relation between the reaction rate and the configuration of the diol. While looking for a general correlation between the rate of oxidation by QDC and the proximity of the hydroxyl groups in the diols, it was observed that 1,4-butanediol reacted at a rate faster than 1,2-ethanediol; similarly, 1,3-butanediol reacted faster than 1,2-propanediol. Thus, compounds having vicinal hydroxyl groups reacted the slowest, indicating that there was no cyclic mechanism operating in these oxidation reactions. The kinetic data revealed that trans-1,2-cyclohexanediol reacted faster than 1,5-pentanediol. In trans-1,2-cyclohexanediol, the two hydroxyl groups were in equatorial positions, and the chromate substituent group would be quite strained. This steric strain would be relieved in the transition state, and hence the decomposition of the chromate ester would be facilitated. In

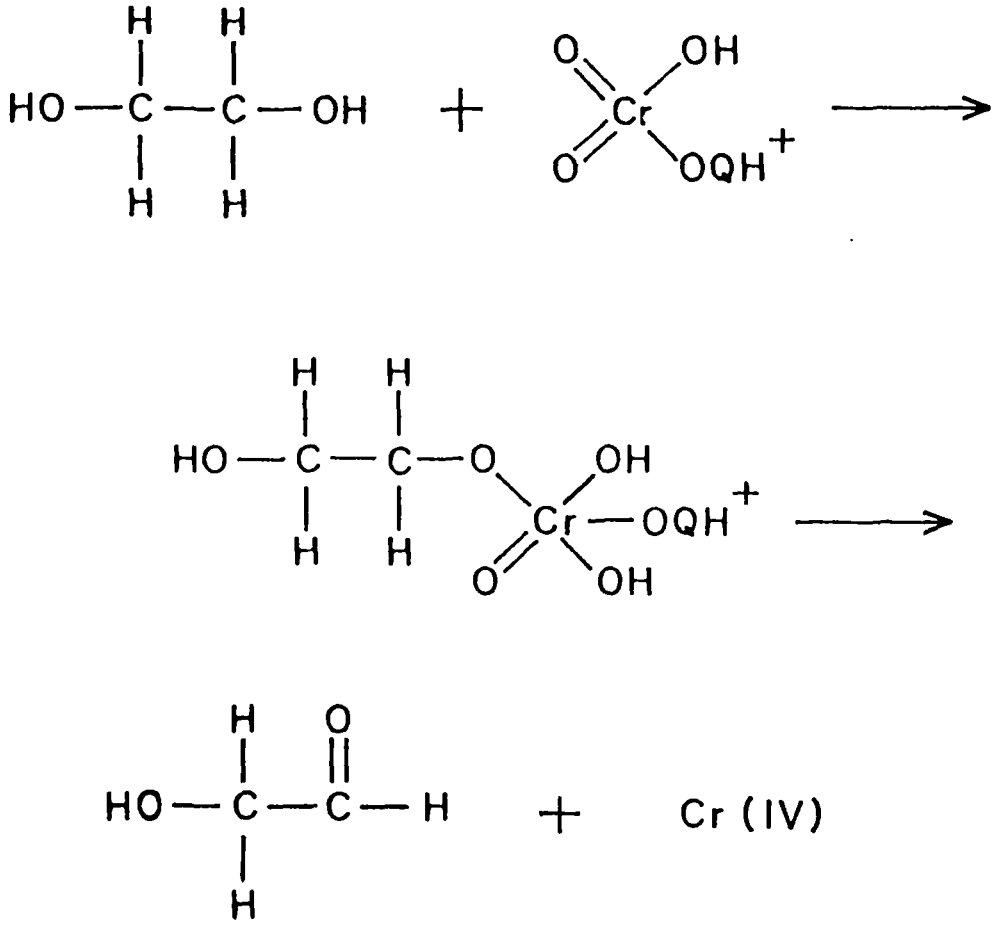
1,5-cyclopentanediol, the hydroxyl groups were quite far apart, and there would not be any possibility of a cyclic mechanism operating in the oxidation reaction. There was thus no evidence for the carbon-carbon bond fission in the QDC oxidation of all these diols. In the absence of products which would have resulted from the carbon-carbon bond fission, it is suggested that, an acyclic mechanism must perforce operate in these oxidation reactions. The major portion of the diol was oxidized in the normal manner, $\diagdown\!\diagup CH(OH) \longrightarrow \diagdown\!\diagup C{=}O$. The fission of the diols could not be effected in the presence of added free acid. It would thus be justified to postulate that all these diols reacted with QDC to produce the corresponding α-hydroxycarbonyl compounds, a pathway which has already been established to be energetically more favourable than that yielding the fission product(34). The rates and the enthalpies would favour the formation of the hydroxy carbonyl products, suggesting that the structure of the transition state was quite near to that of the products. The formation of α-hydroxycarbonyl compounds would suggest that the oxidation

of diols by QDC simulated that of the oxidation of monohydric alcohols by chromic acid (12). Cyclic ester formation involving both the hydroxyl groups was unlikely, and the mechanistic pathway would be an acyclic process through the chromate ester, which would then undergo decomposition by a rate-determining C-H bond fission (Scheme 1).

This mechanistic sequence drew ample support from two excellent correlations :

(a) Periodic acid, lead tetraacetate and phenyliodoso acetate (used primarily to cleave 1,2-diols) do not readily oxidize simple alcohols or oxidize diols to α-hydroxy-carbonyl compounds (34), as do chromic acid or permanganate.

(b) The oxidative cleavage of 1,2-diols by periodate(the Malaprade reaction) is an allowed electrocyclic process, whereas the corresponding reaction of 1,2-diols by chromium(VI) is a forbidden process (77). This excludes a cyclic mechanism, and supports the view that the oxidation of diols by QDC would involve the normal pathway, that is, the conversion of $\diagdown\!\diagup CH(OH) \longrightarrow \diagdown\!\diagup C{=}O$.



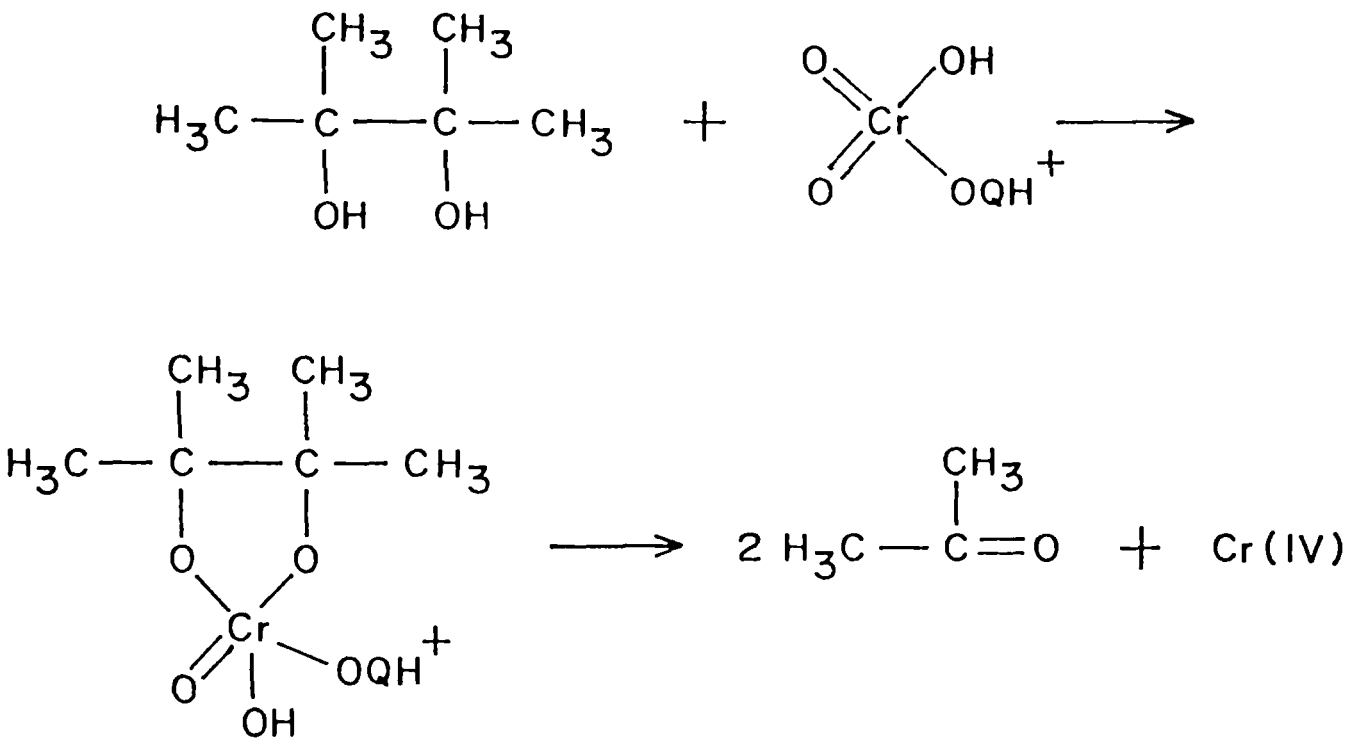
Scheme – 1

The oxidation of pinacol has been studied in detail by several workers (25,33). A solvent isotope effect k_{D_2O}/k_{H_2O} = 2.7 was observed. Further, the monomethyl ether of pinacol was oxidized at a very low rate. The solvent isotope effect suggested that O-H bond cleavage did not occur in the rate-determining step. Since the mono methyl ether was not readily oxidized, it was suggested that the intermediate formed involved a cyclic chromate ester. This decomposition occurred in a manner similar to that suggested for the oxidations by lead tetraacetate and periodic acid, and gave acetone as the major product. Further evidence for cyclic chromate ester formation was found in the observation that, cis-1,2-dimethyl-1,2-cyclopentanediol was oxidized very much more rapidly than the trans-isomer(34). The large difference in rate could not be accommodated for a pathway involving an acyclic intermediate. Hence, the reaction pathway for the oxidation of pinacol was suggested to be via a cyclic chromate ester intermediate.

In the present investigation, it has been observed that the rate of oxidation of pinacol was much higher than

that of any of the other vicinal or non-vicinal diols. Since pinacol did not contain any α-hydrogen atom on the carbon atom, and since it possessed two methyl groups on each of the carbon atoms bearing the hydroxyl group, it is justifiable to propose a change in mechanism with increasing methyl substitution. Hence, the formation of a cyclic chromate ester becomes more possible. This intermediate would undergo decomposition, resulting in the cleavage of the carbon-carbon bond. The major product obtained was acetone, which would be feasible only if the oxidation process involved the formation of a cyclic chromate ester intermediate (Scheme 2).

The data collected in the present investigation demonstrated that application of QDC to the oxidation of diols (vicinal and non-vicinal) led to the formation of α-hydroxycarbonyl compounds in good yields. This efficient reaction could thus prove to be a useful and general route in the synthesis of α-hydroxycarbonyl compounds. The oxidation of pinacol by QDC resulted in the formation of acetone, as a result of cleavage of the carbon-carbon bond.



Scheme – 2

This would be the usual pathway for the oxidation of diols not having a hydrogen atom attached to the carbon atoms bearing the hydroxyl groups.

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CHAPTER 2

KINETICS OF OXIDATION OF α-HYDROXY ACIDS

The oxidation of α-hydroxy acids by various oxidizing agents has been investigated by several workers. The oxidation of α-hydroxy acids by manganic pyrophosphate involved the reversible formation of a cyclic complex, which then underwent reaction with the loss of carbon dioxide and the formation of a free radical (1). This was followed by further extensive oxidation, with tartaric and malic acids being degraded to carbon dioxide and formic acid (1). The kinetics of oxidation of α-hydroxy acids by ceric sulfate in the presence of varying amounts of sulfuric acid was studied (2). The mechanism of this reaction involved the formation of an activated complex, which then decomposed slowly to form a free radical, hydrogen ion and a cerous complex (2). In the oxidation of α-hydroxy acids, by vanadium(V), both VO_2^+ and a protonated species were active, and a dependence on the Hammett acidity constant was observed, resulting in the postulation of a cyclic complex intermediate (3). An organic radical was formed with the liberation of carbon dioxide (3). The oxidation of α-hydroxy acids by chromic

acid proceeded by a mechanism similar to that of the oxidation of secondary alcohols, resulting in the formation of the corresponding keto acid (4). α-Hydroxy acids were oxidized by permanganate to give two sets of products. In basic solution, the principal products were the keto acids, whereas in acid medium, extensive decarboxylation occurred (5). The difference between one-electron and two-electron mechanisms was brought out very lucidly in the oxidation of α-hydroxy acids, indicating the possibility of C-H bond cleavage with chromic acid and vanandium(V), but insignificant cleavage in the oxidation by manganese(III) and cerium (IV) sulfates(6). The kinetics of oxidation of α-hydroxy acids by chromium (VI) and cerium (IV) in varying proportions of acetone-water mixtures has been reported (7). The kinetic data indicated an O-H bond cleavage in Ce(IV) oxidation, while the rate-determining step with Cr(VI) was the cleavage of the C-H bond (7). The kinetics of oxidation of glycolic acid and benzilic acid by chromium (VI) have been reported. Glycolic acid initially produced glyoxylic acid, which subsequently gave formic acid. Benzilic acid was

oxidized to benzophenone (8). The oxidation of α-hydroxy acids by bromine water proceeded via a mechanistic pathway involving oxidative decarboxylation (9). The co-oxidation of tertiary hydroxy acids and a secondary alcohol by chromic acid proceeded by way of oxidative decarboxylation to give the ketone as the major product (10). The oxidation of glycolic acid by Cr(VI) yielded glyoxylic acid, formaldehyde and carbon dioxide at low concentration of acid; at higher concentration of acid, only glyoxylic acid was obtained (11). The oxidation of 2-hydroxy-2-methyl butanoic acid by chromic acid gave ethyl methyl ketone, as a result of extensive decarboxylation (12). The chromic acid oxidation of mandelic acid resulted in the formation of a mixture of benzaldehyde, benzoic acid, phenyl glyoxylic acid and carbon dioxide in varying ratios. This reaction represented the first example of a intramolecular three-electron oxidation in which a C-H and a C-C bond to the same carbon atom were broken simultaneously in the rate-limiting step (13). The oxidation of α-hydroxy acids by pyridinium chlorochromate (Corey's reagent, PCC) has been reported. The reactions were

first-order in each of the reactants. The acid-catalysed reaction was nearly first-order. The mechanism of this reaction involved the cleavage of the C-H bond from the carbon atom bearing the functional groups. All the hydroxy acids were oxidized to the corresponding aldo or keto-acids (14). The kinetics and mechanism of the PCC oxidation of malic acid has been reported (15). Kinetic data pertaining to the oxidation of α-hydroxy acids by 1-chlorobenzotriazole indicated a process of oxidative decarboxylation resulting in the formation of the corresponding aldehydes (16). The oxidation of benzilic acid by oxygen in the presence of copper(I) as catalyst yielded benzophenone, as a result of oxidative decarboxylation (17). The ruthenium-catalysed dehydrogenation of α-hydroxy esters and cyanohydrins with tertiary butyl hydroperoxide has been reported (18). Kinetic studies on the oxidation of glycolic acid by chromium peroxy dichromate pointed towards decarboxylation, with formaldehyde as the oxidation product (19). In perchloric acid solution, the oxidation of α-hydroxy acids by N-bromoacetamide gave the corresponding carbonyl compound

(20). The kinetics of oxidation of mandelic acid and tartaric acid by chloramine-T in alkaline medium, catalysed by palladium (II) ions, has been reported (21). The oxidation of hydroxy acids by pyridinium fluorochromate (PFC) had yielded the corresponding carbonyl compounds as the major product (22). The kinetics of oxidation of hydroxy acids by N-bromosuccinimide, in perchloric acid medium, catalysed by palladium (II), was studied; the oxidation of tartaric acid gave glyoxylic acid and formic acid (23). The oxidation of hydroxy acids by pyridinium hydrobromide perbromide (PHPB), in acetic acid-water mixtures, led to the formation of the corresponding oxo acids (24). The oxidation of α-hydroxy acids by potassium nitroso disulphonate (PNDS, Fremy's radical) in aqueous acetate medium showed a first-order dependence on the oxidant, and a fractional order dependence on the hydroxy acids. The products obtained were the corresponding keto acids (25). Kinetic studies on the oxidation of hydroxy acids by pyridinium bromochromate has been studied, with the corresponding oxo acids being obtained as the product (26). The kinetics of electron

transfer reactions involving pyridinium chlorochromate and hydroxy acids in acid medium, catalysed by ruthenium (III) ions, has been reported (27). Copper (III) periodate and copper (III) tellurate have been used to oxidize α-hydroxy acids, and the mechanism had involved the process of decarboxylation (28). The oxidation of α-hydroxy acids by benzotrimethylammonium tribromide (BTMAB) in 1:1 acetic acid - water led to the formation of the corresponding carbonyl compounds. These reactions were first-order with respect to the oxidant, but Michaelis-Menten-type kinetics were observed with respect to hydroxy acids (29).

PRESENT WORK

The present work is a detailed kinetic investigation of the oxidation of hydroxy acids by quinolinium dichromate (QDC), in acid medium, using dimethyl formamide (DMF) as the solvent.

The hydroxy acids chosen for the purpose of oxidation by QDC have included :

(a) Aliphatic α-hydroxy acids (glycolic acid and lactic acid).

(b) Aliphatic dihydroxy dicarboxylic acid (tartaric acid).

(c) Aromatic α-hydroxy acids (mandelic acid and benzilic acid).

Stoichiometry (vide "Experimental")

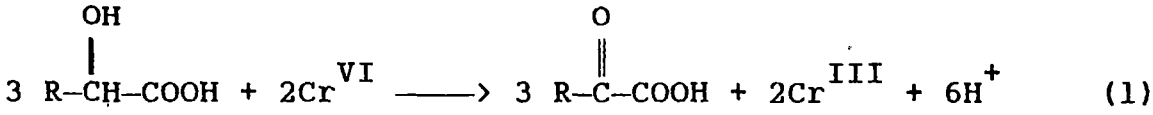
The stoichiometries of all the oxidation reactions were determined. The stoichiometric ratios Δ[QDC]/Δ[Substrate] were in the range of 0.62-0.73 (Table 1).

Table 1: Stoichiometries of the oxidation of the substrates;

[Substrate] = 0.005 M, T = 313 K

$[H_2SO_4]$/M	0.10	0.25	0.50
10^2[QDC]/M	2.50	2.60	2.70
Δ[QDC]/Δ[Glycolic acid]	0.71	0.65	0.68
Δ[QDC]/Δ[Lactic acid]	0.69	0.67	0.73
Δ[QDC]/Δ[Mandelic acid]	0.71	0.73	0.68
Δ[QDC]/Δ[Benzilic acid]	0.66	0.70	0.64
Δ[QDC]/Δ[Tartaric acid]	0.62	0.66	0.68

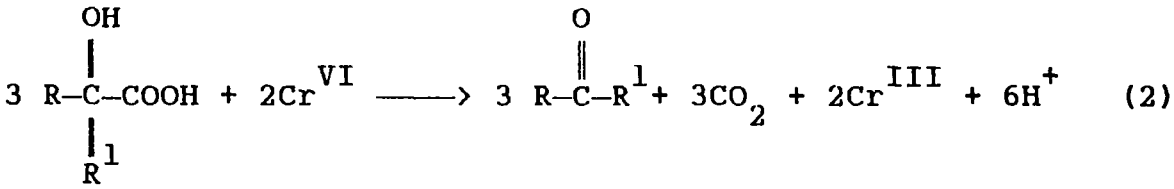
The stoichiometry conformed to the overall equations :



(1)

R = H; Glycolic acid,

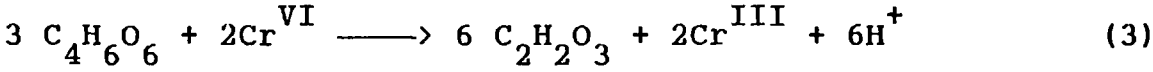
R = CH_3; Lactic acid,



(2)

R = C_6H_5; R^1= H; Mandelic acid,

R = R^1 = C_6H_5; Benzilic acid



(3)

Tartaric acid Glyoxylic acid

Effect of substrate

The rate of the reaction was found to be dependent on the concentration of the substrates. The order of the reaction with respect to the substrate concentration was obtained by changing the substrate concentration, and observing the effect on the rate of the reactions, at constant [QDC] and $[H^+]$. The results have been recorded in Table 2.

Table 2 : Dependence of Rate Constants on the concentration of α-Hydroxyacids in Dimethyl formamide (DMF); [QDC] = 0.001 M, $[H_2SO_4]$ = 1 M, T = 313 K *$[H_2SO_4]$ = 0.075 M

[α-Hydroxy acids]M	0.01	0.025	0.05	0.075	0.10
10^4 X k_1, s^{-1} for :					
Glycolic acid	0.34	0.88	1.88	2.53	3.85
Lactic acid	0.43	1.1	2.35	3.04	4.80
Mandelic acid	3.1	7.3	15.3	22.5	30.7
Tartaric acid	4.1	9.5	19.3	28.5	38.5
*Benzilic acid	2.7	6.75	13.5	20.2	27.3

Plots of k_1, the pseudo-first-order rate constant, against the concentration of the substrate gave straight lines passing through the origin (Figure 1). This indicated that the rate of oxidation was dependent on the first power of the concentration of the substrate. This was further demonstrated by the constancy in the values of k_2, the second-order rate constant.

Effect of oxidant

Under pseudo-first-order conditions, the individual kinetic runs were first-order with respect to the oxidant (QDC). When a constant concentration of substrate (large excess) was used, the pseudo-first-order rate constant (k_1) did not alter appreciably, with changing concentration of the oxidant (QDC), indicating a first order dependence of the rate on the concentration of the oxidant. The rate data have been shown in Table 3.

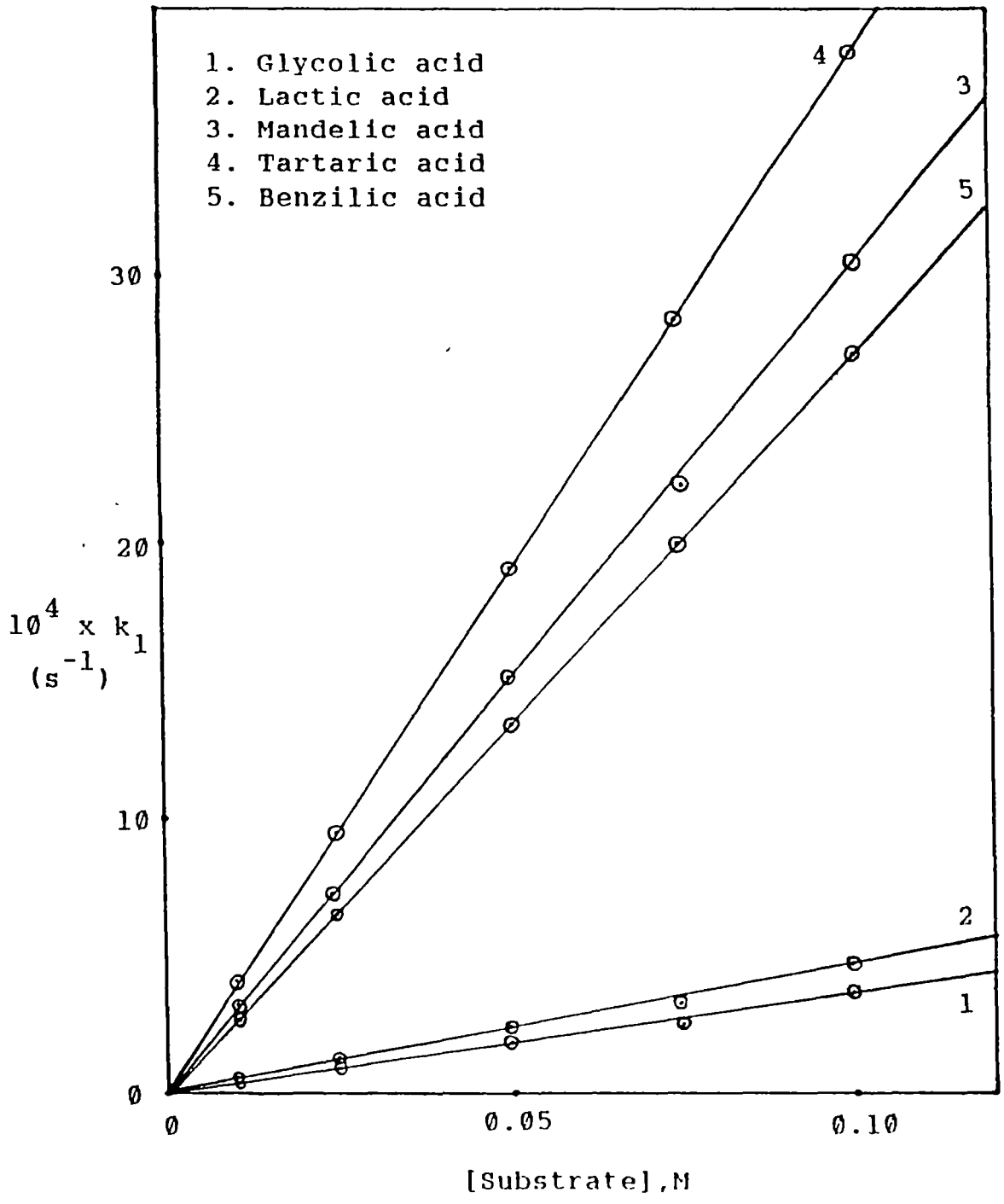


Fig.1. Plots of k_1 against the concentrations of substrates.

Table 3 : Dependence of Rate constants on the concentration of Oxidant, QDC in DMF.

[α-Hydroxy acid] = 0.01M, $[H_2SO_4]$ = 1M, T=313K.

* $[H_2SO_4]$ = 0.075 M

[QDC], M	0.0005	0.00075	0.001
$10^4 Xk_1, s^{-1}$ for:			
Glycolic acid	0.33	0.35	0.34
Lactic acid	0.40	0.41	0.43
Mandelic acid	2.95	3.0	3.1
Tartaric acid	4.0	4.1	4.1
* Benzilic acid	2.6	2.6	2.7

Effect of acid

The reaction was influenced by changes in the acid concentration, and the rate was observed to increase with an increasing concentration of the acid (Table 4).

Table 4: Dependence of Rate Constants on the concentration of acid [H_2SO_4], in DMF; [α-Hydroxy acid] = 0.01 M, [QDC] = 0.001 M, T=313K.

[H_2SO_4],M	0.50	0.75	1.0	1.25	1.50
10^4 X k_1,s^{-1} for:					
Glycolic acid	0.17	0.24	0.34	0.41	0.49
Lactic acid	0.21	0.32	0.43	0.54	0.66
Mandelic acid	1.5	2.2	3.1	3.7	4.5
Tartaric acid	1.9	3.0	4.1	5.2	6.3
[H_2SO_4],M	0.025	0.050	0.075	0.10	0.125
Benzilic acid	0.9	1.8	2.7	3.8	4.5
10^4 X k_1,s^{-1}					

Plots of log k_1 against log [H^+] were linear, with slopes equal to unity (Figure 2-3), indicating that the rate of the reaction was dependent on the first power of the concentration of the acid.

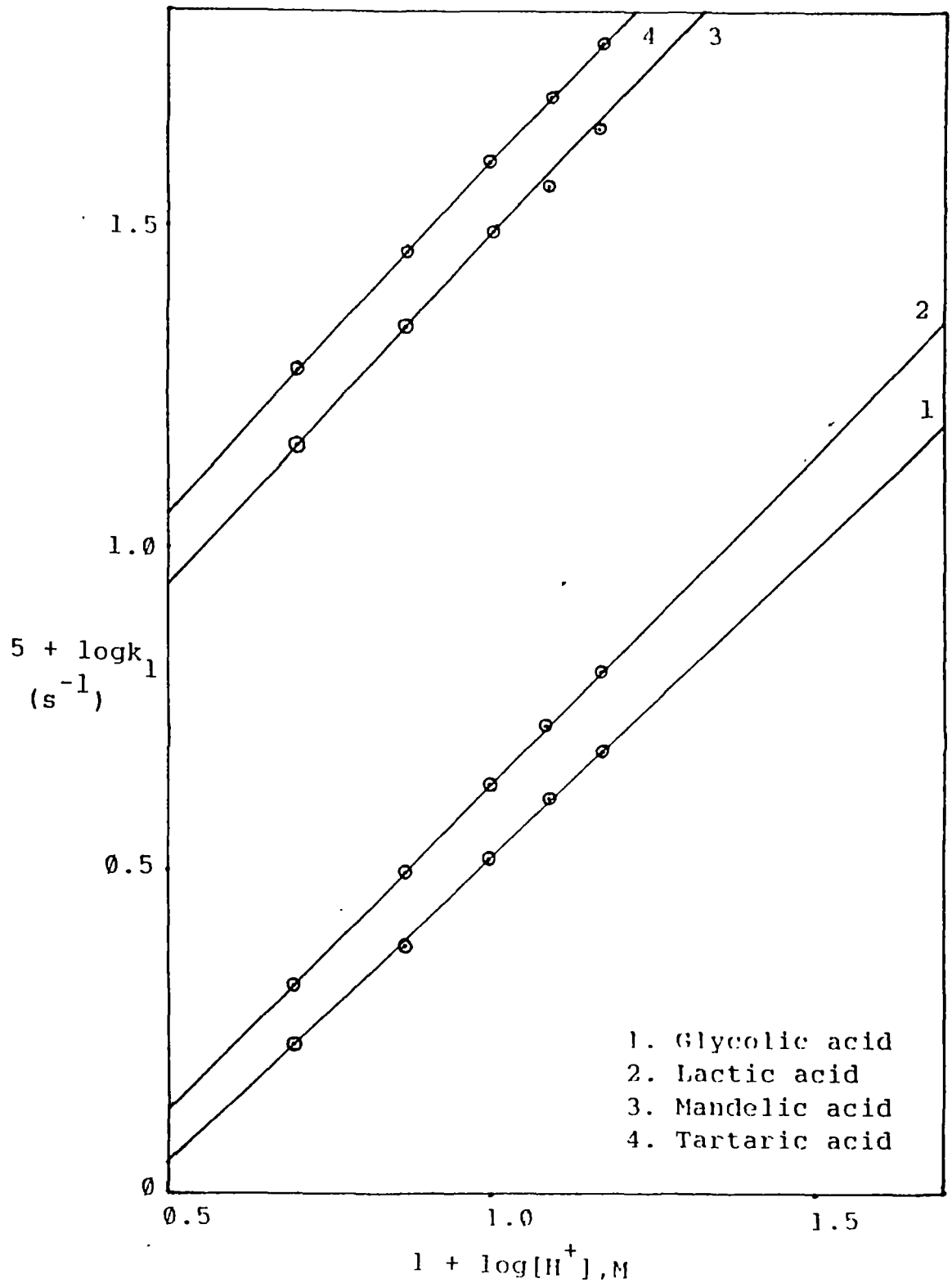


Fig.2. Plots of log k_1 against log[H^+]

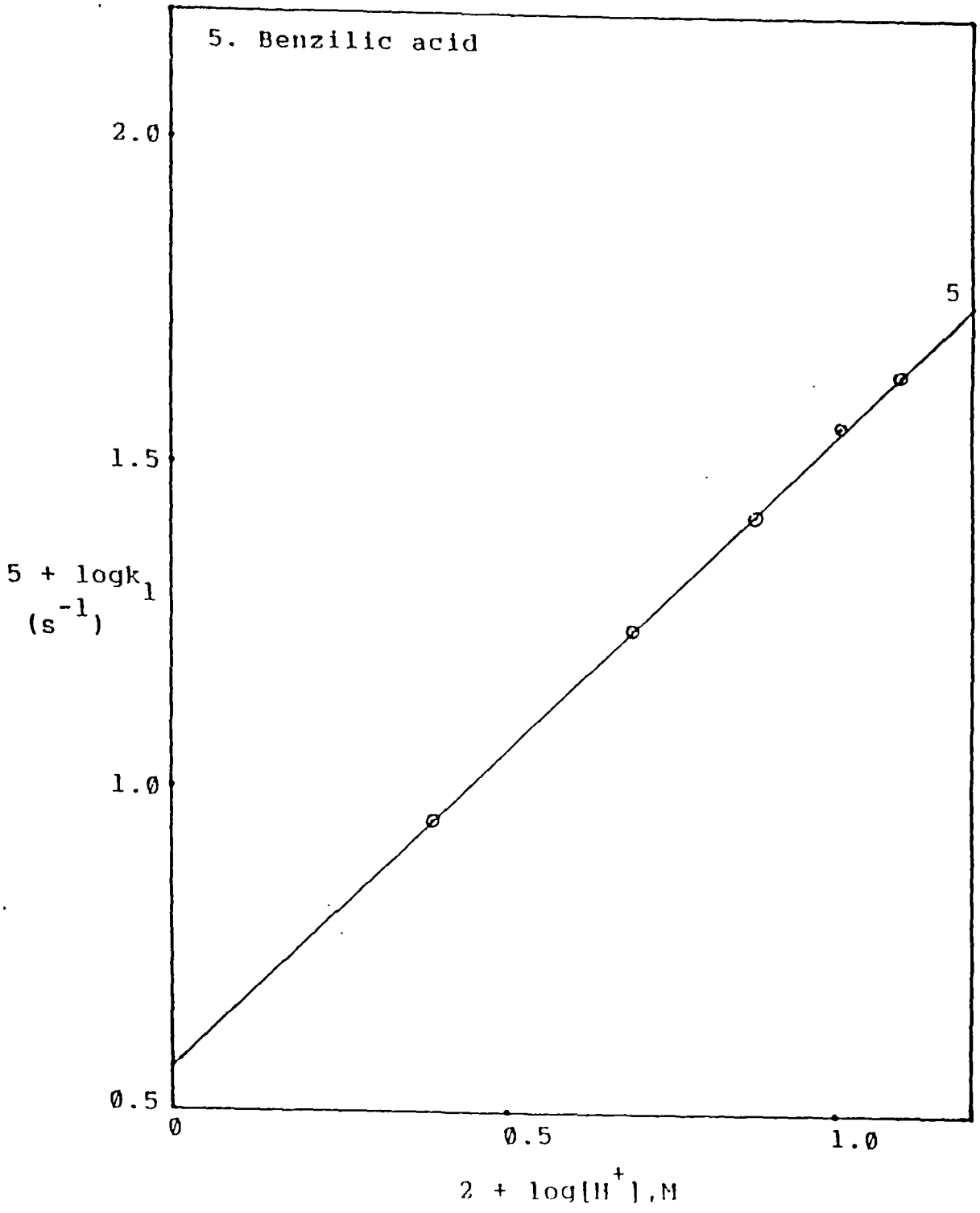


Fig.3. Plot of log k_1 against log[H^+]

The linear increase in the rate of oxidation with acidity suggested the involvement of a protonated chromium (VI) species in the rate-determining step. There have been earlier reports of the involvement of protonated Cr(VI) species in chromic acid oxidation reactions (30). Protonated Cr(VI) species have been observed in p-toluenesulphonic acid medium, in nitrobenzene-dichloromethane mixtures (31).

Rate law

Under the present experimental conditions, wherein pseudo-first-order conditions have been employed for all the kinetic runs, the observed rate law can be expressed as :

$$\text{Rate} = -\frac{d[Cr(VI)]}{dt} = k\,[\text{Substrate}]\,[QDC]\,[H^+] \qquad (4)$$

Effect of solvent

The reactions involving ionic reactants are susceptible to solvent influences. In the present investigation, the solvent was observed to play an important role. The acid-catalysed oxidation of the substrates was studied in solutions containing varying

proportions of DMF and water. For each of the substrates oxidized by QDC, the rate of oxidation was slowest in those solvent mixtures that contained the largest proportions of DMF and increasing proportions of water had resulted in an increase in the rate of oxidation (Table 5).

Table 5: Dependence of Rate Constants on the Solvent Composition (DMF : H_2O); [α-Hydroxyacid]= Ø.Ø1 M, [QDC]= Ø.ØØ1 M, $[H_2SO_4]$=1 M, T=313K.

*$[H_2SO_4]$ = Ø.Ø75 M

Dielectric Constant(D)	37.6	39.7	41.8	43.9	46.1
(DMF: H_2O,%,v/v)	(1ØØ:Ø)	(95:5)	(9Ø:1Ø)	(85:15)	(8Ø:2Ø)
$1Ø^4$ x k_1, s^{-1} for:					
Glycolic acid	Ø.34	Ø.61	1.42	1.84	2.91
Lactic acid	Ø.43	Ø.77	1.5Ø	2.3Ø	3.6Ø
Mandelic acid	3.1	4.Ø	4.9	5.9	6.5
Tartaric acid	4.1	4.4	4.7	4.9	5.1
* Benzilic acid	2.7	4.6	6.8	7.9	1Ø.5

The dielectric constants for DMF-water mixtures have been estimated from the dielectric constants of the pure solvents (32).

In the present investigation, in going from 80% DMF to 100% DMF, the polarity decreased. This decrease in polarity of the medium caused a decrease in the rate of the reaction (Table 5). Plots of log k_1 against the inverse of dielectric constants were linear, with positive slopes (Figure 4). This suggested an interaction between a positive ion and a dipole (33), and was in consonance with the observation that, in the presence of an acid, the rate-determining step involved a protonated chromium (VI) species.

On the basis of the solvating power of the solvent, a correct prediction of a qualitative nature could be made regarding the rate of the reaction in different solvent media. Solvent polarity can be used to rationalize the rate of the reaction and to account for the formation of a cationic intermediate. The decrease in the rate of the reaction, with increasing proportions of water (that is, a

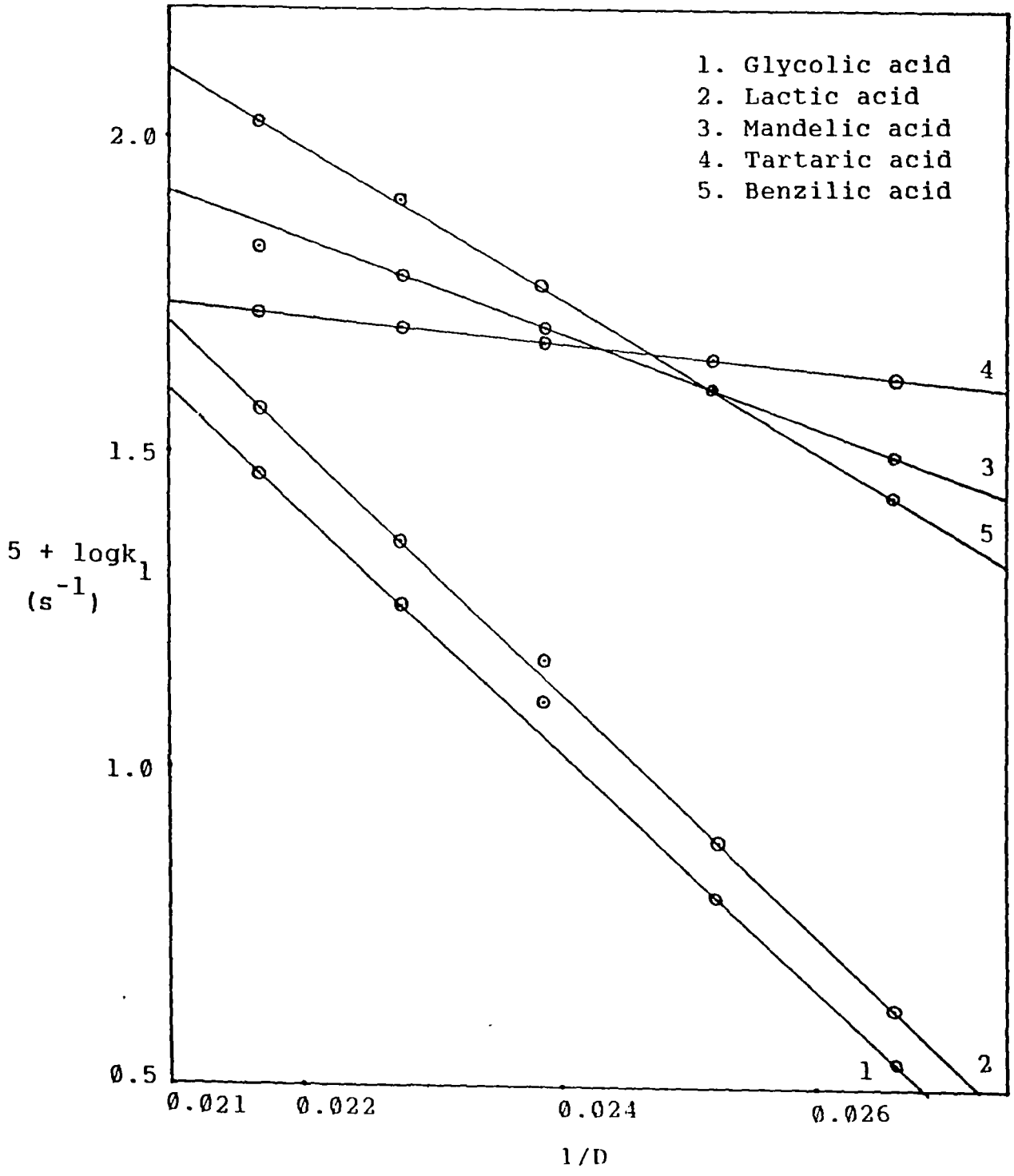


Fig.4. Plots of log k_1 against the reciprocal of dielectric constant.

more polar medium), may be related in part, to the conversion of the substrate to a positively charged species. A similar explanation had been advanced to account for the formation of a positively charged species, in the nitration of some aromatic compounds, in sulfuric acid media (34). The observed dependence of the reaction rate on solvent polarity (Table 5), supported the separation of charge in the transition state. In the rate determining step, therefore, the conversion of the substrate to a cationic intermediate would involve a destruction of charge. This would lead to a decrease in the rate of the reaction, in going from a less polar to a more polar solvent medium (that is, increasing proportions of water). The effect of a change in the solvent composition on reaction rates would also depend on factors such as solvent-solute interactions (35,36), and on solvent structure.

Effect of temperature

The rates of the reactions were influenced by changes in the temperature (Table 6).

Table 6: Dependence of Rate Constants on Temperature.

[α-Hydroxy acid] = 0.01 M, [QDC]=0.001 M,

$[H_2SO_4]$=1M ; * $[H_2SO_4]$ = 0.075 M.

Temperature K	303	308	313	318	323
10^4 X k_1, s^{-1} for:					
Glycolic acid	0.20	0.27	0.34	0.42	0.51
Lactic acid	0.28	0.37	0.43	0.51	0.64
Mandelic acid	2.05	2.58	3.1	4.0	4.5
Tartaric acid	2.07	3.43	4.1	5.1	6.0
* Benzilic acid	1.70	2.14	2.71	3.3	4.3

Plots of log k_1 against the inverse of temperature were linear (Figure 5), suggesting the validity of Arrhenius equation. The slopes of the plots were used to calculate the activation energies (vide "Experimental : calculations"). The activation parameters have been evaluated, and have been shown in Table 7.

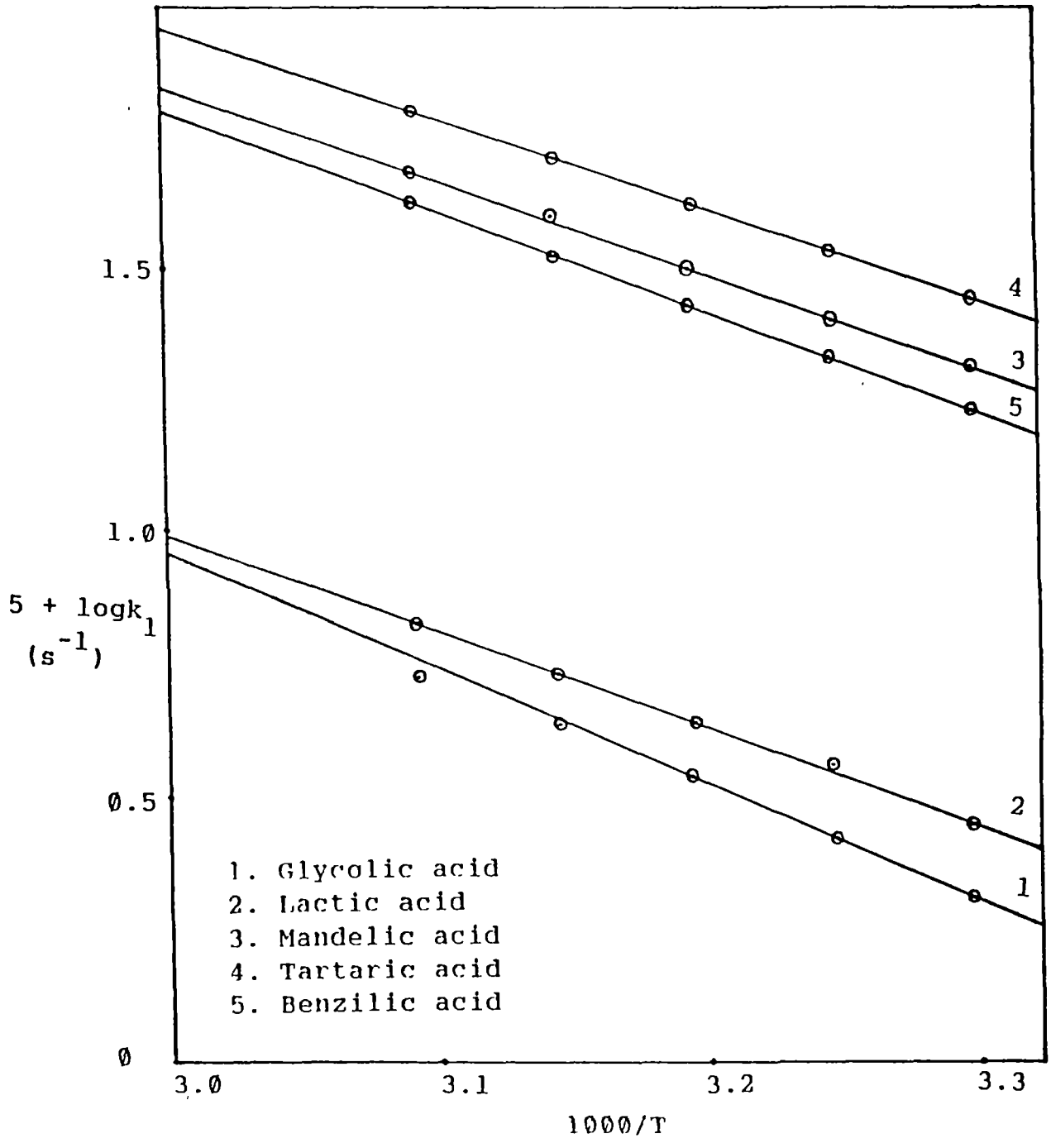


Fig.5. Plots of log k_1 against the reciprocal of temperature.

Table 7: Activation Parameters

α-Hydroxy acids	E ($kJ\ mol^{-1}$)	$\Delta H^{\neq}$ ($kJ\ mol^{-1}$)	$\Delta S^{\neq}$ ($JK^{-1}mol^{-1}$)	$\Delta G^{\neq}$ ($kJ\ mol^{-1}$)
Glycolic acid	32	29	-247	109
Lactic acid	33	30	-242	106
Mandelic acid	31	29	-233	103
Tartaric acid	33	30	-223	100
Benzilic acid	36	33	-217	104

Error limits: E ± 2 $kJ\ mol^{-1}$; $\Delta H^{\neq}$ ± 2 $kJ\ mol^{-1}$; $\Delta S^{\neq}$ ± 3 $JK^{-1}mol^{-1}$; $\Delta G^{\neq}$ ± 2 $kJ\ mol^{-1}$

The oxidation of all the substrates was characterized by negative entropies of activation. This would suggest that the transition state formed was considerably rigid, resulting in a reduction in the degrees of freedom of the molecules (37). Differences in the extent of solvation of the substrates, in the ground state and in the transition state, might also contribute to the negative entropies of activation (38). The similarities in $\Delta G^{\neq}$ values

for all the substrates arose due to changes in $\Delta H^{\neq}$ and $\Delta S^{\neq}$ values, and emphasized the probability that all these reactions involved similar rate-determining steps.

Induced polymerization

In the present investigation, since all the reactions were performed under nitrogen, the possibility of induced polymerization was tested. It was seen that there was no induced polymerization of acrylonitrile, or the reduction of mercuric chloride (39). This indicated that a one-electron oxidation was unlikely. Control experiments were performed in the absence of the respective substrates. The concentration of the oxidant (QDC) did not show any appreciable change.

Structural influences on the rates of oxidation

Since the structure - reactivity correlation gives an insight into the nature of the transition state, and throws some light on the mechanistic pathway of the reaction, an attempt was made to correlate the structure of the α-hydroxy acids with reactivity. The introduction of an

electron-donating methyl group enhanced the rate of oxidation (lactic acid > glycolic acid). Mandelic acid reacted faster than glycolic acid (and lactic acid), owing to the stabilization of the intermediate chromate ester by the phenyl group, through the resonance effect. The oxidation of benzilic acid by QDC had to be carried out at much lower acidities. With the presence of the two phenyl groups in its structure, the intermediate chromate ester could be further stabilized by their presence, through the resonance effect, resulting in the rate of oxidation of benzilic acid being the fastest in the series. Thus, the rates of oxidation of the hydroxy acids, under investigation, differed by factors which could be attributed to the effects of the substituent group, R, in facilitating the formation of the intermediate chromate ester. Hence, the order of reactivity observed :

Benzilic acid > Mandelic acid > Lactic acid > Glycolic acid,

could be justifiably rationalized.

Mechanism

It would be pertinent to examine the reaction pathways which have been proposed for the oxidation of α-hydroxy acids by various oxidizing agents. It has been shown that with Mn(III) pyrophosphate, the reaction pathway involved the reversible formation of a cyclic complex, which then underwent decarboxylation, resulting in the formation of a free radical (1). For some hydroxy acids, such as tartaric and malic acids, further extensive oxidation was observed, resulting in the formations of formic acid and carbon dioxide (1). Lead tetraacetate was observed to cleave α-hydroxy acids (40). This reaction involved a coordination of the hydroxyl group to the lead atom, followed by the loss of carbon dioxide. Alternatively, there was the possibility of coordination of both, hydroxyl and carbonyl groups, to the lead atom, followed by the decomposition of a cyclic intermediate (40). For the reaction between α-hydroxy acids and vanadium (V), the rate was dependent on the acidity constant, and a cyclic complex was formed (3). The formation of an organic radical was confirmed (tests with

acrylonitrile), with the liberation of carbon dioxide(3). In acid permanganate, the reaction with α-hydroxy acids involved a process of decarboxylation, resulting in the formation of benzaldelyde (41). The reaction between α-hydroxy acids, and ceric sulfate involved the rapid formation of an activated complex, which then decomposed slowly to form a free radical, H^+ ion, and a cerous complex (2). The reaction exhibited first-order dependence on each of the reactants, and an oxygen-hydrogen bond rupture was suggested (2). The oxidation of α-hydroxy acids by chromic acid proceeded by a mechanism similar to that of the oxidation of a secondary alcohol, wherein there was a cleavage of the C-H bond in the rate-determining step (4). A different reaction mechanism was suggested for the one-electron oxidation of α-hydroxy acids. The kinetic isotope effect for the oxidation of mandelic acid and α-deuteromandelic acid, (k_H/k_D=8.6) indicated that C-H bond cleavage occurred with chromic acid, but played only a minor part in the oxidations by manganese (III) and cerium (IV) sulfates (6). Further, with one-electron oxidants, the

oxidation rates for α-hydroxy acids were much more alike, and differed only by factors attributed to the effects of the substituent group, R, in facilitating the formation of the radical intermediates. Hence, the order of reactivity for the oxidation of α-hydroxy acids by one-electron oxidants (manganic sulfate and ceric sulfate) were as follows :

Mandelic acid > Lactic acid > Glycolic acid (6). In comparing the rates of oxidation of α-Hydroxy acids by Cr(VI) and Ce(IV), using varying proportions of acetone-water mixtures, the reactions were observed to be first-order with substrate and first order with the oxidants (7). It was further observed that the rate of oxidation with Cr(VI) was much faster than that with Ce(IV). This was rationalized on the basis that the point of rate-determining fission was different. In the case of Cr(VI) oxidation, there was the cleavage of the C-H bond with the loss of proton via an ester mechanism, as suggested in an earlier investigation (42). In the case of Ce(IV) oxidation, the rate-determining step was an O-H bond fission, confirmed by

the negligible kinetic isotope effect, k_H/k_D = 1.2 (6). The chromic acid oxidation of mandelic acid had yielded novel results. The observation that mandelic acid was oxidized to an almost equimolar mixture of benzaldehyde and benzoic acid, was interpreted by a mechanism, according to which an intermediate cyclic complex of mandelic acid and chromic acid decomposed in a three-electron oxidation-reduction step, with synchronous C-C and C-H bond cleavage (13). This reaction was the first example of an intramolecular three-electron oxidation, wherein there was the simultaneous cleavage of C-H and C-C bond to the same carbon atom, in the rate-determining step (13). Pyridinium chlorochromate (PCC, Corey's reagent) was used for the oxidation of hydroxy acids in 1:1 dichloromethane- nitrobenzene solution (14). The order of reactivity was observed as :

α-hydroxy butyric acid > lactic acid > glycolic acid. It was apparent that the introduction of an alkyl group had resulted in an increase in the rate of oxidation. Thus, electron donating groups increased the rate of oxidation, which indicated the presence of an electron

deficient carbon centre in the transition state. The kinetic isotope effect (k_H/k_D = 5.8Ø) indicated a cleavage of the C-H bond from the carbon atom bearing the functional group. All these kinetic results pointed to a hydride ion transfer in the rate-determining step. The products obtained from these oxidation reactions were the corresponding aldo or keto acids. The oxidation of substituted mandelic acids by permanganate, in alkaline medium, showed a first-order dependence of the rate on the oxidation of both, substrate and oxidant (43). The products and stoichiometric studies indicated that phenyl glyoxylic acid was obtained as the major product. A primary kinetic isotope effect (k_H/k_D = 3.9Ø) was observed, for the oxidation of mandelic acid by permanganate. All these results were explained in terms of a mechanism that involved the initial addition of a C-H bond to a manganese oxo double bond. The resulting organometallic compound then decomposed, by the homolytic cleavage of the Mn-C bond, to give manganate (VI) and a free radical (43). In the oxidation of mandelic and tartaric acids by chloramine-T, in alkaline medium, catalysed by Pd(II) ions,

it was shown that mandelic acid was oxidized to benzaldelyde, while tartaric acid gave glyoxal (21). The oxidation of glycolic, lactic, mandelic and malic acids by pyridinium hydrobromide perbromide (PHPB), in acetic acid-water mixtures, yielded the corresponding oxo acids (24). A primary kinetic isotope effect value (k_H/k_D = 5.07), for the oxidation of mandelic acid by PHPB, was very close to the value obtained in the oxidation of mandelic acid by bromine (44). This confirmed the cleavage of the C-H bond in the rate-determining step. These kinetic results were interpreted in terms of a mechanism involving hydride ion transfer to the oxidant. The oxidation of hydroxy acids (glycolic, lactic and mandelic acids) by potassium nitrosodisulfonate (PNDS, Fremy's radical), in aqueous acetate medium, revealed that one mole of hydroxy acid consumed two moles of PNDS (25). The products of oxidation were identified as the corresponding oxo acids. The mechanism proposed for this oxidation reaction involved a fast pre-equilibrium step leading to the formation of an adduct. The adduct disproportionated, in a slow step,

generating an intermediate radical. This radical then reacted with another molecule of PNDS, yielding the product. The observed order of reactivity was :

Mandelic acid > Lactic acid > Glycolic acid. Mandelic acid reacted much faster as a result of the stabilization of the intermediate R-$\dot{C}$(OH)-COOH radical, due to the presence of the phenyl ring (25). Copper (III) compounds have now been found to be useful for the oxidation of organic substrates. Copper (III) periodate and copper tellurate have both been used for the oxidation of α-hydroxy acids (28). The oxidation of α-hydroxy acids (benzilic, mandelic and citric acids) by Cu(III) periodate or Cu(III) tellurate gave the corresponding carbonyl compounds (28). The oxidation of α-hydroxy acids by benzyl trimethyl ammonium tribromide (BTMAB), in 1:1 acetic acid-water mixtures, yielded the corresponding carbonyl compounds (29).

It has now become amply clear that α-hydroxy acids can undergo a process of oxidation by different pathways. Depending on the nature of the oxidizing agent employed, there was the possibility of variations in the kinds of

products obtained for the oxidation of α-hydroxy acids.

It has been reported that the two pathways available for the oxidation of α-hydroxy acids have been the following :

(1) The oxidation pathway leading to the formation of the corresponding aldo-acids or keto acids.

(2) The oxidation process leading to the formation of the corresponding carbonyl compound, as a result of carbon-carbon bond cleavage, and a process of oxidative decarboxylation.

The literature is replete with examples wherein α-hydroxy acids underwent a process of decarboxylation. The oxidation of α-hydroxy acids by a variety of oxidants such as manganese (III) pyrophosphate (1), lead tetracetate (40), vanadium (V) in acid medium (3), ceric sulfate in sulfuric acid (2), acid permanganate (41), bromine-water (9), chromic acid (6-8, 10-12), 1-chlorobenzotriazole (16), chromium peroxydichromate (19), oxygen in the presence of copper (I) as catalyst (17), N-bromoacetamide in perchloric acid medium

(20), chloroamine-T in alkaline medium, catalysed by Pd(II) ions (21), N-bromosuccinimide in perchloric acid (23), copper (III) periodates and copper (III) Tellurates in alkaline medium (28)- all proceeded via a mechanism involving oxidative decarboxylation and a cleavage of the carbon-carbon bond to yield the corresponding aldehydes or ketones.

In spite of the fact that α-hydroxy acids reacted with several oxidants, resulting in the cleavage of the carbon-carbon bond and oxidative decarboxylation, several investigations have been carried out, wherein the α-hydroxy acids were converted to the corresponding aldo or keto acids. Such investigations were also directed towards oxidative methods for the preparation of α-aldo acids or α-keto acids from α-hydroxy acids, which would attempt to avoid or reduce the magnitude of oxidative decarboxylation. When the oxidations of α-hydroxy acids were carried out with oxidants such as ceric sulfate in sulfuric acid (6), cerium (IV) in acetone-water mixtures (7), chromic acid (13), pyridinium chlorochromate in dichloromethane-nitrobenzene

solution (14,15), tertiary butyl hydroperoxide catalysed by ruthenium (III) ions (18), pyridinium fluorochromate (PFC) (22), alkaline permanganate (43), pyridinium hydrobromide perbromide (PHPB) in acetic acid-water mixtures (24), potassium nitrosodisulfonate (PNDS, Fremy's radical) in aqueous acetate medium (25), pyridinium bromochromate (26), pyridinium chlorochromate in acid medium catalysed by ruthenium (III) ions (27), and benzotrimethyl ammoniumtribromide (BTMAB) in acetic acid-water mixtures (29), the products obtained were the corresponding aldo acids or keto acids. All the above oxidation processes, wherein α-hydroxy acids were converted to the corresponding α-aldo or α-keto acids, had suggested the absence of any carbon-carbon bond cleavage or oxidative decarboxylation.

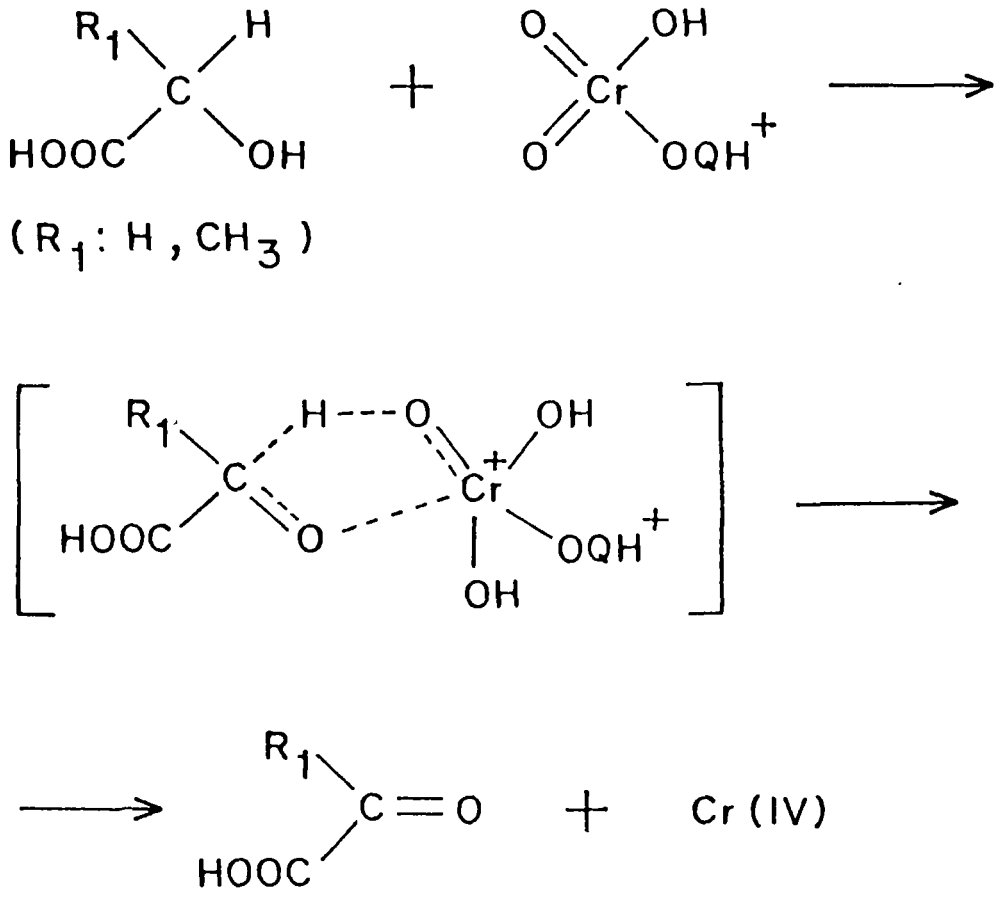
In the present investigation, the kinetic data and the nature of the products formed would help in deciding the reaction pathways for the oxidation of α-hydroxy acids by quinolinium dichromate (QDC), in acid medium. The present experimental data indicated that QDC was able to oxidize the α-hydroxy acids by both pathways. The nature of the pathway

for the oxidation process by QDC seemed to depend on the nature of the α-hydroxy acids.

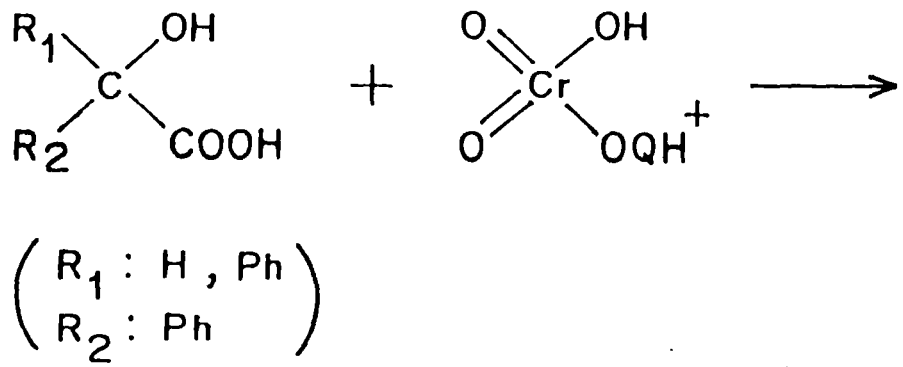
The oxidation of glycolic acid and lactic acid by QDC, in acid medium, resulted in the formation of the corresponding aldo and keto acids (glyoxylic acid and pyruvic acid) respectively. The formation of these products clearly indicated the absence of any oxidative decarboxylation. There was no evolution of carbon dioxide at any stage of these oxidation processes. Further, there was no cleavage of the carbon-carbon bond, as envisaged by the nature of the products obtained. If the carbon-carbon bond had been cleaved, then the products would have been formaldehyde and acetaldehyde (from the oxidation of glycolic acid and lactic acid, respectively). These products were not obtained. Thus, the reaction pathway could be visualized as proceeding via a hydride ion transfer in the rate-determining step. The hydride ion transfer would involve the prior formation of a chromate ester (45), which would undergo decomposition to give the products (glyoxylic acid and pyruvic acid, from the oxidation of glycolic acid

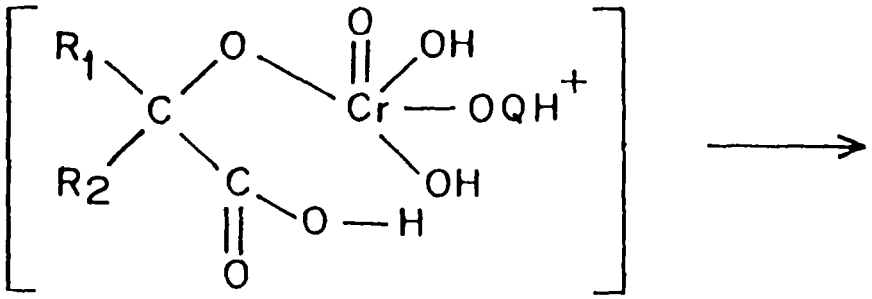
and lactic acid, respectively), as shown in scheme 1. The products obtained, in each case, were characterized by spectral analysis, and by the preparation of the corresponding 2,4-dinitro phenylhydrazone derivatives (vide "Experimental : Product Analysis").

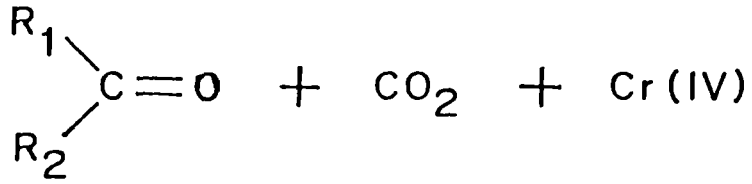
The oxidation of mandelic acid and benzilic acid by quinolinium dichromate (QDC), in acid medium, gave benzaldehyde and benzophenone respectively, as the major products, with carbon dioxide being evolved. This clearly indicated that α-hydroxy acids containing phenyl group(s) could facilitate the process of decarboxylation, as a result of the stabilization of the chromate ester by the phenyl group(s), through the resonance effect. The process of oxidative decarboxylation, in these oxidation processes, could be interpreted by a mechanism by which the intermediate chromate ester (formed by the reaction between these α-hydroxy acids and QDC), underwent decomposition, with the cleavage of the carbon-carbon bond (Scheme 2). The formation of benzaldehyde (from mandelic acid) and benzophenone (from benzilic acid) was confirmed by spectral



Scheme – 1


R1
OH
C
R2
COOH
+
O
OH
Cr
O
OQH+
(R1 : H , Ph
R2 : Ph)


R1
O
O
OH
C
Cr — OQH+
R2
C
OH
O — H
O


R1
C=O
R2
+
CO2
+
Cr(IV)

Scheme – 2

analysis, and by the preparation of the respective 2,4-dinitrophenyl hydrazone derivatives (vide "Experimental: Product Analysis").

It can thus be justifiably proposed that quinolinium dichromate, in acid medium, could oxidize aliphatic α-hydroxy acids, having primary or secondary OH groups (glycolic and lactic acids), to the corresponding aldo or keto acids in good yields. In the case of the aromatic α-hydroxy acids, QDC in acid medium was able to oxidize α-hydroxy acids having secondary or tertiary OH groups (mandelic acid and benzilic acid), by a process involving the cleavage of the carbon-carbon bond, leading to oxidative decarboxylation.

The reaction sequence involving the formation of the chromate ester intermediate satisfactorily explained the observed kinetic data. The ester would be better stabilized in the presence of solvents of high polarity. That is, an increase in the polarity of the solvent medium would accelerate the rate of oxidation (Table 5). Further, the variation in the reaction rate for the oxidation of

α-hydroxy acids by QDC (Table 2) could also be reconciled with the ester mechanism, since the chromate ester formation was likely to be little influenced by structural changes (46).

The oxidation of tartaric acid by Mn(III) pyrophosphate involved the reversible formation of a cyclic complex, which then underwent carbon-carbon bond cleavage, resulting in the formation of a free radical and the loss of carbon dioxide (1). Further extensive oxidation followed, with tartaric acid being degraded to carbon dioxide and formic acid. Manganous ions (Mn^{2+}) were observed to retard the rate of oxidation. In many respects, the oxidation of tartaric acid was similar to that for the oxidation of pinacol by Mn(III) pyrophosphate (47). The rupture of its oxidation products, and the absence of oxidation with dimethyl tartarate, showed that tartaric acid exhibited both kinds of behaviour due to the presence of the two hydroxyl groups. The similarity in the nature of oxidation of tartaric acid and pinacol by Mn(III) pyrophosphate thus indicated that a similar mechanism was involved in both

these oxidation reactions. The mechanism involved the rapid, initial, reversible formation of a chelated manganic complex, and a change in the colour of the solution (pink–>brown) in the case of tartaric acid clearly showed the occurrence of a complex formation. The final oxidation product, in the oxidation of tartaric acid by Mn(III) pyrophosphate, was formic acid and carbon dioxide (47).

The kinetics of oxidation of tartaric acid by chloramine-T in alkaline medium, in the presence of palladium (II) ions as catalyst, reported a first order dependence of the rate on each, substrate and the catalyst. The products obtained from this oxidation reaction were glyoxal, glyoxylic acid and formic acid (21). When low concentrations of chloramine-T were used, tartaric acid was oxidized primarily to glyoxal (21).

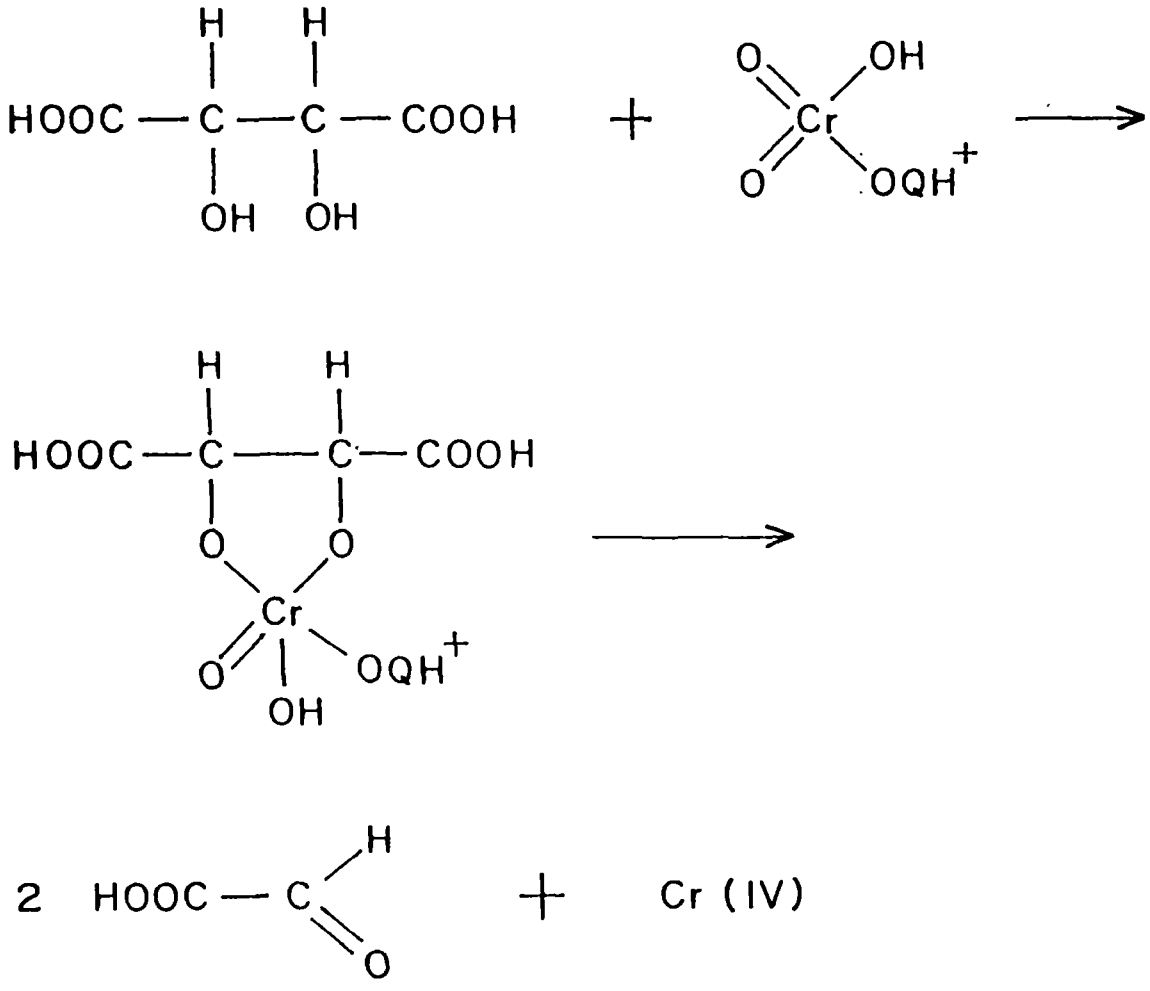
The kinetics of oxidation of tartaric acid by N-bromosuccinimide in perchloric acid medium, catalysed by palladium (II) ions, showed a first-order dependence on the concentration of each, substrate and catalyst (23). The oxidation products of tartaric acid were characterized as

glyoxylic acid and formic acid (23).

In the present investigation, the oxidation of tartaric acid by QDC, in acid medium, in the presence of DMF as solvent, indicated a first-order dependence on the concentrations of each of the reactants-substrate, QDC, and H^+ ions. The oxidation product obtained from tartaric acid was glyoxylic acid. This was characterized by ir-spectroscopy, wherein bands were obtained at 1730 cm^{-1} (saturated aldehyde), and 3450 cm^{-1} (O-H stretching). Further, the 2,4-DNP derivative of the product (glyoxylic acid) was prepared (mp 124-125^{o}C). Since the product from the aqueous layer was obtained in trace amounts, there was the possibility of the glyoxylic acid undergoing a process of oxidative decarboxylation to give formaldehyde (vide experimental: "Product Analysis") which could then be oxidized to formic acid. Thus, in the present investigation, the kinetic data and the nature of the products formed, would help to decide the reaction pathway for the oxidation of tartaric acid by QDC, in acid medium. The formation of glyoxylic acid, as the major product, indicated that there

was a cleavage of the carbon-carbon bond bearing the two hydroxyl groups in tartaric acid. The reaction pathway involved the formation of a cyclic chromate ester, which underwent symmetrical carbon-carbon bond cleavage to give glyoxylic acid as the major product. There was the possibility of a similarity in the nature of oxidation pathways, for the oxidations of tartaric acid and pinacol by QDC. Both these compounds possess hydroxyl groups on adjacent carbon atoms, which would facilitate the formation of a cyclic chromate ester, wherein there would be some amount of steric strain in the transition state. This strain would be relieved when the cyclic intermediate would undergo further oxidation involving a process of bond cleavage occurring between the two carbon atoms containing the hydroxyl groups. Although the rates of oxidation of pinacol and tartaric acid by QDC were quite divergent (pinacol >> tartaric acid), yet the similarity in the oxidation pathways can be justifiably rationalized, on the basis of the nature of the products formed and the cleavage of the carbon-carbon bond involved in the final step of the oxidation process.

The mechanistic sequence for the oxidation of tartaric acid by QDC in acid medium is shown in Scheme 3.


H H
HOOC — C — C — COOH
OH OH
O OH
Cr
O OQH+
H H
HOOC — C — C — COOH
O O
Cr
O OQH+
OH
2 HOOC — C H
O
Cr (IV)

Scheme – 3

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SUMMARY

SUMMARY

Hexavalent chromium compounds have been widely used as oxidizing agents reacting with diverse kinds of organic substrates. The mechanism of oxidation varies with the nature of chromium(VI) species and the solvent used. The development of newer chromium(VI) reagents for the oxidation of organic substrates continues to evince keen interest. Over the years, a large number of novel chromium(VI) oxidizing agents have been introduced especially for complex or highly sensitive substances where great selectivity and effectiveness, coupled with mildness of conditions, are prerequisites for success.

Some of the chromium(VI) reagents which have been used as efficient oxidizing agents have included:
Chromium trioxide; chromyl chloride; Jones reagent - a solution of chromium(VI) oxide in concentrated sulfuric acid(1); Collins reagent- dipyridinium chromium(VI) oxide in dichloromethane(2); chromium(VI) oxide adsorbed on solid supports such as graphite, silica, alumina, silica gel, and

celite(3,4); Corey's reagent - pyridinium chloro-chromate(PCC) in dichloromethane(5); pyridine oxodiperoxo chromium(VI) reagent - a complex of chromium pentoxide with pyridine(6); pyridinium dichromate(PDC) used either in solution in dimethylformamide or as a suspension in dichloromethane(7); bis-tetrabutyl ammonium dichromate (TBADC) in refluxing dichloromethane(8); Chaudhuri's reagent-pyridinium fluorochromate in dichloromethane(9); 4-(dimethylamino)pyridinium chlorochromate(10); tetrabutyl ammonium chlorochromate (TBACC) in chloroform(11); bis-(trimethylsilyl) peroxide (BTSP) in dichloromethane, in the presence of pyridinium dichromate(PDC)(12); pyridinium chlorochromate(PCC) in conjunction with 3,5-dimethyl pyrazole(DMP) in dichloromethane(13,14); chromium(VI) oxide diperoxide(15); diverse chlorochromate reagents such as benzyltrimethyl ammonium chlorochromate (BTMACC), tetrabutyl ammonium chlorochromate(TMACC) in dichloroethane(16); some fluorochromates such as tetramethyl ammonium fluoro-chromate(TMAFC) and tetrabutyl ammonium fluoro chromate(TBAFC) also in dichloroethane(16); tetrakis

(pyridine) silver dichromate in refluxing benzene(17); peroxyacetic acid as the stoichiometric oxidant and a catalytic amount of 2,4-dimethylpentane-2,4-diol cyclic chromate in carbon tetrachloride-dichloromethane mixtures (18); chlorotrimethylsilanechromium trioxide(19); benzotriazole in conjunction with pyridinium chlorochromate(PCC) in dichloromethane(20); 2-cyanopyridinium chlorochromate and powdered molecular sieves in dichloromethane(21); 3-carboxy pyridinium dichromate and 4-carboxypyridinium dichromate in pyridine(22); a small quantity of anhydrous acetic acid added to pyridinium dichromate(PDC) and freshly activated molecular sieve powder in dichloromethane(23); chromium peroxide complexes(24); imidazolium dichromate(IDC) in dimethylformamide(25); pyridinium bromochromate(PBC) in chloroform(26); benzyltriethyl ammonium chlorochromate (BTACC) generated in situ under phase transfer conditions in refluxing chloroform(27); biphosphonium dichromate reagents(28); zinc-dichromate trihydrate in dichloromethane(29); catalytic amounts of chromium trioxide and an excess of aqueous

t-butylhydroperoxide(30); cyanopyridinium chlorochromate (CPCC) in dichloromethane(31); pyridinium chlorochromate in conjunction with silica gel and by the use of the ultrasound technique(32); pyridinium chlorochromate(PCC) in chloroform, using anhydrous acetic acid as a catalyst (33); 1-methyl imidazolium chlorochromate (MCC) and imidazolium chlorochromate (ICC) in chloroform (34); isoquinolinium chlorochromate in dichloromethane (35); ferric dichromate, polyvinylpyridine supported zinc dichromate, and polyvinylpyridine supported ferric dichromate, taken in acetonitrile(36), and chromium trioxide in the presence of wet aluminium oxide taken in hexane (37).

The most recent chromium (VI) reagent which has been introduced for the oxidation of organic substrates has been quinolinium fluorochromate (QFC), used in chloroform as solvent (38). This reagent has been used for the oxidation of alcohols, polycyclic arenes and diphenyl sulfide, and the yields reported have been excellent (38).

The reagent employed in the present investigation has been quinolinium dichromate (QDC), $(C_9H_7NH^+)_2Cr_2O_7^{2-}$.

This reagent was first reported to have been used for the oxidation of primary and secondary alcohols to aldehydes and ketones respectively, and for the oxidation of aldehydes to acids(39). This reagent has now emerged as a very useful and versatile oxidant, and has been used for the oxidation of a variety of organic substrates. When taken in dimethylformamide or in dimethylformamide-water mixtures, in the presence of an acid, quinolinium dichromate (QDC) was found to be very efficient for the oxidation of benzyl alcohols (40), arylalkanes (41), diphenylamines (42), polynuclear aromatic hydrocarbons(43,44), toluene and substituted toluenes(44,45), fluorene(46), amino acids(47), benzoin(48), styrenes(49), unsaturated acids(50), bicyclic alcohols(51), cyclic alcohols(52), and allylic alcohols(53).

The present investigation focuses attention on the kinetic features pertaining to the oxidation of various organic substrates by quinolinium dichromate (QDC) in acid medium, using water and water-acetic acid mixtures (in the case of diols), and dimethylformamide and dimethyl-formamide-water mixtures (in the case of α-hydroxy acids),

as the solvents, under a nitrogen atmosphere. The rationale governing the present kinetic investigation has been to enlarge the scope of this versatile oxidizing agent, quinolinium dichromate (QDC), in acidic medium, and to provide experimental evidence for the mechanistic pathways of reactions involving diverse organic substrates. The substrates which have been used for the purpose of oxidation by quinolinium dichromate (QDC), in acid medium, using water and water-acetic acid mixtures, (in the case of diols), and DMF and DMF-H_2O mixtures (in the case of α-hydroxy acids), have included the following :

1. Diols - Chapter 1

(a) Acyclic vicinal diols (1,2-ethanediol, 1,2-propanediol, 1,2-butanediol and pinacol).

(b) Cyclic vicinal diol (trans-1,2-cyclohexanediol).

(c) Acyclic non-vicinal diols (1,3-butanediol, 1,4-butanediol and 1,5-pentanediol).

2. α-Hydroxy acids - Chapter 2

(a) Aliphatic α-hydroxy acids (glycolic acid, lactic acid,

and tartaric acid).

(b) Aromatic α-hydroxy acids (mandelic acid and benzilic acid).

Chapter 1 - Kinetics of Oxidation of Diols

The kinetics of oxidation of diols (vicinal and non-vicinal) by quinolinium dichromate (QDC) has been studied in acid medium, using water and water-acetic acid mixtures as the solvent, under a nitrogen atmosphere. The progress of the reaction was followed spectrophotometrically, by observing the disappearance of chromium(VI) at 440 nm. For all the diols studied, stoichiometric ratios, Δ[QDC]/Δ[substrate], in the range 0.65 - 0.72 were obtained. The rate of the reaction was found to be dependent on the first powers of the concentration of each reactant (substrate, oxidant and acid). The linear increase in the rate of oxidation with acidity suggested the involvement of a protonated chromium(VI) species in the rate-determining step.

The reaction has been found to be slowest in those solvent mixtures that contained the largest proportions of water, and increasing proportions of acetic acid resulted in an increase in the rate of oxidation. Plots of log k_1 (the pseudo-first-order rate constant) against the inverse of the

dielectric constant were linear, with positive slopes. This suggested an interaction between a positive ion and a dipole (54), and was in consonance with the observation that, in the presence of an acid, the rate-determining step involved a protonated chromium (VI) species.

The reactions were studied over a range of temperatures, and it was observed that the Arrhenius equation was obeyed. Plots of log k_1 against the reciprocal of temperature were linear. The activation energies and the different activation parameters were evaluated. The reactions were characterized by negative entropies of activation. This suggested an ordered transition state, relative to the reactants. The isokinetic temperature, obtained from the plot of $\Delta H^{\neq}$ against $\Delta S^{\neq}$ was 250K. Although current views do not attach much physical significance to isokinetic temperature, a linear correlation between $\Delta H^{\neq}$ and $\Delta S^{\neq}$ is usually a necessary condition for the validity of the Hammett equation. It was further found that the values for the free energies of activation ($\Delta G^{\neq}$) were nearly constant, indicating that the same mechanism operated for the

oxidation of all the diols studied in this investigation.

There was no induced polymerization of acrylonitrile or the reduction of mercuric chloride. This indicated that a one-electron oxidation was unlikely.

It seemed pertinent to attempt a general correlation between the rate of oxidation of all these diols by QDC and the proximity of the hydroxyl groups. The observed order of reactivity for the oxidation of diols by QDC showed that :

(a) 1,4-butanediol > 1,2-ethanediol ;

(b) 1,3-butanediol > 1,2-propanediol ;

(c) trans-1,2-cyclohexanediol > 1,5-pentanediol ;

(d) pinacol was oxidized at a rate faster than any of the other diols under investigation.

The order of reactivity showed that compounds having vicinal hydroxyl groups reacted the slowest, which indicated that there was no cyclic mechanism operating in these oxidation reactions. Hence, the order of reactivity observed in (a) and (b) above could be justified.

For the diols listed in (c) above, the order of reactivity could be rationalized on the basis of a difference in the ease of ester decomposition.

For pinacol, the rapid rate of reaction was ascribed to steric crowding of the methyl groups and the absence of an α-hydrogen atom. Relief in the steric strain resulted in a rapid rate of decomposition of the cyclic chromate ester. The net result was the cleavage of the bond between the vicinal alcohol carbon atoms.

For the diols listed in (a), (b) and (c) above, the mechanistic pathway could also be confirmed by the nature of the products obtained. In the absence of products which would have resulted from carbon-carbon bond fission, it is suggested that an acyclic mechanism would be operating in these oxidation reactions. The major part of the diol was oxidized in a manner $\backslash / CHOH \longrightarrow \backslash / C{=}O$. It was further observed that the fission of these diols could not be brought about in the presence of added free acid. Hence, it would be justified to postulate that all these diols reacted with quinolinium dichromate (QDC) to give the corresponding

α-hydroxycarbonyl compounds. Such a pathway was established to be energetically more favourable than that yielding the fission product, to the extent of 15 kcal per mole or more (55). It was further observed that the rates of oxidation and the enthalpies of activation favoured the formation of the hydroxycarbonyl compounds, which suggested that the structure of the transition state was quite near to that of the products. Cyclic ester formation involving both the hydroxyl groups was thus unlikely. The mechanistic pathway would be an acyclic process via the chromate ester, which then underwent decomposition by a rate-determining carbon-hydrogen bond fission.

This mechanistic pathway was supported by the following correlations :

(a) Oxidizing agents such as periodic acid, lead tetraacetate and phenyliodoso acetate (used primarily to cleave 1,2-diols) do not readily oxidize diols to α-hydroxycarbonyl compounds (55), as do oxidizing agents such as chromic acid or permanganate.

(b) The Zimmerman treatment of electrocyclic reactions

showed that the oxidative cleavage of 1,2-diols by periodate was an allowed electrocyclic process. The corresponding reaction of 1,2-diols by Cr(VI) was shown to be a forbidden process (56). This excluded the operation of a cyclic mechanistic pathway and supported the view that the oxidation of diols by QDC involved the normal pathway, that is, the conversion of $\backslash/CHOH \longrightarrow \backslash/C{=}O$.

The rate of oxidation of pinacol was much higher than the rate of oxidation of any of the other vicinal or non-vicinal diols. Since, there was no hydrogen atom on the carbon atom bearing the hydroxyl groups, a change in mechanism with increasing methyl substitution was proposed. Here, the formation of a cyclic chromate ester became more probable. This intermediate underwent decomposition, resulting in the cleavage of the carbon-carbon bond. The major product obtained was acetone, which would be possible only if the oxidation process involved the formation of a cyclic chromate ester intermediate.

Under the experimental conditions employed in the

present investigation, all the vicinal and non-vicinal diols were oxidized by quinolininum dichromate (QDC), in acid medium, to the corresponding α-hydroxycarbonyl compound. The products obtained were characterized by the respective 2,4-dinitrophenylhydrazone derivatives and by ir analysis.

Under the present experimental conditions employed in the present investigation, pinacol was oxidized by QDC, in acid medium, to acetone, which was characterized by its 2,4-dinitrophenylhydrazone derivative.

In the present investigation, the kinetic data obtained showed that quinolinium dichromate could be used to oxidize diols (vicinal and non-vicinal) to give the corresponding α-hydroxycarbonyl compounds in good yields. It can be suggested that this efficient reaction could prove to be a very useful and general route for the synthesis of α-hydroxycarbonyl compounds. The oxidation of pinacol by quinolinium dichromate had resulted in the formation of acetone, due to the cleavage of the carbon-carbon bond. Such a mechanistic pathway indicated that this could be the general sequence for the oxidation of diols which do not

possess a hydrogen atom attached to the carbon atom bearing the hydroxyl groups.

Chapter 2 - Kinetics of Oxidation of α-Hydroxy acids

The oxidation of α-hydroxy acids by various oxidants is an important and well-known reaction. Earlier work on the oxidation of α-hydroxy acids have been reported, wherein oxidants such as manganic pyrophosphate(57), ceric sulfate(58,59), vanadium(V)(60), 1-chlorbenzotriazole(61), oxygen in the presence of copper(I) as catalyst(62), N-bromoacetamide(63), chloramine-T in alkaline medium(64), N-bromosuccinimide(65), pyridinium hydrobromide perbromide (66), potassium nitrosodisulfonate(67), copper (III) periodate and copper(III) tellurate(68), benzotrimethyl-ammonium tribromide(69) have been employed. Chromic acid and various other chromium(VI) oxidizing agents(70-81) have also been used for the oxidation of α-hydroxy acids.

The present work is a detailed kinetic investigation of the oxidation of α-hydroxy acids (glycolic acid, lactic acid, mandelic acid, benzilic acid and tartaric acid) by quinolinium dichromate (QDC), in acid medium, using dimethylformamide (DMF) and dimethylformamide - water (DMF-H_2O) mixtures as the solvent, under a nitrogen

atmosphere. The course of the reactions was monitored by observing the disappearance of chromium(VI) at 440 nm, spectrophotometrically. The stoichiometric ratios, Δ[QDC]/Δ[Substrate], were in the range 0.64 - 0.73. The rate of the reaction was observed to be dependent on the first powers of the concentrations of each reactant (substrate, oxidant and acid). The rate of oxidation showed a linear increase with acidity, which suggested the participation of a protonated chromium(VI) species in the rate-determining step.

The role of the solvent in these oxidation reactions was investigated. It was observed that the rate of oxidation decreased with decrease in the polarity of the medium, in going from 80% DMF to 100% DMF. Plots of log k_1 (pseudo-first-order rate constant) against the reciprocal of the dielectric constant were linear, with positive slopes, indicating an ion-dipole type of reaction.

The effect of changes in temperature on the rate of the reaction was studied, and the Arrhenius equation was found to be valid. The activation energies and the other

activation parameters were evaluated. The negative entropies of activation($\Delta S^{\neq}$) indicated that the transition state formed was considerably rigid, resulting in a reduction in the degrees of freedom of the molecule. The similarities in $\Delta G^{\neq}$ values for all the substrates arose due to changes in $\Delta H^{\neq}$ and $\Delta S^{\neq}$ values, and emphasized the probability that all these reactions involved similar rate-determining steps.

It was observed that there was no induced polymerization of acrylonitrile or the reduction of mercuric chloride. This indicated that a one-electron oxidation was quite unlikely.

It has been established that α-hydroxy acids could undergo a process of oxidation by different mechanistic pathways. Based on the nature of the oxidizing agent used, there was the possibility of variations in the kinds of products obtained, for the oxidation of α-hydroxy acids. It has been reported that the two pathways available for the oxidation of α-hydroxy acids, have been as follows :

(a) The oxidation pathway resulting in the formation of the corresponding aldo- or keto-acids.

(b) The oxidation process leading to the formation of the corresponding carbonyl compounds (due to carbon-carbon bond cleavage), and a process of oxidative decarboxylation.

In the present investigation, the experimental data indicated that quinolinium dichromate(QDC) was able to oxidize the α-hydroxy acids by both these pathways. The nature of the pathway for the oxidation process seemed to be dependent on the nature of the α-hydroxy acids.

The oxidation of glycolic acid and lactic acid by QDC, in acid medium, had resulted in the formation of the corresponding aldo- and keto-acids (glyoxylic acid and pyruvic acid respectively), which clearly indicated the absence of any oxidative decarboxylation. There was no cleavage of the carbon-carbon bond, as seen by the nature of the products obtained. Hence, the reaction pathway could be visualized as proceeding by way of a hydride ion transfer in the rate-determining step. The hydride ion transfer could involve the prior formation of a chromate ester (82), which

could then undergo decomposition to give the products. The products obtained (glyoxylic acid and pyruvic acid respectively), were characterized by spectral analysis and by the preparation of their corresponding 2,4-dinitrophenylhydrazone (DNP) derivatives.

The oxidation of mandelic acid and benzilic acid by QDC, in acid medium, yielded benzaldehyde and benzophenone respectively, as the major product, with the evolution of carbon dioxide. The formation of these products indicated that α-hydroxy acids containing phenyl group(s) would facilitate the process of decarboxylation, owing to the stabilization of the chromate ester by the phenyl group(s) through the resonance effect. The mechanistic pathway involved the formation of the intermediate chromate ester, which underwent decomposition with the cleavage of the carbon-carbon bond, and the evolution of carbon dioxide. The formation of the respective products (benzaldehyde and benzophenone) was confirmed by spectral analysis and by the preparation of the respective 2,4-dinitrophenylhydrazone (DNP) derivatives.

In the present investigation, the kinetic data obtained indicated that quinolinium dichromate, in acid medium, could oxidize aliphatic α-hydroxy acids having primary or secondary hydroxyl groups (glycolic and lactic acids), to the corresponding aldo- or keto-acids in good yields. In the case of aromatic α-hydroxy acids, quinolinium dichromate, in acid medium, could oxidize α-hydroxy acids having secondary or tertiary hydroxyl groups (mandelic acid and benzilic acid), by a process involving the cleavage of the carbon-carbon bond leading to oxidative decarboxylation. The reaction sequence, which involved the formation of the chromate ester intermediate, satisfactorily explained the observed kinetic data. The ester formed would be better stabilized in the presence of solvents of high polarity. Thus, an increase in the polarity of the solvent media accelerated the rate of oxidation. Further, variation in the reaction rate for the oxidation of α-hydroxy acids by QDC was in conformity with the ester mechanism, since the chromate ester formation was likely to be little influenced by structural changes.

In the present investigation, the oxidation of tartaric acid by QDC, in acid medium, had yielded glyoxylic acid, which was characterized by spectral analysis and by its 2,4-dinitrophenylhydrazone (DNP) derivative. Since, this product was obtained in trace amounts, it could be suggested that there was the possibility of glyoxylic acid undergoing a process of oxidative decarboxylation to yield formic acid. The formation of glyoxylic acid indicated that there was the cleavage of the carbon-carbon bond bearing the two hydroxyl groups in tartaric acid. The mechanistic pathway involved the formation of a cyclic chromate ester, which underwent symmetrical carbon-carbon bond cleavage to give glyoxylic acid. The presence of hydroxyl groups on adjacent carbon atoms would facilitate the formation of a cyclic chromate ester, involving some amount of steric strain in the transition state. There would be a relief of the steric strain when this cyclic intermediate underwent further oxidation. This would involve a process of bond cleavage, occurring between two carbon atoms containing the hydroxyl groups.

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