THE SOILS AND TUNNEL-GULLY EROSION
OF A SMALL CATCHMENT IN THE
WITHER HILLS
BLENHEIM

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CHAPTER I

INTRODUCTION

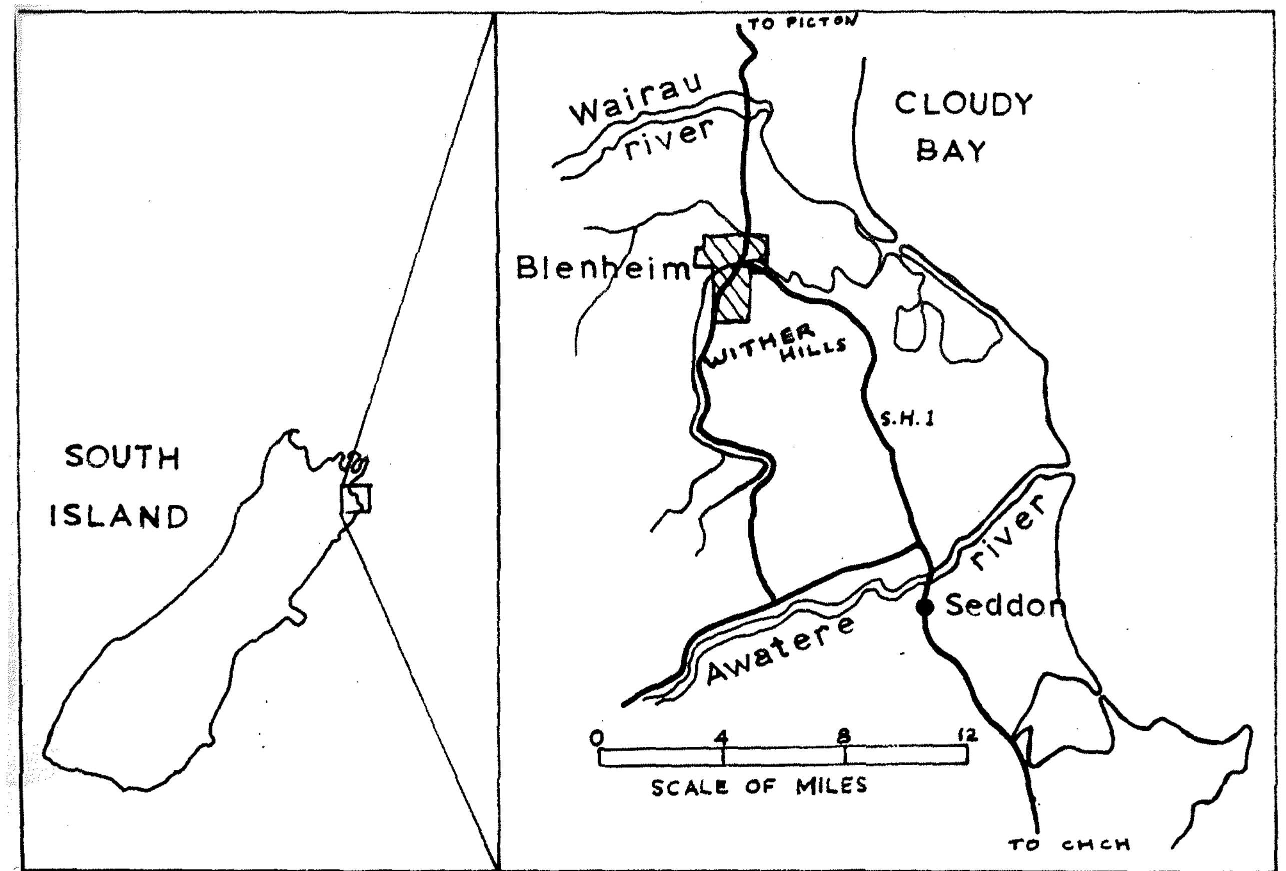
1.1 GENERAL INTRODUCTION

The Wither Hills encompass a range of strongly rolling and steep land rising to a maximum altitude of 422 m (1385ft) a.s.l. south of Blenheim in Marlborough province. They comprise the northern section of the dividing range between the lower Wairau and Awatere valleys, and are demarcated to the west by the Taylor river and to the east by the Dashwood Pass and State Highway No 1. (fig 1).

The Wither Hills are particularly prone to tunnel-gully erosion, a compound erosion form initiated by subsurface tunnelling followed by collapse of surface and followed by deep, open gullying. Tunnel erosion has also been reported from the U.S.A., China, Turkey, South Africa, and Australia, and described under a variety of names such as piping, pothole erosion, rodentless erosion, subcutaneous erosion and underrunners. But all refer to an essentially similar subsoil erosion process whereby downslope movement of subsoil particles causes the formation of underground cavities. Subsequent enlargement leads to their eventual collapse to produce open gullies.

Tunnel-gully erosion has been observed in many localities in New Zealand, particularly in areas to the east of the main mountain chains in both North and South Islands where sub-humid climates predominate. A close relationship appears to exist between the reported incidence of tunnelling and the type of

Fig.1 LOCATION



soil in which it occurs. Yellow-grey earths formed from loessial deposits comprise the major group in which tunnel erosion has been observed. These soils occur in environments with sub-humid climates of less than 750mm (30ins) average annual rainfall in parts of Hawkes Bay, Wairarapa, Marlborough, Canterbury and Otago. However similar erosion forms have been reported in soils from mudstone and other sedimentary materials in North Auckland and the Waikato region and from volcanic ash in the Central North Island. These tunnelled soils occur in moist climates with average annual rainfalls up to 1750mm (70ins).

The Wither Hills exhibit the most severe forms of tunnel-gully erosion in New Zealand and has seriously interfered with agricultural production both on the hills themselves and on the plains below. In its extreme forms this type of erosion may cause considerable damage to large areas downstream from the erosion source through deep accumulation of transported sediments in addition to the loss of production on the tunnel-gullied sites. Less severe tunnel-gully erosion may still adversely affect production downstream through blockage of drains and ephemeral water courses as well as increasing the risk of stream and river overflow. Sediment discharged into water courses from tunnel-gully erosion pollutes the water flow and decreases its quality and usefulness regardless of purpose for which it is required. Hence for permanent, continuous land use at maximum production according to its capability, the treatment and control of tunnel-gully erosion is of prime importance, even though the productivity of the soils subject to erosion may be low.

1.2 OBJECT OF THE INVESTIGATION AND METHOD OF APPROACH

The primary aim of this research is to study in detail the soil pattern and erosion characteristics of a small representative catchment in the Wither Hills, and to determine the interrelationship between soil properties, both field and laboratory, on the initiation of tunnel erosion and its sequential development into open gullying.

The basic steps of this approach to the problem of tunnel-gully erosion are briefly outlined below:

1. A survey of the soils of the representative catchment in order to delimit the problem. It was noticed from cursory examination of the Wither Hills that tunnel-gully erosion was not prevalent over every section of the landscape. The lower spurs and ridges seemed to be relatively free of tunnel gullies, although minor ones were apparent in isolated localities. The main ridges and higher slopes of the hills were definitely devoid of this erosion form although scars of former slips were evident.

2. (a) A detailed study of a toposequence on those soils where the tunnel-gully problem was most acute. This involved intensive field and laboratory determinations in an effort to relate pedological, chemical and physical properties to the incidence and severity of erosion.

(b) In addition this detailed study was used to characterise these soils as typical of the dry-subhygrous, central yellow grey earth subgroup, on the basis of their morphology, chemistry, mineralogy and physical properties.

3. To fully describe the process of tunnel-gully formation as it occurs in the field.

4. To compare the tunnel-gullied soils of the Wither Hills with:

(a) soils from other regions showing similar erosion forms,

(b) with soils in similar environments but not liable to tunnel-gully erosion.

It was thought that such a comparison using morphological properties and selected laboratory determinations would help explain the susceptibility of some soils to tunnel-gullying and also the actual process of tunnel formation.

Considerable time was devoted to the soil survey to gain as much information as possible on the geomorphology and pedology of the representative catchment so as to relate slope development and soil formation which were seen to be interdependent. Hence, an attempt to understand the genesis of these soils is an essential part of the work as not all yellow grey earths have exactly the same pedogenic history.

The ultimate aim of the whole study was to elucidate the tunnel-gully erosion pathway on the Wither Hills, and to provide such data that practical methods could eventually be devised to control existing tunnel-gullies.

CHAPTER II

REVIEW OF THE LITERATURE

2.1 HILLSLOPES AND SOIL GENESIS

Moss (1966) suggested there are at least two different approaches to the study of slope - soil relationships:

(i) study of catenae in which changes in soil characteristics from summit to valley bottom are related to variations in slope, and

(ii) examination of planation surfaces and depositional features in relation to soils, thus relating soil development to erosional history.

The former approach is exemplified by Pallister (1956), Ollier (1959), and Webster (1965). The latter is typified by Ruhe (1969), Butler (1959), Ruhe and Walker (1968), Jessup (1960), and McCraw (1967, 1968).

The catenary concept was introduced by Milne (1935). He defined the catena as a unit of mapping convenience, a group of soils which are linked interdependently in their occurrence by conditions of topography. They are repeated in the same relationships to each other whenever the same conditions are met with. Milne (loc cit) originally used the catenary concept in an effort to relate soils and landscapes on the ancient African surface, an area of low, subdued relief.

Ruhe (1956), Butler (1959, 1967) and Jessup (1961) and others have stressed the importance of periodic covers of aeolian and alluvial materials on one hand and of erosional cycles on the other.

The concept of 'periodicity' of landscapes and soil formation was evolved by Butler (loc cit). In this theory eras of instability with erosion and deposition are alternated with eras of stability with soil formation. Butler suggested the term groundsurface for the soil landscape and designated the chronological order of ground surfaces as K1, K2, K3,... Kn, from the uppermost (most recent) to the lower and older ones in each region.

The term 'pedomorphic surface' was used by Dan and Yaalon (1968) to describe the relationship between soil landscapes. The pedomorphic surface is similar to Butler's groundsurface but incorporates also the nature of the processes shaping it.

In New Zealand, Taylor (1948) introduced the concept of soil development through the interaction of three processes: (a) soil wasting, (b) the organic cycle, (c) the inorganic cycle or Drift Regime. The Drift Regime relates soil formation to position on the landscape through consideration of the geomorphic and pedologic processes of erosion, accumulation, mixing and flushing.

Soils are regarded as dominantly regressive or dominantly accumulative by Taylor and Pohlen (1962) according to current processes affecting landforms.

2.1.1 Quantitative Toposequence Studies

The relationships between soils on different parts of the landscape have most effectively been approached through the study of toposequences. In this approach a transect from drainage divide to valley floor is described in order to characterize the soils formed on the major elements of the landscape.

Various landform parameters were recorded with soil profile observations by Walker et al (1968) across small loess and drift landscapes in Iowa. Simple regression and correlation were used to examine the relationship between each soil property and landform parameters. Generally, elevation and slope characteristics were the parameters most strongly related to soil properties.

Kingston (1968) measured morphological and physical properties of soils at four different landscape positions in the Moutere Hills, Nelson. Sites were examined at the crest, convex upper slopes, concave lower slopes and concave gully bottoms. Overall relief was strongly rolling. For most soil properties significant trends occurred from crest sites to gully bottoms. Also, site index of _Pinus radiata_ showed a marked increasing trend from crest to gully. Statistical analysis revealed that relative position on the landscape was the variable most highly correlated with site index for _Pinus radiata_. The differences in site indices were attributed by Kingston to long term regressive processes accelerating nutrient depletion on convex positions with the counter processes of accumulation and flushing on concave sites allowing improved tree growth.

Losche et al., (1970) investigated numerous properties of soils on two positions of steeply sloping landscapes in the Southern Appalachian mountains of the U.S.A. One moderately steep soil-landscape comprised highly siliceous sandstone and siltstone parent materials. The soils were very similar to each other in morphological, physical, chemical and mineralogical properties irrespective of position on slope. Losche et al., suggested that the lack of variety of precursor minerals in the highly siliceous parent material was responsible for the uniformity in soils. In contrast, soil differences were noted between upper and lower slope positions on a steeply sloping landscape comprising granitic biotite gneiss parent material. The soils of the lower slope position were of a more advanced stage of weathering than soils of the upper slope sites. No explanation was proposed for the difference.

Ruhe and Walker (1968) used hillslope models to assess the interrelationship of geomorphic and pedologic processes.

Using their hillslope model with open drainage system on loessial soils they found that sola thicknesses and other selected soil properties decreased exponentially from the crest downslope across the shoulder to the backslope. Ruhe and Walker maintained that the shoulder position represented the junction of younger unstable hillslopes with older, stable summits. The relationship between particle size and position on hillslope was examined by Franzmeier et al., (1969). The soils in the middle slope positions contained higher percentage of coarse material than upper and lower sites. The lower slope positions had higher base status which was attributed to seepage and concentration of vegetation litter prior to decay and release of bases.

Investigation of a hillslope from summit to alluvial positions by Kleiss (1970) revealed that particle size variations within the soil A horizons were due to sedimentologic sorting. Mean particle size in the surficial sediments showed a systematic decrease within two separate subsets down the hillslope. The A horizon properties of O.M. content, bulk density, and C.E.C. were dependent on position on slope. Kleiss considered that most of the soil properties were inherited from the sedimentary nature of the surficial material rather than indicating pedologic development.

2.1.2. Summary.

From the brief review of literature presented previously the following points are apparent:

(i) Several approaches to the study of soil-landscape relationships are possible. (Moss 1966).

(ii) No simple hillslope model is applicable to all soil landscapes.

(iii) Slope-soil relationships are complex because of the great variation in soil forming factors within geomorphic regions (Losche et al; 1970) and even within the same hillslope (Kleiss, 1970).

2.2 TUNNEL EROSION IN NATURAL SOILS

2.2.1 Factors of the Environment

In New Zealand the relation between loess derived soils and incidence of tunnel erosion has been mentioned by several investigators. (Gibbs, 1945; Jackson, 1966; Hosking, 1967.) In his appraisal of the severity of tunnel erosion in New Zealand, Cumberland (1944) noted the occurrence of tunnel erosion in Hawkes Bay, Marlborough, Taranaki hinterland, Banks Peninsula, South Canterbury and the mid-Clutha valley. Subsequent correlation of tunnelled soils within these localities (Soil Bureau Staff 1968a) shows that all except those of the Taranaki hinterland are on loess or have sola partly derived from loess. All the soils susceptible to tunnel erosion in the South Island are associated with loessial deposits of varying thickness (Soil Bureau Staff 1968b). These loessial soils liable to tunnelling are classified exclusively into the yellow grey earth soil group (Soil Bureau Staff 1968b).

The presence of pipes in non-aeolian sedimentary materials in North Auckland and the Hamilton Basin have been described by

Ward (1966) and Selby (1967). The occurrence of tunnels in soils from mudstones in the eastern Wairarapa was noted by Jackson (1966). Pipes in volcanic ash and pumice soils in the central North Island have been described by Selby (1970). Australian research shows that soils susceptible to tunnelling are mainly from marine sedimentary materials such as shales, slates, sandstones and quartzites. (Downes, 1946; Newman and Phillips, 1957; Charman, 1969a, 1970). Most Australian investigators have shown that tunnelled soils are correlated with Great Soil Groups particularly the Solonetz, Solodised Solonetz, and Solod groups where salt accumulation has markedly affected soil properties (Downes, 1956; Monteith, 1954; Ritchie, 1963; Charman, 1969b, 1970). In coastal N.S.W. Charman (loc cit) found that the Podzolic group of soils were also liable to tunnelling. In addition Ritchie (loc cit) noted that some Red-Brown Earths were tunnelled in N.S.W.

In the U.S.A. it appears that most soils showing tunnelling are derived from alluvium. (Fletcher and Carroll, 1948; Fletcher et al, 1954; Brown, 1962.) From a study of tunnelled soils in eight semi-arid regions of the U.S.A. Parker (1963) found that the parent materials ranged from sands to clays.

The relation between tunnelled soils and subhumid or semi-arid climates with droughty summers is acknowledged by most researchers to date (Gibbs, 1945; Downes, 1946; Newman and Phillips, 1957; Brown, 1962; Parker, 1963; Hosking, 1967). In contrast, Selby (1967) mentions the occurrence of pipes in the Waikato area of the North Island with annual rainfalls over 1500mm (60ins) and with moist summers. Similarly Ward (1966) described piping in North Auckland under annual rainfalls of up to 1750mm (70ins). Another climatic feature commonly quoted is the likelihood of irregular high intensity storms (Downes, 1946; Newman and Phillips, 1957; Brown, 1962; Ward, 1966;) in areas subjected to tunnelling. In a discussion of piping in arid regions of the U.S.A. Peterson (1954) concluded that climate has little or no influence on piping since it is as likely to be found in Montana as in Arizona.

The association between tunnel erosion and prior land denudation due to overgrazing by stock and/or rabbit infestation has been stressed by numerous investigators (Gibbs, 1945; Downes, 1946; Newman and Phillips, 1957; Fletcher and Carroll, 1948; Brown, 1962; Parker, 1963; Hosking, 1967). On the other hand, Cumberland (1944) noted tunnelling processes in various soils all with tough, "matted swards". Likewise Ward (1966) found pipes most commonly situated in pasture lands although some were found under manuka scrub and rain-forest. In coastal N.S.W. the presence of tunnels under well covered pasture and forest was noted by Charman (1969, 1970).

Tunnels have been described on various classes of slopes varying from gently undulating (Brown, 1962; Charman, 1969, 1970; Parker, 1963;) and rolling land (Ward, 1966) to moderately steep and steep (Gibbs, 1945; Charman, 1969; Miller, 1971). Gibbs (loc cit) noted that although some tunnels occured on slopes of 10 degrees they were the headward continuation of tunnels on steeper gradients downslope. Charman (1970) mentioned the presence of tunnels on slopes ranging from gently undulating to moderately steep on his study area in N.S.W. In the North Auckland region Ward (1966) found that tunnels were most commonly situated on slopes less than 12 degrees.

2.2.2. Soil Properties

Detailed morphological, physical and chemical properties of soils susceptible to tunnelling are rare in the literature. Generally only brief descriptions of a few selected morphological properties such as texture and structure have been included in discussions on tunnelling - similarly, few investigators have included adequate chemical or physical data to substantiate their claims as to the soil properties associated with the tunnelling process.

Dispersibility and soil cracking are the two soil properties almost universally stated as being crucial in tunnel erosion processes.

The importance of sodium salts or exchangeable sodium in promoting deflocculation of clay particles has been described by numerous researchers (Gibbs, 1945; Downes, 1956; Brown, 1962; Fletcher and Carroll, 1948; Fletcher et al.; 1954; Monteith, 1954; Charman, 1969, 1970; Miller, 1971). In Australia Downes (1956) outlined the properties of the Solod soil group as being acid throughout, with low content of soluble salts and low exchangeable calcium, making subsoils readily dispersible on wetting. In the Hunter Valley of N.S.W. Monteith (1954) states that tunnels are formed in the Solodised Solonetz and Solod soils which are characterized by sodium clays easily dispersed on saturating with water. Detailed laboratory examination of soil samples from piping areas in Southern Arizona led Fletcher and Carroll (1948) to the conclusion that tunnel erosion is primarily caused by high exchangeable sodium. However subsequent work by Fletcher et al (1954) on the exchangeable sodium analyses for soils from five areas subject to piping showed that sodium in the exchange complex ranged from zero to greater than 90%.

On this basis they suggested that while sodium may contribute to the severity of tunnel erosion it is by no means necessary for the occurrence of tunnelling.

In explanation of the ready dispersibility of many soils in coastal N.S.W., Charman (1969, 1970) suggests that the continual leaching effect of rainfall charged with cyclic salt maintains the high exchangeable sodium content of soils susceptible to tunnelling.

For tunnelled soils in Colorado, Brown (1962) postulated that in the later stages of tunnel formation the continued washing of excess salts in soil cracks leaves sodium salts of low concentration able to disperse the soil aggregates.

The role of exchangeable sodium and soluble sodium salts in affecting dispersion of clay particles has been comprehensively studied in relation to tunnelled soils on the Port Hills by Miller (1971). In general he found that the higher the exchangeable sodium percentage the greater was the soil dispersion, using the dispersibility test devised by Ritchie (1963).

The importance of soil dessication in initiating surface cracks extending into the subsoil has been propounded by most researchers (Gibbs, 1945; Cumberland, 1944; Downes, 1946; Fletcher and Carroll, 1948; Newman and Phillips, 1957; Brown, 1962; Parker, 1963; Hosking, 1967; Ward, 1966; Miller, 1971).

Several Australian authors have commented on the ability of the strong columnar structures in subsoils of Halomorphic soils to channel water between structural columns, particularly when the overlying horizons are bared and sheet eroded (Monteith, 1954; Downes, 1956).

As evidence in verification of observed cracking in tunnelled soils from Colorado, Brown (1962) measured volumetric shrinkage values of between 20% and 40% determined on puddled soils. It must be noted though, that his samples were oven dried and probably exaggerate the actual shrinkage under field conditions.

Ritchie (1963) used the standard Keen-Rackowski method of measuring volume expansion of disturbed samples when wetted. He stated that soils showing a volume expansion of greater than 10% were highly susceptible to tunnelling. The same criterium was applied by Charman (1969, 1970) in coastal N.S.W. to determine soils susceptible to tunnelling.

For tunnelled soils on the Port Hills, Miller (1971) obtained linear expansions (vertical direction) of between 0.059% and 0.127% for samples with moisture contents at approximately field capacity. Although these values represent a very low degree of swelling, he none-the-less observed unmistakeable signs of cracking associated with tunnelling.

In Hosking's (1967) study area on the Port Hills it was recorded that considerable cracking occurred on the exposed surface soil during times of moisture deficiency, but that tunnels formed only when cracks extended into the subsoil.

On the severely tunnelled Wither Hills, Gibbs (1945) measured soil fissures from 3mm (0.12in) to 9mm (0.36in) in width and 305mm (1ft) to 3.6m (12ft) long which extended deeply into the subsoil.

After studying piping in eight semi-arid regions of the U.S.A., Parker (1963) concluded that a <u>cracking potential existed in all soils where piping occurred. It was especially greatest at depths where the pipes were formed</u>. He stated that swelling clays, particularly montmorillonite were common in subsurface horizons. The clays were highly dispersed on wetting but shrank on drying to leave deep fissures between soil aggregates.

In North Auckland, Ward (1966) noted that soils susceptible to tunnelling had structureless A horizons which were subject to cracking on dessication. This was particularly so where the pipes were best developed. Swelling clays (metahalloysite and montmorillonite) characterized the surface and subsurface horizons of piped soils.

The importance of a hardpan in relation to the tunnelling process was stressed by Gibbs (1945). Its role in preventing collapse and in acting as a roof to the tunnel was a feature of the tunnelling process. Hosking (1967) noted the presence of a similar hardpan on the Port Hills and suggested that it acted in a similar capacity to that stated by Gibbs.

Other investigators have described hard, compact impermeable soil layers but <u>in all cases they occur below a highly dispersible layer and appear to act as tunnel floors</u>.

Soil texture does not appear to be correlated with the incidence of tunnelling. Tunnels have been described in soils with textures ranging from sands to clays. In New Zealand most tunnelled soils have textures that are predominantly silty (Gibbs, 1945; Cumberland, 1944; Miller, 1971), although Jackson (1966) has described tunnels from loessial deposits near Wellington which have clay loam textures. Also in Northland Ward (1966) has described pipes in clayey soils, as has Selby in the Hamilton basin (1967). The tunnelled soils in Victoria and N.S.W. are mainly clay (Monteith, 1954; Downes, 1956; Charman, 1969, 1970; Newman and Phillips, 1957).

In Colorado, Brown (1962) studied pipes formed in soils of widely varying texture, from silt loam to clay. An analysis of variance to determine the statistical significance of the differences in texture indicated that they were not significant.

2.2.3 Processes of Tunnel Erosion

The simple tunnelling process as envisaged by Cumberland (1944) was that water moving down subsoil cracks removed the highly erodible silt particles of the subsoil thus carving out a tunnel. The final stage is the collapse of the roof as the tunnel enlarges to form open gullies.

The proposed mechanisms of tunnelling on the Wither Hills were described in some detail by Gibbs (1945). The major stages as he outlined the process are:

(i) surface runoff was intercepted by cracks and rabbit holes to cause soaking of the silty C horizon. Voids were developed in this horizon by (a) the packing effect of alternate wetting and drying, (b) packing effect of deflocculation resulting from solution of soluble salts and (c) removal of particles in suspension into the loose gravels beneath.

(ii) Once formed the voids were rapidly enlargened by the scouring and backtrickling action of flowing water.

(iii) The compact B horizon above the C (horizon) was relatively impervious and remained stable after the removal of silt from beneath it.

(iv) Tunnel enlargement caused localised subsidence and finally complete collapse to form an open gully.

The reconstruction of the tunnelling process by Gibbs (loc cit) indicates that formation of an outlet is not necessary for the development of tunnels.

Observations made on the Port Hills by Hosking (1967), indicated that the soil hardpan acted similarly in forming a tunnel roof as outlined by Gibbs (loc cit). However, Hosking (loc cit) stated that some sort of outlet was necessary before the system of subsoil cracks united to form a tunnel.

Australian studies by Downes (1946), Monteith (1954) and Newman and Phillips (1957), stressed the importance of outlet formation before tunnelling took place.

The tunnelling mechanism proposed by Downes (loc cit) and Newman and Phillips (loc cit) briefly is:

(i) Water enters soil at an area of increased infiltration (cracks, rabbit burrows, tree stump holes etc). Dispersion of subsoil occurs.

(ii) The excess water exerts hydrostatic pressure and causes surface breakthrough lower down slope.

(iii) Tunnels then develop rapidly both up and downslope.

(iv) General collapse of the complete tunnel to form an open gully is the final stage.

Monteith (loc cit) proposed that sheet erosion exposed the columnar structures in the C horizon of susceptible halo-morphic soils. Water concentration in the cracks between columns eventually found a pressure release point in the side of a gully. The subsoils were easily dispersed and flowed from saturated areas leaving behind a tunnel.

From detailed field examination in Southern Arizona, Fletcher and Carroll (1948) concluded that two conditions were necessary for piping:

(i) water must have access to the subsoil at a greater rate than the substratum can absorb it, and

(ii) there must be a ready outlet for the resultant lateral flow of water. They distinguished two basic processes of tunnelling. In one method tunnels were initiated at exposed, vertical banks by the washing out of highly dispersible subsoil particles and extended upslope towards their water sources. In the other process tunnels were formed by soil cracking and/or dispersion of subsoil particles with outlets forming downslope due to hydraulic pressure.

After further studies of piping in five different areas in Arizona, Fletcher et al., (1954) found that pipe outlets universally occurred at free faces; (entrenched waterways, ditches, or any soil cut deeper than 60cms). From their brief description of erosion processes it appears that most tunnels originate upslope of the outlets.

In discussion of piping processes in the semi-arid regions of the U.S.A., Parker (1963) noted that pipes were usually developed in the vicinity of gullies which provided a free face for the initiation of pipes.

In the three tunnelled areas of Colorado studied by Brown (1962) it was postulated that tunnel initiation took place at the walls of gullies. The basic stages of the process he envisaged are:

(i) A steep hydraulic gradient was created by the formation of a large gully in a valley floor.

(ii) Soil cracking occurred throughout the profile from dessication.

(iii) Soil structures are highly aggregated because of very high salt contents.

(iv) When subjected to subsurface flow towards the gully the highly aggregated soil structures reacted like sand. Granules from the gully wall are washed away creating a depression which progressively deepens and widens.

(v) Continued washing of soil adjacent to cracks leaches out the excess salt. The remaining sodium salts then disperse the aggregates and initiate even more accelerated erosion.

In the Whangarei area of Northland, Ward (1966), found that the preferred locations for tunnelling erosion features are downslope of water collection zones, e.g. near valley heads, reservoirs and in ground depressions. Only a limited number of examples of pipe discharge into gullies were observed. He suggested that the pressure exerted by swelling clays in the subsoil when wetted may be of importance in the formation of pipes down which water is forced. The ready dispersion of clay particles was considered to further assist subsurface movement causing pipe enlargement. Ward (loc cit) stressed the importance of the localization of continuous or near continuous supply of subsurface seepage water. He considered it more important in the development and initiation of piping than large flows during storms.

Miller (1971) concluded that cracking resulting from dessication of the soil is a major factor in the initiation of tunnel-gullies on the Port Hills. The initial widening of shrinkage cracks was considered to be the result of dispersion. Slaking of soil aggregates would be operative in the larger cracks and partially formed tunnels. No mention was made of the tunnelling process beyond this stage. Nor was the existence of an outlet considered to be essential. Miller (loc cit) did not elaborate on the fate of the dispersed particles and slaked aggregates. Tunnel initiation within natural soil pores and from exposed faces were not considered to be of importance in the sites studied.

2.3 TUNNELLING FAILURE OF SMALL EARTH DAMS.

It is considered relevant to review this aspect of tunnel erosion on disturbed soils because of possible affinities to the process as occurring in natural, undisturbed soils. In addition the past failure of many small dams and stock ponds on the Wither Hills constitutes a problem requiring further investigation.

Research in Australia on the problem of failure of small earth dams has distinguished between tunnelling due to deflocculation of clay particles and that caused by the erosive action of seepage. (Wood et al., 1964; Rosewell, 1970). The process of 'post-construction deflocculation' and subsequent removal of clay particles has been described in some detail by Wood et al., (loc cit).

Laboratory studies in model dams have shown that deflocculation occurs behind the wetting front, with tunnels forming as the soil disperses. Initiation of tunnels occurs on the upstream face of the dam. A continuous tunnel is formed upon emergence of dispersed particles on the downstream face. (Rosewell loc cit).

In the alternative type of tunnelling it is considered that seepage water concentrates at an exit point on the downstream face of the dam. Sufficient seepage velocity carries away soil aggregates or macro-particles. Continuation of the process produces a pipe formed by headward erosion, finally emerging at the upstream face. (Rosewell, loc cit).

Many investigators have shown the dependence of embankment dispersibility on the cation exchange status of clay particles and the electrolyte composition of impounded water. (Ritchie, 1963; Wood et al., 1964; Rallings, 1966).

Rallings (loc cit) carried out detailed laboratory investigations into cation exchange phenomena on soils from failed dams and cation concentrations of dam water. These studies verified the results of previous workers (Quirk and Schofield, 1955; Collis-George and Smiles, 1963; Wood et al., 1964), that dispersibility is governed by the proportion of sodium on the exchange complex and the electrolyte content of the soil solution.

Ritchie (1963) recognized the importance of maximum compaction during dam construction in preventing tunnelling failure in highly dispersible soils. The failure of dams due to deflocculation requires the presence of voids large enough for dispersed clay particles to traverse without causing blockage and cessation of the erosion process. From laboratory evidence Wood et al., (loc cit) suggested an upper limiting value of permeability for dispersible earth fill of 10^{-5} cm/sec. Most investigators have recognized that prevention of tunnelling failure can be achieved by adequate compaction at moisture contents close to optimum (Ritchie, 1963; Wood et al., 1964; Rallings, 1966).

2.4 SUMMARY OF TUNNELLING PROCESSES IN NATURAL SOILS.

From the review of tunnel erosion it appears that two basic tunnelling processes occur in natural soils. In the first process tunnels are formed during periodic dessication and saturation of the soil. Dessication allows crack formation into subsoils. Subsequent saturation causes high concentrations of water into cracks. Detachment of soil particles from the sides of cracks is accomplished mainly by dispersion.

Gibbs (loc cit) did not consider tunnel formation with outlets as described above. In his theory voids were formed by soil packing effects and eluviation of clay into the loose gravels beneath the tunnelling sites. The enlargement and eventual link-up of voids, formed the tunnels. Outlets were thus only of minor importance in Gibbs theory. In some instances detachment of soil particles without dispersion may occur at the free faces (Brown, 1962). Where outlets form at free faces then it appears that tunnel development normally proceeds upslope. In contrast, where outlets are formed by surface breakthrough, tunnels usually initiate and develop to some extent from positions upslope of the outlet.

In the second process of tunnel formation, continuous or near continuous subsurface flow is responsible for the movement of soil particles downslope (Ward 1966). Dispersion and cracking need not necessarily be involved. However Ward (loc cit) suggested that both were involved in tunnel development in the Whangarei area. Outlets may or may not form at exposed faces. Some tunnels exit into bogs and other water collecting zones (Ward, loc cit). For volcanic ash and pumice soils an outline of tunnel initiation and development from a free face is described by Selby (1970). It would appear that prolonged subsurface seepage was primarily responsible for tunnel formation. This process of tunnel formation appears to be analogous to the failure of earth dams by seepage.

A diagrammatic representation of the basic tunnelling processes is outlined in table 1 below.

TABLE 1. SUMMARY OF BASIC TUNNELLING PROCESSES.

(1) DRY TUNNEL SYSTEMS;

Tunnel formation due to periodic dessication and saturation of the soil.

(contd)

(i) Cracking and dispersion prerequisites

(a) Outlet at free face.	(b) Outlets formed on slopes
e.g. Monteith (1954)	e.g. Downes (1946)
Fletcher & Carroll (1948)	Newman & Phillips (1957)
Parker (1963)	Fletcher & Carroll (1948)
Fletcher et al., (1954)	Hosking (1967)
	Gibbs (1945)
Charman (1969, 1970)	Miller (1971)

Cumberland (1944)

(ii) Cracking only initially - outlet at free face

e.g. Brown (1962)

(2) WET TUNNEL SYSTEMS;

Tunnel formation due to continuous or near continuous subsurface flow.

(i) Outlet at free face	(ii) Outlet into bogs & swamps, etc.
e.g. Selby (1967, 1970)	e.g. Ward (1966)
Ward (1966)	

2.5 SOIL PROPERTIES AFFECTING SLAKING, DISPERSION AND CRACKING

From consideration of the previous section it is apparent that cracking, slaking and dispersion of soils are the properties almost universally stated as being important in the tunnelling process.

Emerson (1954) stated that soil aggregate breakdown consists essentially of two separate processes;

(i) slaking, which comprises the macroscopic breakup of unsaturated aggregates,

(ii) dispersion in which part of the colloidal fraction goes into suspension.

Aggregate stability has been investigated by numerous researchers using various methods of analysis such as wet sieving (Yoder, 1936), end-over-end shaking (Ritchie, 1963), and permeability measurements (Quirk and Schofield, 1955). It is difficult to separate the effects of slaking and dispersion with these techniques because both processes normally occur simultaneously in wet sieving and end-over-end shaking. Analyses of aggregate stability therefore take into account dispersion of the colloidal fraction.

Studies of aggregate stability have shown that several physico-chemical properties are directly involved in the breakdown of aggregates and hence dispersion. The major properties as outlined by Emerson (loc cit) are:

(i) bonding of clay crystals by organic or inorganic compounds,
(ii) electrolyte content of the wetting liquid,
(iii) type of clay minerals present.

In addition Emerson and Dettman (1960) and Rallings (1966) found that pH affected dispersion of the colloidal fraction.

2.5.1. Dispersion of Clay Particles

2.5.1.1. Effect of Moisture Content

Dispersion can only occur when the individual clay particles are surrounded by water films. During dehydration the films are reduced in thickness to such an extent that adjacent particles are held together by strong cohesive forces. Dispersion of the same particles requires rehydration of the clay so that every particle is again surrounded by a water film (Baver, p.49, 1956).

The effect of initial moisture content on the degree of dispersion was clearly shown by Puri and Keen (1925).

Their results indicated that greatest dispersion was obtained with soils having the highest initial moisture content.

The relationship between water content and dispersion for different clay minerals was outlined by Emerson (1968) using remoulded soil aggregates. The practical significance of such a relationship was realized when applied to field cultivation and surface crusting of soil by rainfall.

Experiments on artificial and natural soil aggregates by Collis-George and Smiles (1963) indicated that the effects of severe drying or drying and heating could confer considerable stability to aggregates.

2.5.1.2. Bonding of Clay Particles by Organic and Inorganic Compounds

The soil colloidal material is responsible for cementing primary particles into stable aggregates. The soil colloidal material comprises three major groups, the clay particles themselves, the sesquioxides, and organic colloids (Baver, 1956, p.135). It is well known that organic matter and oxides of Al and Fe cement clay particles. Their removal is essential for mineralogical study of the clay fraction.

(a) Organic Matter Influences on Aggregation and Dispersion

Greenland (1965) has concisely summarised the salient studies to date relating soil aggregation to organic material. The close correlation between water stable aggregation and per cent carbon has been well documented (Baver, 1935, p.139; Chester et al., 1957).

The influence of polysacharides, particularly those produced by microbial activity, on the improved aggregation of soil particles has been shown by many investigators

(Martin, 1946; Rennie et al., 1954; Chester et al., (loc cit); Chatterjee and Jain, 1970).

Greenland (loc cit) suggested that adsorption of humic material takes place mainly through ionic linkages involving polyvalent cations or oxides as intermediaries between the humic material and clay particles. Adsorption of polysaccharides is thought to be primarily due to physical adsorption forces.

Studies of the dispersion of soil particles by Edward and Bremner (1967) indicated that difficultly dispersible particles in mineral soils of high base status were microaggregates ($<$ 250 microns) consisting largely of clay and humified organic material linked by polyvalent cations. They questioned the zeta potential concept (diffuse double layer) in dispersion of colloidal particles. The fact that their soil samples contained from 1.52 to 9.6 per cent organic carbon may help explain the importance of organic material and non-significance of zeta potential in their theory of microaggregate-formation as being a solid phase reaction.

The effect of organic matter on soil crumbs was stated by Emerson (1959) to prevent the dispersion of sodium saturated particles. The organic material was considered to form linkages between clay particles which restrain the diffuse double layer swelling of the clay.

The experiments of Collis-George and Smiles (loc cit) showed that the presence of organic matter conferred a degree of stability in both natural and artificial aggregates over and above that predicted from the sodium adsorption ratio and electrolyte concentration.

In contrast, the results of Rowell et al., (loc cit) indicated that the only effect of relatively high organic matter

(4%) in dispersion, was to cause slightly less sensitivity to electrolyte concentrations at varying exchangeable sodium percentage than a subsoil sample with 1.3 per cent organic matter. In all other aspects of dispersion the topsoil and subsoil samples were very similar.

(b) <u>The Role of Inorganic Compounds on Dispersion</u>

The role of 'free' iron oxides in acting as cementing agents in aggregate formation has been investigated over a wide range of soils.

A positive correlation between the degree of aggregation and the free iron oxide has been found by several investigators (Lutz, 1936; quoted in Baver 1956, p.144; Chester et al., loc cit; Arca and Weeds, 1966; Singh and Chatterjee, 1966).

From investigations on red-coloured soils containing from 2 to 15 per cent iron oxides, Deshpande et al (1964) concluded that iron oxides were present as discrete crystals and did not cement soil particles. Further research by Deshpande et al (1968) on a similar range of red-coloured soils, revealed that iron oxides may play some part in enhancing the stability of micro- and macroaggregates. Most of the iron oxides in the clay fraction were present as small discrete particles with only minor amounts present as 'active' bonding agents. They considered <u>aluminium oxides to be the major inorganic bonding materials.</u>

After studying the behaviour of kaolinite clays, Greenland and Oades (1968) concluded that the association of iron hydroxides with clay surfaces is dependent on surface characteristics of the iron compounds and clay and the properties of the medium in which they are produced. Hence <u>considerable variation is to be expected between content of</u>

free iron oxides and degree of aggregation or dispersion.

Recent studies on aggregation by Chatterjee and Jain (1970) showed a direct relationship between microaggregation (<0.02mm) and extractable sesquioxides, particularly alumina.

Fieldes (1961) has suggested that differences in aggregate stability and structure between the YBE and YGE soil groups is controlled by marked differences in amounts of free iron and aluminium in the two groups.

(c) Colloidal Clay Cementation Effects

The formation of aggregates from primary particles should be related to the content of finer particles in the soil that may act as material to be aggregated (Baver, 1956; p.135).

That a positive correlation exists in many soils between the degree of aggregation and clay content has been revealed by numerous researchers (Baver, 1956, p.135; Chester et al., 1957; Chatterjee and Jain, 1970; Arca and Weeds, 1966; Singh and Chatterjee, 1966).

Chester et al., (loc cit) noted that the relationship was of greater significance in those soils with high clay content. They quoted Heinonen (1955, see Chester et al., loc cit) in support of their claim.

In their dispersion tests, Edward and Bremner (1967) found that soils with high sand content were more readily dispersed than those with finer textures.

2.5.1.3. Electrolyte Composition and Concentration of the Soil Solution

Considerable research has centred on the electrolyte composition and content of soil solutions and cation exchange phenomena of soil colloids in an attempt to explain dispersion and flocculation of clay particles (Jenny, 1938 quoted in Baver 1956, P.33; Quirk and Schofield, 1955; Collis-George and Smiles, 1963; Rallings, 1966; Rowell et al., 1969).

The influence of high levels of exchangeable sodium on the decreased aggregation of soils and reduction in other physical properties is well documented (Martin and Richards, 1959; Reeve et al., 1954).

The theoretical considerations of exchangeable sodium and the cation composition of soil solutions has been outlined by Rallings (1966). The effect of sodium in the exchange complex is to cause large expansion in the positively charged diffuse double layer surrounding each clay particle. This expansion decreases the attractive forces (van der Waals) between adjacent clay particles. If the double layers are expanded then repulsive forces due to the interaction of the positively charged double layers may predominate while the colloids are still some distance apart. A net repulsive force acting between the particles means that they are dispersed in solution. Dry soils containing appreciable exchangeable sodium deflocculate or disperse when wetted due to hydration of the exchangeable sodium causing expansions of the double layer. Polyvalent cations are not hydrated to the same extent and consequently do not expand the double layer sufficiently to cause a net repulsive force when wetted.

Cations in the soil solution (electrolyte) from dissociation of neutral salts have two main effects on dispersion.

(i) due to total cation concentration independent of the type of cations and

(ii) cation exchange phenomena between cations in the soil solution and those on the colloidal fraction.

The first effect due to total cation concentration causes the suppression of the double layer. At a sufficiently high concentration depending on the proportion of sodium in the exchange complex, a net attractive force will exist and cause flocculation of clay particles.

The second effect of cation exchange between the soil and soil solution affects the proportion of sodium on the exchange complex. Richards (1954) stated that the exchangeable sodium percentage (E.S.P.) varies with both the concentration of cations and the relative proportions of Na^+ to Ca^{++} and Mg^{++} in the water in equilibrium with the soil. The concentration and relative proportion of cations in the water is described by the sodium adsorption ratio (S.A.R.):

$$S.A.R. = \frac{(Na^+)}{\sqrt{\frac{(Ca^{++}) + (Mg^{++})}{2}}}$$

where (Na^+), (Ca^{++}) and (Mg^{++}) are the concentrations of cation in the soil solution expressed as me/litre. Richards (loc cit) related the equilibrium E.S.P. to the S.A.R. by the regression equation:

$$E.S.P. = \frac{100\,(-0.0126 + 0.01425\ S.A.R.)}{1 + (-0.0126 + 0.01475\ S.A.R.)}$$

The E.S.P. may also be defined in terms of the exchange complex:

$$E.S.P. = \frac{(Na^+)}{C.E.C.} \times 100$$

where (Na^+) is the concentration of sodium on the exchange complex expressed in me% and the C.E.C. is the cation exchange capacity of the soil in me%.

The relationship between major changes in soil permeability and the concentration of salts in the percolate was shown graphically by Quirk and Schofield (1955) using an illitic soil with varying E.S.P. (fig 2). The decrease in

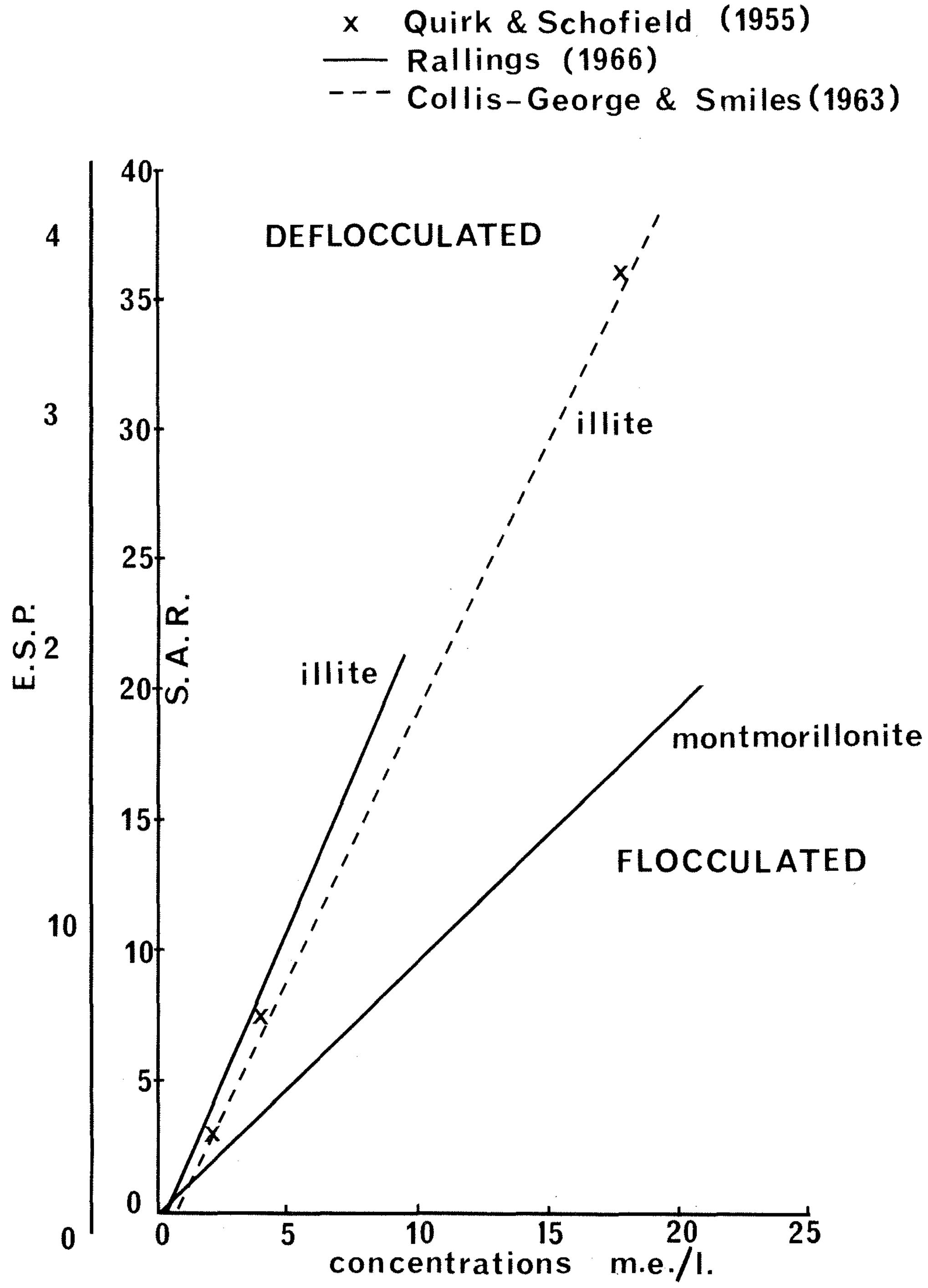


Figure 2

Relationship between S.A.R. (& E.S.P.)
and Electrolyte Concentration
(from Rallings, 1966)

permeability was due mainly to dispersion although they did recognize that swelling was of importance also.

Collis-George and Smiles (1963) used the S.A.R. calculated from cation concentrations in the soil solution to determine the stability of soil suspensions, i.e. whether dispersed or flocculated. They supplied considerable energy to the dominantly illitic clay systems by vigorous shaking. They then measured the maximum concentration at which the suspension remained dispersed. The experiments were conducted at neutral pH. (fig 2). This approach was used by Rallings (loc cit) to relate the S.A.R. and electrolyte concentrations to the stability of soil suspensions. He obtained values for both illitic and montmorillonitic soils at pH 7.0. (see fig 2).

<u>2.5.1.3.1. Energy Considerations of the Dispersion Process</u>.

Rallings (loc cit) suggested that energy for dispersion was provided by a number of sources such as the flow of water through the soil profile, hydration energies, thermal energies and energy from entrapped air (slaking). He stated that the energy level at which dispersion occurred would depend on the relationship between E.S.P. (or S.A.R.) and the electrolyte concentration.

The results of Rowell et al (1969) using leaching experiments similar to Quirk and Schofield (loc cit) indicated analogous conclusions to Rallings (loc cit). They found that when small mechanical stresses were applied, such as the flow of permeating water through the soil, the proportion of clay which swelled and dispersed depended directly on the E.S.P. With high values of E.S.P. the percolates were very turbid while at low E.S.P. the percolates were much clearer. <u>The total amount</u>

of clay dispersed varied with the magnitude of the mechanical stress applied. They found that large mechanical stresses (vigorous shaking) may disperse most of the clay even at low E.S.P. The application of stress to clay affects the electrolyte concentration at which dispersion occurs. The larger the stress the higher the electrolyte concentration at which dispersion occurs. Thus dispersion at low stress is dependent primarily on the relation between E.S.P. and electrolyte concentration.

The effect of time of shaking on degree of dispersion of soil has been shown by Puri and Keen (1925) and Ritchie (1963). Tests were conducted by Ritchie (loc cit) on a variety of soils at different times of shaking ranging from 10 mins to 1 hour. He found that differences between dispersible and non-dispersible soils were most noticeable with a short shaking time (10 mins).

2.5.1.4. Effect of Clay Type on Dispersion.

Quirk and Schofield (1955) stated that the relationship between E.S.P. and electrolyte concentration was unique for all clay except kaolinite at low pH. The work of Rallings (loc cit) revealed that while the relationship was valid for illitic soils, montmorillonitic soils dispersed at higher electrolyte concentrations than illites for equivalent S.A.R.'s and soil pH's. He found that kaolinites at neutral pH would not disperse at all.

The investigations by Emerson (1968) on the content of moisture required for dispersion of remoulded aggregates indicated that kaolinite was more stable to dispersion than illite, i.e. it required greater initial moisture content.

2.5.1.5. Effect of pH on Dispersion.

Emerson and Dettman (1960) found that the clay-clay attractive forces in crumbs from acid soils were greater than in crumbs from similar soils but containing free calcium carbonate. They considered that the effect of trivalent cations was dominant in very acid soils where Al^{3+} existed in solution.

Rallings (loc cit) discovered that soils of low pH (<4.5) and high E.S.P. often would not disperse in distilled water contrary to expectations. He suggested that the presence of large concentrations of exchangeable Fe^{3+} and Al^{3+} could be responsible for flocculation at low pH's. Both Richards (1954) and Rallings (loc cit) found that the relationship between E.S.P. and S.A.R. is influenced by the presence of alkaline earth carbonates and by soil pH.

2.5.2. Soil Cracking.

The significance of soil cracking in tunnel initiation has been outlined in the sections on soil properties and processes in tunnelled soils. A brief review of the major factors influencing shrinkage cracking is presented here.

Miller (1971) has summarised some of the pertinent factors affecting soil cracking. Soil cracking is due primarily to linear shrinkage resulting from progressive drying of the soil. Soil shrinkage is a property of soils dependent on their capacity to swell when wetted and contract when dried. The degree of shrinkage is determined by the extent of dessication and various physical, chemical and minerological properties of the soil.

Rowell et al., (1969) stated that these soil properties included:

(i) type and amount of clay present,

(ii) exchangeable cations on the clay,

(iii) concentration and composition of electrolytes,

(iv) presence of other materials such as the sesquioxides and organic matter. They noted that similar parameters are involved in the dispersion of clay.

The structural development of the soil also influences the degree of shrinkage. Stirk (1954) measured the shrinkage of natural soil aggregates and found a stage of shrinkage due to the presence of large pores in the soil. The pores were the result of structural development.

Most studies on the shrink-swell potential of soils have measured volume expansion or volume shrinkage. It has been shown by Aitchison and Holmes (1953) that linear shrinkage can be taken as one third of volume shrinkage.

2.5.2.1. Effect of Clay Type on Shrinkage

According to Baver (1956, p.90) the expanding-lattice types of colloids (montmorillonite) swell considerably more than the fixed-lattice types (halloysite, kaolinite).

The swelling of montmorillonite occurs by both intraparticle and interparticle expansion. (Norrish 1954).

Fieldes (1968) separated the micaceous clay minerals into non-expanding types and those that are expanding/contracting in the soil. He listed mica, illite, chlorite and vermiculite-(1) as non-expanding clay minerals. Vermiculite - (2) and montmorillonite are considered to be expanding/contracting types.

2.5.2.2. The Nature of Adsorbed Cations and Electrolyte on Shrinkage

Baver (1956, p.90) has ascribed the order of swelling of exchangeable cations for montmorillonite as:

$$Na > K > Ca = Ba > H.$$

The swelling of Li - and Na - clays increases with the concentration of these ions on the exchange complex.

The effect of varying solution concentrations and composition on the swelling of extracted soil clays was studied by McNeal et al., (1966). Greater swelling was obtained with increasing E.S.P. especially at low solution concentrations.

Swelling also increased with increasing montmorillonite content. Soils high in Kaolinite and sesquioxides or in amorphous material were comparatively stable. Rowell et al., (1969) also found greater swelling of illitic soils with increased E.S.P. and low electrolyte contents.

2.5.2.3. Effect of Clay Content on Shrinkage

Several investigators have demonstrated that shrinkage is greatest in soils of high clay contents (Tempany, 1917; Haines, 1923; Holmes and Stace, 1968; and Stirk, 1954).

Holmes and Stace, (loc cit) obtained a significant correlation between volume change and clay content. The regression equation was:

$$\text{Volume change } (\%) = -9.32 + 0.68 \text{ clay } \%.$$

They used remoulded soil blocks with clay contents between 14 and 50 per cent.

For soils of high clay content ($>45\%$), Stirk (1954), found that as much as half the total shrinkage occurred on the dry side of wilting point. For soils lower in clay content ($< 34\%$) most of the total shrinkage occurred in the field moisture range (pF 2.0 to pF 4.2).

Miller (1971) obtained very low linear expansions $\leq 0.136\%$ for some loessial soils on the Port Hills, Canterbury.

Clay contents were between 18 - 20% and dominated by illites and vermiculite - (2). Although some samples had high E.S.P's and low solution concentrations it appears that the measuring technique altered the cation exchange status (Miller, loc cit). He suggested that the size distribution of loess particles was effective in accommodating the swelling of the clay fraction. Field observations confirmed that soil cracking into the subsoil did occur.

2.5.2.4. Role of Sesquioxides and Organic Matter.

Little has been published on the influence of organic materials and oxides of Al and Fe in shrinkage of soils.

Emerson (1959) proposed that one of the effects of organic matter on soil crumb stability was to restrain the diffuse double layer swelling of clay particles.

Deshpande et al (1964) on studies of red coloured soils found that precipitation of iron oxides failed to reduce swelling. However precipitation of aluminium oxides caused a large reduction in swelling.

2.5.2.5. The Value of Moisture Tensions Reached During Dessication.

It has been shown that there is a positive relationship between shrinkage and moisture tension. (Stirk, 1954). Conversely Quirk (1964) has shown a negative correlation between volume expansion and moisture tension.

In areas prone to seasonal drought conditions, moisture tensions above wilting point commonly occur in the upper soil layers. In New Zealand, the soils classified into subxerous and subhygrous moisture classes experience moisture contents below wilting point during part of the year. These two moisture classes are characteristically represented by the B.G.E. and Y.G.E. soil groups respectively (Soil Bureau Staff 1968 a).

The depth to which wilting point tensions reach depends on the extent of evaporation from the soil surface. This in turn is influenced by factors such as cultivation, mulches and type of vegetation carried. It has been shown conclusively that some tillage practices and mulching techniques conserve moisture and prevent excessive dessication (Richards et al., 1952; Baver, p.281).

Field and laboratory studies have shown that evaporation from shrinkage cracks may equal or exceed that from the surface soil (Adams and Hanks, 1964). Laboratory studies showed that evaporation from the side walls of cracks may vary from 35 to 91 per cent of that from a comparable area of surface soil depending on the soil moisture content.

Thus, once cracks develop in the surface horizons of the soil dessication of deeper horizons may follow through evaporation from within crack systems.

CHAPTER III

METHODS

3.1 SELECTION OF STUDY AREA

The Wither Hills was selected as a region within which to undertake this study primarily because they display some of the most severe tunnel-gully erosion in the country.

A catchment of 81.7 ha (202 acres) area was selected for detailed study on the following bases:

(i) the area displays an array of soils and erosion forms typical of much of the Wither Hills. The degree of seriousness of tunnel-gully erosion ranges from nil to extreme,

(ii) the catchment is relatively small yet fully representative,

(iii) the site is only 1 km (0.6 miles) from the meteorological station on the Ministry of Works soil conservation reserve,

(iv) it is one of the few accessible and representative areas still undisturbed by erosion control programmes.

3.2 SOIL SURVEY PROCEDURE

3.2.1. Preparation

Initial preparation consisted of stereoscopic examination of air-photos at 160m to 1cm scale (20ch to 1 inch) covering the representative catchment. Boundaries delineating marked changes in type and severity of erosion, physiography and vegetative cover were outlined on the airphotos. Familiarization with the study area was achieved by a rapid reconnaissance survey. The broad boundaries plotted in the laboratory generally agreed well with those located in the field. Severe erosion had exposed many complete soil sections up and down slope enabling rapid comparison of soil profiles.

From brief observations during the reconnaissance survey it was thought that a toposequence existed in the lower section of the catchment where tunnel-gully erosion was most severe. The soil parent materials appeared to be of loessial origin. Slope angles ranged from nearly flat to gently undulating on sections of the ridge crests to steep on the midslope or backslope positions. Soil profiles appeared to vary according to position on the slope. Several morphological differences were noted between footslope and backslope profiles. It was decided to investigate in more detail a transect from valley bottom to ridge crest.

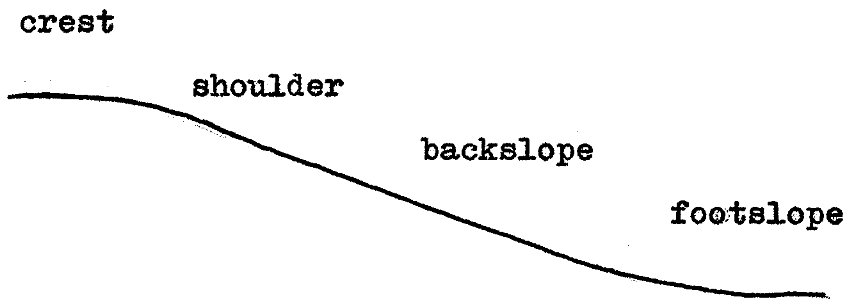
3.2.2. Detailed Survey.

The survey procedure consisted of traverses around the edge of the catchment and across the main drainage lines from boundary to boundary. A succession of broad traverses was made to identify the major soil series. Soil pits were dug at key sites to record detailed profile descriptions. Samples were collected for further examination in the laboratory. Once the major soil pattern had been established, a series of closely spaced traverses were made within each mapping unit to define the series variation. Use of a soil auger enabled rapid comparisons of soil horizon thicknesses, colour and texture etc.

3.2.3. Descriptive Terminology.

Soil profile descriptions were made in accordance with Taylor and Pohlen (1962) and type and severity of erosion described according to the S.C. & R.C.C. manual (1969).

Slope positions were defined as follows:



A detailed field study of tunnel-gully erosion was undertaken at the end of the soil survey.

3.2.4. Compilation of Soil Map

During the field survey tentative soil boundaries were established on the air-photos. On completion of the survey the soils so identified and described were related to the landscape as a whole, including formation and relative age of landscape. Butler's periodicity concept of 'K cycles' was used in an attempt to show the relationship between pedomorphic surfaces and landscape evolution. This approach showed the relationship between soils and landscape within major soil units as well as between them.

The soil series boundaries located during the survey were re-examined in the laboratory under the stereoscope. Minor modifications were made to suit the scale and scope of the proposed soil map. Profile descriptions recorded in the field were compared with each other as a further check on soil unit boundaries.

A base map of the catchment at a scale of approx 80m/cm (10ch / inch) was constructed from data shown on the air-photos. The catchment boundary and features such as fence lines and major water courses were transferred from the air-photos at a scale of 160m/cm (20ch/inch) and enlarged twice using an aero-sketchmaster (Carl Zeiss, model m243e).

Similarly, soil boundaries were located on the base map using the 'aero-sketchmaster'. It is acknowledged that considerable error exists in such transcription, both from distortion in the air-photos and in transferring data from air-photos to the map. However it was not the intention to show accurately the spatial dimensions of the soil units but to illustrate the general soil pattern only.

3.2.5. Soil Erosion Map.

This was constructed in a similar manner as the soil map from an identical base map. Boundaries marked on the air-photos delineating types and degree of erosion were transferred to the base map (80m/cm) with the 'aero-sketchmaster'.

3.2.6. Toposequence Study.

After the preliminary survey it was decided to further investigate a modal soil transect from valley bottom to ridge crest on the predominantly loessial soils in the lower left hand section of the catchment.

A soil site was selected at each of four positions on the hillslope; crest, shoulder, backslope and footslope position, where tunnel-gully erosion had considerably altered the landscape. The soil at each slope position was selected on the basis of being modal for that particular hillslope component. Site characteristics of slope shape, angle and aspect were chosen as representative of each hillslope component. To check on soil morphology being representative a series of three to four soil pits or gully-side sections were excavated across slope within a distance of approx. 20 metres (22 yards) at the proposed slope position. Semidetailed profile descriptions were recorded and checked for uniformity at each slope site. It was found that no obvious morphological differences occurred at each slope position.

A soil pit was dug at each hillslope position on a site thought to be least affected by the recent tunnel-gully and sheet erosion, as near to a straight line from gully bottom to ridge crest as possible (plate 1). Further data on the toposequence sites is shown in table 2.

TABLE 2

LANDFORM CHARACTERISTICS OF THE TOPOSEQUENCE SOILS

hillslope component	aspect	slope shape	slope angle	approx distance from main drainage line
footslope	easterly	slightly concave	20 degrees	20 m
backslope	"	straight	25 degrees	70 m
shoulder	"	convex	19 degrees	101 m
crest	northerly	straight	9 degrees	111 m

The toposequence sites are approx 363m to 435m from the lower boundary fence crossing the main drainage line of the catchment.

It was not feasible to select and sample toposequence sites randomly using statistical procedures because of the prohibitive amount of field work involved. It is realized that the selected sites are only truly representative within narrowly defined limits (approx 20m). <u>However because of the lack of obvious soil profile variation within each hillslope component examined</u>, <u>it is considered valid to assume the toposequence to be representative of much of the loessial soil landscape in the lower section of the catchment</u>.

3.2.6.1. Sampling Procedure

Each of the toposequence sites was described fully. Samples were collected from each horizon on a volume-weight basis. Samples were also collected from weathered soil materials underlying the parent materials of the surface soils at two sites in the lower catchment. The location and description of these sites are given in table 3. The soil samples were collected from vertical gully sides after scraping off the external crust (15 - 20cms) of soil material.

TABLE 3

LOCATION OF SOIL SAMPLES FROM BENEATH TOPOSEQUENCE PARENT MATERIALS

Approx distance from main drainage line	Hillslope component	Slope Angle	Depth from surface
240 m	backslope	30 degrees	1.6m
212 m	backslope	25 degrees	1.2 - 2.0m

3.3 SAMPLING FROM OUTSIDE THE STUDY CATCHMENT.

It was decided to compare the tunnel-gullied soils of the Wither Hills with several loessial soils from outside Marlborough which did not have tunnel-gully erosion and had been classified as subhygrous Y.G.E.'s.

It was hoped that comparison of morphological and physical properties between the tunnelled Wither Hill soils and the non-tunnelled ones from outside the region would help explain the difference in erodibility.

Two soils derived from loess were selected from South Canterbury:

(a) Claremont silt loam from the Geraldine Downs.

(b) Timaru silt loam from Waitohi.

Site features are outlined in table 4. Profile descriptions are presented in the appendices.

TABLE 4

LAND FORM CHARACTERISTICS

OF THE TIMARU AND CLAREMONT SOILS.

Soil series	Slope position	Slope angle	Shape	Aspect
Timaru	upper backslope	12 degrees	convex	north
Claremont	upper backslope	20 degrees	straight	north west

3.4 FIELD STUDIES OF TUNNEL-GULLY EROSION.

Following the soil survey of the Wither Hills study catchment, an intensive investigation was undertaken to trace the origin and development of tunnel-gullies. This was achieved by detailed observation and measurement of the different stages of erosion evident in the catchment.

It was thought that careful observation of the existing stages of tunnel-gullying should enable a satisfactory explanation of the probable erosion processes. The laboratory determinations would then provide evidence for or against theories proposed on field data alone.

The most intensive field work was undertaken in the vicinity of the toposequence sites as these were the only soils in the catchment subjected to chemical and physical analyses. However further observations and measurements were carried out on most of the tunnel-gullied areas in the catchment.

The field work consisted of:

(1) Detailed traverses in the tunnel-gullied areas both across slope and up and downslope. A few traverses were made on loessial soils not obviously tunnelled. All relevant site and erosion features were noted, such as tunnel outlets, sedimentation, length and direction of tunnels.

(2) Excavation of cross-sections through the various stages of tunnel-gully erosion.

Measurements were recorded of all salient features, such as depth of tunnel from surface, internal diameter of tunnels and width of open gullies, etc. Cross sections were recorded diagrammatically and photographically.

(3) Description of morphological features associated with tunnelling, e.g. structure, texture, cracks, infillings etc., of the horizon within which tunnels occurred.

3.5 LABORATORY DETERMINATIONS.

These were undertaken for two main reasons:

(1) To determine the basic physical, chemical and mineralogical properties of the toposequence soils. With this information it was hoped to elucidate any variation due to position on the landscape and as far as possible to characterize the soils as typical subhygrous central Y.G.E.'s of Marlborough.

(2) To determine the soil properties causing tunnel-gully erosion.

3.5.1. Chemical Analyses.

Table 5 illustrates the tests and samples used.

TABLE 5

CHEMICAL ANALYSES AND SAMPLES TESTED

Chemical Analyses	Toposequence Soils	Samples Tested Soils from below Parent Materials	South Canterbury Soils
pH	x	x	x
Organic carbon	x	x	x
Cation exchange capacity (C.E.C.)	x		
Total exchangeable bases (T.E.B.)	x		
Base saturation %	x		
Soluble salt-conductivity	x	x	
- cations	x	x	
- anions	x		
Free iron oxide	x	x	
Total phosphorus	x	x	

All tests carried out on air-dry soil ground to pass through a 2mm sieve unless otherwise stated.

(i) pH. Measured in water with a glass electrode using a 1:2.5 soil suspension after standing overnight.

(ii) Organic Carbon. The method of Walkley and Black (1934) and Walkley (1947) was used.

(iii) Soluble Salts (a) Conductivity. An estimate of the total soluble salt content was measured by the electrical conductivity of a 1:5 soil : water extract (Metson 1956). The conductivity of the soil extract was measured by a direct reading Radiometer conductivity meter (model CDM2e). Results were corrected for temperature according to Richards (loc cit). Only those solutions with conductivities $>$ 0.03mmho/cm were retained for cation analyses.

(b) Soluble Salt Cations. A 20cc aliquot of 1:5 soil : water extract was diluted and sufficient strontium chloride added to a subsample to give a concentration of 2000 ppm Sr^{2+} ions. A series of reference samples containing known concentrations of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} ions were used to construct calibration curves. The cations in the soil solution were then determined by comparison with the reference samples using the methods outlined below.

cation	method	wavelength	instrument
Ca	flame photometry	4227nm	techtron spectro-photometer
Mg	atomic absorption	2852nm	model AA100
K	flame photometry	k filter	X117EEL flame
Na	flame photometry	Na filter	photometer

It was found that K was negligible in all samples.

(c) Soluble Salt Anions. Only the chloride and sulphate anions were determined from the 1:5 soil : water extracts. Chloride ions were determined volumetrically by the 'Mohr Titration Method' using silver nitrate with potassium chromate as indicator.

Sulphate ions were measured by the Johnson-Nishita method in which sulphate is reduced to sulphide.

(iv) Cation Exchange Capacity. The C.E.C. was determined by distillation of ammonia following leaching of soil with ammonium acetate and washing with ethanol.

Final titration was against 0.1NHCI using a mixed indicator in boric acid (Metson, 1956,p.105).

(v) Exchangeable Cations. The ammonium acetate leachate from the C.E.C. determination contained cations from the exchange complex and from soluble salts. The total cation concentrations of leachates were determined by the methods outlined before for soluble salt cations. The values thus obtained were corrected for cation concentrations from soluble salts to arrive at exchangeable cation concentration values.

i.e. Exchangeable cations = total cations in ammonium acetate leachates minus soluble salt cations.

(vi) Total Exchangeable Bases (TEB). TEB was derived as a summation of the levels of exchangeable bases in each sample. (Metson 1956, footnotes p.105). TEB = exch (Mg^{++}+Ca^{++}+Na^{+}+K^{+}).

(vii) Base Saturation (BS%) - by calculation where

$$BS = \frac{TEB}{CEC} \times \frac{100}{1} \%$$

(viii) Total Phosphorus. Total P was determined by sodium carbonate fusion with digestion in $7NH_2SO_4$. The concentration of P was measured colorimetrically on a "spectronic 20" at 880mu wavelength, using the method of Alexander and Robertson (1970) as modified from Fogg and Wilkinson (1958).

(ix) Free Iron Oxides. The free iron oxide was initially extracted by a citrate - dithionite procedure for eight subsoil samples from the toposequence sites. A different extraction method was applied to all soil samples from the Wither Hills.

(a) Citrate - Dithionite reduction method (Aquilera and Jackson, 1953). Four iron extractions were carried out on each soil sample.

(b) Single dithionite extraction with 16 hours shaking (Olson 1965, p.971).

Several methods of determination of the iron in the soil extracts were attempted, and a volumetric procedure was finally adopted. Ferric ions were reduced to ferrous with Sn Cl_2 and then titrated with potassium dichromate using barium diphenylamine sulfonate as indicator. (Olson, loc cit).

(c) Comparison of the two Iron Extraction Methods.

Because eight of the toposequence soils were subjected to both iron extractions, it was possible to determine the variation, if any, between the two methods. In addition, a comparison enabled a check on methodology, as a close relationship should theoretically exist between iron contents determined by each method.

A linear regression analysis showing the relationship between the two methods is shown in Appendix D.

The regression equation is :

(dithionite with shaking) $\%Fe_2O_3 = 0.083 + 0.61\ \%Fe_2O_3$ (citrate-dithionite).

r=0.98 The regression is highly significant ($<$ 1%).

As would be expected the four citrate-dithionite extractions removed considerably more iron than the single dithionite extraction with 16 hours shaking.

The highly significant regression equation shows that experimental technique was quite satisfactory.

3.5.2. Physical Determinations.

(i) Bulk density. These were measured only for the toposequence soils. For topsoils, volume-wt samples were collected in the field. Subsoil bulk densities were measured in the laboratory using large undisturbed clods by the displacement of sand method.

(ii) Particle Size Distributions. Determined for all soil samples. For particles between the size range of 0.063mm and 0.002mm (silt + clay) the hydrometer method of Gandahl (1967) was used with sodium hexametaphosphate as dispersing agent. The removal of organic matter with hydrogen peroxide was not considered necessary for the Wither Hills soils, as they dispersed readily in sodium hexametaphosphate. Destruction of organic matter was required in topsoils on the Timaru and Claremont soils.

A sieve analysis was carried out on particle sizes in the range 0.063mm to 2.0mm.

Following determination of particle sizes within the range 2.0mmto 0.002mm, particle size distribution curves were constructed.

(iii) Determination of Fine Clay Content (< 0.0002mm)

The measurement of the content of clays finer than 0.0002mm was carried out for samples from the six horizons of the shoulder toposequence site only. Four clay sizes were determined : 0.002mm, 0.001mm, 0.0005mm and 0.0002mm fractions, using the pipette method of Handy and Davidson (1953).

(iv) Coefficient of Soil Dispersion.

Ritchie (1963) used the 'Dispersal Index' to distinguish dispersive soils from non-dispersive soils :

$$\text{Dispersal Index} = \frac{\text{Total material } (< 0.002\text{mm})}{\text{Material} < 0.002\text{mm by mechanical dispersion only.}}$$

Mechanical dispersion in the absence of a chemical dispersing agent was achieved by end-over-end shaking. Ritchie (loc cit) found that a shaking time of 10 minutes distinguished between dispersible and non-dispersible soils. Soils with a dispersal index of less than 3.0 were stated by Ritchie (loc cit) to be susceptible to tunnel erosion.

In this study it was decided to use the method of Ritchie (loc cit) but to express the results as a percentage according to Katchinskii (1958) :

$$\text{Coeff. of dispersion (K)} = \frac{\text{material} < 0.002\text{mm by mechanical dispersion}}{\text{Total material} < 0.002\text{mm}} \times \frac{100}{1}$$

In this method all results are confined within a suitable percentage range thus avoiding the possibility of obtaining very large values for non-dispersible soils.

The standardised test procedure outlined by the Soil Conservation Service of N.S.W. and as employed by Miller (pers comm) was used in this study.

Air-dry samples of 50 gms were each placed in 1 pint bottles together with 250 mls distilled water. The bottles were attached to a 64cm diam. wheel and rotated for 10 mins at 18 rpm. Nearly all the samples were tested by this method. In addition, samples of the toposequence soils were rotated on the wheel for 30 mins to provide a comparison of coefficients of dispersion with shaking at 10 mins. A further four samples at moisture contents greater than air-dryness were also tested.

A complete hydrometer analysis was carried out on each sample after rotation. Particles and aggregates larger than 0.063mm were carefully collected on a 230 mesh sieve and oven dried. Sieve analyses (5mins shaking) were then carried out on these samples to determine the content of the different sized soil aggregates. An aggregate size distribution curve was then constructed. It is realized that this procedure is not entirely satisfactory as aggregate breakdown may occur during oven drying and especially during sieve shaking. Also, it is probable that some aggregate breakdown occurred during collection of the >0.063mm fraction in which the entire soil sample was deposited on a 0.063mm sieve and washed with water. This treatment probably had greatest effect on microaggregates held together (flocculated) purely on electro-chemical considerations without cementation. It would be expected that washing with water considerably dilutes the electrolyte solution in contact with the soil particles thus allowing dispersion. However, since all samples were treated uniformly it is expected that this method shows relative differences in dispersion and aggregation, thus allowing valid comparison between samples.

(v) Slaking and Dispersion Tests on Soil Aggregates.

It was observed in preliminary experimentation on several soil samples from the Wither Hills that small subsoil aggregates disintegrated more rapidly than small aggregates from topsoils when immersed in distilled water. Most of the breakdown occurred without evidence of dispersion because only a few samples were surrounded by cloudy suspensions. The breakdown is therefore considered to be slaking due to release of entrapped air as small bubbles were observed during aggregate disintegration.

Emerson (1954) has outlined factors influencing soil slaking due to entrapped air. The major factors affecting degree of slaking are : rate of wetting, initial moisture content of soil, and the pore geometry of the soil. Slaking of soils may also be important in the tunnelling process as indicated by Henin and others, Dettman (1958), Brewer and Blackmore (1956), and Panabokke and Quirk (1957).

The simple slaking tests used in this study involved visual observation of the disintegration of air-dry soil aggregates completely immersed in distilled water. These tests were conducted on all samples. To assess the influence on slaking of moisture contents above air-dry five samples from the shoulder site were investigated at field moisture contents. Time did not allow more comprehensive studies on aggregate breakdown at varying rates of wetting or of varying moisture contents.

In the slaking tests used here, six soil aggregates of approx. 1cm in diameter were selected randomly from each soil horizon and placed in petri dishes. The aggregates were not necessarily natural aggregates as most subsoil samples had to be broken by hand to obtain the required size. Distilled water was carefully added to each dish so as not to unduly agitate the soil. The degree of breakdown of each soil aggregate was noted at set intervals after adding distilled water - at time zero, 5,10,20,50 and 100 minutes.

The appearance of each crumb was noted for signs of dispersion and its extent of breakdown into smaller aggregates was estimated as a fraction of the original crumb size. According to the degree of disintegration of each crumb, a factor was applied at each time interval so as to arrive at a slaking index which was considered to be representative of slaking for each sample. The higher the index the greater is the degree and extent of slaking.

Emerson (1960) proposed a 'crumb' test in order to identify dispersive soils susceptible to piping. It involved dropping air-dry soil crumbs into a beaker of distilled water. Emerson (loc cit) maintained that if the E.S.P. of the soil was greater than 8.0 a cloud of dispersed clay formed around the crumbs. Such soils were considered as being dispersive and susceptible to piping. A similar test was used by Rallings (1966).

This dispersive test was incorporated into the slaking test outlined above, with observations made at each time interval on the state of the liquid/solid interface of each crumb. Notes were made on the degree of cloudiness if dispersion had occurred.

(vi) Soil Swelling Observations.

The importance of soil shrinkage has been frequently mentioned in discussion of tunnelling erosion. Gibbs (1945) indicated the role of soil cracking in initiating tunnel-gullies on the Wither Hills.

It was considered that swelling tests would indicate susceptibility to shrinkage cracking on drying, and perhaps the position in the profile in which tunnelling was initiated. However work by Miller (1971) has revealed that even soil with very low volume expansions may experience cracking sufficient to initiate tunnels. It was originally intended to measure volume expansion on undisturbed samples but lack of readily available equipment meant that this approach was not practicable.

Careful visual observations were made of soils in the study catchment for evidence of cracking and measurements were collected accordingly. Diagrammatic and photographic evidence were also obtained.

3.5.3. Mineralogical Analyses - these were carried out on the crystalline clay fractions of the eight subsoils previously subjected to four citrate - dithionite extractions. Soil clays were obtained by centrifugation.

The slides were examined with a Phillips PW 1310 diffraction unit. The following clay slides were prepared and examined,

(i) K saturated at 20 degrees Centigrade.
(ii) K saturated and heated to 550 degrees Centigrade.
(iii) Mg saturated at 20 degrees Centigrade.
(iv) Mg saturated with glycerol solvation at 20 degrees Centigrade.

Mineral identification was that detailed by Claridge (1969) and Fieldes (1968). The relative abundance of the clay minerals identified was estimated on a basis of peak heights according to Fieldes (loc cit) and Claridge (loc cit).

CHAPTER IV

SOIL SURVEY OF THE REPRESENTATIVE CATCHMENT

4.1 FACTORS OF THE ENVIRONMENT

4.1.1 Geology and Physiography.

The basement rocks of the catchment comprise the upper beds of Pre-pleistocene conglomerates (Branch and Dagger, 1934). The Geological survey (1962) classify them as upper middle Tertiary sediments of the Taranaki series. The conglomerates are mainly poorly sorted greywacke and jasperoid argillite deposits probably of fluviatile origin (Branch and Dagger, loc cit).

Superimposed irregularly on the surface of the conglomerates are varying thicknesses of loess, previously described by Gibbs (1953) as loess-like sandstone. These deposits are now known to be fine grained sediments transported from the flood plain of the Wairau river by aeolian processes. They are almost certainly of Quaternary age.

Landforms are typical of deeply dissected hill country with very narrow valley bottoms, steep hillsides and narrow rolling to moderately steep ridge crests.

The size of the catchment is 81.7 ha (202 acres) and is approx. 1.8km (5,900ft) long, with an average width of 464m (1520 ft). It is elongated in shape and faces nearly due north. The altitudinal range is from 31m (100 ft) a.s.l. at the lower boundary to 381m (1250 ft) at the head of the catchment (fig 1).

Alterations to the macro- and micro-topography have ensued from the widespread, severe tunnel-gully and gully erosion. The large scale erosive processes have removed much of the original land surfaces and underlying materials to create deep depressions and ravines in the landscape (plate 1).

4.1.2 Climate.

The closest meteorological station is situated at the Wither Hills Soil Conservation Reserve (latitude 41° 33' S long. 173° 58' E) some 1000 m (50 chains) to the west of the representative catchment. The station is sited on level to gently rolling terrain at an altitude of 32m (106 ft). Detailed meteorological data have been recorded since 1949. Relevant data are outlined in Table 6.

TABLE 6. CLIMATIC DATA WITHER HILLS RESERVE

Mean annual rainfall (20 years record)	650mm (25.6ins)
Rain days	105
Highest recorded annual rainfall (1953)	913mm (35.9ins)
Lowest " " " (1969)	410mm (16.1ins)
Maximum recorded 24 hour rainfall (May 1966)	99mm (3.88ins)
Mean annual evaporation (raised pan, 12 years record)	1270mm (50.0ins)
Mean annual potential evapotranspiration (P.E.T.)	657mm (25.8ins)
Mean monthly temperature - February (10yrs record)	18.0°C
" " " - July (" ")	7.2°C
Mean annual temperature (" ")	12.9°C
Maximum recorded temperature	34.8°C
Bright sunshine (annual average)	2,430 hours

The raised pan evaporation was converted to P.E.T. using the conversion factor (0.5) of Finkelstein (1961).

The combination of high sunshine hours and 'foehn-like' North West winds produce high summer evaporation. The monthly relationship between P.E.T. and rainfall is outlined in Table 7.

TABLE 7

MONTHLY RAINFALL AND P.E.T.

	Jan	Feb	Mar	Apr	May	June	
Rainfall (mm)	53	38	46	58	73	58	
P.E.T. (mm)	122	92	51	38	18	13	
	July	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	66	63	43	48	53	51	650mm
P.E.T. (mm)	13	20	38	61	89	102	657mm

Separate conversion factors were applied to seasonal evaporation figures according to Finkelstein (loc cit). Table 7 shows that the average annual rainfall is fairly evenly distributed with only slight seasonal variation. However, considerable monthly variation in rainfall is a feature of the climate. The January rainfall over the 20 year period (1950 - 1969) has varied from 2.5mm to 152mm with a standard deviation of 45.7mm. In contrast monthly P.E.T. values show greater uniformity.

The average P.E.T. (405mm) for the summer months (Nov, Dec, Jan, Feb) is over twice that of the average rainfall (195mm) for the same period. Summer droughts are a feature of the climate.

Values of P.E.T. and a balance sheet of moisture for Blenheim show that the station is typical of the climate in which the Y.G.E. soil group is situated. (Soil Bureau Staff 1968a, p.32). Blenheim is described as a subhumid mesothermal '1' station typical of the Y.G.E. zone. The Wither Hills come under the same classification.

It seems certain that the climate of the representative catchment is somewhat drier than that recorded at the Soil Conservation Reserve. The greater exposure to the prevailing North West winds with increasing altitude on the Wither Hills means correspondingly greater soil dessication. In addition the amount of rainfall actually entering the soil would be considerably less than that recorded because of surface run-off on the steep slopes, even under a complete vegetative cover.

4.1.3. Vegetation and History of Land Use.

4.1.3.1. Primitive Vegetation.

Indications are that the primitive vegetation before Polynesian arrival, consisted in a dominant coastal hardwood forest type with scattered podocarp (Holloway, 1959). Destruction of these forests was complete at a very early date many centuries before European occupation, probably because of recurrent burning but possibly also because there had been actual reduction in rainfall (Holloway, loc cit). From a consideration of all salient information to date, however, Molloy (1969) reached the conclusion that there is no convincing proof of a major change in post-glacial climate other than a general rise in temperature about 10,000 years ago.

Much evidence of the early Polynesian moa hunters exists on the Wairau boulder bank some 9 km (5.6 miles) east of Blenheim. It is quite possible that their influence extended to the Wither Hills area.

4.1.3.2. History of Land Use.

European occupance of the Wither Hills apparently dates from the arrival of C.B. Wither in the mid 1840's with the establishment of a pastoral run between the Taylor and Dashwood passes. No detailed records exist of the condition of the land at this period.

The earliest map of the Wairau district (1849, at a scale of one inch to one mile) shows the Wither Hills as part of a 'high grassy range'.

The Blenheim archivist (Brayshaw, pers comms.) states that an early photograph (1850) of the Wither Hills shows a complete vegetative cover of dominantly tussock grassland with no visible sign of erosion. A photograph taken about 1900 of part of the Wither Hills some 2.25 km (1.4 miles) to the west of the representative catchment shows severe tunnel-gully erosion on the lower slopes. It would appear then that the onset of severe tunnel-gullying took place well before the turn of the century, probably coincident with the rabbit invasions of the mid 1860's. Oblique aerial photographs of the representative catchment taken in 1944 show very severe vegetative depletion in addition to the severe tunnel-gully erosion. Air photos taken three years later show slightly improved vegetative cover. The most recent aerial photograph shows a much improved vegetative cover but no obvious increase in the numbers and severity of tunnel-gullying.

The pastoral history of the representative catchment is uncertain but it has probably been continuously grazed since the mid 1840's. There is no doubt that the catchment has suffered from overgrazing by stock and rabbits and by fire at various stages during European occupance.

4.1.3.3 Present Vegetation.

The dominant vegetation on sunny exposed hillslopes of the representative catchment is danthonia grassland (Danthonia spp.) with a high proportion of associated low fertility tolerant grasses such as barley grass (Hordeum murinam), needle grass (Stipa variabilis), brome grass (Bromus spp.) and sweet vernal (Anthoxanthum odoratum).

On the higher sections of the catchment a low density cover of silver tussock (Poa spp.) occurs in association with the danthonia and other low fertility grasses. The grasslands generally form a complete dense cover in concave and southerly aspect sites and thins out to a low density, less vigorous cover on steep northerly facing slopes and ridge crests.

Manuka scrub (Leptospermum scoparium) forms dense stands on some sheltered southerly slopes with scattered tauhinu (Cassinia spp.) and danthonia grassland.

A moderately dense stand of well established shrubland occurs along the main drainage line in the upper right hand section of the catchment. It is composed of hoheria (Hoheria spp.), Mahoe (Melicytus ramiflorus) and koromiko (Hebe parviflora). Regeneration of young hoheria seedlings is occuring onto adjacent bare gravels from the sides of the main drainage line.

The main streambed of the middle and lower reaches is heavily infestated with gorse (Ulex europaeus), matagouri (Discaria toumatou), broom (Cytisus scoparius) and sweet brier (Rosa spp.) The broom is spreading onto the hillslopes of the middle and upper left hand section of the catchment. Several small blocks of poplar (Populus spp) and <u>pinus radiata</u> have been established in the main streambed for soil conservation purposes.

4.2 PREVIOUS SOIL SURVEYS OF THE WITHER HILLS.

The most comprehensive soil survey and map to date of the Wither Hills is that by Gibbs and Beggs (1953). This survey differentiated three soil 'types' on the Wither Hills; Waihopai stony sandy loam, and Wither hill soils subdivided into silt loam and shallow silt loam. The silt loam hill soils are formed from deep loess-like sandstone, while the shallow silt loam soils are formed where the loess-like sandstone is shallow and stones from the underlying conglomerate are incorporated in the soil horizons. The shallow silt loam soils occur on the ridges and steeper slopes associated with the silt loam hill soil (Gibbs and Beggs, loc cit).

The silt loam Wither hill soils are subject to both sheet and tunnel-gully erosion, while the shallow silt loams are prone to slip erosion. Slight sheet and gully erosion occur on the Waihopai soils (Gibbs and Beggs, loc cit).

These three soils are described as soil types. The Wither silt loams and shallow silt loams are classified as yellow-grey earth hill soils with a warm, subhumid climate. The provisional soil map of Awatere, Kaikoura, and part Marlborough counties (Gibbs and Beggs, loc cit) at a scale of 4 miles to the inch differentiates the three soil 'types'.

The 1968 soil map of eastern Marlborough (Soil Survey Staff, 1968b) at the same scale, shows the Wither hill soils and the Waihopai steepland soils as two separate soil sets. No attempt has been made to differentiate the Wither shallow silt loam from the silt loam hill soil.

4.3 THE SOILS OF THE STUDY CATCHMENT.

4.3.1. <u>The Soil Mapping Units</u>.

Three soil series were surveyed and mapped in the representative catchment. They comprise the Waihopai series formed from greywacke gravels, the Wither series from loessial deposits and the Vernon series from mixed loess and gravels (fig. 3). These soil series correspond to the three soil 'types' previously surveyed in the Wither Hills (Gibbs and Beggs, loc cit).

Because of the wide variation in topography and to a lesser degree to differences in soil texture (stoniness) it was considered that the mapping units should be defined as soil series rather than soil types as outlined by Taylor and Pohlen (1962, p.136).

4.3.1.1. <u>The Wither Series</u>.

These soils are formed from deep loess 1m to 3m (3.3ft to 10ft) deposited on greywacke gravels. Much of the loess contains isolated small greywacke stones and gravels distributed non-uniformly throughout. Stones have been observed in profiles in all parts of the landscape where thick loess occurs. The mode of incorporation into the loess is uncertain unless the loess has been extensively redeposited with some mixing in of the gravels by colluvial processes. Vegetation consists of a thin cover of danthonia and exotic low fertility grass species. Manuka is dominant on shady faces. The topography ranges from rolling crests and footslopes to steep and very steep backslopes on predominantly eastern and western aspects. Soil drainage classes range from well drained on steep slopes to moderately well drained on gently undulating and rolling footslopes. Sheet and tunnel-gully erosion have been prevalent over much of the Wither series.

The modal soil type is the Wither silt loam developed on steep backslopes in the lower section of the catchment.

A simplified profile is outlined below.

A_1	14cms	Dark yellowish brown (10YR 3/4) silt loam; friable; weakly developed very fine crumb and fine and medium granular structure; abundant roots; indistinct boundary,
A_3	11cms	Dark greyish brown (10YR 4/2) silt loam; friable; weakly developed fine crumb and nutty structure; many roots; indistinct boundary,

Fig. 3

SOIL MAP OF REPRESENTATIVE CATCHMENT WITHER HILLS

B_1	15cms	Brown to dark brown (10YR 4/3) clay loam; firm; very weakly developed fine blocky structure (almost structureless); slightly vesicular; few roots; indistinct boundary,
B_2	22cms	Brown to dark brown (10YR 4/3) clay loam; firm; moderately developed fine to medium prismatic structure, breaking in part to medium blocky; thin discontinuous clayskins; few faint yellowish red mottles; few roots; indistinct boundary,
C_x	22cms	Brown to dark brown (7.5YR 4/4) clay loam; firm to very firm; moderately developed medium blocky structure; thin discontinuous clayskins; few roots; indistinct boundary,
uB/C_x	20cms	Dark yellowish brown (10YR 4/4) clay loam; very firm; massive, in place, but moderately developed very fine nutty structure present, possibly relict structure; few to many relict infilled faunal channels.

The B_1 horizons described in all subsequent soils of the Wither series varied in texture from a heavy silt loam to clay loam and all were characterized by the lack of structural development. Structural components if at all recognized in the B_1 were only very weakly developed.

Wither soils formed in the lower hillslope positions normally contained larger, brighter and more numerous mottles and concretions in the subsoils than the soil members higher in the landscape.

The massive C_x horizon - (fragipan) was a prominent feature of all exposed loessial sections except those in the lower backslope and footslope positions where it did not protrude as a pronounced ledge in the 1.5m profile depth.

4.3.1.2. The Waihopai Series.

These soils are formed on massive 'in-situ' greywacke gravels of Tertiary age. Very minor additions of loess probably have been incorporated on surfaces of most of these soils.

The topography ranges from narrow rolling ridge crests, long moderately steep to steep backslopes, to strongly rolling footslopes. This series occurs most commonly on the steeper slopes at the head of the catchment. Drainage classes range from well drained on steep slopes and ridges to moderately well drained in footslopes and toeslopes. Vegetative cover is similar to the Wither series. Isolated slip erosion has occurred in these soils. The modal soil type is represented by the Waihopai stony silt loam developed on moderately steep to steep backslopes at the head of the catchment. A simplified profile is outlined below.

A	22cms	Grey brown to brown (10YR 5/2-5/3) stony silt loam; friable; weakly to moderately developed fine crumb and medium granular structure; many roots; indistinct boundary,
B_1	16cms	Dark yellowish brown (10YR 4/4) stony silt loam; friable; weakly to moderately developed fine granular/nutty structures; many roots; indistinct boundary,
B_2	35cms	Dark yellowish brown (10YR 4/4) stony silt loam; friable; weakly to moderately developed very fine and fine nutty structures; many roots; thin discontinuous clayskins around stones and peds (10YR 4/3); indistinct boundary,
C	ON	Dark yellowish brown (10YR 4/4) stony gritty heavy silt loam; firm; moderately developed fine nutty structure; clayskins thicker and more continuous than B horizon; some reddish iron-staining around and between stones; few roots.

Associated soils developed on adjacent footslopes and toeslopes often contain considerable admixtures of loess and strictly belong to the Vernon series. For convenience they have been grouped in the Waihopai series. The soils developed in the lower parts of the Waihopai landscape have deeper and darker topsoils with more strongly developed granular structures than soils formed on steeper slopes and convex sites. Subsoils in lower slope positions are characterised by numerous concretions and mottling. Differences in soil morphology due to aspect are slight.

4.3.1.3. The Vernon Series. *

These soils are formed in mixed loess and gravel deposits. They are most commonly developed in downslope positions where active colluviation and mixing of loess with gravels has occurred. Where the degree of stoniness is slight these soils grade into the Wither series. With increasing content of stones and shallowness of topsoil this series grades into Waihopai soils. The topography ranges from strongly rolling to moderately steep secondary ridges and steep backslopes to strongly rolling footslopes and toeslopes. Drainage classes vary from well drained on interfluves and backslopes to moderately well drained in footslope sites. Vegetative cover is similar to that on the Wither series.

Tunnel-gully and minor slip erosion occur on these soils. The modal soil type is the Vernon silt loam with stones, developed on lower backslopes midway up the catchment. A profile formed on a 26 degree lower backslope with easterly aspect is as follows :

* (The Vernon series is not an established Soil Bureau soil unit and has been devised for convenience in terminology).

A_1	15cm	Dark grey brown (10YR 4/2) silt loam, with stones and boulders; friable; weakly developed fine crumb and fine and medium granular structures; many roots; indistinct boundary,
B_1	13cm	Pale brown (10YR 6/3) silt loam with stones and boulders; friable; weakly developed fine prismatic breaking to fine blocky structure; abundant fine vesicular pores; indistinct boundary,
B_2	12cm	Yellowish brown (10YR 5/4) clay loam with stones and boulders; firm; moderately developed fine prismatic breaking to fine blocky structures; thin, discontinuous clayskins; many fine vesicular pores white silty material between cracks; indistinct boundary,
1uB	30cm	Yellowish brown (10YR 5/4) stony clay loam; firm to very firm; strongly developed fine prismatic breaking to fine blocky structure; thick, continuous clayskins around peds and stones; many reddish iron-stained streaks (5YR 4/8) and mottles; many dark organic matter stained streaks,
1uC	30cm	Yellowish brown (10YR 5/6) very compact stony clay loam to clay; very firm; moderately developed very fine nutty structure; thin, discontinuous clayskins; few dark organic matter stained streaks with associated reddish iron staining,
2uB	on	Remnants of an old weathered surface, in undisturbed gravels.

The abundance and size of mottles and concretionary material increases on footslope sites.

4.3.2. <u>The Detailed Soil Pattern of the Study Catchment</u>.

The interrelationship between the detailed soil pattern and position on the landscape is more clearly evident using the concept of 'K cycles' after Butler (1959).

Figure 4 shows idealised cross sections of the typical soil-landscapes from gully bottom to ridge crest within each soil series.

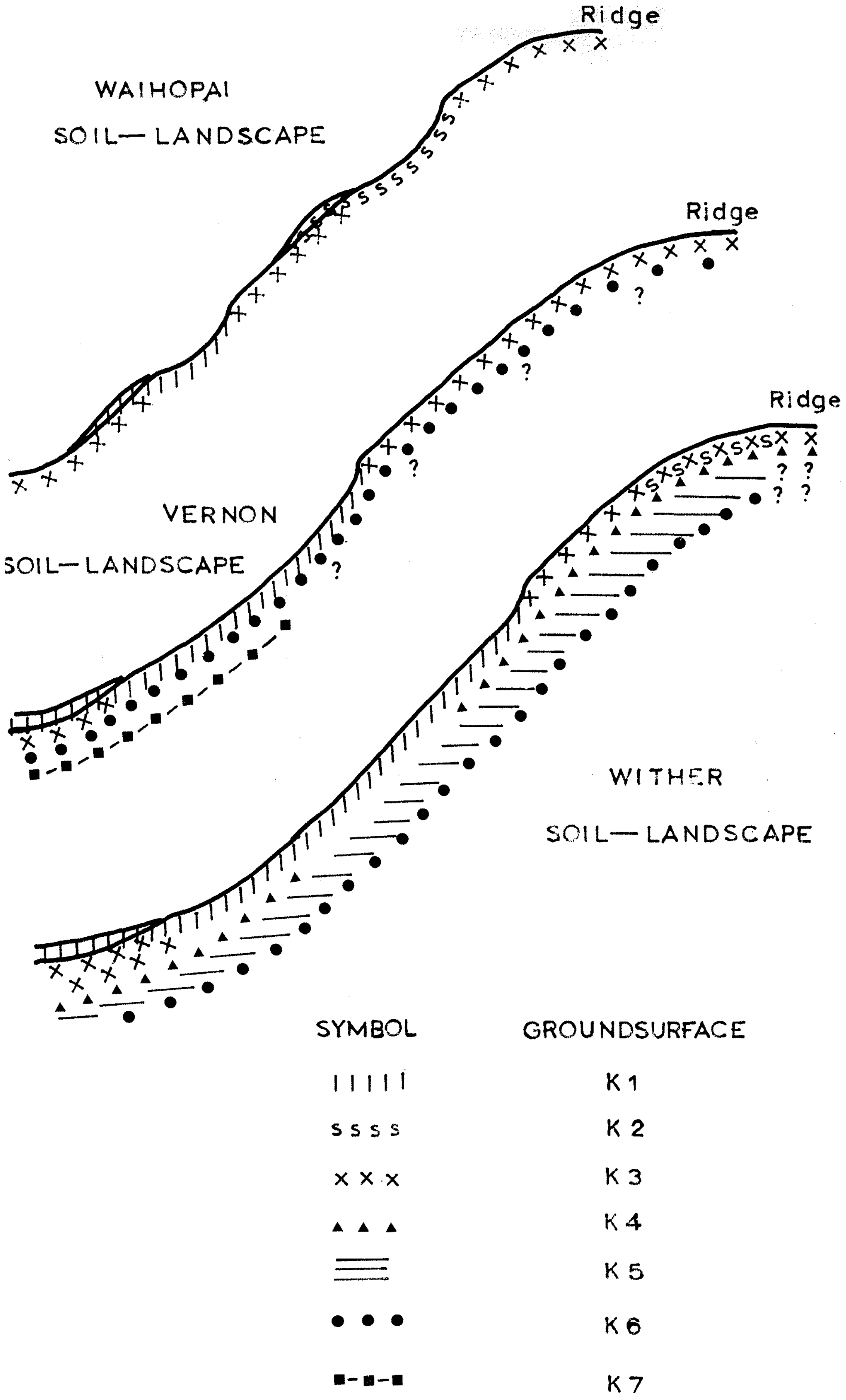


FIGURE 4. IDEALISED CROSS—SECTIONS THROUGH TYPICAL SOIL—LANDSCAPES OF THE THREE SOIL SERIES SHOWING SEQUENCE OF GROUNDSURFACES

The groundsurface is defined as a soil forming landscape marking a period of landscape stability (Butler, loc cit). Successive periods of instability with erosion / deposition have subsequently altered the original groundsurfaces. In some instances groundsurfaces have been completely stripped by erosive processes, whereas others have been preserved by total burial from subsequent depositions. More commonly only parts of a groundsurface are removed by erosion and deposited elsewhere, burying part of the same groundsurface in the process. Subsequent soil formation on the exposed materials initiates a new groundsurface. The groundsurfaces in figure 4 are designated K1, K2, K3,...K7 in chronological order from the uppermost (most recent) to the lower and older ones (Butler, loc cit).

It should be noted that figure 4 only attempts to show the representative soil-landscape variation within each soil series. Not all parts of the landscape in each soil unit show the pattern of groundsurfaces as indicated in figure 4. The relationship between groundsurface, landform and erosion characteristics, and soil pattern is outlined in table 8. The tentative age of each groundsurface is also shown in the table. Age relationships were established on the basis of degree of soil development in each groundsurface and its stratigraphic position. Soil profile development increases from K1 to K6. In the absence of absolute dating methods (e.g. radiocarbon) only relative ages could be estimated. The advanced stage of weathering and deep burial of the K6 groundsurface infers formation during the initial stages of the late Pleistocene era. Suggate (1965) identified four glacial moraines in the Wairau Valley. The oldest moraine was correlated with the Waimaungan Glaciation. The next moraine in the sequence was assigned to

TABLE 8 . GROUNDSURFACE SEQUENCE ON THE WITHER HILLS.

Groundsurface and Tentative Age.	Parent Material	Land form and Erosion Characteristics	Soils. Series, phases and types
K1 (Post European times)	(1) Loess	(a) Shoulders, Backslopes, Footslopes, severe tunnel-gullies & their Detritus.	-Undifferentiated recent soils on newly exposed and deposited parent materials.
	(2) Mixed Loess & Gravels	(a) Backslopes, footslopes. Severe tunnel-gullies & Detritus.	— " " "
	(3) Gravels	(a) Backslopes - slips (b) Streambed - Alluvium	-Waihopai (truncated phase) -Undifferentiated recent soils.
K2 (Post Polynesian times)	(1) Gravels	(a) Old slip surfaces on steep backslopes. (b) Debris from above on Lower backslopes.	-Waihopai (Shallow phase.) - Waihopai (hill phase).
	(2) Loess	Shoulders & backslopes. Dark, O.M. stained infillings.	-(see text)
K3 (Post-Glacial)	(1) Gravels	(a) Stable ridges, shoulders & backslopes. (b) Accumulative Sites on footslopes-toeslope.	-Waihopai stony silt loam. -Waihopai (cumulative phase).
	(2) Mixed Loess & Gravels	(a) Subsidiary ridges & backslopes (b) Lower Backslopes, footslopes & Toeslopes.	- Vernon stony silt loam. - Vernon silt loam with stones
	(3) Loess	(a) Crests, shoulders, backslopes, footslopes & toeslopes.	-Wither silt loam.
K4 (Late Otiran or early Otiran?)	loess	Underlying crests, shoulders, backslopes and footslopes.	Compact 'Fragipan' - a paleosol remnant
K5 (Early Otiran or Post Waimean?)	Loess with minor gravels	(a) Underlying shoulders, backslopes & footslopes.	Remnant of an older paleosol.
K6 (Post Waimean or Post Waimaungan?)	Mixed loess & gravels	Underlying shoulders, backslopes & footslopes.	Remnant of a more ancient paleosol.
K7 (Post Waimaungan or Post Porikan?)	Gravels	Underlying backslopes & footslopes.	Paleosol remnant in undisturbed gravels.

the Waimean Glaciation while the 2 youngest deposits were correlated to the Otiran Glaciation. A similar age sequence if applied to the paleosols would place the K6 groundsurface into the immediate post Waimaungan era (Terangian paleosol) and designate the K5 groundsurface as a post Waimean (oturian) paleosol. Also the abundant, rounded iron-manganese nodules up to 7mm in diameter prevalent throughout most of the K5 groundsurfaces on steep backslopes is considered evidence of interglacial (oturian) weathering and soil formation. The possibility that the K5 and K6 groundsurfaces are younger than suggested is indicated in table 8 showing tentative age correlations for the complete sequence of groundsurfaces.

4.3.2.1. Soils Comprising the K1 Groundsurface.

This groundsurface consists of newly exposed parent materials resulting from recent erosive processes. It includes all those soils initiated since European occupation of the area as well as contemporary surfaces resulting from recent erosion. Profile differentiation is absent or at the most rudimentary with only A horizon development. Although the K1 groundsurface covers a considerable total area its distribution within the catchment is irregular and it is not feasible to map out as a separate soil unit.

A simplified profile of a recent soil formed in debris from tunnel-gully erosion is outlined below. The site is a sloping footslope in which silty debris has been deposited on a K3 surface and since colonised by grass.

19cms Pale brown (10YR 6/3) silt loam; weakly developed fine crumb and granular structure; very friable; many roots; distinct boundary, UA 12cms Light brown grey (10YR 6/2) silt loam; friable; weakly developed medium prismatic breaking to fine blocky structure; many roots; indistinct boundary.

A recent soil formed on a newly exposed slip surface in the Waihopai soils is described below. This soil (Waihopai truncated phase) is formed on a steep backslope (30 degrees) with a sparse vegetation of native and introduced grasses.

A 2cms Pale brown (10YR 6/3) stony silt loam; friable; weakly developed fine crumb and granular structure; few roots; distinct boundary,

uB/C ON Yellowish brown (10YR 5/4) stony gritty clay; very firm; strongly developed fine blocky structure breaking to very fine nutty; thick, continuous clayskins; some white silty material in cracks.

4.3.2.2. Soils Comprising the K2 Groundsurface.

This surface occurs on isolated areas of the Waihopai soils in the representative catchment and as a buried soil in some footslopes of the Wither series outside the catchment. In Waihopai soil-landscapes it comprises the remnants of ancient slips and their detritus estimated to have occurred many centuries ago. It is difficult to date the soils formed on this groundsurface but, because their profiles are more developed than the K1 groundsurface soils then it is presumed they are considerably older. A 'Polynesian' time has been assigned to this groundsurface since it is thought to have originated during a period of instability coincidental with Polynesian activity in the area. Molloy (1964), Leamy (1969) and others have suggested 'Polynesian' fires as the cause of erosion/ deposition in various parts of the country before European arrival.

No comparable K2 groundsurface was recognised in the Vernon soil-landscape. The presence of what appear to be fossil infilled tunnels comprising accumulations of dark grey organic material occurring up and down slope in Wither soils may also represent the remains of ancient tunnels or gullies of Polynesian age. The origin and significance of these dark 'infilled' materials is unknown. They are described in more detail in the section on tunnel-gully erosion.

Evidence for the recognition of the K2 surface in the Waihopai soil-landscape rests mainly on the presence of large depressions indicative of old slip or slump surfaces. Profiles are less differentiated with shallower horizons than soils on the K3 groundsurfaces.

The soil phases of the K2 surface have been distinguished as the Waihopai shallow phase and the Waihopai hill phase. The former occurs on the old slip surfaces while the latter has formed on debris from the slips. Their extent is very minor in the study catchment.

The shallow phase soil occurs most commonly on steep upper backslopes under a complete vegetative cover of grassland species.

A typical profile described just below the main ridge in the upper right hand catchment, with a 31 degree slope is presented below;

A	14cms	Grey brown (10YR 5/2-5/3) stony silt loam; friable; weakly developed fine crumb and medium granular structure; many roots; indistinct boundary,
uB	9cms	dark yellowish brown (10YR 4/4) stony silt loam; friable; weakly developed fine granular and nutty structure; thin discontinuous clayskins around stones; many roots; indistinct boundary,

uC	ON	dark yellowish brown (10YR 4/4) stony gritty heavy silt loam to clay loam; firm; moderately developed very fine nutty structure; thin discontinuous clay-skins; reddish iron-staining common around stones; few roots.

A representative profile description of the hill phase soil on a moderately steep lower backslope (20 degrees is as follows :

A	2cms	dark grey (10YR 4/1) silt loam with stones; friable; moderately developed fine crumb and medium granular structure; many roots; indistinct boundary,
AB	7cms	dark greyish brown (10YR 4/2) silt loam with stones; friable; weakly developed medium crumb and granular/nutty structures; many roots; indistinct boundary,
BC	ON	yellowish brown (10YR 5/4) stony heavy silt loam; friable/firm; weakly developed fine nutty structure; very thin discontinuous clayskins around stones; isolated reddish iron-staining particularly near stones.

Adjacent Waihopai hill phase profiles comprised stony silt loam and bouldery silt loam A horizons.

The detritus of most K2 slips on steep slopes have been distributed over a wide area and incorporated into the A horizons of the K3 groundsurfaces below the slips. These soils downslope of the K2 slip surfaces are not distinguishable as Waihopai hill phase soils. They are classified as Waihopai stony silt loams.

4.3.2.3. <u>The K3 Groundsurface</u>.

This surface covers the majority of the present soils in the catchment. Profile development is greater than the K2 groundsurfaces. The soils are presumed to be of post-glacial origin prior to Polynesian interference. These soils have already been described in some detail as the major soil mapping units.

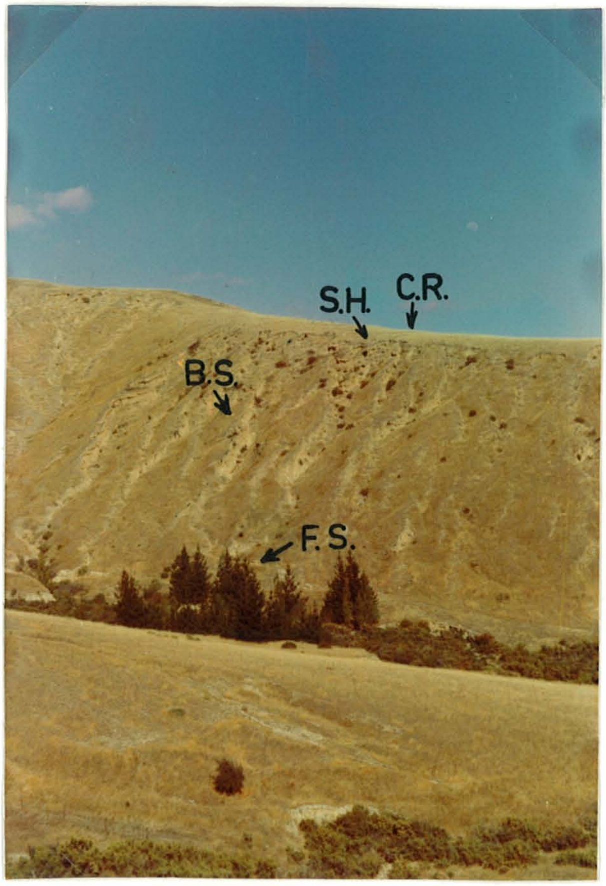


Plate 1 . Location of toposequence sites on severely tunnel-gullied L.H.S. of catchment.

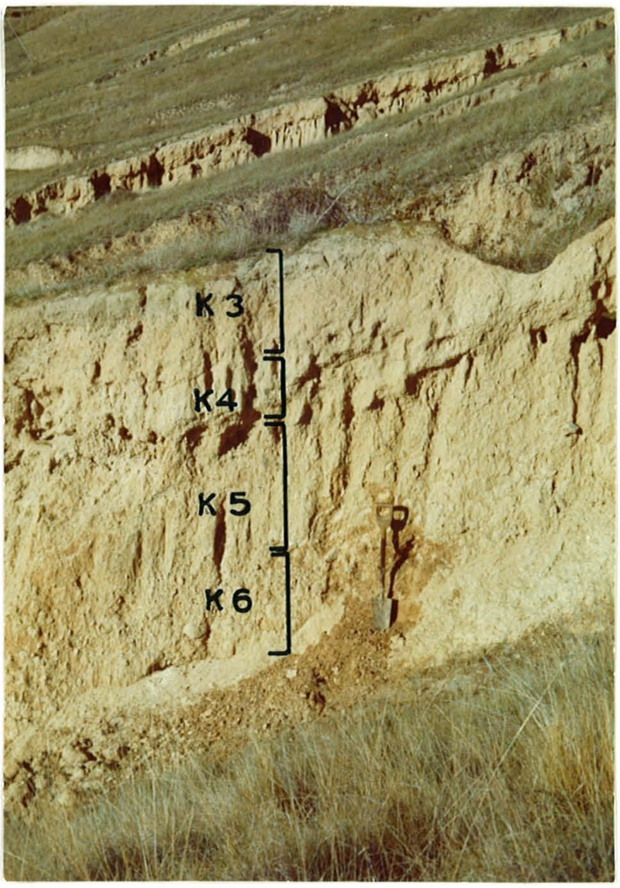
F.S. Footslope site

B.S. Backslope site

S.H. Shoulder site

C.R. Crest site

Plate 2 . Groundsurface sequence (K3, K4, K5, K6) in Wither soil-landscape.



In the Waihopai series the stony silt loam is developed on stable gravels on steep backslopes and moderately steep to rolling ridge crests and shoulders. Sites range from slightly regressive (ridge crests) to moderately regressive (steep backslopes). Accumulative soils designated as the Waihopai cumulative phase, occur in the lower footslope and toeslope positions near gully bottoms. They are formed on a mixture of loess and fine colluvium with the greywacke gravels.

A typical profile of Waihopai cumulative phase developed on a steep (26°) concave gully bottom is :

A	25cms	dark grey (10YR 4/1) stony silt loam, some boulders; friable; strongly developed fine crumb and granular structure; some coarse cast granules; many roots; indistinct boundary,
B	31cm	yellowish brown (10YR 5/4) stony, bouldery silt loam; friable; very weakly developed medium crumb and granular structure (almost structureless); thin, discontinuous brown clayskins around stones; many roots; indistinct boundary,
C	ON	yellowish brown (10YR 5/4) heavy silt loam with many stones and boulders; firm; moderately developed fine nutty structures; thin, discontinuous clayskins; few roots.

This phase is distinguished from the Waihopai stony silt loam by the thick, deep, dark coloured A horizon with strongly developed crumb and granular structures.

The Vernon silt loam with stones and the Wither silt loam have been described as modal soils of the Vernon and Wither series respectively. The transition between the Vernon and Wither series is generally not sharp, although changes from one series to the other may occur within several metres.

4.3.2.4. <u>The K4 Groundsurface</u>.

This surface occurs beneath the Wither K3 groundsurface except where exposed by recent severe tunnel-gully and sheet erosion. The K4 groundsurface comprises the most prominent part of the compact fragipan observed in the Wither soil profile. Field evidence that the fragipan is a remnant of a pre-K3 cycle of weathering and soil formation is outlined below :

(i) Morphology of the fragipan.

(a) Fossilized soil faunal remains. Few to many, large fossil infilled burrows occur in the fragipan horizon but evidence of similar soil faunal activity is entirely absent from subsoil horizons above the pan.

(b) Structure. The weakly to moderately developed coherent, very fine nutty structure comprising the compact pan differs markedly from the prismatic structures recorded for most other South Island YGE fragipans. The fragipan structural components closely resemble those described in paleosols immediately beneath the pan.

(ii) Profile position in the landscape. In some footslope sites the fragipan is absent in the upper 1m of the profile but a compact, prominent horizon, similar to the fragipan in higher slope positions, occurs at a depth greater than 1.5m. The soil material from the surface down to 1m has a gradational texture profile similar to the K3 groundsurface soils above the fragipan in higher slope positions. In crest sites the fragipan appears to be closer to the surface than in backslope and shoulder sites. It is suggested that a phase of erosion/deposition subsequent to formation of the K4 groundsurface caused differential accumulation on top of the K4 groundsurface in mid and lower slopes.

The concave footslope site would be expected to accumulate greater material than sites higher up the slope.

(iii) Observation of fragipan soils outside the representative catchment. Brief study was made of a Wither soil with prominent fragipan on a rolling dissected terrace some 8.1km (5 miles) east of the representative catchment. A distinct layer of small to medium stones occurred immediately on top of the compact pan in the C_x horizon position. The fine material (< 2.0mm) above the pan had a gradational texture profile similar to that of the Wither soils already described.

The stony layer comprised relatively unweathered greywacke stones with thin, discontinuous clayskins on external surfaces. The stone layer is undoubtedly of colluvial/fluvial origin and represents an unconformity with the fragipan horizon below.

Recognition of the K4 groundsurface in the Vernon soil landscape is uncertain. The K4 surface is not identified in Waihopai soil-landscapes.

4.3.2.5. The K5 and K6 Groundsurfaces.

These surfaces occur beneath the K3 and K4 groundsurfaces except where exposed by recent tunnel-gully erosion.

In the Wither series the K5 begins immediately under the fragipan from which it is readily distinguished. The K5 consists of an accumulation of loess of varying thickness and includes some stones and boulders. Horizon differentiation is not pronounced. The presence of abundant spherical manganese nodules up to 7mm in diameter were a feature of most of the K5 surfaces examined. Where the round concretions were absent the presence of thick manganese streaks between peds were noted. The K5 groundsurface is thickest in shoulder positions (up to 1.0m) and thins out downslope and on crest sites.

Plate 3. Profile of the Waihopai stony silt loam developed in undisturbed greywacke gravels.

Plate 4. Ground-surface sequence (K3, K6, K7) in Vernon soil-landscape.

The K6 groundsurface occurs some 2 metres below the present landscape surface. It has not been traced beneath all the Wither soil-landscapes. Erosion of the K6 surface prior to deposition and formation of the K5 would account for its absence in some sites.

The K6 groundsurface is characterized in backslope and footslope positions by the presence of many strongly weathered stones and boulders. Thick continuous clayskins surround the stones and occur along internal fracture planes. The incidence of stones and boulders decreases upslope. In all sites where the K6 surface was traced, the fine fraction (< 2.0mm) comprised a clay or gritty clay texture. Structures varied from strongly developed medium blocky in sites with few stones to strongly developed fine nutty in stony and bouldery sites.

A typical section through the Wither series on a steep backslope in the lower left hand section of the catchment is as follows :

(plate 2)

K3	0-84cms	Wither silt loam. Refer profile description of
K4	84-100cms	fragipan Wither mapping unit,
K5	100-190cms	yellowish brown (10YR 5/4) clay loam; few stones; very firm; moderately to strongly developed medium blocky breaking to fine nutty structure; thin, continuous clayskins but thick around stone; small (<2.0mm) fossil infilled faunal channels common; thick black manganese streaks perpendicular to surface; numerous salt specks,
K6	190-240cms	brown (7.5YR 5/4) stony clay; very firm; strongly developed very fine nutty structures; thick continuous clayskins; prominent reddish iron staining around stones.

The K5 groundsurface appears to be absent in the Vernon and Waihopai series.

Assuming uniform aeolian fall-out of the loess over the upper section of the catchment, the present irregular soil pattern in this area infers erosion of the loess either immediately after deposition or at some later stage after soil formation. If the latter occurred then the present surfaces devoid of substantial loess (Waihopai and Vernon series) may contain remnants of the K5 or K6 groundsurfaces in their lower soil profiles.

Evidence that the K6 surface does in fact comprise the lower subsoil and parent material of some or most of the Vernon soils is given below :

(i) Morphological features of the K6 surface recognized under Wither soils closely resembles the uB and uC horizons of Vernon soils.

(ii) On the lower L.H.S. of the catchment Vernon soils occur on footslopes, lower backslopes and in concave sub-catchments in association with Wither soils on higher slope positions (refer map 1). Close examination reveals that the strongly weathered stony horizons in the Vernon soils can be traced upslope into the Wither soils where it appears as the K6 groundsurface in the sequence of paleosols.

It is possible that some Vernon soils result from weathering of mixed loess and gravels due to erosion/deposition phases more recent than that forming the K6 surface.

The K6 groundsurface has been recognized in stony soils classified as Waihopai series on steep backslopes and rolling ridge crests of the lower catchment section. Its position in the profile on steep backslopes depends on the degree of erosion and varies from 0-2cm below the surface on recent slip surfaces to 20cms deep on older slips and 60cms deep on stable backslopes.

On crest sites the K6 groundsurface occurs some 20-30cms down the profile.

It seems likely that these stony soils are formed from disturbed Tertiary gravels and not from undisturbed 'in-situ' gravels as are the Waihopai soils of the upper catchment. Because the stone content is high and the loess content negligible compared to that in the Vernon series it is suggested that these soils should strictly be classified as Vernon - Waihopai intergrades.

4.3.2.6. <u>The K7 Groundsurface</u>.

This surface was recognized only beneath the lower Vernon soil landscapes where severe gully erosion has formed deep vertical sections into the underlying Tertiary gravels. It is possible that a similar groundsurface occurs beneath the lower Wither soil landscapes.

A profile recorded beneath the Vernon mapping unit (plate 4) is as follows :

K3	0-40cms	Vernon silt loam with stones (refer mapping
K6	40-100cms	unit description)
K7 uB	100-120cms	reddish yellow and yellow (7.5YR 6/8 dry and 10YR 8/6 dry) stony, gritty clay; very firm; strongly developed fine blocky structure breaking to very fine nutty; thick continuous clayskins; dark organic matter stained streaks with prominent reddish iron staining, indistinct boundary,
	ON	reddish yellow (7.5YR 6/8 dry) very stony gritty loam; most stones split by fracture planes with clayskins in cracks; prominent reddish iron stainings.

4.3.3. Summary.

The soil pattern of the representative catchment has been explained in terms of Butler's (1959) periodicity concept of groundsurfaces. Seven distinct groundsurfaces (K1, K2...K7) of Mid and Late Pleistocene age have been recognized on the basis of profile development and stratigraphic position. The K4 to K7 groundsurfaces exist as paleosol remnants except where exposed by recent severe sheet and tunnel-gully erosion. The K4 groundsurface occurs as a relict fragipan in the Wither soil series. Differentiation of the K4 surface was uncertain in the Vernon series. In many Vernon soils the compact, stony clay loam pan is a relict feature comprising the K6 groundsurface. The K1, K2, and K3 groundsurfaces are of post glacial origin and comprise the weathering mantle found in the present landscape.

4.4 THE PATTERN OF EROSION IN THE REPRESENTATIVE CATCHMENT.

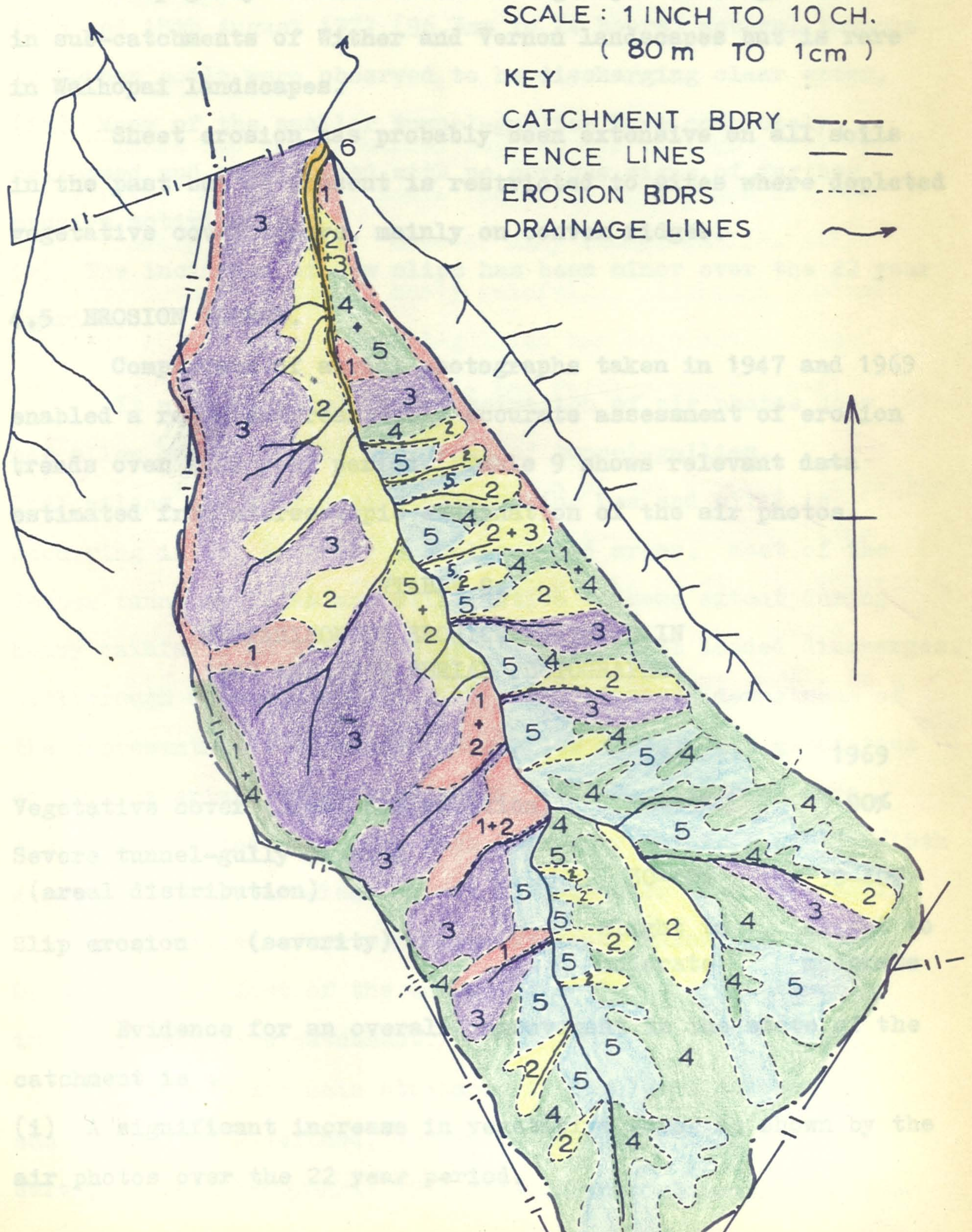
The type of erosion is correlated with the soil series while severity of erosion shows close correlation with position in the landscape and a less obvious relationship with the soil series and slope aspect (fig. 5).

Tunnel-gully erosion occurs in both the Wither and Vernon series. It is most severe in Wither soils and on exposed, sunny aspect Vernon soils. On shady aspect Vernon soils tunnel-gullying is slight to moderate. Backslopes of Vernon landscapes and backslopes and shoulder positions of Wither landscapes show the most severe tunnel-gully erosion. In both soil-landscapes tunnel-gullying is less severe on concave footslopes and very minor on convex ridge crests.

Slip erosion is most common in the Waihopai series but also occurs to slight extent in Vernon soils. In estimating the severity of slip erosion the incidence of older revegetated

Fig. 5

SOIL EROSION OF REPRESENTATIVE CATCHMENT WITHER HILLS



LEGEND

TUNNEL-GULLY EROSION (WITHER, VERNON SERIES)

- NIL-SLIGHT — 1
- MODERATE — 2
- SEVERE — 3

SLIP EROSION (WAIHOPAI SERIES)

- NIL — 4
- SLIGHT-MODERATE — 5

RECENTLY ACCUMMULATED SEDIMENTS — 6

slips was taken into consideration as well as the most recently exposed slips. In the Waihopai landscape slight to moderate slip erosion occurs in the upper backslope and in steep lower backslope positions. The slips are shallow with the slip surface some 60-70cms below the original land surface.

Deep gully erosion occurs along major drainage outlets in sub-catchments of Wither and Vernon landscapes but is rare in Waihopai landscapes.

Sheet erosion has probably been extensive on all soils in the past but at present is restricted to sites where depleted vegetative cover occurs, mainly on convex ridges.

4.5 EROSION TRENDS.

Comparison of aerial photographs taken in 1947 and 1969 enabled a rapid and reasonably accurate assessment of erosion trends over a 22 year period. Table 9 shows relevant data estimated from stereoscopic examination of the air photos.

TABLE 9.

COMPARISON OF EROSION FEATURES IN
1947 AND 1969 AERIAL PHOTOGRAPHS.

	1947	1969
Vegetative cover (areal distribution)	50-55%	90%
Severe tunnel-gully erosion (areal distribution)	30-40%	30-40%
Slip erosion (severity)	slight to moderate	slight to moderate

Evidence for an overall improvement in the state of the catchment is :

(i) A significant increase in vegetative cover as shown by the air photos over the 22 year period.

(ii) No measurable difference between the 1947 and 1969 air photos of major erosion features. The pronounced, vertical tunnel-gully heads in the shoulder positions on the left hand side of the lower catchment have not advanced upslope to any significant extent.

(iii) Immediately after the high intensity rainfall of the 17th and 18th August 1971 (96.3mm in 24 hours) several tunnels in Vernon soils were observed to be discharging clear water.

(iv) Many of the smaller tunnel-gullies have completely collapsed and revegetated with no obvious signs of further erosive activity.

(v) The incidence of new slips has been minor over the 22 year period.

It must be noted that examination of air photos does not allow comparison of the depth of tunnel-gullies. Indications are that active downcutting has and still is occurring in the severely tunnel-gullied areas. Most of the deeper tunnel-gullies are still active to some extent during heavy rainfalls as evidenced by their sediment loaded discharges. Marlborough Catchment Board silt traps situated downstream of the representative catchment accumulate substantial quantities of fine materials after heavy rain. These silt traps were completely filled after the high intensity rainfall of 17th/18th August 1971. After cleaning out in September they were again completely filled after a subsequent heavy rainstorm during October 1971. Most of the entrapped sediment originated in the representative catchment.

Although the main streambed in the lower catchment section showed a defined, degrading channel during the soil survey in late 1970/early 1971 considerable alteration to the shape of the streambed by large scale gravel movement was observed immediately after the high intensity rainfalls of August and October 1971. It was apparent that scouring of most of the deep gullies at sub-catchment outlets had contributed substantial quantities of coarse debris to the main streambed.

4.5.1. Conclusions.

There has been a marked improvement in vegetative cover since 1947. On an areal basis tunnel-gully erosion has not significantly increased. However many tunnel-gullies still actively downgrade during heavy rainfalls. Although headward movement of the severe tunnel-gullies has apparently ceased it has not reached natural grade and further massive soil movement must eventually be expected.

It is considered that extension of the present vegetative cover into the exposed surfaces of collapsed tunnel-gullies would help reduce soil loss and retain soil moisture. However any attempt to significantly decrease the existing severe tunnel-gully erosion by natural revegetation must surely be a long term process measureable in decades.

CHAPTER V

THE TOPOSEQUENCE

5.1. FACTORS OF THE ENVIRONMENT

The location of the four toposequence sites is shown in fig. 3 and plate 1.

Topographic characteristics have been outlined in table 2. Drainage classes range from moderately well drained on footslopes to well drained on backslope, shoulder and crest sites.

The vegetative cover of all four sites is typical of most of the catchment, comprising danthonia-dominant grassland with 'low fertility' introduced grasses such as hairgrass, goose grass and sweet vernal.

Parent materials comprise fine textured loess plus rare additions of greywacke stone fragments ($<$ 2.5cms).

5.2. PEDOLOGY.

5.2.1. Profile Characteristics

Detailed profile descriptions of the toposequence soils are presented in appendix A. A schematic representation is shown in figure 6.

Because the fragipan is considered to be a distinguishing characteristic of most YGE soils from loess the uB/C_x horizon comprising the K4 groundsurface has been included in the morphology of the toposequence profiles.

5.2.1.1. Morphological Variation Across the Toposequence

The principal changes in profile morphology involve the position, thickness, texture and gammate features of the fragipan, the degree and abundance of subsoil mottles and nodules and the incidence of fine gravels.

(i) The Fragipan

(a) Position and Thickness. A prominent fragipan occurs in exposed vertical sections in backslope and shoulder sites as a distinct ledge some 60cms from the surface. Deep exposed sections do not occur on crest sites but a compact fragipan analogous to that in shoulder sites has been determined from examination of soil pits. An obvious fragipan is absent from the upper 1m in the footslope profile but a protruding compact horizon resembling the fragipan of higher slope positions has been observed at a depth greater than 1.5m. The fragipan is thickest in the shoulder profile (50–55cm) and thins downslope. In the backslope, shoulder and crest sites the fragipan comprises the C_x horizon of the K3 groundsurface and the uB/C_x horizon of the K4 groundsurface.

(1) Structure and Gammation. The C_x horizon in backslope, shoulder and crest profiles has moderately developed medium to coarse blocky structure breaking to moderately developed very fine nutty structures. In the shoulder profile the dark-reddish iron-staining surrounding the blocky peds together with vertical root traces gives a net-gammate pattern. On exposed gully sections the decayed root traces are commonly bleached a light grey colour and enhance the net-gammate pattern. The uB/C_x horizon of the shoulder profile has weakly to moderately developed, coherent, very fine nutty structure with a secondary very coarse prismatic and coarse blocky structures. Thin root traces with weakly gleyed adjacent ped surfaces extend down between the coarse prisms giving a weak subgammate pattern.

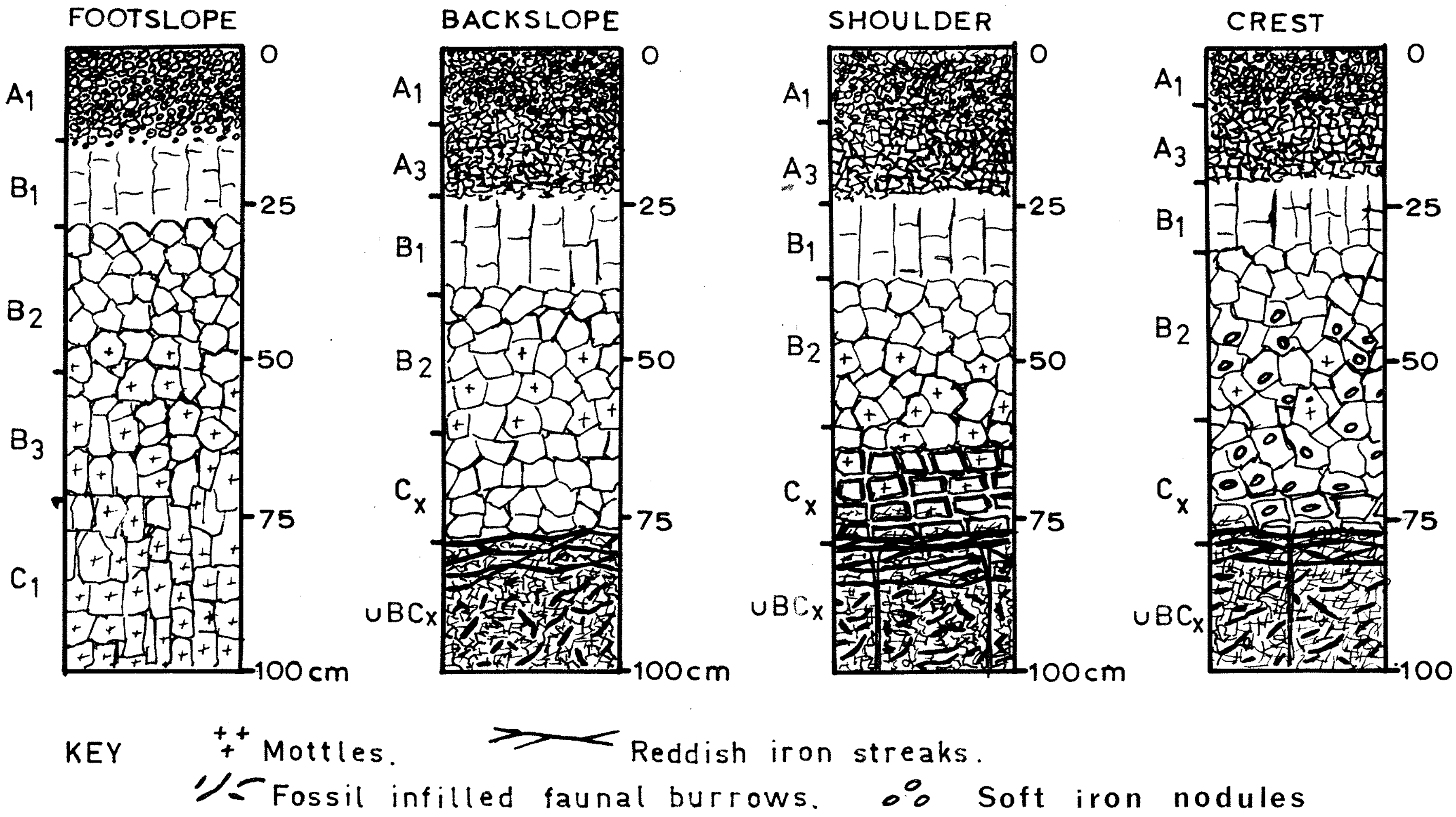


Fig. 6 SCHEMATIC REPRESENTATION OF TOPOSEQUENCE SOILS

The fragipan in the crest site has similar features although the C_x horizon is less obviously net-gammate. There is no suggestion of net-gammation in C_x horizon of the backslope profile. The uB/C_x horizon of this site has weakly to moderately developed, coherent, very fine nutty structure which is massive 'in situ' and non-gammate.

(c) Texture. The C_x and uB/C_x horizons of the fragipan in backslope and crest sites have clay loam textures. In the shoulder profile the C_x horizon is a clay loam while the uB/C_x horizon is a heavy silt loam. This textural difference in fragipans in shoulder sites has been observed in Wither soils of similar landscape positions outside the representative catchment.

(d) Fossil Faunal Features. The uB/C_x horizons all contained evidence of former soil faunal activity. Few to many elongated infilled faunal channels or fossil casts up to 3cms long and 5mm in diameter with dark brown coatings occurred randomly. They are assumed to be the remains of former earthworm habitation. Many smaller infilled burrows or fossil pellets thought to be of faunal origin were discerned in the uB/C_x horizons. Similar features were observed in the compact horizon some 1.5m below the surface in the footslope site.

(ii) Mottles and Nodules. The many prominent, reddish mottles and fine manganese nodules of the footslope subsoil decrease to few/many faint mottles in the other toposequence subsoils. Likewise the abundant prominent mottles of the footslope C_1 horizon decrease to few/many fainter mottles and iron-stained streaks around peds in upslope C_x and uB/C_x horizons. Manganese nodules are absent from subsoils and fragipan horizons of the backslope, shoulder and crest sites.

Few to many soft iron nodules occur in the B_2 and C_x horizons of the crest profile. They are absent from soils in other landscape positions.

(iii) A Horizon Thickness and Colour. The A horizons are thickest in the backslope (25cm) and shoulder (24cm) sites and thinest in the footslope (14cm). The dark A horizon colour of the shoulder profile is a distinctive feature. Both A_1 and A_3 horizons have darker values than corresponding A horizons of other toposequence profiles.

(iv) Gravelly Inclusions. Small subangular and rounded gravels up to 1cm diameter were rare (less than 2% by visual estimation) in most profiles. The crest profile has very minor gravel contents in all horizons except the A_1. The C_1 horizon of the footslope has the greatest proportion of small gravels by visual estimation (2-3%) than any other horizon in the toposequence.

5.3 LABORATORY ANALYSES

5.3.1. Physical Properties.

(1) Bulk Density. Bulk densities increase down each profile (table 10). They range from medium values (1.1-1.3gm/cc) in topsoils to high values (1.4 - 1.6gm/cc) in subsoils and fragipans. There is little difference in bulk density values between fragipans and B horizons although the fragipans appear to be more compact in the field. It is suggested that the higher clay content of subsoils relative to their respective fragipan horizons is responsible for the uniformity in bulk density.

(ii) Particle Size Distribution.

The International (N.Z.) texture classification for each profile horizon is presented in table 10. Particle size distribution curves for the shoulder profile are shown in the appendices.

Textures are gradational with depth in all four toposequence profiles as clay contents increase from (13 – 21%) in topsoils to reach maximum values (34 – 35%) in the lower subsoils with a decrease in C horizons. The distribution of fine clay ($<$ 0.0002mm) in the shoulder profile shows a more exaggerated gradient, increasing from (5%) in the A_1 horizon to (21%) in the B_2 horizon followed by a decrease to (9%) in the uB/C_x horizon.

TABLE 10

BULK DENSITIES AND TEXTURE ANALYSES OF THE TOPOSEQUENCE SOILS

PROFILE HORIZON	SAMPLE THICKNESS	BULK DENSITY	TEXTURE ANALYSIS % Coarse sand	Fine sand	Silt	Clay
	(cm)	(gm/cc)	(2.0-0.2mm)	(0.2-0.02mm)	(0.02-0.002mm)	($<$0.002mm)
Footslope						
A_1	14	1.25	1.0	47.0	38.5	13.5
B_1	15	1.40	1.0	39.0	36.0	24.0
B_2	20	1.44	1.5	34.0	34.5	30.0
B_3	16	1.53	1.5	34.5	29.0	35.0
C_1	25	1.61	1.5	47.5	24.0	27.0
Backslope						
A_1	14	1.20	0.5	46.5	32.0	21.0
A_3	11	1.30	-	45.0	31.0	24.0
B_1	15	1.50	-	37.0	28.0	35.0
B_2	22	1.64	-	37.0	28.0	35.0
C_x	22	1.50	-	37.0	31.0	32.0
uB/C_x	16	1.63	-	40.0	30.0	30.0

(contd..)

Shoulder						
A_1	12	1.08	0.5	48.0	34.5	17.0
A_3	12	1.25	1.0	43.0	36.0	20.0
B_1	10	1.60	0.5	37.5	33.0	29.0
B_2	26	1.62	-	37.0	29.0	34.0
C_x	25	1.58	-	38.0	28.5	33.5
uB/C_x	15	1.64	1.0	47.0	30.0	22.0
Crest						
A_1	8	1.10	2.0	50.0	33.0	15.0
A_3	12	1.36	1.0	39.0	38.0	22.0
B_1	10	1.46	1.0	35.0	33.5	30.5
B_2	30	1.62	1.0	35.0	29.0	35.0
C_x	25	1.64	1.0	44.0	25.0	30.0
uB/C_x	15	1.56	1.0	37.0	32.0	30.0

5.3.2. Chemical Properties.

(i) pH and Percent Base Saturation. Figure 7 shows profile distribution curves for pH and percent base saturation. In the footslope pH increases down the profile to reach slightly alkaline values in the C_1 horizon. Correspondingly percent base saturation increases to attain values greater than 100% in the B and C horizons. The other toposequence soils show an increase in pH in the subsoils followed by a decrease in fragipans. Although the percent base saturation follows similar trends they are still disproportionately high in most cases. The C_x horizon of the shoulder profile has pH 4.6 and percent base saturation of 81%. Such a combination of low pH and high base status is a departure from the normal. However similar instances of low pH and high base saturation have been recorded in loessial paleosols from South Canterbury (Runge, pers comms). The reason for such phenomena cannot be satisfactorily explained.

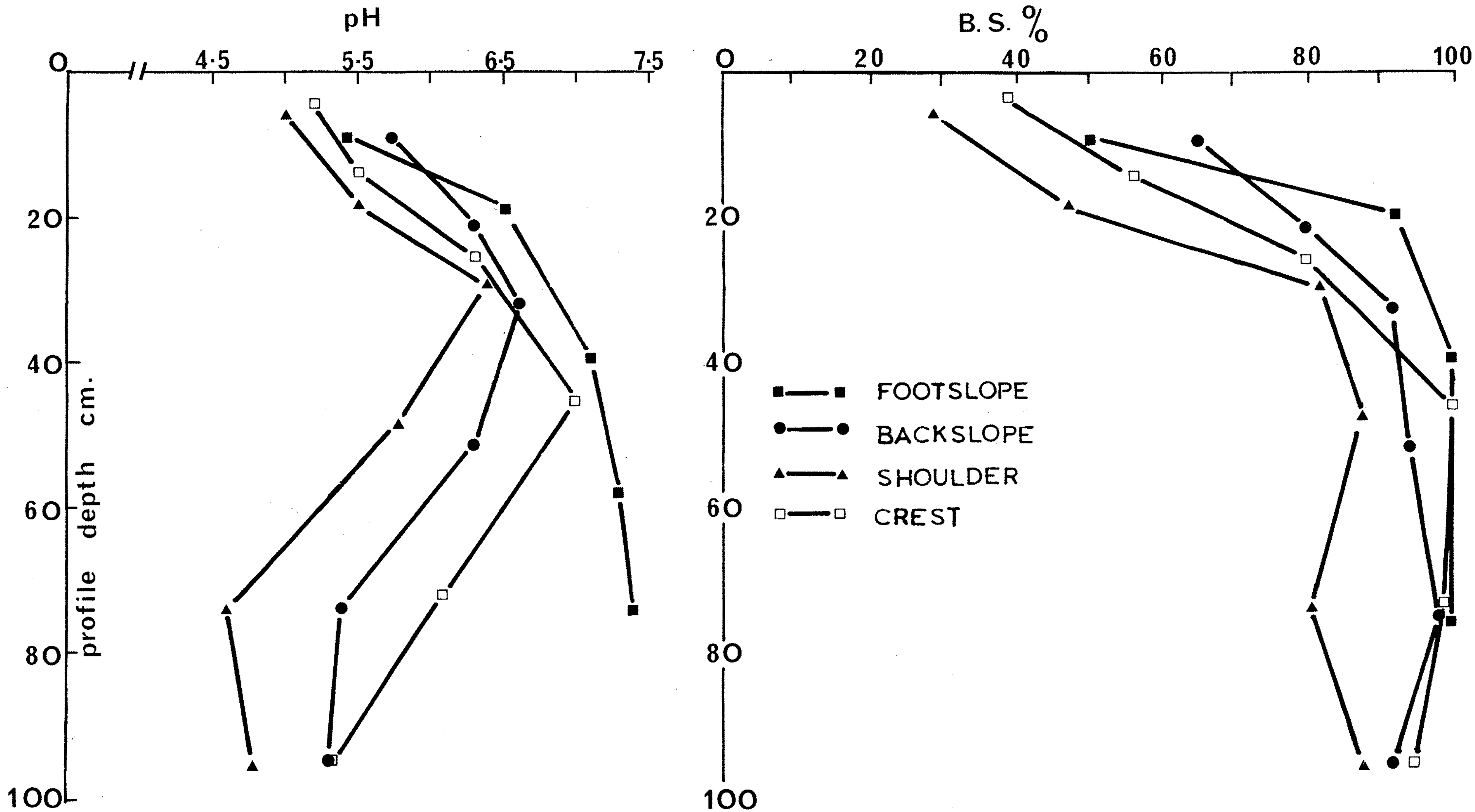


Fig. 7 pH & % Base Saturation

(ii) Exchangeable Cations and C.E.C. The C.E.C. varies slightly from low values (8 - 10me%) in topsoils and upper subsoils to medium values (12 - 15me%) in lower subsoils and fragipans. Maximum C.E.C. generally occurs in the horizons of greatest clay content. There is only minor variation in C.E.C. values between the toposequence profiles for corresponding horizons.

Exchangeable calcium values are low (2 - 5me%) in all horizons of the toposequence. Levels of exchangeable magnesium increase from medium (1 - 3me%) in topsoils to high and very high (4 - 8.5me%) in subsoils and fragipans. Exchangeable potassium ranges from low to medium (0.3 - 0.8me%) in topsoils and decreases to very low (0.05 - 0.3me%) in subsoils and C horizons. The general trend for exchangeable sodium is to increase down the profile from low and very low (0.05 - 0.3me%) in topsoils to high and very high levels (0.7 - 3.1me%) in the lower horizons. These data are presented in detail in the appendices.

(iii) Organic Carbon. The percent organic carbon (figure 8) is low in all profiles. Very low values (0.3 - 0.8%) occur in subsoils and fragipans while topsoils are also low to very low.

(iv) Soluble Salts. Values for the conductivity of the 1:5 soil:water extract are given in the appendices. Analyses of soluble salt cations are presented in table 16 chapter VII, while those for anions are outlined in the appendices.

Sodium chloride is the dominant salt. Minor quantities of calcium and magnesium salts occur in the fragipan of the shoulder and crest profiles. A very small content of sulphate occurs in the lower subsoils of all sites.

It is considered that the sodium chlorides and sulphates are cyclic salts deposited from the atmosphere.

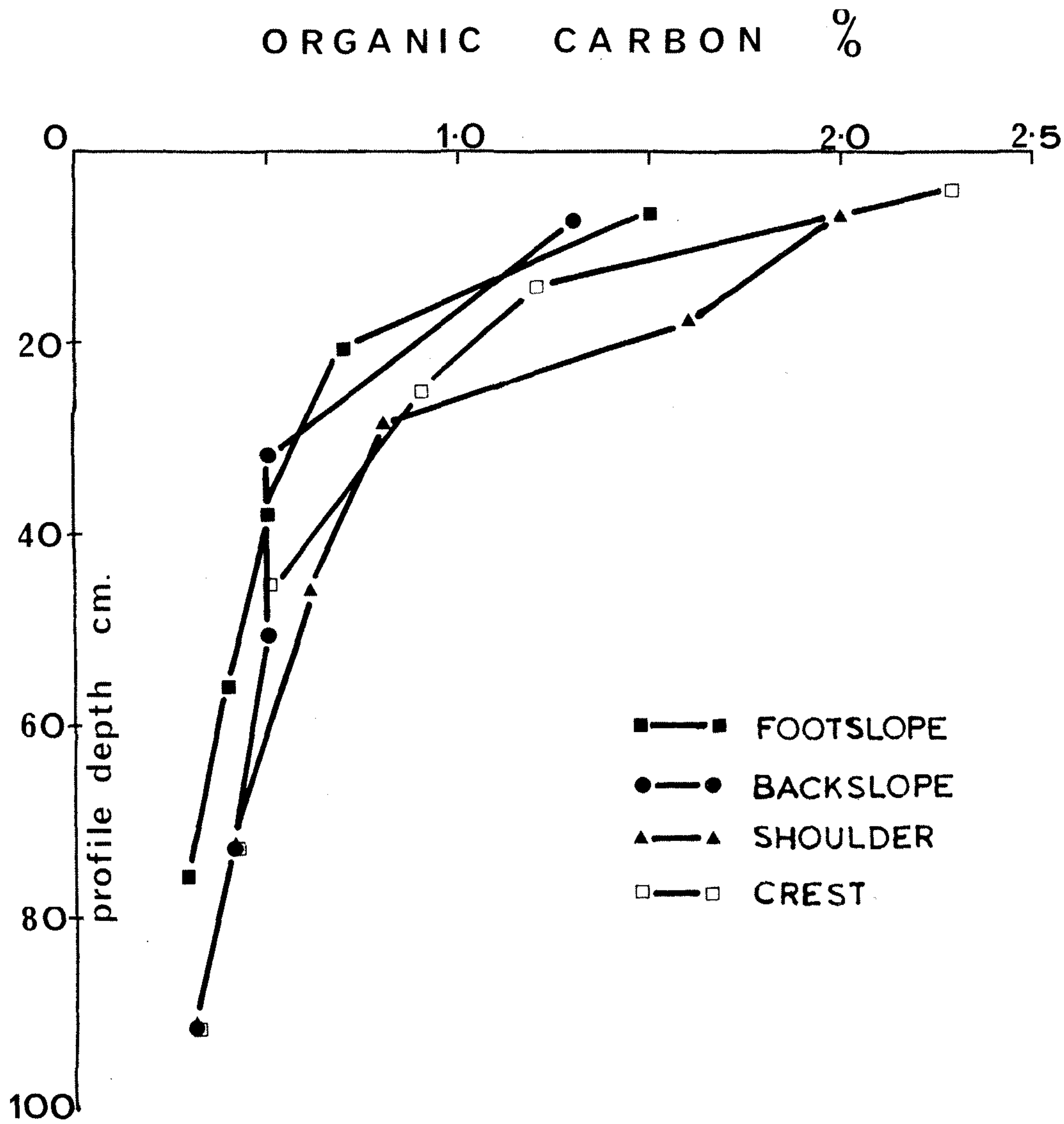


Fig. 8 ORGANIC CARBON %

The proximity to the sea plus the present sub-humid climate with weak leaching regime has enabled accumulation of cyclic salts in the deep subsoils and parent materials. The calcium and magnesium salts may be derived as weathering products from the loess, but more probably originate as cyclic salts also. The percentage soluble salts are rated from very low to medium. (0.2 - 2.9me%)

(v) Free Iron Oxide. Profile distribution of free iron oxide content is presented in figure 9. These values were determined from the single dithionite extraction. The comparison between this method and the multi-extraction citrate-dithionite method is shown in the appendices. The values in figure 9 show that the subsoil iron oxide contents are greater than those in topsoils, particularly in the shoulder site. The maximum percent iron oxide occurs in the C_x horizon of this profile. The crest site is distinguished by its uniform level of iron oxide down the profile. The multi-extraction citrate-dithionite values of iron oxide for the eight subsoils analysed are similar in value to those reported for the subsoils of the Timaru silt loam (Soil Bureau Staff 1968a).

(vi) Total Phosphorus. The profile distribution of total P is shown in figure 9. The A horizons of all soils show greater levels than their respective subsoils and fragipans. It is expected that this difference is due to relatively higher levels of organic P in topsoils. Total P values in topsoils and subsoils are rated at low to medium overall. The C_x horizon of the shoulder profile has the highest total P content (ppm) of subsoils and fragipans. The lower horizons of the crest profile show uniform total P values somewhat analagous to the trend in free iron oxide. A simple linear regression analysis of total P and iron oxide is outlined in the appendices.

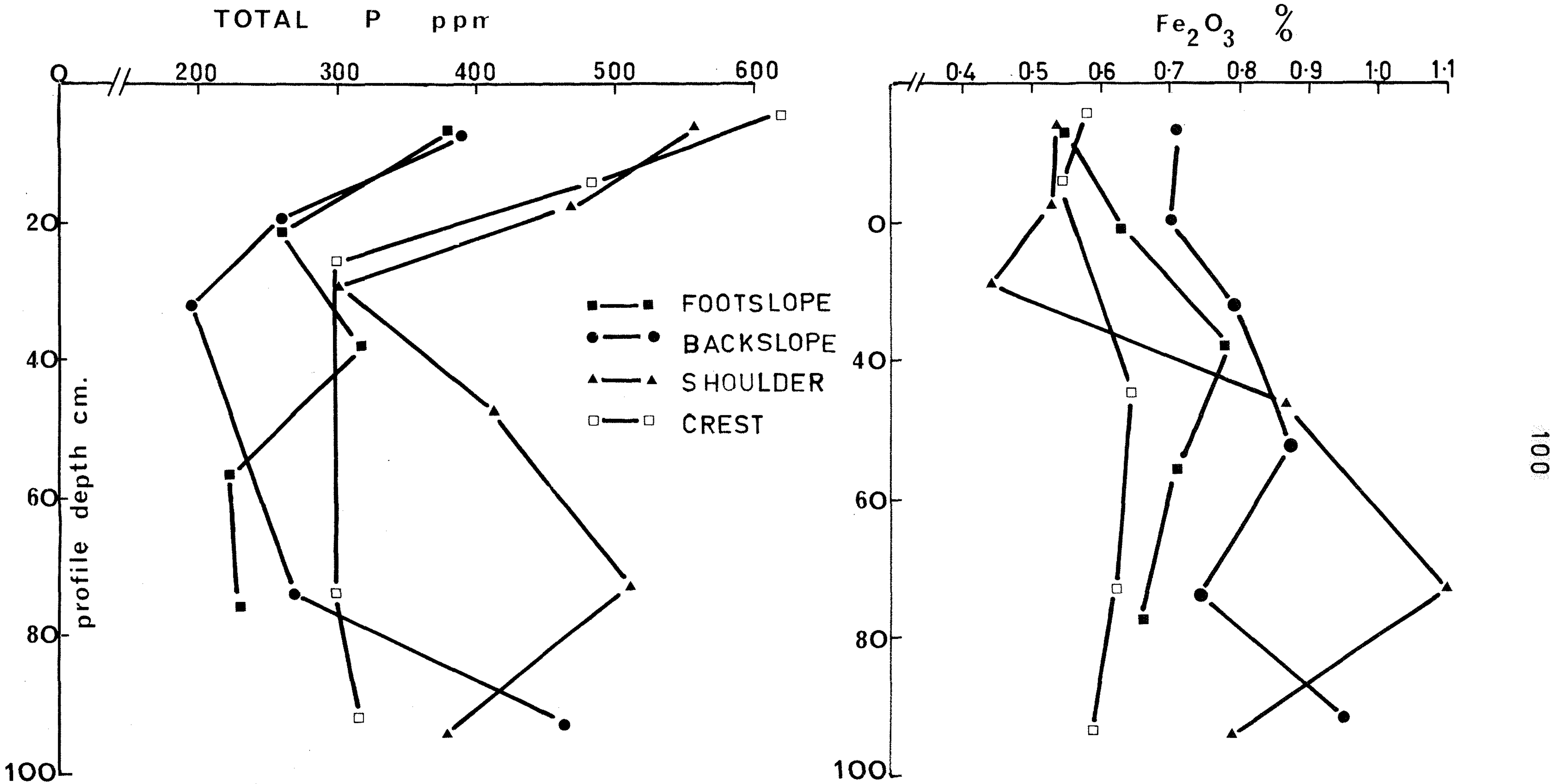


Fig. 9 TOTAL P(ppm) & % FREE Fe_2O_3

The regression is significant at the 5% level showing that there is some correlation between total P and free iron oxide contents in these horizons. It is suggested that iron-bound forms of phosphorus in the lower horizons are responsible for the relationship.

(vii) Volume-weights of Total P, Free Iron Oxides and Organic Carbon.

Table 11 lists the weight per unit area of total P, free iron oxides and organic carbon for each profile down to a depth of 90cms.

TABLE 11

VOLUME-WEIGHTS OF TOTAL P, IRON OXIDE AND ORGANIC CARBON PER 90cm PROFILE.

	Organic C Kg/m^2-90cm	Total P Kg/ha -90cm	Free Iron Oxide Kg/m^2-90cm
Footslope	7.72	3610	8.96
Backslope	7.75	3640	10.40
Shoulder	11.00	5980	10.8
Crest	9.60	4710	9.31

The shoulder profile is distinguished by its greatest content of organic carbon, total P and free iron oxide. The footslope has the least content of all three. The apparent close relationship between organic carbon and total P for the four sites is not statistically significant.

5.3.3. Clay Mineralogy.

Table 12 outlines the approximate percentage content of the major clay minerals detected by x-ray diffraction. In addition all samples contained low to very low kaolin, feldspar and quartz, but these were not in sufficient quantity to warrant recording on a percentage basis.

TABLE 12

COMPOSITION AND CONTENT OF MAJOR CLAY MINERALS

Profile	Horizon	Mica (Illite) %	Interstratified Mica-vermiculite %	Vermiculite %
Footslope	B_2	30	50	20
	C_1	50	40	10
Backslope	B_2	25	60	15
	uB/C_x	30	55	15
Shoulder	B_2	35	55	10
	uB/C_x	40	50	10
Crest	B_2	35	50	15
	uB/C_x	50	40	10

Note : Vermiculite here is equivalent to vermiculite - 2 of Soil Bureau.

The K^+ 20 degree C treatment produces sharp peaks between 10.25 and 10.4 angstroms for most samples. The sample from the footslope B_2 horizon has a sharp peak at 10.85 angstroms indicating resistance to collapse due to greater content of vermiculite layers. As the K^+ 550 degree C treatment produces sharp 10 angstrom peaks little chloritic material can be present (Campbell, pers comms).

All the samples are essentially similar in composition and content of clay minerals. No trends are apparent in the limited range of subsoil and paleosolic horizons.

The assemblage and proportion of micaceous clay minerals is intermediate between that of subsoils from the Timaru silt loam (southern YGE) and the Matapiro silt loam (central YGE) (Soil Bureau Staff 1968a).

The absence of chloritic clay minerals is notable, particularly since chlorite zone III schists comprise basement rocks on the opposite side of the Wairau river. They contribute substantial material to the Wairau floodplain, the source of much of the loess of the Wither Hills.

5.4 CONCLUSIONS

(i) The shoulder profile stands out from profiles in the other three landscape sites because of the following morphological and chemical features :

(a) The prominent, thick fragipan which is net-gammate in its upper section (C_x) and sub-gammate in the lower part (uB/C_x).

(b) The uB/C_x horizon is a silt loam whereas the uB/C_x in backslope and crest sites is a clay loam.

(c) The A_1 and A_3 horizons have darker values than corresponding A horizons in all other toposequence sites.

(d) The C_x and uB/C_x horizons have lower pH's than corresponding horizons elsewhere in the toposequence.

(e) The C_x horizon has the highest percentage of free iron oxides.

(f) The 90cm profile depth has the greatest content of free iron oxide, organic carbon, and total P on a volume-weight basis.

(ii) The footslope profile is distinctive because :

(a) It lacks a recognizable fragipan even though the bulk density of the C_1 - horizon is as high as that of the C_x and uB/C_x horizons elsewhere in the toposequence.

(b) The subsoil and C_1 horizons contain many prominent mottles and nodules.

(c) The pH increases down the profile to alkaline values in subsoils and C_1 - horizon.

(d) The 90cm profile depth has the least content of organic carbon, total P, and free iron oxides on a volume-weight basis.

(iii) The backslope and crest profiles are very similar in morphological, physical, and chemical properties.

(iv) On a volume-weight basis for the 84cm profile depth (in order to eliminate the influence of the paleosolic uB/C_x horizon) the shoulder profile still has the greatest content of organic carbon, total P, and free iron oxides.

(v) The type and content of clay minerals in the lower horizons of the toposequence profiles is very similar for all landscape sites.

(vi) The K4 groundsurface (uB/C_x horizon) and lower K3 groundsurface (B_2 and C_x horizons) are not distinguishable on the basis of composition and proportion of clay mineralogy. It is assumed that the K4 groundsurface formed under a moderate weathering environment similar to that which has occurred in the lower horizons of the K3 groundsurface.

CHAPTER VI

SOIL GENESIS

6.1 SLOPE DEVELOPMENT AND SOIL GENESIS

The interrelationship between soil genesis and landscape evolution has been previously noted in the description of different-aged groundsurfaces resulting from successive cycles of erosion/deposition.

The six cycles of erosion/deposition recognized in the representative catchment indicates the dominant role of the drift regime during successive intervals.

It is considered that the last two erosion/deposition phases of post glacial age have been induced by human activity, while the previous four were caused by climatic change at the onset of glacial stages. All six phases of landscape instability are thought to be primarily due to disturbance and depletion of the existing vegetation. It is generally accepted that climatic change rather than the climate itself has had greater disturbance upon vegetation (Butler, 1959; Jessup 1961).

6.1.1. The Drift Regime and Slope Development

The significant alteration to the landscape by recent erosive processes has already been briefly described. Rapid and intense tunnel-gully erosion has produced marked changes to the loessial landscape while isolated slip erosion on gravels has effected only minor changes. The rates and intensity of slip and tunnel-gully erosion preceding formation of the K2 groundsurface appear to have been significantly less than that initiating the K1. Because the catchment is an open system most deposition debris has been removed by fluvial processes. During these two periods erosion has been dominant with a net regressive effect on landscapes in the catchment.

The specific forms and rates of erosion in the Pleistocene phases of instability can only be guessed at, but it seems likely that slow mass movement (solifluction) was of major importance. The role of tunnel-gullying in glacial times is unknown but it is assumed to have been negligible. The absence of fossil gullies in the K4, K5 and K6 groundsurfaces tends to confirm this theory.

The influx of new parent materials from outside the catchment has counteracted the landscape regression produced by erosive processes within the catchment. It is thought that the most active erosion generally occurred prior to loess accumulation but it is conceivable that both were concurrent with overall net accumulation at the conclusion of the unstable era.

The principal source of loess has been wind deflation of the adjacent Wairau floodplain with possibly minor contributions from deflation of part of the continental shelf exposed during the low sea levels of glaciations.

It appears likely that the Pleistocene glacial phases of instability encompassed long time intervals, allowing rudimentary soil formation on the newly exposed materials. Raeside (1964) envisaged soil formation during slow accumulation of loess in South Canterbury with soil compaction processes operating under a weak grassland regime.

The presence of numerous fossil infilled faunal channels throughout the K4 and K5 groundsurfaces is indicative of an active organic regime during formation of these surfaces. It is possible that accumulation of the K4 and K5 loess was slow with the organic regime keeping pace with the incorporation of recent loess additions. Alternatively climatic conditions may have been moister thus favouring increased organic activity throughout the two deposits of loess.

The presence of thick manganese streaks and large, spherical nodules in the K5 surface would also appear to indicate climate as a dominant causal factor. The factor of time is probably important also (Taylor and Pohlen, 1958, p.107).

Butler (1959) proposed the occurrence of a "sloughing zone" on the steeper slopes of hillsides in south-east Australia where the soil mantle was completely stripped away at each erosive phase. On sites downslope with flatter grades an 'alternating zone' occurred where erosion was less effective with truncated paleosols below each mantle.

The vertical sequence of groundsurfaces in loessial landscapes particularly in the lower catchment would infer analagous 'alternating zones'. The K4, K5 and K6 groundsurfaces are remnants of previous soil mantles which have probably endured partial erosion followed by subsequent loess accumulation. The loess has buried each former soil layer preserving it from further erosion until recent times (figure 4). The absence of buried soils in the Waihopai soil-landscapes of the upper catchment suggests they represent the 'sloughing zone' of Butler (loc cit). Vernon soil-landscapes represent intermediate zones in which partial sloughing of the K4 and K5 groundsurfaces has occurred while the K6 surface has been preserved as a remnant paleosol.

Mixing processes of the drift regime have operated in most of the catchment landscapes during the phases of accelerated erosion/deposition particularly those of the Pleistocene glaciations. Mixing has been most marked in sites where composite gravel-loess materials predominate. The presence of few isolated gravels and small stones irregularly distributed in all loessial deposits suggests that active mixing processes (solifluction) occurred on loess covered landscapes as well.

6.2 GENESIS OF THE WITHER SILT LOAMS

6.2.1. Wasting Regime.

(i) State of Weathering. The dominant clay mineral fraction of subsoils (illites and interstratified mica-vermiculite) is at an early stage of weathering in the micaceous weathering sequence. It is thought that the clay minerals (kaolins) at an advanced stage in the micaceous sequence are largely acquired from deposition in the loess. It is possible that a small proportion of kaolins is derived from the 'in-situ' weathering of feldspars.

The free iron oxide content (multi extraction citrate-dithionite method) for subsoils and fragipans and total P values are intermediate between those of the Timaru silt loam, classified as a moderately weathered, southern yellow grey earth, and the Matapiro silt loam (moderately weathered, central YGE).

(ii) State of leaching. The very high percentage base saturation in subsoils and parent materials and presence of soluble salts indicate a weak leaching regime.

(iii) Illuviation.

(a) Clay illimerization. The role of clay movement is significant in all four toposequence soils. Evidence that preferential accumulation of clay has occurred in subsoils is provided by the following :

(1) The presence of distinct clayskins in B_2 (or B_3) horizons. Clayskins coating aggregates or lining soil pores are generally considered proof of clay illimerization (Taylor and Pohlen 1962, Soil Survey Staff 1967).

(2) The ratio of percent fine clay (< 0.0002mm) to percent total clay (< 0.002mm) for the shoulder profile is greatest in the B_2 horizon. (See appendices for detail of profile distribution of fine clays).

Table 13 outlines the ratio percent fine clay to percent total clay for all horizons of the shoulder profile.

TABLE 13

CONTENT AND RATIO OF FINE CLAY

TO TOTAL CLAY IN THE SHOULDER PROFILE

Horizon	Fine Clay % (< 0.0002mm)	Total Clay % (< 0.002mm)	Fine clay % / Total clay %
A_1	4.5	17.0	0.26
A_3	5.0	20.0	0.25
B_1	13.0	29.0	0.45
B_2	21.0	34.0	0.62
C_x	19.0	33.5	0.57
uB/C_x	9.5	22.0	0.43

The fact that argillic horizons usually have higher ratios of fine to total clay than the other horizons of the pedon suggests that clay is preferentially moved (Mckeaque and St.Arnaud, 1969). It is assumed thatthe other three profiles have similar textural properties.

(3) The gradational clay textural profiles which rise to maximum values in B_2 (or B_3) horizons. Thorp, et al; (1959) recalculated the particle size distribution on a clay free basis for all horizons in the Miami silt loam. The marked difference in particle size fractions between upper and lower horizons was attributed to stratification in the parent material. The higher clay percentage of lower horizons was therefore not considered to be due to illuviation.

Recalculation of the particle size distribution for Wither silt loams on a clay free basis is outlined in table 14 for all horizons of the toposequence profiles. (U.S.D.A. texture classification).

TABLE 14

PARTICLE SIZE ON A CLAY FREE BASIS FOR ALL TOPOSEQUENCE SOILS.

Profile	Horizon	Medium Sand 0.5-0.25mm	Fine Sand 0.25-0.1mm	V.Fine Sand 0.1-0.05mm	Silt 0.05-0.002
Footslope	A	0.5	1.9	15.1	82.9
	B_1	0.5	2.6	12.7	84.5
	B_2	1.4	1.9	12.1	84.7
	B_3	1.5	2.3	13.1	83.2
	C_1	1.4	4.1	15.1	79.5
Backslope	A_1	1.2	1.9	15.9	81.3
	A_3	0.7	2.0	14.5	83.2
	B_1	0.2	2.3	14.6	83.2
	B_2	0.1	1.6	14.5	83.9
	C_x	0.1	2.1	12.5	85.3
	uB/C_x	0.1	2.7	14.3	82.9
Shoulder	A_1	0.2	2.6	22.8	74.4
	A_3	0.4	2.5	20.9	76.2
	B_1	0.3	1.8	16.2	81.7
	B_2	0.2	1.7	17.6	80.6
	C_x	0.2	1.7	12.0	86.2
	uB/C_x	0.3	2.6	19.0	78.1
Crest	A_1	2.1	3.9	14.8	79.7
	A_3	1.3	2.6	16.8	80.0
	B_1	1.4	3.2	10.4	84.4
	B_2	0.8	1.5	13.0	84.5
	C_x	0.7	2.4	14.7	81.9
	uB/C_x	0.4	3.0	13.7	82.6

There are no marked differences in each particle size fraction in any of the toposequence profiles. The slight increase in silt percentage and decrease in percent very fine sand in the C_x horizons of the backslope and shoulder soils may represent the stratigraphic boundary between two separate loess layers already proposed on morphological grounds.

However similar particle size trends occur in the footslope B_3 horizon. It is not known whether the slight change in silt and very fine sand content represents further stratification in the footslope profile or is due to slight differential subsoil and parent material weathering. The general uniformity of the finer particle size fractions in subsoils is thought to be evidence that maximum clay accumulations in the B_2 (or B_3) horizons are due primarily to illuvial processes and probably to some preferential weathering 'in-situ'.

(4) Exchangeable sodium content. The high proportion of exchangeable sodium (up to 16%) in subsoils may be significant in enabling ease of clay dispersion necessary for translocation. Several researchers have stressed the role of exchangeable sodium in clay illimerization in artificial and natural soils (Swindale 1960; Papadakis, 1969).

b) Free Iron Oxides. The percent free iron oxides (single extraction dithionite method) show an increase down the profile to reach maximum values in the lower subsoil or C horizons. (Figure 9). This trend may be due to different weathering conditions in the B horizons but is more probably due to leaching of iron compounds from upper horizons. (Soil Bureau Staff 1968a p.110).

4. Mottling and Concretions. The prominence of mottles and concretions in footslope positions is attributed to flushing processes of the drift regime.

5. Pan Formation. The bulk of the prominent fragipan recognized in the field comprises a relict feature inherited from a previous phase of weathering and soil formation (K4 groundsurface). Its massive, compact nature is assumed to be due to former shrink-swell phenomena and perhaps to burial by the K3 loess deposit.

The C_x horizon of the K3 groundsurface represents a stratigraphic disconformity with the uB/C_x beneath in the backslope, shoulder and crest sites. It is assumed that the C_x was formerly massive and more compact similar to the uB/C_x. Weathering and other soil forming processes since deposition of the K3 have disintegrated the C_x horizon to form the medium and coarse blocky structures with weak net gammation.

There is no distinct fragipan in the footslope profile but the high bulk densities of 1.4 to 1.6 gm/cc in subsoils and C_1 horizon indicate considerable compaction. It is suggested that the accumulative nature of the footslope profile has caused development of a diffuse fragipan.

6.2.2. <u>The Organic Cycle</u>.

The average organic carbon content of the toposequence soils (9.02 Kgm/m^2-90cm). is less than that calculated for the Timaru silt loam (14.9 Kgm/m^2- 90cm). These figures indicate a weak organic regime in Wither soils but the low organic carbon content is also due to moderate to severe sheet erosion since European occupation. It would be expected that the Wither soils contained greater organic matter in the surface horizons prior to human interference. The influence of the extensive pre-Polynesian coastal hardwood/Podocarp vegetation on soil formation is not known.

Soil mixing by organisms has been weak. The presence of few cast granular structures in the A and B_1 horizons indicates slight soil faunal activity. The general absence of earthworms and other soil macro-fauna was a feature of the detailed soil survey. It is assumed that change in moisture regime consequent upon disturbance of the landscape with severe sheet and tunnel-gully erosion has created soil conditions now alien to the habitation of most soil macro-fauna.

6.2.3. The Drift Regime.

(i) Accumulation and Regression.

It is difficult to determine the relative extent of accumulative and regressive processes on the Wither silt loams in the absence of major landscape instability due to human interference.

The occurrence of the K4 groundsurface at a greater depth below the surface in footslope sites than other landscape positions attests to the accumulative processes of concave sites. The absence of gammation and lack of a prominent fragipan similar to the C_x in higher slope positions is attributed to the accumulative nature of footslopes in which the intensity of these soil forming processes is diminished.

Backslope, shoulder and crest positions are considered slightly regressive because of the presence of the K4 groundsurface nearer to the surface in these sites. As noted in Chapter V the shoulder soil profile is more distinctive than the other three. It is concluded that the shoulder site is the least regressive and most stable of the toposequence soils. The fact that underlying paleosols are thickest in shoulder positions provides further evidence of landscape stability in these sites. This characteristic of shoulder positions has been observed in all loessial areas within the representative catchment and elsewhere on the Wither hills. It would be expected that crest sites exhibit greater stability because of much gentler slopes and presumably least erosion from surface runoff etc. However the soil pattern of the representative catchment refutes this assumption. On crest sites Wither soils are confined to the lower catchment boundaries. In mid and upper catchment areas the Waihopai soils are predominant on ridge crests with Wither soils occurring on adjacent shoulder sites (figure 3).

Reasons for the apparent greater regressiveness of ridge crests are uncertain but may be related to the narrowness of crests causing active shedding of newly deposited material. Alternatively loess may never have been deposited on ridge crests in mid and upper catchment areas.

For loessial soils in an open drainage system in Iowa, Ruhe and Walker (1968) maintained that the shoulder position represented the junction of younger unstable hillslopes with older more stable summits. It is suggested that the much greater width of ridge crests in their study area than in the Wither Hills is a major reason for the difference in stability in this landscape position.

(ii) Soil Mixing. The overall similarity of soil development in all four sites is considered evidence of lack of active soil mixing or creep processes. There is only minor difference in profile morphology and physical, chemical and mineralogical properties between backslope soils on steep slopes, shoulder soils on moderately steep slopes and crest soils on rolling slopes. Well developed modal Wither silt loams have been observed on very steep slopes of 33° in the upper catchment area.

According to Soil Survey Staff (1967) the significance of a clay illuvial horizon is that it marks the dominance of silicate clay translocation over processes that mix soil horizons. Because its formation is relatively slow its presence indicates soil stability and shows the impress of time as a soil forming factor (Soil Survey Staff 1967; Parsons et al; 1970). The development of pronounced argillic horizons in all toposequence soils is considered strong evidence of soil stability in the representative catchment.

The presence of few, isolated greywacke gravels and small stones mixed in the loess of most horizons of the toposequence soils infers either that (a) slow mixing in of stones from the underlying paleosols has occurred since deposition of the loess of the K3 groundsurface, or that (b) the loess has been subjected to rapid mixing of stones from ridge crests during the phase of erosion/deposition separating the K3 and K4 groundsurfaces, or that (c) there has been slow mixing of stones originating from ridge crests after the initial loess deposition.

It is difficult to envisage the first process as stones are scarce in the K4 groundsurface and this remnant paleosol shows unmistakeable signs of stability itself. The third process of continuous slow mixing during soil formation appears improbable because of the development of pronounced argillic horizons in the K3 groundsurfaces. It is tentatively concluded then that the occurrence of isolated stones in Wither soils in all landscape positions is the result of initial mixing during deposition of the material now forming the K3 groundsurface. As stated previously the drift regime processes have been most active during intermittent intervals of marked instability rather than acting continuously throughout soil forming time.

(iii) Flushing. The prominent mottles and concretions in the lower horizons of the footslope profile are due to infiltration of surface runoff and the internal movement of moisture from upslope sites rather than to the effect of a high water table. The alkaline pH and 100% base saturation of these horizons is attributed to internal flushing processes whereby the cation exchange sites are kept fully replenished by bases carried in solution in internal seepage.

6.3 CLASSIFICATION OF THE WITHER SILT LOAMS.

(i) Footslope Profile.

Weakly enleached moderately clay illuvial moderately mottled pallic soil from compact moderately argillised loess.

(ii) Backslope Profile.

Weakly enleached moderately clay illuvial weakly subgammate pallic soil with strongly developed fragipan from moderately argillised greywacke loess.

(iii) Shoulder Profile.

Weakly enleached moderately clay illuvial weakly net-gammate pallic soil with strongly developed fragipan from moderately argillised loess.

(iv) Crest Profile.

Weakly enleached moderately clay illuvial weakly net-gammate pallic soil with soft iron nodules and strongly developed fragipan from moderately argillised greywacke loess.

The modal soil is represented by the backslope profile which comprises the most abundant soil in the Wither series. It may be simply classified as a weakly leached moderately weathered central yellow-grey earth with clay illuvial B.

6.4 PEDOGENIC PROCESSES AS EXPRESSED BY THE MORPHOLOGY OF THE GROUNDSURFACE.

The relative extent of the soil forming processes in each groundsurface has been determined on morphological features and are shown in table 15.

The pedogenic processes are weakly expressed in the K1 groundsurfaces primarily because of the shortness of the time factor and does not necessarily mean that the soil processes are weak.

Similarly the advanced weathering shown by the K5, K6 and K7 groundsurfaces may be the result of soil processes of low to moderate intensity over long time intervals rather than highly intensive weathering processes of short duration. For the Timaru loess layers Raeside (loc cit) assumed pedogenic processes of broadly similar intensity in each layer but of differing duration to explain major morphological differences in degree of weathering.

6.5 SUMMARY AND CONCLUSIONS

At least six separate periods of pronounced erosion / deposition have occurred during the mid and late Quaternary history of the representative catchment.

'Sloughing' and 'alternating' zones analagous to those described in south east Australia by Butler (loc cit) have been recognized in the representative catchment. Waihopai soils occupy sloughing zones, Wither soils occur on alternating zones, while Vernon soils occupy intermediate zones where active erosion and mixing of loess with gravels has taken place. The detailed soil pattern of groundsurfaces (K1, K2, K3,....K7) is a direct result of the drift regime processes of erosion, deposition and mixing during successive intervals of landscape instability.

The modal Wither silt loam is classified as a weakly enleached moderately clay illuvial weakly subgammate pallic soil with strongly developed fragipan from moderately argillised loess from greywacke. The argillic B_2 horizon with distinct clayskins, maximum clay content and highest ratio of fine clay to total clay indicates soil stability and shows the impress of time as a soil forming factor. The Vernon and Waihopai soils have similar argillic features of pronounced clayskins and heavier textures in lower subsoils.

Continuous clayskins are prominent morphological characteristics of the K5 and K6 groundsurfaces indicating considerable stability during their formation and during subsequent erosive phases.

The concept of landscape periodicity (Butler, loc cit) with intervals of stability and soil formation alternating with intervals of instability (erosion/deposition) thus most adequately explains the late Quaternary history of soil formation in the representative catchment.

TABLE 15

COMPARISON OF PEDOGENIC PROCESSES IN THE GROUNDSURFACES

PEDOGENIC PROCESSES	GROUNDSURFACES K1	K2	K3
I <u>Wasting Regime</u>			
Weathering	Negligible to very weak	slight to moderately weathered slight iron staining	moderately w'd slight to moderate iron staining textural B horizon
Illuviation	"	textural B/C horizon slight clay movement thin discontinuous clayskins	slight to moderate clay movement thin discontinuous clayskins
Leaching	"	?	weak in Wither & Vernon soils.
Mottling-Nodules	"	slight iron staining on concave sites	distinct iron-staining in foot-slopes
Pan form'n	slight compaction	moderate compaction in B/C horizons	strong compaction C_x horizon
II <u>Organic Regime</u>			
Melanization	very weak to weak	weak	weak to moderate
Mixing	negligible soil fauna	weak	generally weak
III <u>Drift Regime</u>			
Erosion	negligible on vegetated soils moderate-severe on bare soils	negligible-weak	backslopes & crests slightly regressive
Deposition	"	"	footslopes slightly accumulative
Mixing	negligible	negligible	negligible
Flushing	"	slight iron-staining in concave sites	distinct iron-staining in foot-slope sites

(contd..)

TABLE 15 (contd)

PEDOGENIC PROCESSES	K4	K5, K6 & K7
I Wasting Regime Weathering	moderately weathered heavy silt loams to clay loams	mostly strongly weathered clay loams to stony clays distinct reddish iron-staining around stones
Illuviation	slight clay movement very thin discontinuous clayskins	moderate to strong clay movement. Thick continuous clayskins
Leaching	weak. moderate to high soluble salts	moderate to high soluble salt content
Mottling - Nodules	reddish iron-staining and few manganese streaks in upper part	large prominent manganese nodules in K5
Pan form'n	strongly compact uB/C_x horizon	moderate to strongly compact. No prominent pans obvious
II Organic Regime Melanization Mixing	unknown but numerous relict infilled faunal channels suggest a moderate to strong organic regime	unknown but dark organic streaks in K6 & K7 and numerous relict infilled faunal channels in K5
III Drift Regime Erosion	unknown	unknown
Deposition	"	"
Mixing	"	"
Flushing	"	"

CHAPTER VII

TUNNEL-GULLY EROSION

7.1. FIELD DESCRIPTION

The following sections are based on detailed observations and measurements of the different stages of tunnel-gully erosion recognized in the representative catchment.

7.1.1. Soil Cracking.

The presence of small voids and extensive cracking in lower subsoils was the most distinctive feature of the four soil excavations of the toposequence.

Large cracks up to 3.0mm wide were noted in the B_2 horizons of all four soils. In all cases they extended up into the B_1 and down into the C_x horizons as very thin, hair-line cracks. In the crest profile 9 distinct cracks ($\leq$ 1.0mm width) were observed in a horizontal distance of 55cms at the junction of the B_1 and B_2 horizons. All cracks extended from the middle of the A_3 horizon down into the lower B_2 horizon. Thin coatings (less than 1.0mm) of white coloured fine sandy loam were generally associated with the crack linings.

Only where vegetative cover was absent did obvious cracking occur on the soil surface. Most stock tracks traversing loessial soils showed soil cracking to some extent (plate 5). The maximum width of surface cracks in plate 5 is 3.0mm. Others up to 5.0mm in width were observed on stock tracks elsewhere in the catchment.

Several small rounded voids up to 70mm in diameter were noted in the B_2 horizons of the backslope, shoulder and crest toposequence profiles. They rapidly diminished in size to crack proportions in both upslope and downslope directions.

Plate 5.
Soil cracking
under stock
track.
(Wither series)

Plate 6.
Tunnel discharge
from an open face.
Lower R.H.S. of
catchment.
(Vernon series.)

Similar small cavities were observed elsewhere in subsoils of the Wither series.

7.1.2. Tunnel Outlets.

7.1.2.1. At Exposed Sections in Toeslope Positions.

Examination of vertical sections in footslope and toeslope positions in Vernon and Wither soils revealed many tunnel outlets at free faces. Outlets occurred above a maximum depth of approx. 45-50cms. Most outlets ranged in diameter from 3.0cms to 25cm, (plate 6).

7.1.2.2. Outlets on Footslope Surfaces.

Tunnel outlets in Wither soils were recorded on upper footslopes and footslope/lower backslope inflexions at several locations. These outlets were characterized by small diameter (less than 10.0cms) holes with fan shaped deposits spread downslope from the openings. In the representative catchment the outlets led from deep collapsed tunnels and open gullies further upslope. Plate 7 shows sediment discharge from this type of outlet immediately after the high intensity storm of August 18th - 19th 1971. Discharge from a tunnel outlet in a nearby catchment during the closing stages of the same storm is illustrated in plate 8. Vegetation cover is lucerne-dominant pasture. The tunnel was uncollapsed over its entire length.

7.1.3. Position of Tunnels in the Soil Profile.

Numerous profile sections showed that most tunnels formed in the same subsoil horizons as those in which distinct cracking and voids occurred. The profile position in which small tunnels were most prevalent was the upper B_2 horizon. The largest diameter uncollapsed tunnels (up to 71.0cms diameter) extended from lower A horizons to the upper uB/C_x horizons.

Plate 7.
Tunnel discharge
from an upper
footslope site.
Lower L.H.S.
of catchment.
(Wither series).

Plate 8.
Tunnel discharge
from footslope
site in reworked
area outside the
representative
catchment.
(Wither series).

In several exposed sections on shoulder sites small tunnel outlets (less than 10.0cms) were observed at depths of 2.0 - 3.0 metres from the surface. In these locations the tunnels were usually developed in loess immediately on top of the underlying tertiary gravels.

Large cavities and short tunnels beneath the compact uB/C_x horizon of the Wither soils were also noted in some deep backslope sections in loess.

The presence of deep-sited tunnels in both landscape positions was associated with shallow tunnelling in the K3 groundsurface above. It is considered that the tunnels and holes formed below the Wither K3 groundsurface are secondary erosion forms developed subsequent to primary tunnelling within the K3 surface.

7.1.4. Initiation of Tunnels.

7.1.4.1. Primary Tunnels.

The close association between extensive cracks, voids, and small tunnels in the same profile horizon infers a cause and effect relationship. It is suggested that the voids result from enlargement of subsoil cracks. The linking of isolated voids up and down slope would form complete tunnels. This procedure is essentially that proposed by Gibbs (1945) with the exception of position of tunnel initiation in the profile.

7.1.4.2. Secondary Tunnels.

These appear to be developed from similar cracking processes as above. Cracking down into the K4 and K5 groundsurfaces is believed to be initiated by tunnelling in the K3 above. The resultant dessication of the lower K3 and K4 surfaces forms shrinkage cracks which are ultimately enlarged into voids and small tunnels in the lowermost layers.

Few of these deep seated tunnels were observed in the representative catchment.

7.1.5. Stages of Tunnel-Gullying.

Three distinct stages of tunnel-gully development were observed in the field :
(i) uncollapsed tunnels, (ii) collapsed tunnels,
(iii) open gullies.

7.1.5.1. Uncollapsed Tunnels.

Tunnels are generally located a short distance upslope from outlets at free faces particularly in footslope and lower backslope position. Shorter tunnels occur in the upper shoulder/crest positions with outlets discharging from free faces at shoulder sites. Tunnels are generally less than 70 - 80cms in diameter and occur above the uB/C_x horizon. Excavated cross-sections showed the presence of clods from lower topsoil horizons together with subsoil material collapsed from the sides. (Plate 9).

7.1.5.2. Collapsed Tunnels.

These occur in all positions in the landscape but are rare on ridge crests.

Severity of collapse varies from isolated, small holes in tunnel roofs to continuous surface depressions extending from footslope to shoulder sites. All stages of tunnel collapse excavated in cross section showed subsoil debris from lateral erosion of one side wall in addition to topsoil material from roof cave-ins, with generally sloping walls on the other side (plate 10). Cross sections of the collapsed tunnels are asymmetric (figure 10). Gibbs (1945) considered this feature due to major collapse of deep tunnels beneath the compact layer (fragipan).

Plate 9.
Tunnel prior to roof collapse.

Plate 10.
Renewed tunnelling in subsoil debris from collapse of the original tunnel.

Measurement of cross sections in collapsed tunnels showed the surface at one side to be slightly higher than the other. It is suggested that the slight downward slope across tunnels is sufficient to cause preferential lateral erosion and collapse of walls on the downslope side during flows through the tunnels.

Sections through all stages of tunnel collapse revealed the <u>presence of extensive cracking and renewed tunnelling within the heavy textured subsoil debris from prior wall collapse</u> (plates 10 and 11).

7.1.5.3. <u>Open Gullies</u>.

Open gullies represent the terminal stages in the tunnel-gully erosion sequence. Most have breached the compact uB/C_x horizon of the K3 groundsurface. Depths from landscape surface to bottom of gully range from 1.2m to 4.0+m. All have the characteristic vertical wall on one side. Collapse of the vertical wall is characterized by the separation of large prismatic sections from the original surface (plate 12).

Some of the deeper gullies (2.5+m) have partially collapsed tunnels in gully bottoms. It is probable that they result from further tunnelling in debris from collapse of vertical walls.

All gully heads occur in the shoulder position in the landscape. From field evidence it appears that the formation of open gullies proceeds in a headward direction from footslope and lower backslope positions. The occurrence of vertical sections at shoulder sites with numerous tunnel outlets is considered due to collapse of the downslope sections of the tunnels rather than subsequent tunnel initiation from free faces.

Plate 11.
Deepening of tunnel formed in subsoil debris from collapse of roof and side walls.

Plate 12.
Formation of open gully from collapse of renewed tunnels similar to plate 11.

The marked decrease in headward movement of gullies onto ridge crests apparently results from the reduction in slope angle and diminished catchment area of individual gullies.

7.1.6. Idealized Sequence of Stages of Tunnel-gullying.

This sequence of events is based primarily on observations of the numerous stages of tunnel-gully erosion in the catchment. It was not possible to trace the complete sequence in any one tunnel-gully.

The 12 stages in the proposed sequence are :

(i) Depletion of vegetation with resultant loss of soil structure and decreased infiltration allows dessication of the solum.

(ii) Resultant shrinkage cracks extend from the surface to deep subsoil.

(iii) Enlargement of subsoil cracks forms small cavities or voids mainly in the B_2 horizons.

(iv) Small tunnels are formed above the compact fragipan (Wither series) and by enlargement and linkage of individual cavities up and down slope.

(v) Outlets form at lower backslope/footslope inflexions and at free faces of footslopes, due to hydrostatic pressure exerted by water and sediments in tunnels.

(vi) Further tunnel enlargement causes isolated collapse of sections of tunnel roofs.

(vii) Lateral erosion of subsoil adjacent to collapsed roof causes cave-in of tunnel side-walls.

(viii) New tunnel formation occurs in collapsed subsoil material.

(ix) Complete collapse of entire tunnel eventuates with new tunnel formation in subsoil debris from side walls.

(x) Vertical walls on one side of tunnel-gully are caused by preferential lateral erosion. Opposite walls are smooth and sloping.

(xi) Further enlargement of tunnels breaches the compact C_x horizons, and the collapse of massive side sections forms open gullies.

(xii) Continued lateral and vertical erosion through to the underlying tertiary gravels form deep open gullies.

Plates 5 to 12 and figure 10, illustrate the main stages of the tunnel-gully erosion sequence.

It is believed that burrows excavated in subsoils during the rabbit infestations of the past have greatly facilitated tunnel formation in the loessial soils, particularly by rapid development of stage (iii) above.

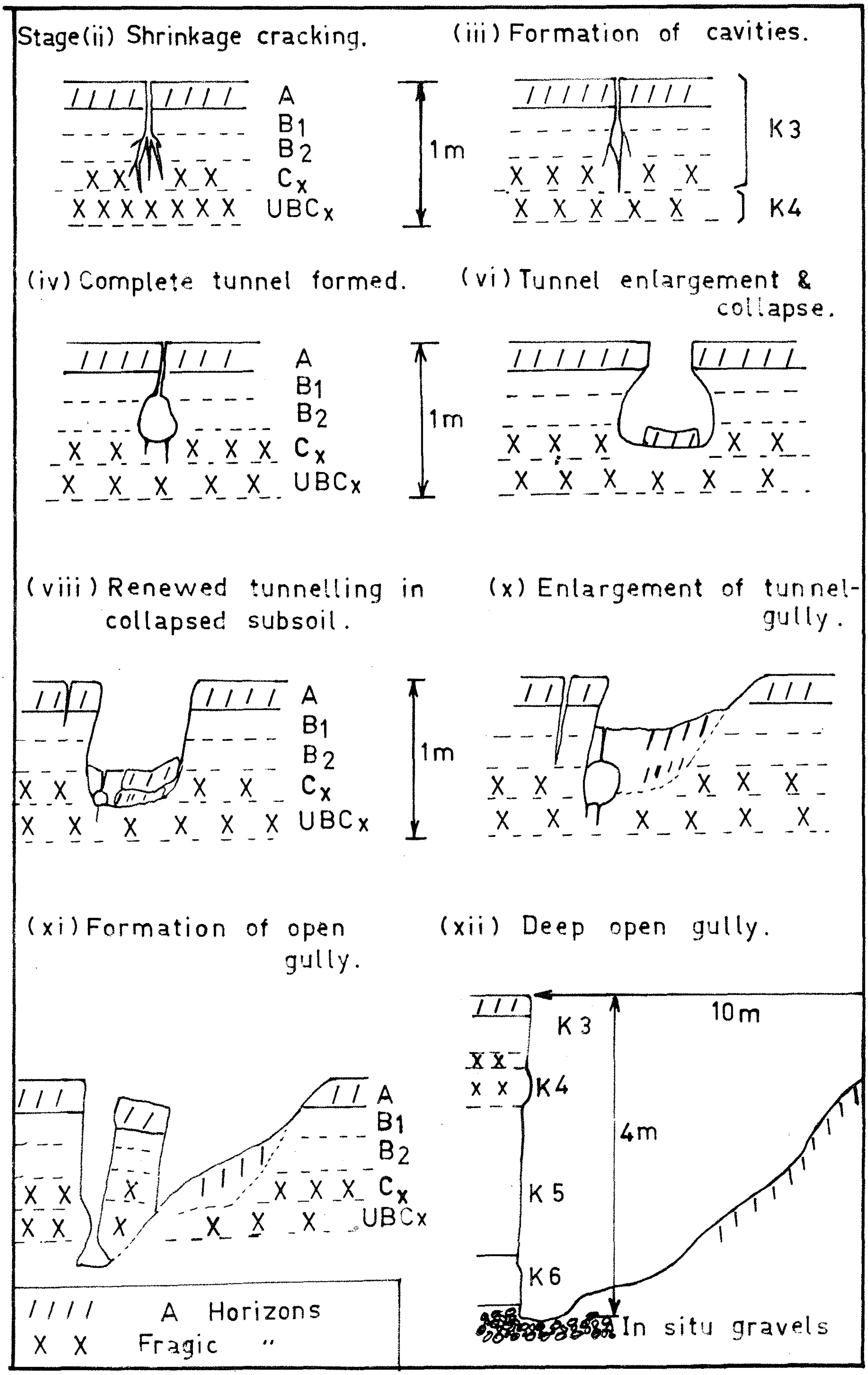
This sequence of tunnel-gullying differs markedly from that outlined by Gibbs (loc cit) in that the majority of tunnels originate in the B_2 horizon above the compact fragipan which acts as a tunnel floor and not as a tunnel roof as proposed by Gibbs. The few tunnels observed in the lowermost loess layers (K5 and K6 groundsurfaces) are considered to be secondary erosion forms resulting from primary tunnel-gullying in the B_2 horizon (K3 groundsurface). Most secondary tunnels examined in the representative catchment were sited directly on top of the compact Tertiary gravels which acted as tunnel floors.

The stony soils of the Vernon series do not appear to follow the complete sequence as outlined. Open gullying develops at their outlets and works headward in the absence of prior roof collapse and renewed tunnel formation in the debris (Plate 13).

It has been assumed that tunnel outlets in footslopes and free faces of toeslopes have resulted from hydrostatic pressure in tunnels upslope.

Fig. 10 SCHEMATIC SEQUENCE OF TUNNEL-GULLYING ON STEEP BACKSLOPES, WITHER HILLS.

(Refer to text for explanation of stage numbers & groundsurfaces - K3 --- K6.)



The possibility of headward erosion beginning at free faces cannot be discounted.

7.1.7. Fine Sandy Loam Accumulations in Subsoils of Wither Series.

The cross section through the toposequence footslope soil revealed a circular deposit (30cms diameter) of white coloured, fine sandy loam interposed between the bottom of the A horizon and top of the B_3 horizon. This material exhibited horizontal layering indicative of water deposition. The fine sandy loam was traced upslope some 3.0 metres before petering out. No trace was found of the deposit downslope from the section. A further smaller patch of similar material was noted between 70 and 75cms from the surface. It was established that the texture of these materials is similar to the thin, white coloured films lining subsoil cracks. It is thought that the fine sandy loam in cracks is due to eluviation of clay and fine silt from the surfaces of cracks leaving behind the coarser textured particles, or sorting by fluvial action.

The circular patches of fine sandy loam are assumed to have accrued from infilling of a former tunnel which has had its outlet blocked.

7.1.8. Organic Matter Accumulation.

Numerous sections through Wither soils on shoulder sites and several on backslopes revealed deep accumulations of dark grey organically stained (A horizon) material (silt loam) from the surface down to upper C_x horizon (plate 14). Typical dimensions were 60 - 70cms deep by 50 to 60cms wide.

Most accumulations on shoulder sites were adjacent to collapsed tunnels with a surrounding network of fine cracks infilled with whitish fine sandy loam.

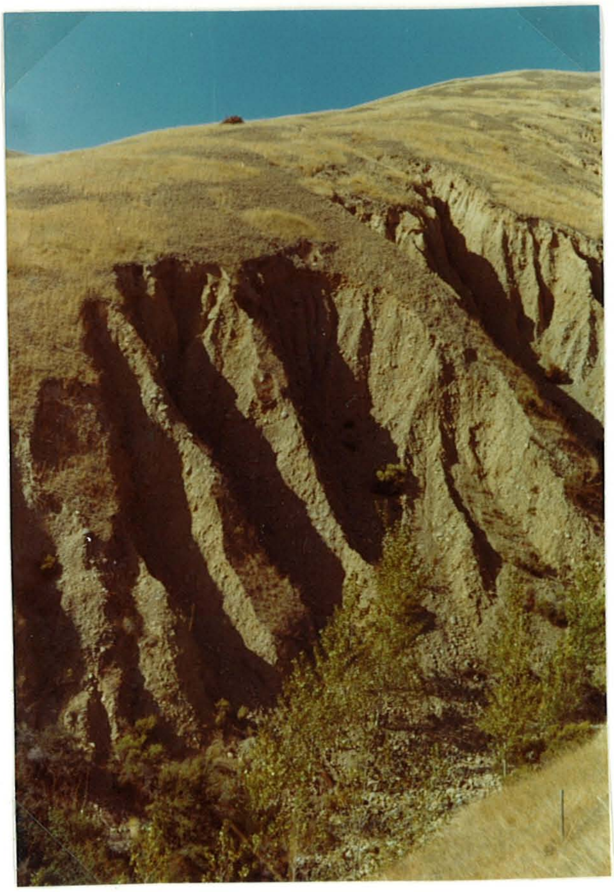


Plate 13.
Headward gully erosion into underlying Tertiary gravels from tunnel-gully erosion in soils of Vernon series.

Plate 14.
Organic matter infilling at shoulder site (Wither Series).

The accumulations observed on backslopes were not associated with tunnels although thin veins of fine sandy loam were present. The dark grey accumulations on shoulder sites were traced upslope into ridge crests some 3-4m before becoming indistinguishable from the normal topsoil.

It is believed that these accumulations represent infilled tunnels which have since been subject to a more active organic regime than adjacent soils because of better moisture conditions. The dark grey material is assumed to be due to organic matter from this regime. There is no evidence of layering or sedimentologic sorting.

Whether the infillings have accumulated in European times or earlier is unknown. Reasons for suspecting an earlier date probably contemporaneous with the Polynesian era are :

(i) The surface of most dark grey material is in the same plane as adjacent non-eroded surfaces. Few occur in depressions associated with European tunnel erosion.

(ii) The depth and width of the accumulations suggest an organic cycle which has operated for a longer interval than the European era. Footslopes and other concave sites which receive additional moisture from seepage and run-off from upslope sites do not show similar accumulations of organic matter.

(iii) Several accumulations in backslope sites occur at an angle to the side walls of present gullies suggesting that these are infillings of a prior erosion cycle.

7.2 LABORATORY ANALYSES

7.2.1. Soil Cracking.

7.2.1.1. Shrinkage Tests. Oven-drying and air-drying tests were carried out on all samples from the toposequence soils.

Duplicate samples were puddled in 'Keen boxes' (5.4cms internal diameter x 1.57cms depth). One set was dried at room temperature for 12 hours while the other set was dried at 105 degrees C for 12 hours.

The results from both tests revealed that all A and B_1 horizons shrank from the sides of their containers (up to 1.0mm wide) but did not crack noticeably. The samples from all B_2 horizons showed slight lateral shrinkage and marked internal cracking up to 2.0mm for oven drying. The C_x (and B_3) and uB/C_x horizon samples showed very slight lateral shrinkage and only slight internal cracking for both dessication procedures.

While these tests show that saturated, disturbed subsoil samples may crack substantially under different dessication conditions they do not necessarily resemble the responses by saturated, undisturbed soil under field conditions. Likewise it is thought that volume change experiments on undisturbed clods in the laboratory are unrealistic because of marked dissimilarities between the testing procedure and actual field conditions.

It is concluded that the only reliable indication of soil response to dessication is provided by observations and measurements of the soil profile in the field.

7.2.1.2. <u>Predictions from physical, chemical and mineralogical Properties</u>.

The high clay content, high E.S.P. and low electrolyte content of subsoil samples, particularly the B_2 horizons would be expected to confer a high degree of shrinkage under summer dessication. The average P.E.T. for the four summer months at the Wither Reserve is over twice the average precipitation during the same period.

Very high moisture tensions in subsoils would be expected under summer conditions, especially where cracking to the surface has occurred.

Predictions of marked shrinkage in the B_2 horizons of the toposequence profiles are verified by field observations of distinct crack systems in this horizon and by dessication of puddled samples in the laboratory.

7.2.2. Clay Dispersion.

7.2.2.1. Electrolyte Content and Concentration.

Analyses of soluble salt cations for the toposequence soils and the K5 and K6 groundsurfaces are presented in Table 16.

The exchangeable sodium percentages (E.S.P.) for the toposequence soils are derived from the cation exchange data of the appendices. The E.S.P. for the K5 and K6 groundsurfaces are calculated from the S.A.R. according to the procedure of Richards (1954).

Comparison with the relationship of Rallings (1966) between E.S.P. and electrolyte concentration for illitic soils predicts that most of the samples are dispersible with respect to their electro-chemical properties. Except for those samples (24, 25, 27) with high electrolyte concentration it would be expected that the remaining soils disperse upon leaching with distilled water.

7.2.2.2. The 'Crumb' Test.

Results are shown in Table 17 for air-dry samples from all soils and for five samples at initial moisture contents greater than air-dryness. The E.S.P. and pH of all samples are shown for comparative purposes.

TABLE 16

SOLUBLE SALT CATIONS AND E.S.P.

PROFILE HORIZON	SAMPLE No.	DEPTH (cm)	SOLUBLE SALT CATIONS Ca^{2+} (me%)	Mg^{2+} (me%)	Na^{+} (me%)	Total (me%)	ESP (%)
Footslope							
A	1	0-14	-	-	-	Tr	1
B_1	2	14-29	-	-	-	Tr	8
B_2	3	29-55	-	-	-	Tr	14
B_3	4	55-70	-	-	0.2	0.2	16
C_1	5	70-90	-	-	1.2	1.2	18
Backslope							
A_1	6	0-14	-	-	-	Tr	4
A_3	7	14-25	-	-	-	Tr	3
B_1	8	25-40	-	-	-	Tr	6
B_2	9	40-62	-	-	0.1	0.1	8
C_x	10	62-84	-	-	1.1	1.1	18
uB/C_x	11	84-100	-	-	1.4	1.4	22
Shoulder							
A_1	12	0-12	-	-	-	Tr	3
A_3	13	12-24	-	-	-	Tr	2
B_1	14	24-34	-	-	-	Tr	8
B_2	15	34-60	-	-	0.3	0.3	11
C_x	16	60-85	0.1	0.1	1.3	1.5	9
uB/C_x	17	85-100	0.2	0.2	2.2	2.6	11
Crest							
A_1	18	0-8	-	-	-	Tr	0.5
A_3	19	8-20	-	-	-	Tr	1
B_1	20	20-30	-	-	-	Tr	4
B_2	21	30-60	-	-	0.7	0.7	10
C_x	22	60-85	0.2	0.4	2.3	2.9	7
uB/C_x	23	85-100	0.2	0.2	2.0	2.4	8
K5	24	120-140	0.05	1.1	6.8	8.0	15
	25	140-170	0.2	2.3	6.8	9.3	11
	26	140-160	-	0.2	4.1	4.3	20
K6	27	200	1.0	6.7	11.0	18.7	9

Tr = trace only recorded

TABLE 17

DISPERSION OF SOIL 'AGGREGATES'

('CRUMB TEST')

SAMPLE No.	STATE OF SOLUTION AROUND SOIL 'AGGREGATES' Air - Dry	Field Moisture	pH	ESP
1	clear	-	5.4	1
2	clear	-	6.5	8
3	very light suspension	-	7.1	14
4	moderate suspension	-	7.3	16
5	moderate suspension	-	7.4	18
6	clear	-	5.7	4
7	clear	-	6.3	3
8	clear	-	6.6	6
9	light suspension	-	6.3	8
10	light suspension	-	5.4	18
11	light suspension	-	5.3	22
12	clear	clear	5.0	3
13	clear	clear	5.5	2
14	clear	light suspension	6.4	8
15	light suspension	moderate suspension	5.8	11
16	clear	-	4.6	10
17	clear	light suspension	4.8	11
18	clear	-	5.2	0.5
19	clear	-	5.5	1
20	clear	-	6.3	4
21	light suspension	-	7.0	10
22	clear	-	6.1	7
23	clear	-	5.3	8
24	clear	-	4.4	15
25	clear	-	4.7	11
26	moderate suspension	-	6.4	20
27	clear	-	4.4	9

Dispersion of soil 'crumbs' is indicated by the presence of a cloudy suspension in the solution surrounding the 'crumbs'.

The results show that dispersion occurs over a wide range of E.S.P. values. Emerson (1960) stated that dispersion of soil 'crumbs' would indicate an E.S.P. of 8 or greater. In the air-dry samples the minimum E.S.P.at which dispersion has taken place is 8. Not all samples with this value have dispersed (2, 14, 23) and several other 'crumbs' with higher E.S.P.have also failed to disperse. The latter group all have very low pH (less than 4.8). Rallings (loc cit) noted that some Australian soils with pH (less than 4.5) did not disperse. He proposed that bonding by Aluminium oxides at these low pH levels was responsible for the discrepancy. It seems probable that an analogous situation exists with the Wither soils. In addition the electrolyte concentration of samples 24, 25 and 27 may have been high enough to aid flocculation even though the soluble salt in the crumbs has been considerably diluted.

The effect of initial moisture content is illustrated by the comparison of samples 12, 13, 14, 15 and 17 at both air dryness and field moisture. All samples with an E.S.P. of 8 and above have dispersed. For sample 15 greater dispersion has occurred at the higher moisture content. The effects of low pH in preventing dispersion appears to have been removed to some extent at moisture contents greater than air-dryness.

7.2.2.3. <u>The Dispersal Index</u>.

Values for the dispersal index (D.I.) expressed as a per cent for samples at air-dryness and selected samples at field moisture are compared in table 18. The D.I. values of air-dry samples after 10 minutes and 30 minutes agitation are also shown.

TABLE 18

DISPERSION INDICES (D.I.)

SAMPLE No.	DISPERSION Air – (10mins)	Dry (30mins)	INDICES(%) Field Moisture (10mins)	FIELD MOISTURE CONTENT (%)	E.S.P.
1	21	30	-		1
2	21	29	-		8
3	24	41	53	10	14
4	56	66	77	12	16
5	67	74	-		18
6	18	38	-		4
7	-	33	-		3
8	25	45	-		6
9	48	63	-		8
10	74	82	69	12	18
11	65	71	-		22
12	21	35	-		3
13	18	25	-		2
14	19	34	-		8
15	62	70	80	13	11
16	39	-	-		10
17	40	59	-		11
18	13	27	-		0.5
19	-	29	-		1
20	16	29	-		4
21	34	47	-		10
22	27	43	-		7
23	27	44	-		8
24	12	-	-		15
25	21	-	-		11
26	56	-	-		20
27	7	-	-		9

Particle and aggregate size distribution curves from which D.I. values are computed are presented in appendix C for samples from the shoulder profile.

The per cent moisture content is based on oven drying at 105 degrees C for 24 hours. The increase in D.I. values from 10 minutes to 30 minutes agitation is marked in all samples tested. The relationship between the D.I. values at the two agitation intervals is expressed by the linear regression :

$$D.I.\% \ (30mins) = 18.4 + 0.84 \ D.I.\% \ (10mins)$$

It is statistically highly significant. (less than 1%). $F = 103$ for 18 d.f. $r = + 0.92$. The regression explains 85% of the total variation between the two variables. The effect of initial moisture content is clearly shown by the D.I. values for samples 3, 4 and 15. The D.I. for these samples at field moisture is markedly greater than D.I. at air-dryness. This trend parallels that for dispersion of soil 'crumbs' at varying initial moisture values. Sample 10 at field moisture showed a slight reduction in D.I. compared to that of air dryness. No ready explanation is available for this behaviour.

<u>The General increase in D.I. with increasing E.S.P.</u> <u>is a major feature of the experiment</u>.

The relationship between D.I. and E.S.P. for all samples is illustrated in figure 11 and is expressed by the linear regression :

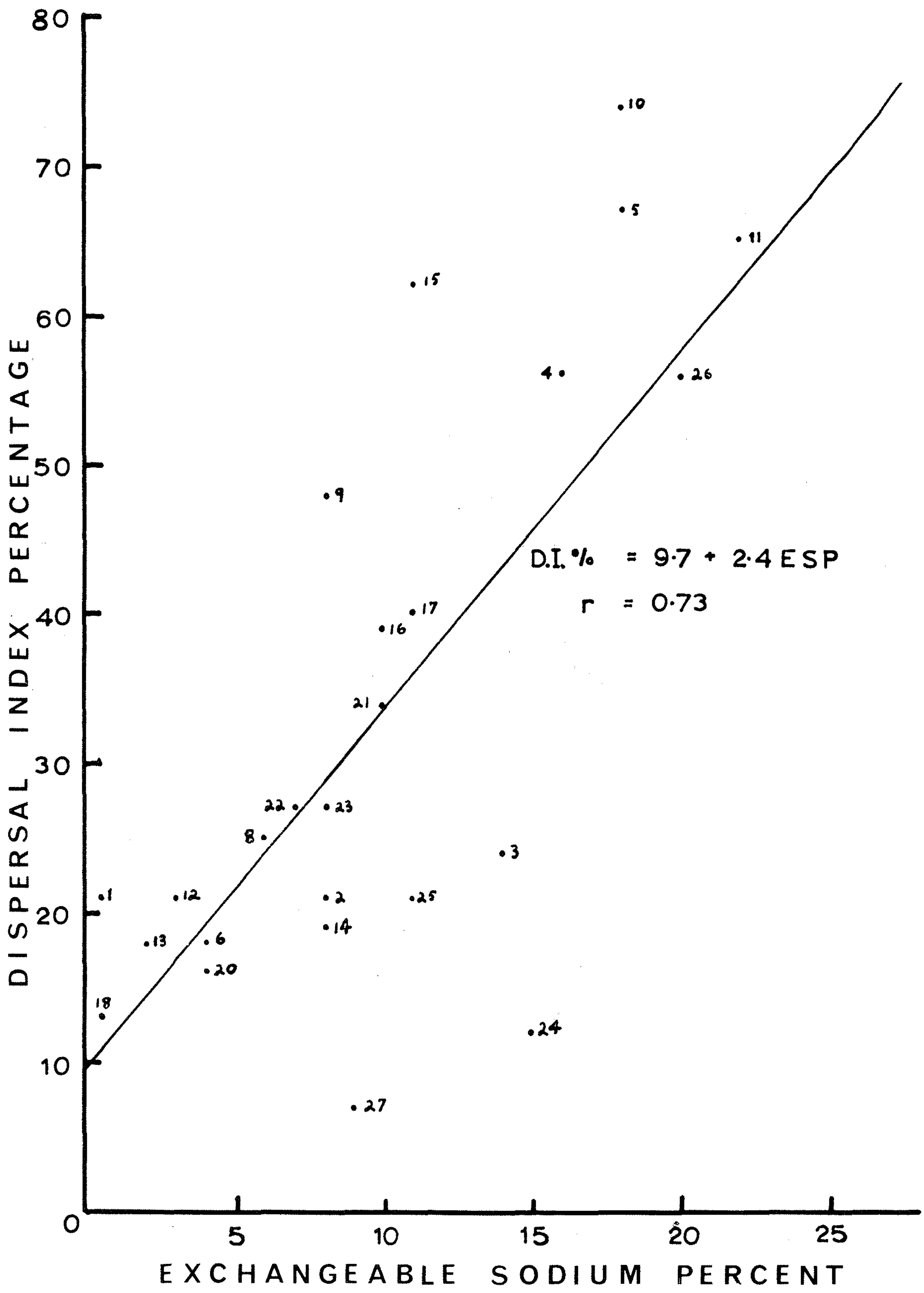
$$D.I. \ (10 \ mins) = 9.7 + 2.4 \ E.S.P.$$

It is highly significant (less than 1%)

$F = 25.5$ for 23 d.f. $r = + 0.73$

Approximately 53% of the total variation in D.I. is explained by variation in E.S.P.

Fig. 11 D.I.% vs E.S.P.



The relationship between D.I. and E.S.P. is improved by omitting those samples which are not dispersible according to the electro-chemical data of Rallings (1966) and others. These samples (24, 25, 27) have high electrolyte content and remain flocculated in distilled water without application of external energy. When energy is applied by rotation, slight dispersion takes place as evidenced by the low D.I. values.

The linear regression for the samples with low electrolyte content is :

D.I.% (10 mins) $= 10.7 + 2.65$ E.S.P.
$F = 53$ for 20 d.f. $r = + 0.85$

The regression is highly significant (less than 1%) and explains 72% of the total variation between D.I. and E.S.P.

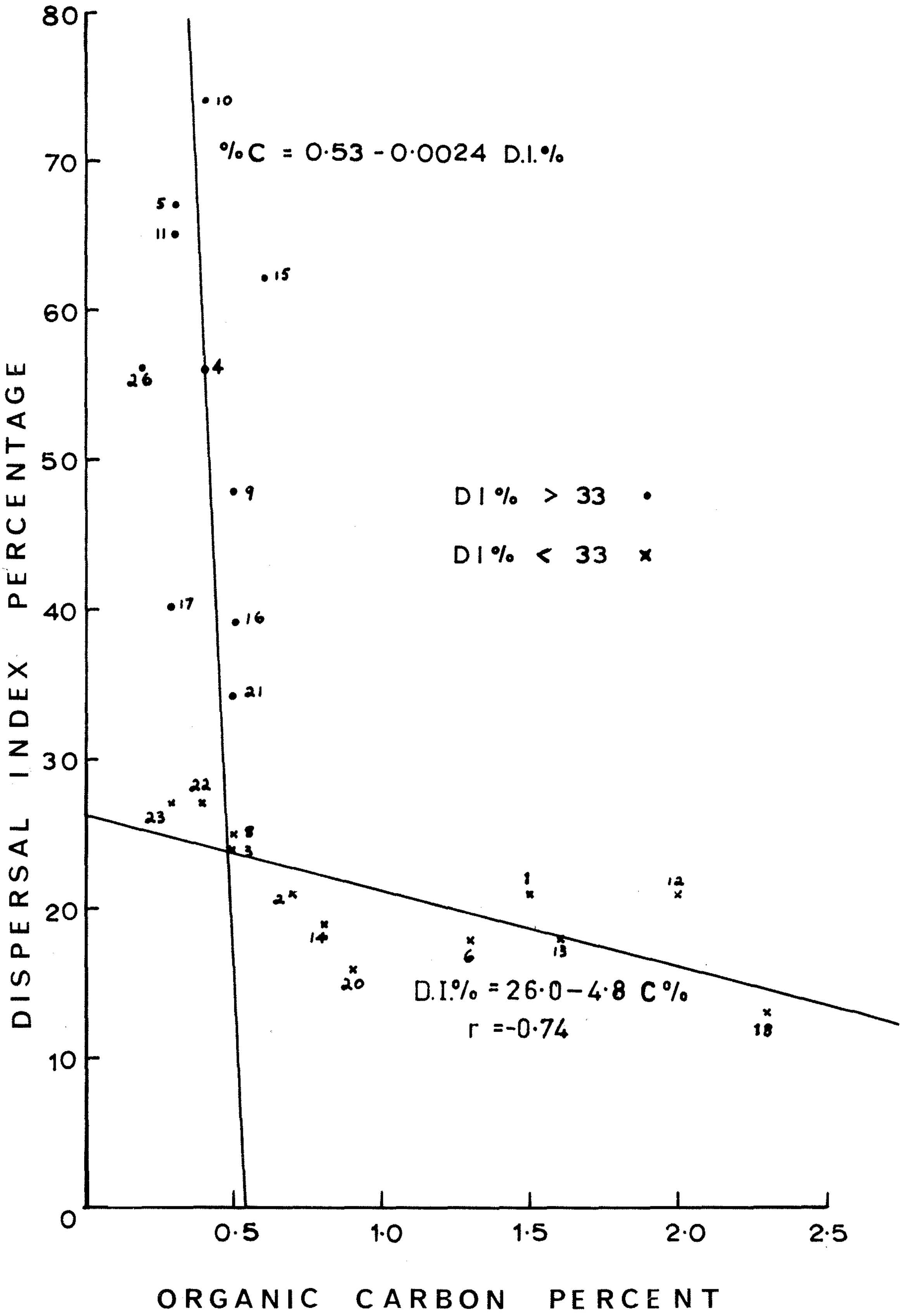
Ritchie (1963) stated that soils with a D.I. of less than 3.0 (i.e. D.I.% greater than 33%) were dispersible and susceptible to tunnelling. Reference to table 18 shows that all topsoils and B_1 horizons of the toposequence soils are non-susceptible to tunnelling on this criterion. All toposequence sites had at least one subsoil horizon with D.I. greater than 33% particularly in the footslope and backslope profile where lower subsoils and C horizons were highly dispersible. Only one paleosol sample had a D.I. greater than 33%.

The rotation of samples tends to obscure the effect of low pH on dispersibility. The C_x and uB/C_x horizons of the shoulder profile (samples 16 and 17) have low pH yet are susceptible to tunnelling on Ritchie's (loc cit) criterion. Samples 24, 25 and 27 are non-dispersible (D.I. less than 33) because of high electrolyte content and low pH.

7.2.2.4. Organic Bonding.

The relationship between D.I. and organic carbon for most samples is shown in table 19 and graphically represented by figure 12.

Fig. 12 D.I.% vs ORGANIC C %



The high electrolyte content samples with low pH (24, 25, 27) have been omitted from figure 12. The logarithmic relationship evident in fig 12 is expressed in linear form by the regression of D.I. on the reciprocal of organic carbon (fig 22 of the appendices).

The regression equation is : $D.I.\% = 13.8 + 11.0 \frac{1}{C\%}$

$F = 15.5$ for 20 d.f. and is highly significant (less than 1%).
$r = 0.66$ The regression thus explains only 44% of the total variation between these two variables.

Samples which are dispersible (D.I. greater than 33%) show a distinct grouping of low organic carbon values while the non-dispersible samples (D.I. less than 33%) are spread over a wide range of organic carbon values. The linear regression for dispersible samples is of the form :

% organic carbon = 0.53 - 0.0024 D.I.% (greater than 33%).
The standard deviation of 0.13% organic carbon shows that the dispersible soils contain low organic carbon within a narrowly defined range.

The regression equation for non-dispersible samples is :

D.I. % = 26.0 − 4.8 organic carbon %

$F = 11.9$ for 10 d.f. and is highly significant (less than 1%).

$r = 0.74$. Approximately 55% of the total variation in D.I. is explained by the variation in organic carbon.

The fact that several non-dispersible soils contain low organic carbon is consistent with the view that one or more other properties are responsible for clay particle cohesion.

7.2.2.5. <u>Cementation Effects of Free Iron Oxides and Colloidal Clay</u>

Table 19 shows the D.I. and free iron oxide for most samples.

TABLE 19

DISPERSION INDICES, ORGANIC CARBON

IRON OXIDES AND TOTAL CLAY (< 0.002mm).

SAMPLE No	D.I. % (10mins)	ORGANIC C %	IRON OXIDE %	TOTAL CLAY %
1	21	1.5	0.55	13.5
2	21	0.7	0.63	24.0
3	24	0.5	0.78	30.0
4	56	0.4	0.71	35.0
5	67	0.3	0.67	27.0
6	18	1.3	0.71	21.0
8	25	0.5	0.79	35.0
9	48	0.5	0.84	35.0
10	74	0.4	0.74	32.0
11	65	0.3	0.95	30.0
12	21	2.0	0.54	17.0
13	18	1.6	0.53	20.0
14	19	0.8	0.44	29.0
15	62	0.6	0.87	34.0
16	39	0.5	1.10	33.5
17	40	0.3	0.79	22.0
18	13	2.3	0.55	15.0
20	16	0.9	0.59	30.5
21	34	0.5	0.65	35.0
22	27	0.4	0.63	30.0
23	27	0.3	0.59	30.0
24	12	0.2	0.87	42.0
25	21	0.2	0.75	31.0
26	56	0.2	0.87	34.0
27	7	0.3	0.57	46.0

There is no significant statistical relationship between the two variables. It appears that the content of free iron oxides is insufficient to markedly affect dispersive properties of the soil samples.

There is no obvious correlation between D.I.% and the % clay ($<$ 0.002mm) for all samples. However the fact that samples 24 and 27 have very low dispersal indices and high clay contents (greater than 40%) may be significant. This relationship is confounded by the high electrolyte content and low pH of the two samples so that no definite conclusion may be drawn.

7.2.3. <u>Slaking</u>.

The cumulative indices for slaking experiments on air dry samples from time zero until 100 minutes is given in table 20.

The degree of aggregate breakdown increases down the soil profile, being least for topsoils and generally greatest for C horizons. An exception is the C_x horizon of the shoulder profile which is relatively more resistant to slaking than its B_2 horizon above.

The nil to relatively low aggregate breakdown in the A_1 horizons is due to their greater organic matter content than subsoils and parent materials. A close linear correlation exists between the slaking index (S.I.) and organic carbon (figure 13). The regression equation is highly significant where S.I. = 97.6 − 52.2 organic carbon %, and r = − 0.79. Approximately 62% of the variation in slaking is explained by the variation in organic carbon.

7.2.4. <u>Macro-Aggregation</u>.

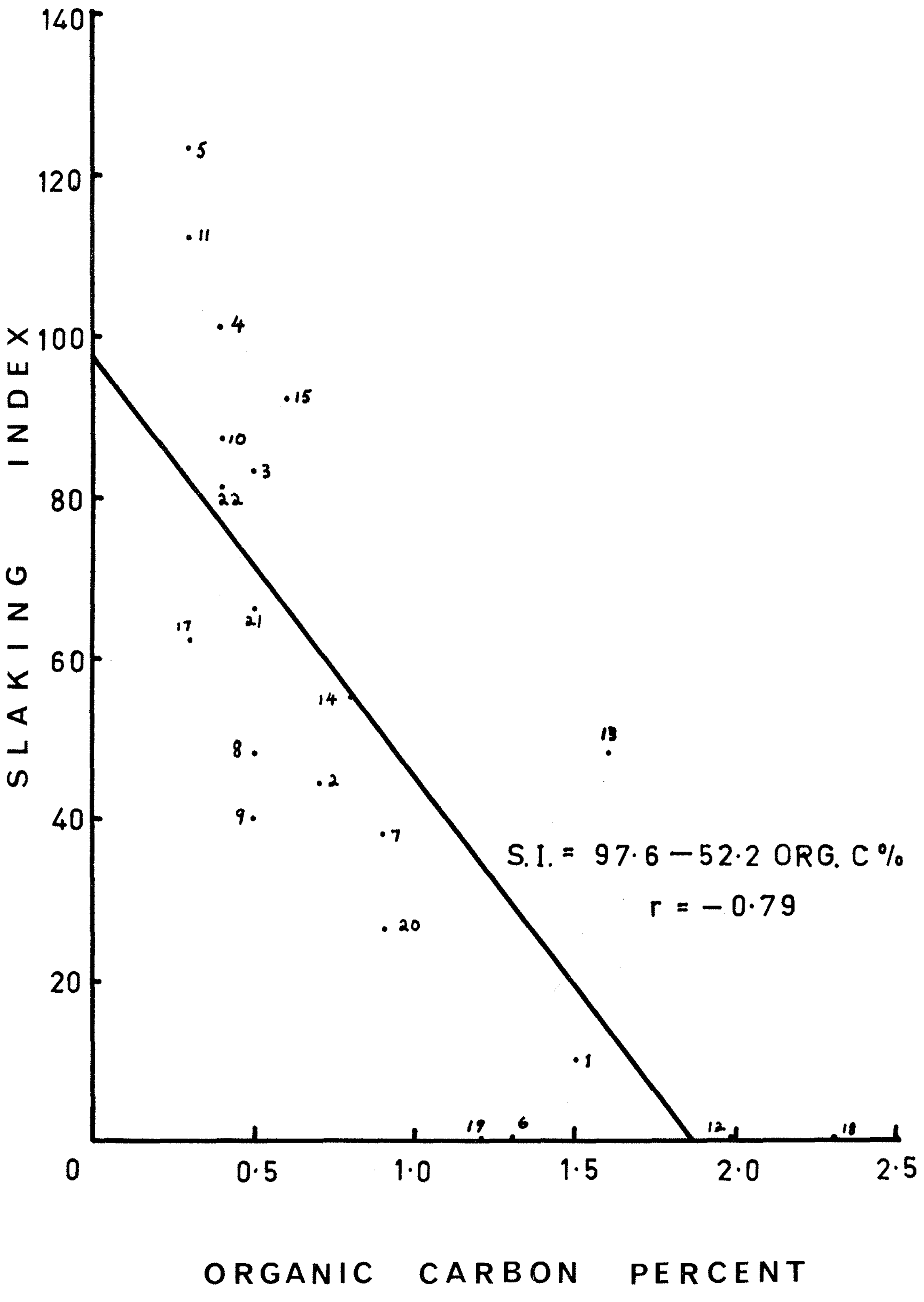
The construction of particle size distribution curves at the completion of the dispersion tests enables calculation of the macro-aggregation ratio.

TABLE 20

DISPERSION INDICES, SLAKING INDICES AND MACRO-AGGREGATION RATIOS.

SAMPLE No	D.I.% (10mins)	SLAKING Air-Dry	INDEX Field Moisture	MACRO-AGGREGATION RATIO
1	21	10	-	14.3
2	21	44	-	7.7
3	24	83	-	8.3
4	56	101	-	3.2
5	67	123	-	2.0
6	18	0	-	16.7
7	-	38	-	-
8	25	48	-	10.0
9	48	40	-	3.0
10	74	87	-	1.82
11	65	112	-	1.67
12	21	0	0	12.5
13	18	48	22	6.3
14	19	55	31	12.5
15	62	92	33	3.0
16	39	-	-	3.0
17	40	62	30	12.5
18	13	0	-	7.7
19	-	0	-	-
20	16	26	-	8.3
21	34	66	-	7.1
22	27	81	-	10.0
23	27	120	-	9.1
24	12	-	-	16.7
25	21	-	-	3.3
26	56	-	-	2.0
27	7	-	-	3.3

Fig. 13 SLAKING INDEX vs ORGANIC CARBON %



An aggregate size range of greater than 0.1mm diameter was selected as the basis of comparison.

$$\text{Macro-aggregation ratio (M.R.)} = \frac{\text{Particles} > 0.1\text{mm after mechanical dispersion only}}{\text{Particles} > 0.1\text{mm after complete dispersion.}}$$

The higher the macro-aggregation ratio the greater is the degree of stability of coarse aggregates. Table 20 lists the results for most samples. It is evident from the table that there is an inverse relationship between D.I. and M.R. The higher the D.I. the lower the M.R. and vice versa.

The linear regression is of the form :

D.I. % = 53.0 - 2.66 M.R.

F = 16.4 for 23 d.f. and r = 0.65. Only 42% of the total variation is explained by the regression.

By omitting the high electrolyte content, low pH samples (24, 25, 27) which probably underwent considerable destruction of aggregates greater than 0.063mm during collection, the correlation is markedly improved. The regression equation becomes : D.I. % = 60.4 - 3.3 M.R. where r = 0.77 and some 60% of the total variation between D.I. and M.R. is explained by this regression.

Although samples with high organic carbon generally have a high macro-aggregation ratio, there is no overall significant correlation between organic carbon and M.R.

7.2.5. Summary.

7.2.5.1. Soil Shrinkage.

Predictions of soil shrinkage based on clay type and content, E.S.P., electrolyte content and degree of dessication are verified by the deep subsoil cracking observed in the field.

7.2.5.2. Electrochemical Data. Comparison of the electrochemical data with the relationship of Rallings (1966) between E.S.P. and electrolyte concentration predict that most of the soils are dispersible. Three samples from paleosols are predicted to remain flocculated on electro-chemical considerations.

7.2.5.3. 'Crumb' Test. (i) The 'crumb' test for air-dry samples shows that topsoils are universally non-dispersive, while only some subsoils disperse when distilled water is added. These samples are of high E.S.P. ($\geqslant$8.0%) and moderate to high pH. Subsoils with high E.S.P. and low pH (4.8) did not disperse.
(ii) Subsoil samples with 12-13% moisture content showed greater dispersibility than at air-dryness (2-3% moisture).

7.2.5.4. Dispersal Index. (i) The dispersal index showed a highly significant positive relationship with E.S.P.
(ii) Samples with high E.S.P., high electrolyte content and low pH exhibited low dispersive properties (D.I. less than 33%).
(iii) Subsoil samples at field moisture generally showed greater dispersion than when air dry.
(iv) Samples showing dispersion in the 'crumb' test generally exhibited the highest D.I. values.
(v) There is an overall negative relationship (logarithmic) between D.I. and organic carbon but the correlation is not close. For non-dispersive soils (D.I. less than 33%) there is a close negative correlation between the two variables. For dispersive soils (D.I. greater than 33%) there is no significant correlation but all samples contained low organic carbon.
(vi) There is no obvious correlation between D.I. and free iron oxides or with clay content.

7.2.5.5. Slaking. (i) The slaking experiments showed that topsoils were resistant to disintegration when immersed in distilled water.

(ii) There was a general increase in aggregate disintegration down the profile.

(iii) Samples at field moisture content were more resistant to breakdown compared to that when air dry.

7.2.6. Conclusions.

It is readily apparent that the two properties which most markedly affect dispersibility are E.S.P. and organic carbon.

The boundary between dispersion/flocculation based on the relationship between E.S.P. and electrolyte content (Rallings 1966) is useful for predicting the stability status of water saturated, low organic content soils.

Subsoils with high E.S.P. and low organic carbon content are normally highly dispersible but the relationship is governed by electrolyte content and pH. Low pH (less than 4.8) may cause flocculation through aluminium bonding as suggested by Rallings (loc cit).

Samples showing dispersion in the 'crumb' test all had a D.I. greater than 33% except that of the footslope B_2 horizon. This sample had a high E.S.P. (14%), low electrolyte content, neutral pH and low organic carbon. The D.I. increased from 24% for this sample with 2% initial moisture content to D.I. of 53% at 10% moisture content. It would appear that initial moisture content is critical in the dispersive properties of these samples by applied mechanical energy.

The effect of initial moisture content on dispersibility and slaking is marked on most other soil samples. Relatively high initial moisture content produces greater dispersion but diminished slaking compared with low moisture levels (air-dry). The former relationship has been described by Puri and Keen (1925) and Emerson (1968).

The latter is probably related to the lower content of entrapped air that would be present in air-dry samples (Emerson 1954).

7.3 THE RELATIONSHIP OF DISPERSION AND SLAKING TESTS TO THE TUNNELLING PROCESS.

Reference to tables 16 and 17 indicates that the top-soils and B_1 horizons of all toposequence profiles are non-dispersive (D.I. less than 33% and negative crumb test). From the same tables it is apparent that all toposequence sites have at least one dispersive subsoil horizon (D.I. greater than 33%). It is significant that in all sites the B_2 horizon samples are dispersive in the 'crumb' test and most have a D.I. greater than 33%. The description of the tunnelling process from field evidence postulated initiation of tunnels in the B_2 horizon. It is considered that the relatively high dispersibilities of the B_2 horizon materials allow clay mobilisation when wetted and enable clay transport once cracks or outlets are formed in this horizon. The D.I. results at different initial moisture contents infer that once the B_2 horizons have been wetted then further application of moisture from percolating rainwater would allow even greater dispersion and transport of clay. The role of dispersion on dry soil is thought to be most important in the initiation of tunnels from cracks. Crack widths and depths are maximal in dessicated soils and minimal in moist soils. Wetting and dispersion of clay particles from crack surfaces initially at low moisture levels would allow greatest movement of clay and coarser particles before swelling processes closed the cracks. Subsequent dessication and crack formation would allow enlargement of fissures to form small cavities through clay illimerization or downward translocation of silt and fine sand.

Increased dispersibility at high moisture contents is probably more significant once enlarged fissures and small cavities have formed.

The role of slaking is considered important in subsequent tunnel enlargement processes, particularly on the wetting of tunnel linings initially at low moisture levels. Slaking probably is only significant once large subsoil cracks or small cavities have already formed from dispersion and movement of clay.

With the linking of subsoil fissures and the formation of defined outlets, particle and aggregate detachment by moving water assumes importance. Samples of the B_3 and C horizons of the footslope soil and C_x and uB/C_x horizons of backslope and shoulder profiles are all dispersible (D.I. greater than 33%). Tunnel enlargement would be expected to proceed rapidly into those layers especially during high intensity storms with large channelised flows down the tunnels.

Open gullies are formed once the C_x and uB/C_x horizons are broached and side walls and roofs collapse inwards.

The occurance of gully heads at shoulder positions in the landscape has been explained by previous inference as due to rapid change to easier slopes and diminuation of catchment area. Now it is evident that in addition the C_x and uB/C_x horizons of the crest profile are non-dispersive (D.I. less than 33% and negative crumb test). This infers that soil properties as well as site conditions are significant factors in the absence of open gullies from ridge tops. The scarcity of tunnels in ridge sites is probably related to similar conditions of easy slope and small catchment area in addition to the medium dispersibility of samples from the B_2 horizon (D.I. = 34%).

The further deepening of open gullies in the footslope and backslope sites is due primarily to particle detachment and transport by channelised flow during high intensity rains. Clay dispersion and the slaking of aggregates are assumed to be significant erosive processes during lighter precipitation. Three of the four paleosol samples from the sides of open gullies were non-dispersive (D.I. less than 33% and negative 'crumb' test) primarily because of high electrolyte content and low pH. The leaching of soluble salts during wetting of the surfaces of open gullies would be expected to result in conditions of high E.S.P. and low electrolyte content. This electro-chemical status results in high dispersibility potential, especially at high moisture contents. Turbid flows in open channels and turbid films on the sides of open gullies have been observed in the field during low intensity rainfalls. These observations indicate dispersive processes in soil materials after removal of flocculating soluble salts.

CHAPTER VIII

PROPERTIES OF OTHER LOESSIAL YELLOW-GREY EARTH SOILS IN THE SOUTH ISLAND.

8.1 TUNNEL-GULLIED SOILS OF THE SOUTH ISLAND.

According to Soil Bureau Staff (1968b) tunnel-gully erosion is confined exclusively to the YGE soil group in the South Island. In this group 14 soil sets are noted as being liable to tunnel-gully erosion. All are derived from predominantly loessial material.

Observations were made of tunnel-gullied loessial soils in the following localities :

(a) The Western flanks of Banks Peninsula, on a low spur just off the Teddington-Motukarara highway,

(b) deeply dissected hill country north-east of the Clarence river, on a high, narrow ridge overlooking the Kekerengu coast,

(c) the southern fringe of the Marlborough Sounds, on a low spur in the Pukaka valley.

The three soil sets examined in these localities were the subhygrous Takahe, the dry hygrous Woodbank hill soils and the hygrous Tua marina hill soils respectively. The Tua marina set is classified as a YGE-YBE intergrade.

Yellow-grey Earth soils in Otago liable to tunnel-gullying include the subhygrous Spylaw steepland soil and the dry hygrous Clydevale hill soil.

Tunnels in all soils occurred preferentially on moderately steep to steep slopes with northerly aspect.

8.1.1. Pedology.

The major morphological features of the Spylaw and Clydevale sets (Cutler, pers comms) together with the Tuamarina hill soil are outlined in table 21.

Considerable morphological variation exists between these soils. All three soils featured compacted C horizons but that of the Tuamarina comprised strongly developed medium blocky structure whereas the other two were massive.

The Takahe and Woodbank soils examined had clay loam 'textural B' horizons with non-gammate, compacted C_x horizons. The B horizons comprised strongly developed coarse blocky structure breaking to fine blocky.

8.1.2. Profile position of tunnels.

In the Takahe, Woodbank and Tuamarina soils the tunnels were sited in the 'textural B' horizons similar to the tunnel position in the Wither soils.

The Spylaw and Clydevale tunnel positions are not known.

Miller (1971) described tunnel initiation in the deep horizons of a loessial soil related to the Takahe on the lower spurs of the Port Hills, Banks Peninsula. This particular soil had a uniform texture profile down to 2.4m (8ft) consisting of fine sandy loams to silt loams, with a maximum clay content of 26%. Three small tunnels were located on the side of a large collapsed tunnel. In each case they were between 1m (40ins) and 1.27m (50ins) below the surface and about 38 to 50mm (1.5 to 2.0ins) in diameter (Miller, loc cit; p.103).

8.1.3. 'Crumb' Test.

Small air-dry soil aggregates or 'crumbs' less than 1cm diameter from the B and C horizons of the Tuamarina soil gave moderately cloudy suspensions when immersed in distilled water.

TABLE 21.

MORPHOLOGY OF THE CLYDEVALE, SPYLAW, AND TUAMARINA SOIL SETS SUSCEPTIBLE TO TUNNEL-GULLY EROSION.

MORPHOLOGICAL PROPERTY	HORIZON	SOIL SET		
		Clydevale hill	Spylaw steepland	Tuamarina hill
Texture		fine sandy loams	fine sandy loams	silt loams
Texture Profile		uniform	uniform	gradational
Structure Grade	A	weak	weak	weak
	B	weak	weak to moderate	moderate
	C	-	"	moderate
Form	A	crumb	crumb	crumb to granular
	B	blocky	crumb to nutty	blocky to nutty
	C	-	prismatic	blocky
Size	A	fine	fine	fine
	B	very coarse	coarse	coarse
	C	massive	massive and coarse	coarse
Consistence	A	friable	friable	friable
	B	firm-very firm	firm-very firm.	firm
	C	very firm	very firm	very firm
Mottling		few, faint	very few, faint	many, distinct
Clayskins		nil	nil	thin, discontinuous
Gammation		nil to very weakly gammate	nil	very weakly net-gammate

These conditions indicate that the subsoil and parent material of the Tuamarina soil are dispersible.

8.1.4. <u>Discussion and Conclusions</u>.

The above data indicate that in soils with gradational texture profiles tunnels occur in the 'textural B' horizons. In soils with uniform texture profiles tunnels occur deeper in the profile in parent materials and lower horizons.

It is suggested that 'textural B' clay loam horizons are more prone to severe cracking on dessication and are easily dispersed thus facilitating tunnel initiation. In soils with uniform textural profiles it appears that dessication cracking is not developed preferentially in any horizon and extends into deeper layers which are easily dispersed.

8.2 NON-TUNNELLED YGE AND YGE-YBE INTERGRADE SOILS.

The subhygrous Timaru soils and dry hygrous Claremont hill soils developed from loess in South Canterbury do not exhibit tunnel-gully erosion. Both are classified as YGE soils. Site factors for these two soils are presented in Chapter III. Both were examined on strongly rolling to moderately steep slopes with exposed northerly aspects.

In Otago the hygrous Warepa hill and Waitahuna hill soils classified as intergrade YGE-YBE soils are not prone to tunnel-gully erosion. Site characteristics for these two soils are similar to those for the adjacent tunnelled Clydevale and Spylaw soils (Cutler, per comms).

8.2.1. <u>Pedology</u>.

Major morphological features of the Warepa hill soil (Cutler, pers comms) together with the Timaru and Claremont soils are outlined in table 22.

TABLE 22

MORPHOLOGY OF NON-TUNNELLED TIMARU, CLAREMONT AND WAREPA SOIL SETS.

		TIMARU HILL	CLAREMONT HILL	WAREPA HILL
TEXTURE PROFILE	HORIZON	Slightly gradational (si l - cy l)	Gradational (si l - cy l)	Uniform gradational (si l)
STRUCTURE				
GRADE	A	weak/moderate	moderate	moderate/weak
	B	" "	weak/moderate	moderate
	C	moderate	moderate	moderate
FORM	A	crumb & granular	nutty	nutty
	B	prismatic	prismatic	blocky
	C	"	"	prismatic
SIZE	A	fine & medium	fine	fine
	B	coarse	"	coarse
	C	very coarse	coarse	"
CONSISTENCE	A	friable	friable	friable
	B	friable/firm	friable/firm	firm
	C	firm	firm	very firm
MOTTLING		few, faint	abundant, distinct	many, distinct
CLAYSKINS		thin, discontinuous	thin, discontinuous	nil
GAMMATION		gammate	gammate	gammate

The B horizons of all three soils are distinctly gammate with thick grey veins between structural units. The compact fragipans in the Timaru and Claremont soils are coarse to very coarsely prismatic with distinct gammation between prisms. Thin, continuous iron staining surrounds the outside surfaces of prismatic peds in the B and C horizons of these two soils, as well as the Warepa hill soil.

8.2.2. Laboratory Tests on the Timaru and Claremont Soils.

Table 23 outlines the results of pH, organic C, D.I., slaking tests and macro-aggregation ratio. The slaking tests were carried out on air-dry soil 'crumbs'. Mechanical analyses for all samples are presented in the appendices.

The 'crumb' test was carried out during determination of the slaking indices. Samples of the B_2 and C horizons of the Timaru soil showed slight cloudiness indicating dispersion of the colloid fraction. The remaining samples did not show any signs of dispersion after 2 hours.

The M.R. shows an inverse trend with D.I., similar to that for Wither soil samples.

TABLE 23. SELECTED LABORATORY PROPERTIES OF THE TIMARU AND CLAREMONT SOILS.

PROFILE HORIZON	SAMPLE DEPTH (cm)	pH	ORGANIC CARBON %	D.I. %	S.I.	M.R.
Timaru						
A	0-18	5.6	3.3	9	0	17
B_1	35-50	6.2	0.6	15	57	13
B_2	50-70	5.8	0.3	37	107	11
C_x	70-90	5.5	0.1	47	120	4

(contd...)

TABLE 23 (contd)

PROFILE HORIZON	SAMPLE DEPTH (cm)	pH	ORGANIC CARBON %	D.I. %	S.I.	M.R.
Claremont						
A	0-16	6.3	3.4	2	0	25
B_1	30-45	5.5	0.4	12	115	16
B_2	45-62	5.8	0.3	19	130	12
C_x	62-80	5.8	0.2	21	131	10

8.2.3. Discussion

The positive crumb test and D.I. values greater than 33% for the Timaru B_2 and C horizons indicates that dispersive conditions exist in the lower subsoils and parent materials.

It is suggested that the dispersibility of these two horizons is due primarily to high exchangeable sodium contents.

The negative crumb tests and low D.I. values for the Claremont subsoils and parent materials is thought to be due to low exchangeable sodium content. The pH level of greater than 4.8 rules out cementation effects by Al^{3+} and Fe^{3+}. In addition the low organic carbon content of these horizons would be expected to have a negligible effect on particle aggregation.

Slaking indices for the subsoils and parent materials of the Claremont and Timaru soils are considerably greater than those for corresponding horizons of the Wither silt loams. It is therefore concluded that slaking of air-dry soil is not significant in tunnel initiation although it may be important in the subsequent enlargement of tunnels.

8.3 DIFFERENCES BETWEEN TUNNELLED AND NON-TUNNELLED LOESSIAL SOILS

8.3.1. Pedology.

Comparison of tables 21 and 22 reveals that their most striking difference is the presence of distinct gammation in subsoils and parent materials of non-tunnelled soils.

Gammation is absent or at the most weakly expressed in parent materials of tunnelled soils.

8.3.2. Laboratory Tests.

Positive 'crumb' tests and dispersal indices greater than 33% indicating high dispersibility occur in subsoils and parent materials of both tunnelled and non-tunnelled soils.

The apparent anomaly of high dispersibility in the subsoil and parent material of the non-tunnelled Timaru soil is tentatively explained by the presence of distinct gammation in these horizons. The thick, grey gammate veins occur between iron stained outer surfaces of prismatic peds in both horizons. 'Crumb' tests on the grey gammate material and reddish-brown ped surfaces showed that neither was dispersive. In contrast the inner ped material showed slight cloudiness, indicating colloid dispersion.

It is thought that subsoil cracking due to dessication follows down the gammate veins. The hard, iron stained outer surfaces of peds protect the prisms from deformation due to clay illimerization and transport downslope. Thus tunnel initiation due to dispersion of crack surfaces is non-operative in the Timaru soil.

8.3.3. Conclusions.

(i) Tunnels do not form in some highly dispersible soils because of the presence of gammate or net-gammate cracks in the dispersive horizons. Dessication cracking into the subsoils and parent materials is thought to follow down the gammate cracks separating peds. The non-dispersive ped surfaces prevent clay movement from the cracks thus inhibiting tunnel initiation.

(ii) The presence of tunnels in dispersible non-gammate loessial soils is due primarily to random dessication cracking into the dispersive horizons in the absence of gammation. The ease of clay dispersion from the cracks and subsequent clay transport through cracks allows tunnel initiation.

(iii) The position of tunnels in the soil profile is dependent on the presence or absence of a 'textural - B' horizon. In dispersible soils with gradational texture profile tunnels are preferentially formed in the 'textural - B' horizon. In soils with uniform texture profiles tunnels usually originate at much greater depths.

(iv) Slaking of air-dry soil does not appear to be of significance in the initiation of tunnels although it may be important in their subsequent enlargement.

(v) Pedological and laboratory studies of a wider range of YGE and YGE-YBE Intergrade soils should be undertaken to test these conclusions.

(vi) This study has shown that it is important to carefully study the field pedology as well as the physical and chemical properties of soils in erosion studies.

CHAPTER IX

SUMMARY AND CONCLUSIONS.

9.1. OBJECT OF THE STUDY.

The aim of this study of a small representative catchment was to :

(i) Study in detail the soil pattern and erosion characteristics typical of the Wither Hills.

(ii) Determine the interrelationship between soil properties, both field and laboratory, on the initiation of tunnel erosion and its sequential development into open gullying.

9.2 METHOD OF APPROACH.

The objective was achieved by carrying out the following:

(i) A detailed soil survey of the representative catchment to define the major soil series and show the variation within each. Particular attention was given to remnant paleosols recognized in deep sections.

(ii) A detailed study of a toposequence on severely tunnel-gullied soils of the Wither series in the lower section of the catchment. Pedological, chemical, physical and mineralogical properties were determined for the four soil profiles of the toposequence to show their relationship to position on the landscape and to each other. Pedological and selected laboratory properties were examined for typical paleosols occurring beneath Wither soils.

(iii) A detailed field description of the process of tunnel initiation and development into open gullies.

(iv) Determination of two major parameters of soil erodibility i.e. the dispersal index (D.I.) and slaking index (S.I.) for all horizons of the toposequence soils and typical underlying paleosols.

Statistical analyses were used to relate these parameters to soil chemical and physical properties.

(v) A comparison of the pedological and selected laboratory properties of Wither soils with those of (a) Yellow-grey earths from other sub-humid regions in the South Island showing tunnel-gully erosion, and (b) Yellow-grey earths in similar environments but not tunnel-gullied.

9.3 DISCUSSION OF RESULTS AND CONCLUSIONS.

As each chapter has been summarised individually this section attempts to relate and discuss the study as a whole.

The soil survey of the representative catchment has shown that it is essential to carry out pedological studies before attempting to explain erosion processes. It has been convincingly shown that the detailed soil pattern is a direct result of successive phases of landscape instability with erosion/deposition alternating with intervals of stability and soil formation. The severe tunnel-gully erosion occurring on the Wither Hills is the most recent phase of landscape instability in a region which has undergone at least five previous cycles of erosion/deposition in its mid and late Quaternary history. <u>Tunnel-gully erosion has occurred only during the two post glacial erosion/deposition phases</u>. It is considered that human disturbance of the natural environment particularly depletion of existing vegetation has initiated these erosive processes.

The four previous phases of instability are considered due to climatic change at the onset of glacial periods with solifluction the major erosive process.

The sequential phases of landscape stability and soil formation have been delimited from recognition of soil forming groundsurfaces of varying age (K1, K2, K3, ... K7) based on degree of profile development and stratigraphic position. Morphological examination of the K3, K4 ..... K7 groundsurfaces revealed the presence of argillic horizons with distinct clay-skins indicating considerable soil stability during their formation.

Further evidence of the argillic B2 horizon in the Wither K3 groundsurface is provided by (a) its maximum clay content, (b) highest ratio of fine clay to total clay, and
(c) over the whole profile there is relatively uniform particle size distribution on a clay free basis. Additional evidence of landscape stability during post glacial times is provided by the overall well-differentiated profiles and well-organised subsoil structures of the K3 groundsurfaces. Thus the severe tunnel-gully erosion prevalent in the representative catchment is considered a man-induced interval of landscape instability out of phase with the known long period of stability revealed by soil properties of the K3 groundsurface.

The study of the toposequence in soils of the Wither series has shown significant differences in profile morphology and chemistry between the accumulative footslope site and the three regressive sites higher up the slope. Footslope profiles are characterized by the absence of a distinct fragipan and by the presence of abundant prominent mottles and manganese nodules in subsoils and parent materials.

The pH increases down the profile to reach alkaline values in the B and C horizons. The base status of these horizons is higher than those of corresponding horizons of sites upslope. This agrees with the findings of Franzmeier et. al., (loc cit) for soils in lower slope positions in Kentucky U.S.A. and Kingston (loc cit) for concave gully sites on the Moutere Gravels, Nelson. The backslope shoulder and crest sites are somewhat similar in morphological, physical, chemical and mineralogical properties. The modal Wither silt loam is represented by the backslope profile which is technically classified as a weakly enleached moderately clay illuvial weakly subgammate pallic soil with strongly developed fragipan from greywacke loess. It is intermediate in general profile morphology and physical, chemical and mineralogical properties between the Timaru and Matapiro reference profiles (Soil Bureau Staff, 1968a).

The field observations and measurements of tunnel-gully erosion show that the position of primary origin of tunnels in Wither soils is the clay loam textured B_2 horizon. Primary tunnels are initiated above the compact fragipan and not below it as proposed by Gibbs (loc cit). The actual mechanism of tunnel initiation with crack formation from surface to subsoil followed by crack widening and formation of voids is essentially similar to that outlined by Gibbs (loc cit). The high clay content of the B_2 horizon with its expanding/contracting clay component of vermiculite -2 and the high E.S.P. - low electrolyte content all contribute to a high cracking potential in the B_2 horizon. However crack formation from surface to subsoil is dependent upon the prior denudation of vegetative cover leading to loss of topsoil structural stability with eventual solum dessication during drought periods.

The process of crack widening and void formation is due to the high dispersibility of subsoils in which the clay fraction is readily dispersed and eluviated from crack walls when wetted.

The high E.S.P. with low electrolyte content on the one hand and the very low organic carbon content on the other are the two soil properties most closely correlated to the high dispersibility of subsoils particularly the B_2 horizon. The subsequent development of primary tunnels involves the linking of individual voids and cracks up and down slope by continued dispersion and eluviation of clay. Outlets are formed in footslope/lower backslope positions in the landscape from hydrostatic pressure exerted by water and sediments in cracks and voids higher up the slope. Tunnel enlargement with roof collapse and renewed tunnel formation in the collapsed materials eventually breaches the compact fragipan to form open gullies. This process of tunnel formation from dessication and cracking of the soil followed by clay dispersion when saturated and formation of outlets on lower hillslopes is similar to that described in Australia (Downes, loc cit; Newman and Phillips, loc cit:), the western U.S.A. (Fletcher and Carroll, loc cit) and the Port Hills, Banks Peninsula (Miller, 1971). In soils without an argillic B horizon tunnels may form in the deeper B or C horizons as in some soils on the Port Hills.

Laboratory tests on the non-tunnelled Timaru soils showed the presence of highly dispersible B and C horizons. The absence of tunnels was explained on the basis of morphological features particularly the presence of distinct gammate cracks in the dispersible horizons. Dessication cracking into the subsoils and parent materials is thought to follow down the gammate cracks separating peds.

The non-dispersive iron oxide encrusted ped surfaces of B and C horizon structures prevent dispersion of the soil mass thus inhibiting tunnel initiation.

Conversely the presence of tunnels in dispersible non-gammate loessial soils in New Zealand is due primarily to random dessication cracking into the dispersible horizons in the absence of gammation. The ease of clay dispersion from the cracks and subsequent clay transport through cracks allows tunnel initiation. It is considered that solum dessication is primarily dependent on vegetation depletion and structural breakdown of the surface horizons as outlined for Wither soils.

Comparison of slaking indices for air-dry samples from B and C horizons showed that greater slaking occurred in the non-tunnelled Timaru and Claremont soils than in the tunnelled Wither soils. Consequently it is considered that slaking of air-dry soil is not important in the initiation of tunnels although it may be of significance in the subsequent enlargement of tunnels in Wither soils.

This study has successfully explained the origin, initiation and development of tunnel-gully erosion in the Wither Hills by thorough examination of pedological and landscape characteristics and determination of physical, chemical and mineralogical properties. This work has succeeded in defining those soil properties directly influencing the tunnel-gully erosion problem which may consequently be rectified in the rehabilitation of these soils. The comparison of pedological and selected laboratory properties has successfully indicated reasons for the presence or absence of tunnel erosion in some loessial soils of the South Island.

<u>The whole study convincingly shows the importance of examining the pedological as well as laboratory properties of the soil landscape when studying erosion processes</u>.

9.4 PRACTICAL IMPLICATIONS

One of the rehabilitation measures used by the Marlborough Catchment Board to treat severe tunnel-gully erosion involves reshaping the landscape by bulldozing the eroded area down to the depth of the deepest tunnel-gully. This treatment causes substantial mixing of soil horizons and generally exposes bare subsoils and paleosols at the surface. Problems in the subsequent revegetation of these disturbed soils appear to be largely due to the very low organic matter content and to the high compaction and lack of structure subsequent to wetting and drying of these materials. The formation of hard surface crusts together with the lack of internal structural development produce conditions of very low infiltration and permeability with high surface run-off. Renewed tunnel formation in dessication cracks has occurred in some treated sites with sparse vegetative cover. It is thus vital to establish and maintain a complete vegetative cover on soils disturbed by bull-dozing as well as on natural, undisturbed Wither soils.

The establishment of adequate vegetation to prevent renewed tunnelling and to provide pastoral production is initially dependent on the amelioration of soil physical conditions to give greater structural development and stability for the absorption and retention of moisture. The basic cause of rapid consolidation and loss of structure is the high dispersibility of subsoils and paleosols with their high exchangeable sodium and low electrolyte contents. These electro-chemical conditions are quickly reached in exposed paleosols by the leaching of excess soluble salts. The very low pH of some C horizons and paleosol samples may also adversely affect plant establishment and vigour. <u>It is evident that chemical treatment to markedly reduce the soil dispersibility is required for the initial improvement in soil physical conditions and establishment of vegetation</u>. Once an active plant cover and organic regime have been achieved the accumulation of organic matter in the soil should retain stable conditions of low dispersibility and structural development in the upper soil layers.

It is therefore recommended that the following investigations be made high priority :

(i) The use of gypsum or other high calcium content materials to replace excess exchangeable sodium and decrease soil dispersibility through flocculation of clay particles.

(ii) Thorough study of available phosphate levels and other essential plant elements particularly those in the underlying strongly weathered paleosols.

(iii) Testing of a greater range of plant materials able to provide complete ground coverage as well as pastoral production under the drought prone environment.

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REFERENCES

ADAMS, J.E. and HANKS, R.J. 1964. Evaporation from soil shrinkage cracks. Proc. Soil Sci.Soc.Am. 28:281-284.

AITCHISON, G.D. and HOLMES, J.W. 1953. Aspects of swelling in the soil profile. Aust. J. Appl. Sci.4:244-259.

ALEXANDER, T.G. and ROBERTSON, J.A. 1970. Ascorbic acid as a reductant for inorganic P determination in the Chang and Jackson fractionation procedure. Soil Sci. 110:361-362.

AQUILERA, N.H. and JACKSON, M.L. 1953. Iron oxide removal from soils and clays. Proc. Soil Sci.Soc.Am. 17:359-64.

ARCA, M.N. and WEEDS, S.B. 1966. Soil aggregation and porosity in relation to contents of free iron oxides and clay. Soil Sci. 101:164-170.

BAVER, L.D. 1956. Soil physics 3rd ed. Wiley, New York. 489p.

BRANCH, W.J. and DAGGER, J.R. 1934. The conglomerates of the lower Wairau Valley, Marlborough. N.Z.J.Sci.Tech.16:121-35.

BROWN, G.W. 1962. Piping erosion in Colorado. J.Soil Wat. Conserv. 17:220-22.

BREWER, R. and BLACKMORE, A.V. 1956. The effects of entrapped air and optically oriented clay on aggregate breakdown and soil consistence. Aust. J. Appl. Sci. 7:59-68.

BUTLER, B.E. 1959. Periodic phenomena in landscapes as a basis for soil studies. C.S.I.R.O. Aust.Soil Publ. 14.

CHARMAN, P.E.V. 1969a. The influence of sodium salts on soils with reference to tunnel erosion in coastal areas. Part I- Kempsey area. J.Soil Cons. N.S.W. 25:331-347.

CHARMAN, P.E.V. 1969b. Part II - Grafton area. J.Soil Cons. N.S.W. 26:71-80.

CHARMAN, P.E.V. 1970. Part III - Taree area. J.Soil Cons. N.S.W. 26:256-268.

CHATTERJEE, R.K. and JAIN, J.K. 1970. Studies on aggregate formation with reference to cementing substances. Soil Sci. and Plant Nutr. 16:231-233.

CHESTERS, G. et.al. 1957. Soil aggregation in relation to various soil constituents. Proc.Soil Sci.Soc.Am. 21:272-77.

CLARIDGE, C.G.C. 1969. Physico-chemical methods for soil analysis. N.Z.D.S.I.R. Soil Bureau Inf.ser. 23.38p.

COLLIS-GEORGE, N. and SMILES, D.E. 1963. An examination of cation balance and moisture characteristic methods of determining the stability of soil aggregates. J. Soil Sci. 14:21-31.

CUMBERLAND, K.B. 1944. Soil erosion in New Zealand, a geographical reconnaissance. Whitcombe & Tombs, Christchurch, N.Z.

DAN, J. and YAALON, D.H. 1968. Pedomorphic forms and pedomorphic surfaces. 9th Int. Congr.Soil Sci. IV:577-584.

DESHPANDE, T.L., GREENLAND, D.J. and QUIRK, J.P. 1964. Role of iron oxides in bonding of soil particles. Nature.201: 107-108.

DESHPANDE, T.L., GREENLAND, D.J. and QUIRK, J.P. 1968. Changes in soil properties associated with the removal of iron and aluminium oxides. J. Soil Sci. 19:108-121.

DETTMAN, M.G. 1958. Water uptake by pure clays and soil crumbs. J. Soil Sci. 9:306-315.

DOWNES, R.G. 1946. Tunnelling erosion in North East Victoria. J. C.S.I.R. 19:283-292.

DOWNES, R.G. 1956. Conservation problems on Solodic soils in the State of Victoria (AUSTRALIA). J.Soil Wat.Conserv. 11:228-232.

EDWARD, A.P. and BREMNER, J.M. 1967. Microaggregate studies in soils. J. Soil Sci. 18:64-73.
EMERSON, W.W. 1954. The determination of the stability of soil crumbs. J. Soil Sci. 5:233-249.
EMERSON, W.W. 1959. The structure of soil crumbs. J. Soil Sci. 10:235-243.
EMERSON, W.W. 1960. The sealing of earth dams. Proc. Arid Zone Tech. Conf. Warburton. Vic. Vol 1. Paper no.38.
EMERSON, W.W. 1968. The dispersion of clay from soil aggregates. 9th Congr. Int. Soil Sci. Soc. 1:617-624.
EMERSON, W.W. and DETTMAN, M.G. 1960. The effect of pH on the wet strength of soil crumbs. J. Soil Sci. 11:149-158.
FIELDES, M. and TAYLOR, N.H. 1961. Clay mineralogy of N.Z. soils. N.Z. Jl. Sci. 4. No. 4.
FIELDES, M. 1968. In Soil Bureau Staff. Soils of New Zealand Part 2. N.Z.D.S.I.R. Soil Bur.Bull. 26 (2).
FINKELSTEIN, J. 1961. Estimation of open water Evaporation in N.Z. N.Z.J. Sci. 4:506-522.
FLETCHER, J.E. and CARROLL, P.H. 1948. Some properties of soils associated with piping in Southern Arizona. Proc. Soil Sci. Soc. Am. 13:545-547.
FLETCHER, J.E. et.al. 1954. Piping. Trans.Am.Geophys.Un. 35:258-263.
FOG, D.N. and WILKINSON, N.T. 1958. The colorimetric determination of phosphorus. Analyst. London.83.
FRANZMEIER, D.P. et.al. 1969. Properties of some soils of the Cumberland Plateau as related to slope aspect and position. Proc. Soil Sci.Soc.Am. 33:755-761.
GANDAHL, R. 1967. Particle size distribution of soil material (hydrometer method). In West European Working Group on soil structure of the International Soil Science Society editor. West European Methods for soil structure.
GEOLOGICAL SURVEY, 1962. Sheet 16, Kaikoura. N.Z.D.S.I.R.
GIBBS, H.S. 1945. Tunnel-gully erosion on the Wither Hills, Marlborough. N.Z. Jl.Sci.Technol.(Ser.A) 27:135-146.
GIBBS, H.S. and BEGGS, J.P. 1953. Soils and agriculture of the Awatere, Kaikoura and part of Marlborough Counties. N.Z.D.S.I.R. Soil Bureau Bull. no.9.
GREENLAND, D.J. 1965. Interaction between clays and organic compounds in soils. Soils and Fert. 28:415-425.
GREENLAND, D.J. and OADES, J.M. 1968. Iron oxides and clay surfaces. 9th Int.Congr.Soil Sci. I:617-24.
HAINES, W.B. 1923. The volume change associated with variations of water content in soil. J.Agric.Sci. 13:296-310.
HANDY, R.L. and DAVIDSON, D.J. 1953. Pipette method to supplement hydrometer test for particle size distribution in soils. Proc.Highway Res.Board. 32:548-555.
HOLLOWAY, J.T. 1959. Report on the soils, vegetation and erosion of the southern portion of the Wairau Catchment. Unpub. report to the Marlborough Catchment Board.
HOLMES, J.W. and STACE, H.C.T. 1968. On the domed structure and anistropy of the B horizon of a solodized solonetz. Austr.J. Soil Res. 6:149-157.
HOSKING, P.L. 1967. Tunnelling erosion in New Zealand. J.Soil Wat.Conserv. 22:149-151.
JACKSON, R.J. 1966. Slips in relation to rainfall and soil characteristics. N.Z.D.S.I.R. Soil Bur.Publ. no.395.
JESSUP, R.W. 1960. Identification and significance of buried soils of Quaternary age in the south east portion of the Australian arid zone. J.Soil Sci. 11:197-205.

JESSUP, R.W. 1961. Tertiary-Quaternary pedological chronology for the south east portion of the Australian arid zone. J. Soil Sci. 12:199-213.
KATCHINSKI, N.A. 1958. Mechanical and microaggregate composition of soils : Methods of investigation. Academy of Sciences of U.S.S.R. Israel Program for Scientific Translations. Jerusalem 1966.
KEEN, B.A. and RACKOWSKI, H. 1921. The relation between the clay content and certain physical properties of a soil. J. Agric. Sci. 11:441-449.
KLEISS, H.J. 1970. Hillslope sedimentation and soil formation in north east Iowa. Proc. Soil Sci. Soc. Am. 34:287-290.
KINGSTON, D. 1968. Some soil properties associated with good and poor regeneration growth in a radiata pine forest on Mapua Hill Soils, Nelson. Thesis M.Agr.Sci. Lincoln College Univ. of Canty.N.Z.
LOSCHE, C.K., McCRACKEN, R.J. and DAVEY, C.B. 1970. Soils of steeply sloping landscapes in southern Appalachian Mountains. Proc.Soil Sci.Soc.Am. 34:473-478.
LUTZ, J.F. 1936. The relation of free iron in the soil to aggregation. Proc.Soil Sci.Soc.Am. 1:43-45.
McCRAW, J.D. 1967. The surface features and soil pattern of the Hamilton basin. Earth Sci.Jnl. 1:59-74.
McCRAW, J.D. 1968. The soil pattern of some New Zealand alluvial fans. 9th Congr.Int.Soil Sci.Soc. IV.
McKEAGUE, J.A. and ST.ARNAUD, R.J. 1969. :Pedotranslocation : Eluviation - Illuviation in soils during the Quaternary. Soil Sci. 107:428-434.
McNEAL,B.L., NORVELL,W.A., and COLEMAN,N.T. 1966. Effect of solution composition in swelling of extracted soil clays. Proc.Soil Sci.Soc.Am. 30:313-317.
MARTIN,J.P. and RICHARDS,S.J. 1959. Influence of exchangeable Hydrogen, and calcium and of sodium and ammonia at different Hydrogen levels on certain physical properties of soils. Proc.Soil Sci.Soc.Am. 23:335-338.
MARTIN, J.P. 1946. Micro-organisms and soil aggregation.II : Influence of bacterial polysaccherides on soil structure. Soil Sci. 61:157-166.
METSON, A.J. 1956. Methods of chemical analysis for soil survey samples. N.Z.D.S.I.R. Soil Bur.Bull 12. 208p.
MILLER,D.K. 1971. Some soil properties affecting tunnel-gully erosion. Thesis M.Agr.Sci. Lincoln College Univ. of Canty. 140p.
MILNE,G. 1935. Quoted in Bushnell,T.M.1945. The catena caldron. Proc.Soil Sci.Soc.Am. 10:335.
MOLLOY,B.P.J. 1969. Evidence for post glacial climatic changes in New Zealand. Jl.Hydrol.(N.Z.) 8:56-67.
MONTEITH,N.H. 1954. Problems of some Hunter Valley soils. J. Soil Cons. N.S.W. 10:127-134.
MOSS,R.P. 1966. Soils and slopes in south west Nigeria. J. Soil Sci. 16:192-209.
NEWMAN,J.C. and PHILLIPS,J.R.H.1957. Tunnel erosion in the Riverina. J.Soil Cons.N.S.W. 13:159-169.
NORRISH,K. 1954. Manner of swelling of montmorillonite. Nature 173:256-57.
OLLIER,C.D. 1959. A two cycle theory of tropical pedology. Jl. Soil Sci. 10:137-148.
OLSON,R.V. 1965. p 971. In Black,C.A.editor. Methods of soil analysis. Agronomy monogram series no.9.

PALLISTER,J.W. 1956. Slope development in Buganda. Geog.Journ. 122:80-87.
PANNABOKKE,C.R. and QUIRK, J.P. 1957. Effect of initial water content on stability of soil aggregates in water. Soil Sci. 83:185-195.
PAPADAKIS,J. 1969. Soils of the world. Elsevier Pub.Co.
PARKER,G.G. 1963. Piping, a geomorphic agent in landform development of the drylands. Int.Assoc.Sci.Hydrol.Pub. 65:103-113.
PARSONS,R.B., BALSTER,C.A. and NESS,A.O. 1970. Soil development and geomorphic surfaces, Williamette Valley, Oregan. Proc.Soil Sci.Soc.Am. 34:485-91.
PETERSON,H.V. 1954. In Fletcher,J.E. et.al. Discussion on Piping. Trans.Am.Geophys.Un. 35:258-263.
PURI,A.N. and KEEN,B.A. 1925. The dispersion of soil in water under various conditions. Jl.Agr.Sci. 15:147-161.
QUIRK,J.P. and SCHOFIELD,R.K. 1955. The effect of electrolyte concentration on soil permeability. J.Soil Sci. 6:163-177.
RAESIDE, J.D. 1964. Loess deposits of the South Island,N.Z. and soils formed on them. Soil Bur.Pub. 310.
RALLINGS,R.A. 1966. An investigation into the causes of failure of farm dams in the Brigalow belt of central Queensland. Water Res. Foundation of Australia Bull.10.
RICHARDS,L.A. 1955. Diagnosis and improvement of saline and alkaline soils. U.S.D.A. Handbook no.60.
RICHARDS,S.J., HAGAN,R.M. and McCALLA,R.M. 1952. Soil temperature and plant growth p.318. In Shaw,B.T. Soil physical conditions and plant growth. Academic Press. New York. 491p.
RITCHIE,J.A. 1963. Earthwork tunnelling and the application of soil testing procedure. J.Soil Cons.N.S.W. 19:111-129.
RENNIE,D.A., TRUOG,E. and ALLEN,O.N. 1954. Soil aggregation as influenced by microbial gums, level of fertility, and kind of crop. Proc.Soil Sci.Soc.Am. 18:399-403.
REEVE,R.C., et.al. 1954. A comparison of effects of exchangeable sodium and potassium upon the physical condition of soils. Proc.Soil Sci.Soc.Am. 18:130-132.
ROSEWELL,C.J. 1970. Investigations into the control of earthwork tunnelling. J.Soil Cons.N.S.W. 26:188-203.
ROWELL,D.L., PAYNE,.D. and AHMAD,N. 1969. The effect of the concentration and movement of solutions on the swelling, dispersion and movement of clay in saline and alkaline soils. J.Soil Sci. 20:176-188.
RUHE,R.V. 1969. Landscapes in Iowa. Univ.Iowa Press.
RUHE,R.V., and WALKER,P.H. 1968. Hillslope models and soil formation.I open systems. 9th Int.Congr.Soil Sci. IV:551-560.
SELBY,M.J. 1967. Aspects of geomorphology of greywacke ranges bordering the lower and middle Waikato basins. Earth Sci.Jnl.1 (1).pp37-58
SELBY,M.J. 1970. Slopes and slope processes. Publ.no.1. Waikato Br.N.Z.Geogr.Soc.(Inc.)
SINGH,B.P. and CHATTERJEE,B.N. 1966. Studies in water stable aggregates of Bihar soils. J.Indian Soc.Soil Sci. 14:25-35.
SOIL BUREAU STAFF 1968a. Soils of New Zealand, Part 2. N.Z.D.S.I.R. Soil Bur.Bull.26(2).
SOIL BUREAU STAFF 1968b. Soils of the South Island, New Zealand. N.Z.D.S.I.R. Soil Bur.Bull.27.

SOIL SURVEY STAFF. 1967. Supplement of soil classification system (7th Approximation). U.S.D.A. 1967.
STIRK,G.B. 1954. Some aspects of soil shrinkage and the effect of cracking upon water entry into the soil. Aust.J.Agric.Res. 5:279-290.
SUGGATE,R.P. 1965. Late Pleistocene geology of the northern part of the South Island, New Zealand. N.Z.D.S.I.R. Geological Survey Bull.n.s.77.
SWINDALE,L.D. 1960. Experimental pedology in columns of Unsaturated soils. Proc.N.Z.Soc.Soil Sci. vol 4.
TAYLOR,N.H. and POHLEN,I.J. 1962. Soil Survey Method. N.Z.D.S.I.R. Soil Bur.Bull. 25.
TEMPANY,H.A. 1917. The shrinkage of soils. J.Agric.Sci.8:312-333.
THORP,J., CADY,J.G. and GAMBLE,E.E. 1959. Genesis of Miami silt loam. Proc.Soil Sci.Soc.Am. 23:156-161.
WALKER,P.H., HALL,G.F. and PROTZ,R. 1968. Relation between landform parameters and soil properties. Proc.Soil Sci. Soc.Am. 32:101-104.
WALKLEY,A. 1947. A critical examination of a rapid method for determining organic carbon in soils. Soil Sci.63:251-264.
WALKLEY,A. and BLACK,I.A. 1934. An examination of the Detjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37:29-38.
WARD,A.J. 1966. Pipe/shaft phenomena in Northland. Jl. Hydrol. (N.Z.) 5:64-72.
WEBSTER,R. 1965. A catena of soils in the Northern Rhodesian Plateau. J. Soil Sci. 16:31.
WOOD,C.L.,AITCHISON,G.D., and INGLES,O.G. 1964. Physico-chemical and engineering aspects of piping failures in small earth dams. C.S.I.R.O. Div. Soil Mech.Colloq. on failure of small earth dams. Melbourne Paper no.29.
YODER,R.E. 1936. A direct method of aggregate analysis and a study of the physical nature of erosion losses. J.Amer.Soc.Agron 28:337-351.

APPENDIX A

TOPOSEQUENCE PROFILE DESCRIPTIONS

1. FOOTSLOPE SITE

Soil Type	:	Wither silt loam
Classification	:	Weakly enleached moderately clay illuvial moderately mottled pallic soil from compact moderately argillised loess from greywacke.
Location	:	Footslope of representative catchment. Approx. 91m (100yrd) from lower boundary fence.
Map Sheet	:	S29/1&2. NZTM 1:25000
Grid Reference	:	257951
Topography	:	Slope 20^{o}. Aspect : East. Landform : concave footslope. Elevation : 49m (160ft)
Drainage	:	Site : Medium to rapid Internal : Imperfectly drained
Vegetation	:	Danthonia spp., hairgrass, goosegrass, sweet vernal.
Parent Material	:	Moderately argillised loess plus few gravels and stones from greywacke.

Profile :

A_1	0-14cms	light grey (10YR 7/2, dry), dark grey brown (10YR 4/2, moist), silt loam; mass hard to very hard, peds slightly hard to hard, peds and mass friable when moist; weakly to moderately developed very fine crumb and fine and medium granular structure; many roots; few very fine pores; indistinct boundary,
B_1	14-29cms	light grey (10YR 7/2, dry), brown to dark brown (10YR 4/3, moist), silt loam; peds and mass extremely hard when dry and friable when moist; weakly developed fine and medium blocky structure with some very thin discontinuous clay skins in fine pores; many roots; many fine and medium pores; indistinct boundary,
B_2	29-48cms	very pale brown (10YR 7/3, dry), brown (10YR 5/3 moist), clay loam; with few fine strongly weathered greywacke gravels (1cm diam.); peds and mass extremely hard when dry, friable to firm when moist; moderately developed medium prismatic structure breaking to coarse blocky; thin, discontinuous clay skins; vesicular pores near cracks; whitish fine sandy loam lining some cracks; many distinct fine black manganese nodules and yellowish red (5YR 4/8) nodules; few roots; indistinct boundary.
B_3	48-64cm	very pale brown (10YR 7/3 dry), brown (10YR 5/3 moist), clay loam; many prominent medium mottles, yellowish red (5YR 5/8 - 4/8 moist) mass and peds extremely hard when dry, firm when moist; moderately developed medium prismatic structure breaking to medium blocky; some ped surfaces covered with whitish fine sandy loam; thin discontinuous clay skins;

B_3 48-64cm (ctd) many distinct very fine black manganese nodules; few roots; indistinct boundary,

C_1 ON very pale brown (10YR 7/3 dry), light yellowish-brown (10YR 6/4 moist), clay loam; with fine, medium and coarse strongly weathered greywacke gravels; abundant prominent medium mottles, yellowish red (5YR 4/6 moist); peds and mass extremely hard when dry, firm when moist; weakly to moderately developed medium prismatic structure with evidence of very fine nutty structures; few to many very fine black manganese nodules; very few roots.

2. BACKSLOPE SITE

Soil Type	: Wither silt loam
Classification	: weakly enleached moderately clay illuvial weakly subgammate pallic soil with strongly developed fragipan from moderately argillised greywacke loess.
Location	: Backslope (or midslope) of representative catchment. Approx. 50m above footslope site.
Map Sheet	: S29/1&2. Grid reference = 256951
Topography	: Slope 25°. Aspect : east. Landform : slightly convex backslope. Elevation : 76m (250ft).
Drainage	: Site : Rapid to very rapid. Internal : moderately well drained.
Vegetation	: Same as for footslope site.
Parent Material	: Moderately argillised loess plus few small greywacke gravels.

Profile :

A_1 0-14cm dark yellowish brown (10YR 3/4 moist) silt loam; mass and peds slightly hard to hard when dry, friable when moist; weakly to moderately developed very fine crumb structure and fine and medium granular structure with few coarse granules; abundant roots; indistinct boundary,

A_3 14-25cms brown (10YR 5/3 dry), dark greyish brown (10YR 4/2 moist), silt loam; peds slightly hard, mass hard when dry, mass and peds friable when moist and weakly to moderately developed fine crumb and very fine to medium nutty structure; many roots; indistinct boundary,

B_1 25-40cm very pale brown (10YR 7/3, dry) brown to dark brown (10YR 4/3 moist), clay loam; mass and peds extremely hard when dry, firm when moist; weakly developed fine and medium blocky structure; slight vesicularity within peds, few roots; indistinct boundary,

B_2 40-62cm very pale brown (10YR 7/3 dry), brown to dark brown (10YR 4/3 moist), clay loam; few faint medium mottles yellowish red (5YR 5/8 moist); peds and mass extremely hard when dry,

B_2 40-62cm(ctd) firm when moist; moderately developed fine and medium prismatic structure breaking to fine and medium blocky with some coarse blocky structure; thin, continuous clayskins around peds; some old (fossil) root traces between peds; few roots; indistinct boundary,

C_x 62-84cm very pale brown (10YR 7/3 dry), brown to dark brown (7.5YR 4/4 moist), clay loam; peds and mass extremely hard when dry, firm to very firm when moist; moderately developed medium and coarse blocky structure breaking to moderately developed very fine nutty structures; thin discontinuous clayskins on ped surfaces; peds slightly vesicular; few living roots; but few to many old root traces and some organic matter staining; few faint dark reddish iron stained streaks parallel to horizon; indistinct boundary,

uB/C_x 84+cm very pale brown (10YR 7/3 dry), dark yellowish brown (10YR 4/4 moist), clay loam; few faint small to medium yellowish red mottles; mass and peds extremely hard when dry, very firm when moist; massive, but very fine nutty structure (possibly relict structure), which becomes more prominent when dry; some old vertical root traces; many small and medium obsolete infilled faunal burrows with dark brown very thin clayskins.

3. SHOULDER SITE

Soil Type : Wither silt loam
Classification : weakly enleached moderately clay illuvial weakly net-gammate pallic soil with strongly developed fragipan from moderately argillised loess.
Location : Shoulder position of representative catchment. Approx. 31m upslope from backslope site.
Map Sheet : S29/1&2. Grid reference : 255951
Topography : Slope 19°. Aspect : east. Landform : slightly convex shoulder position between upper backslope and crest. Elevation : 103m (340ft).
Drainage : Site : rapid.
Internal : moderately well drained.
Vegetation : Same as for backslope.
Parent Material : Moderately argillised loess.

Profile :

A_1 0-12cm light brownish grey (10YR 6/2 dry), very dark greyish brown (10YR 3/2 moist), silt loam; mass and peds hard when dry, friable when moist; weakly developed very fine and fine crumb and medium granular structure, with some coarse granules; abundant roots; indistinct boundary,

A_3 12-24cm — grey (10YR 6/1 dry), dark grey to very dark grey (10YR 4/3 - 3/1 moist), silt loam; peds and mass hard when dry, friable when moist; weakly developed fine crumb and fine and medium nutty structure; many roots; indistinct boundary,

B_1 24-34cm — light grey (10YR 7/1 - 7/2 dry) brown to dark greyish brown (10YR 5/2 - 4/2 moist), clay loam; mass and peds extremely hard when dry, friable to firm when moist; weakly developed medium prismatic breaking to medium blocky structure; peds vesicular; very thin discontinuous clayskins lining peds and pores; few to many roots; indistinct boundary,

B_2 34-60cm — very pale brown (10YR 7/3 dry), brown to dark brown (10YR 4/3 moist), clay loam; many faint medium strong brown (7.5YR 5/8 moist) mottles; peds and mass extremely hard when dry, firm when moist; moderately developed medium and coarse blocky structures, peds very slightly vesicular; thin, discontinuous clay skins around peds and lining pores; few living roots; some old remnant root traces; indistinct boundary,

C_x 60-85cm — very pale brown (10YR 7/3 dry), brown to dark brown (10YR 4/3 moist), clay loam; peds and mass extremely hard when dry, firm when moist; moderately developed medium blocky structure with very fine nutty structures; very thin, discontinuous clay skins around peds; few to many relict roof traces and reddish iron-staining between blocky structures; horizon weakly net-gammate, boundary distinct,

uB/C_x 85+cm — very pale brown (10YR 7/3 dry), brown to dark brown (10YR 4/3 moist), heavy silt loam; mass and peds extremely hard when dry, very firm when moist; massive, but relict weakly to moderately developed, coherent, very fine nutty structure evident; very thin, discontinuous clay skins around nutty peds; several thin, distinct reddish iron-stained streaks parallel to surface and joined by few, vertical, very thin reddish streaks at infrequent intervals; streaks very hard and occur preferentially in upper part of horizon; few relict root traces; many small and medium relict infilled faunal channels with very thin dark brown clay skins.

NOTES : White spots of soluble salts visible over 70% of this horizon on some exposed gully walls.

4. CREST SITE.

Soil Type : Wither silt loam

Classification : Weakly enleached moderately clay illuvial weakly net-gammate pallic soil with soft iron nodules and strongly developed fragipan from moderately argillised greywacke loess.

Location : Ridge crest of lower left hand side catchment boundary.

Map Sheet	: S29/1&2. Grid reference : 255951
Topography	: Slope 9°. Aspect : level. Landform : undulating ridge crest. Elevation : 104m (345ft).
Drainage	: Site : rapid - shedding site. Internal : moderately well drained.
Vegetation	: Same as for footslope site.
Parent Material	: Moderately argillised loess plus few small greywacke gravels.

Profile :

A_1	0-8cm	light brownish grey (10YR 6/2 dry), dark yellowish brown moist, silt loam; peds and mass hard when dry, friable when moist; weakly developed fine crumb and medium and coarse granular structure; abundant roots; indistinct boundary,
A_3	8-20cm	light grey (10YR 7/1 dry), dark greyish brown (10YR 4/2 moist), silt loam; mass and peds very hard when dry, friable when moist; weakly to moderately developed fine and medium nutty structure; peds moderately vesicular; many roots; indistinct boundary,
B_1	20-30cm	light grey (10YR 7/2 dry), brown to dark brown (10YR 4/3 moist), clay loam; mass and peds extremely hard when dry, firm when moist; weakly developed medium blocky structure; peds moderately vesicular; many roots; indistinct boundary,
B_2	30-60cm	very pale brown (10YR 7/3 dry) pale brown (10YR 6/3 moist) clay loam; with few strongly weathered greywacke gravels up to 4cm diameter; mass and peds extremely hard when dry, firm when moist; moderately developed medium blocky structure and very fine nutty structure; thin, discontinuous clay skins; many small yellowish red (5YR 5/8 moist) soft iron nodules; few to many relict dark brown root traces; indistinct boundary,
C_x	60-85cm	very pale brown (10YR 7/3 dry), pale brown (10YR 6/3 moist), clay loam; mass and peds extremely hard dry, very firm moist; moderately developed medium blocky structure and moderately developed very fine nutty structure also evident; very thin discontinuous clay skins around peds; many yellowish red soft iron nodules (up to 2cms diameter); few to many relict root traces and faint reddish iron staining between blocky peds; horizon weakly net-gammate; indistinct boundary,
uB/C_x	85+cm	very pale brown (10YR 7/3 dry), brown to dark brown (10YR 4/3 moist), clay loam; massive but relict, weakly developed, coherent, very fine nutty structure evident; very thin discontinuous clay skins around nutty peds; few faint horizontal and vertical reddish iron-stained streaks; many small and medium relict infilled faunal channels.

APPENDIX B

CHEMICAL ANALYSES FOR TOPOSEQUENCE SOILS AND PALEOSOLS

PROFILE HORIZON	SAMPLE DEPTH cm	pH	ORG. C%	C.E.C. me %	T.E.B. me %	B.S.%	Ca^{2+}	Mg^{2+} me %	K^+	Na^+	FREE IRON OXIDES %	TOTAL P ppm	K25° mmho /cm
Footslope													
A_1	0–14	5.4	1.5	8.0	4.01	50	2.5	1.1	0.33	0.08	0.55	380	-
B_1	14–29	6.5	0.7	10.4	9.54	92	4.4	4.2	0.14	0.8	0.63	260	-
B_2	29–55	7.1	0.5	10.6	11.48	(100)	4.4	5.5	0.08	1.5	0.78	320	-
B_3	55–70	7.3	0.4	12.9	13.22	(100)	4.5	6.5	0.14	2.08	0.71	225	0.04
C_1	70+	7.4	0.3	12.3	12.49	(100)	4.0	6.1	0.14	2.25	0.67	230	0.30
Backslope													
A_1	0–14	5.7	1.3	8.3	5.37	65	2.7	1.7	0.62	0.35	0.71	390	-
A_3	14–25	6.3	0.9	8.9	7.09	80	2.9	3.4	0.51	0.28	0.70	260	-
B_1	25–40	6.6	0.5	13.9	12.81	92	4.5	7.2	0.35	0.76	0.79	195	-
B_2	40–62	6.3	0.5	15.7	14.71	94	4.8	8.5	0.20	1.21	0.84	230	0.04
C_x	62–84	5.4	0.4	13.5	13.29	98	3.3	7.5	0.05	2.44	0.74	270	0.30
uB/C_x	84–100	5.3	0.3	14.5	13.25	92	3.2	6.8	0.1	3.15	0.95	465	0.38

APPENDIX B (CONTD)

PROFILE HORIZON	SAMPLE DEPTH cm	PH	ORG. C%	C.E.C. ME.%	T.E.B. ME.%	B.S.%	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	FREE IRON OXIDES %	TOTAL P ppm	$K25^{o}$ mmho/cm
Shoulder													
A_1	0-12	5.0	2.0	10.0	2.86	29	1.7	0.4	0.48	0.28	0.54	560	-
A_3	12-24	5.5	1.6	10.3	4.85	47	3.0	1.3	0.35	0.20	0.53	465	-
B_1	24-34	6.4	0.8	9.5	7.79	83	3.4	3.4	0.24	0.75	0.44	300	-
B_2	34-60	5.8	0.6	13.6	11.87	88	4.3	5.8	0.22	1.55	0.87	415	0.08
C_x	60-85	4.6	0.5	14.0	11.32	81	3.3	6.4	0.25	1.35	1.10	515	0.38
uB/C_x	85-100	4.8	0.3	11.9	10.46	88	2.9	6.0	0.18	1.34	0.79	380	0.72
Crest													
A_1	0-8	5.2	2.3	10.1	3.9	39	2.4	0.7	0.8	0.05	0.58	620	-
A_3	8-20	5.5	1.2	9.0	5.1	57	2.9	1.5	0.6	0.1	0.55	485	-
B_1	20-30	6.3	0.9	10.9	8.71	80	4.3	3.6	0.41	1.2	0.59	300	-
B_2	30-60	7.0	0.5	14.1	14.24	(100)	5.8	6.8	0.25	1.39	0.65	300	0.21
C_x	60-85	6.1	0.4	13.5	13.35	99	4.7	7.4	0.22	1.0	0.63	300	0.78
uB/C_x	85-100	5.3	0.3	14.0	13.22	95	4.2	7.7	0.24	1.1	0.59	320	0.64
K5	120-140	4.4	0.2								0.87	330	2.0
K5	140-170	4.7	0.2								0.75	330	2.15
K5	140-160	6.4	0.2								0.87	200	1.18
K6	200	4.4	0.3								0.57	200	4.32

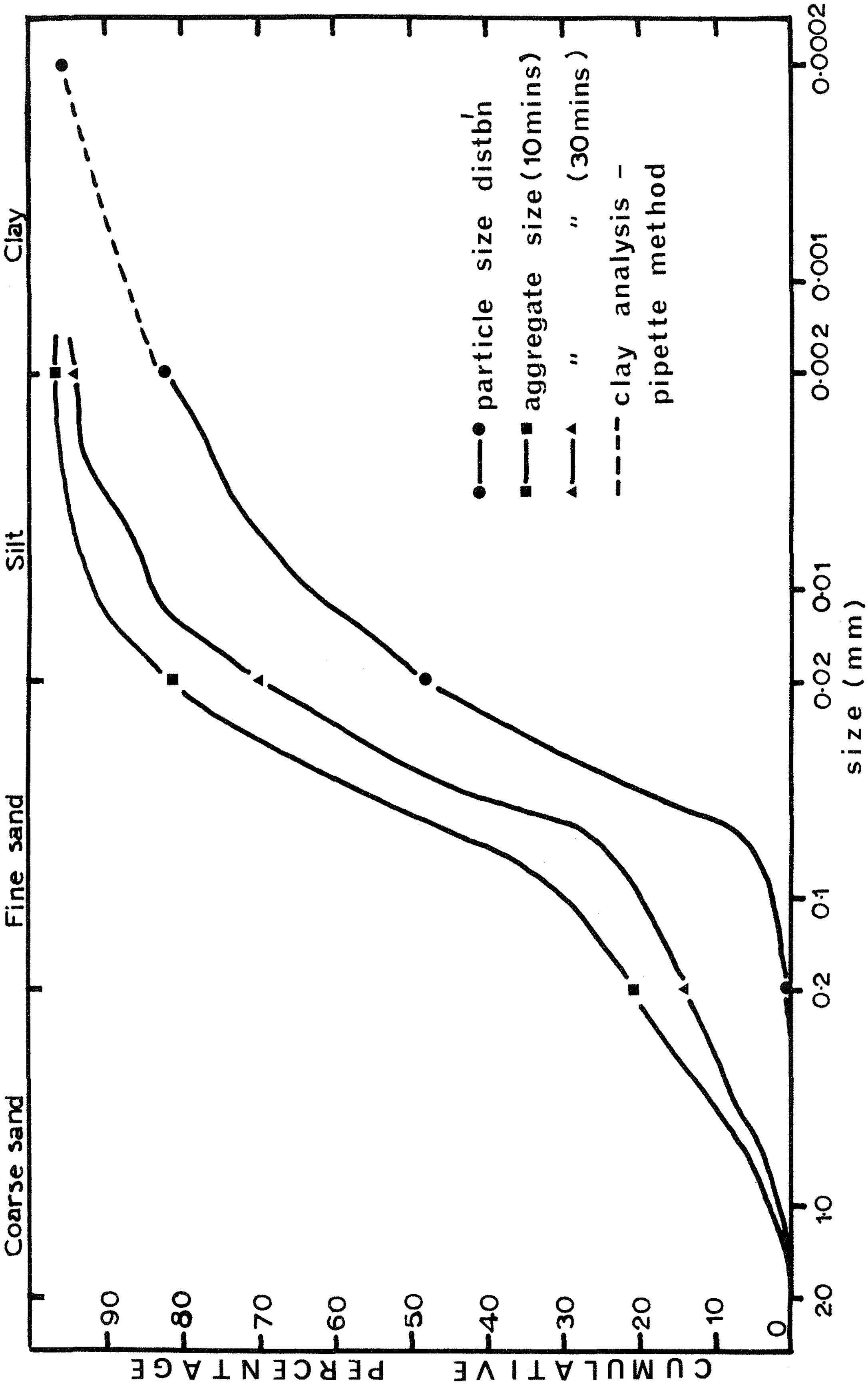
SOLUBLE SALT ANIONS

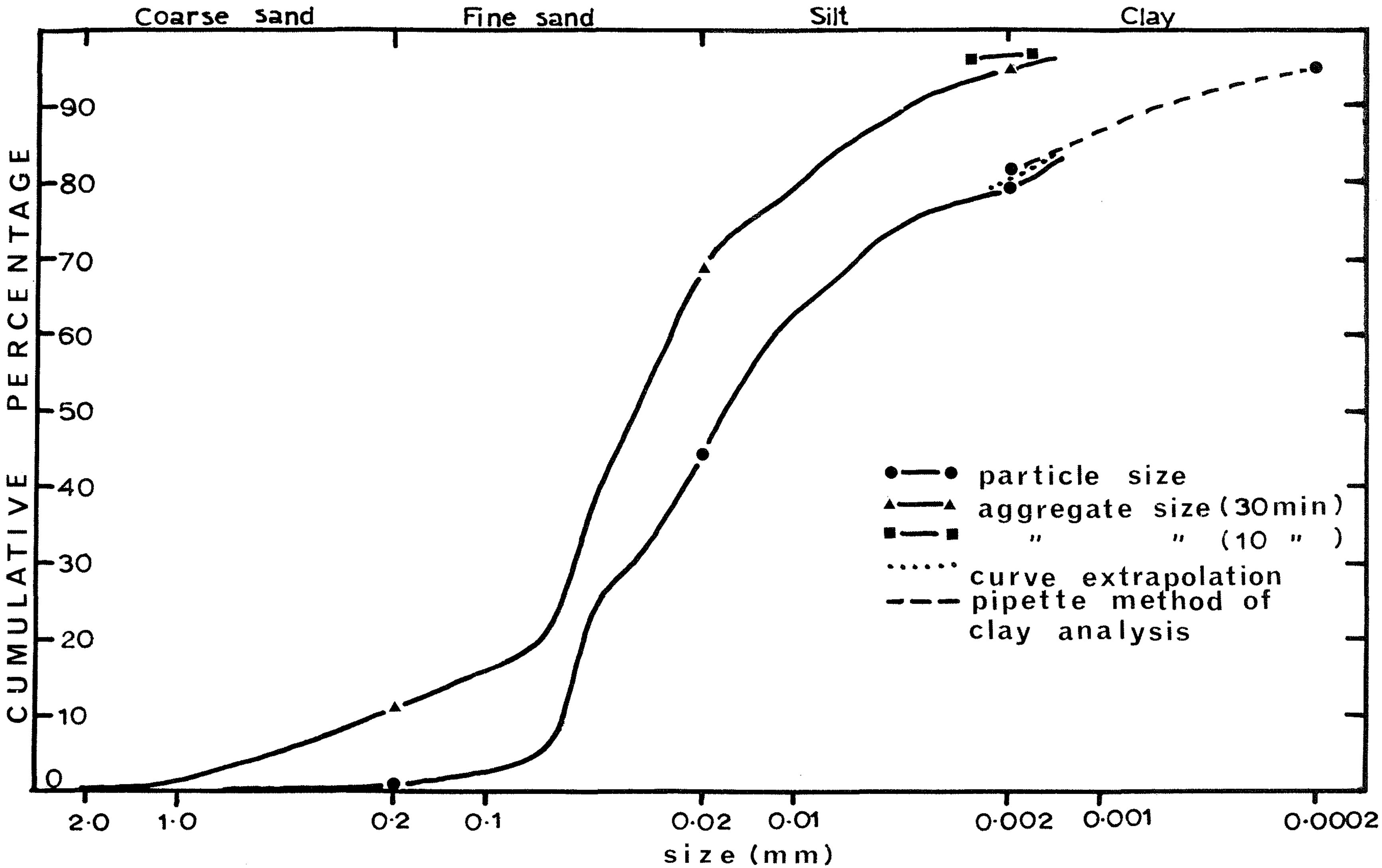
PROFILE HORIZON	SAMPLE DEPTH cm	Cl^- me %	SO_4^{2-} me %	TOTAL me %
Footslope				
A	0-14	-	-	-
B_1	14-29	-	-	-
B_2	29-55	-	-	-
B_3	55-70	0.2	-	0.2
C_1	70+	1.0	0.1	1.1
Backslope				
A_1	0-14	-	-	-
A_3	14-25	-	-	-
B_1	25-40	-	-	-
B_2	40-62	0.1	-	0.1
C_x	62-84	0.8	0.3	1.1
uB/C_x	84-100	1.1	0.3	1.4
Shoulder				
A_1	0-12	-	-	-
A_3	12-24	-	-	-
B_1	24-34	-	-	-
B_2	34-60	0.2	-	0.2
C_x	60-85	0.9	0.2	1.1
uB/C_x	85-100	2.5	-	2.5
Crest				
A_1	0-8	-	-	-
A_3	8-20	-	-	-
B_1	20-30	-	-	-
B_2	30-60	0.6	0.06	0.7
C_x	60-85	2.5	0.4	2.9
uB/C_x	85-100	2.4	-	2.4

APPENDIX C

Particle and Aggregate Size Distribution

Fig. 14 Shoulder profile A1 horizon



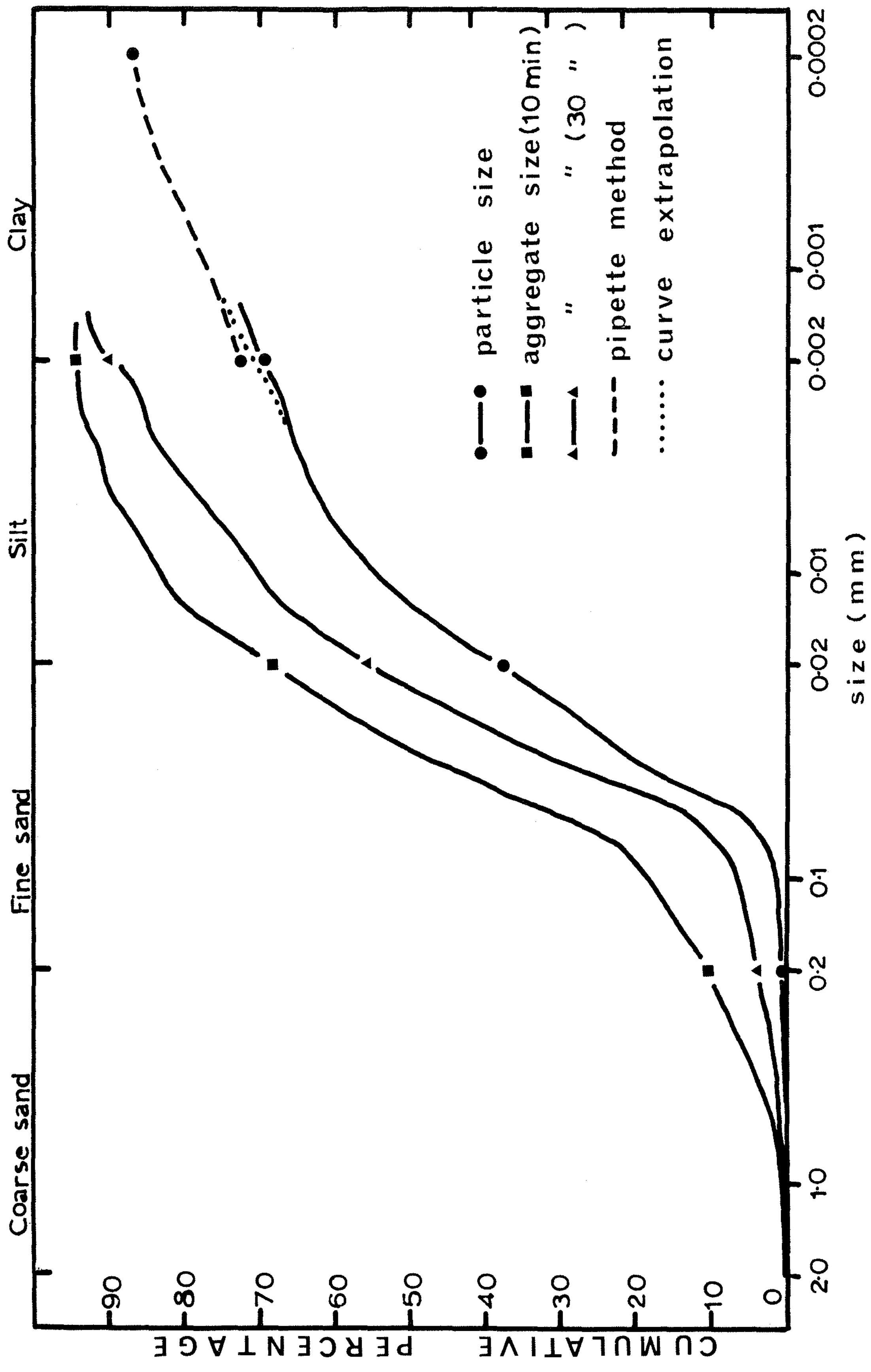


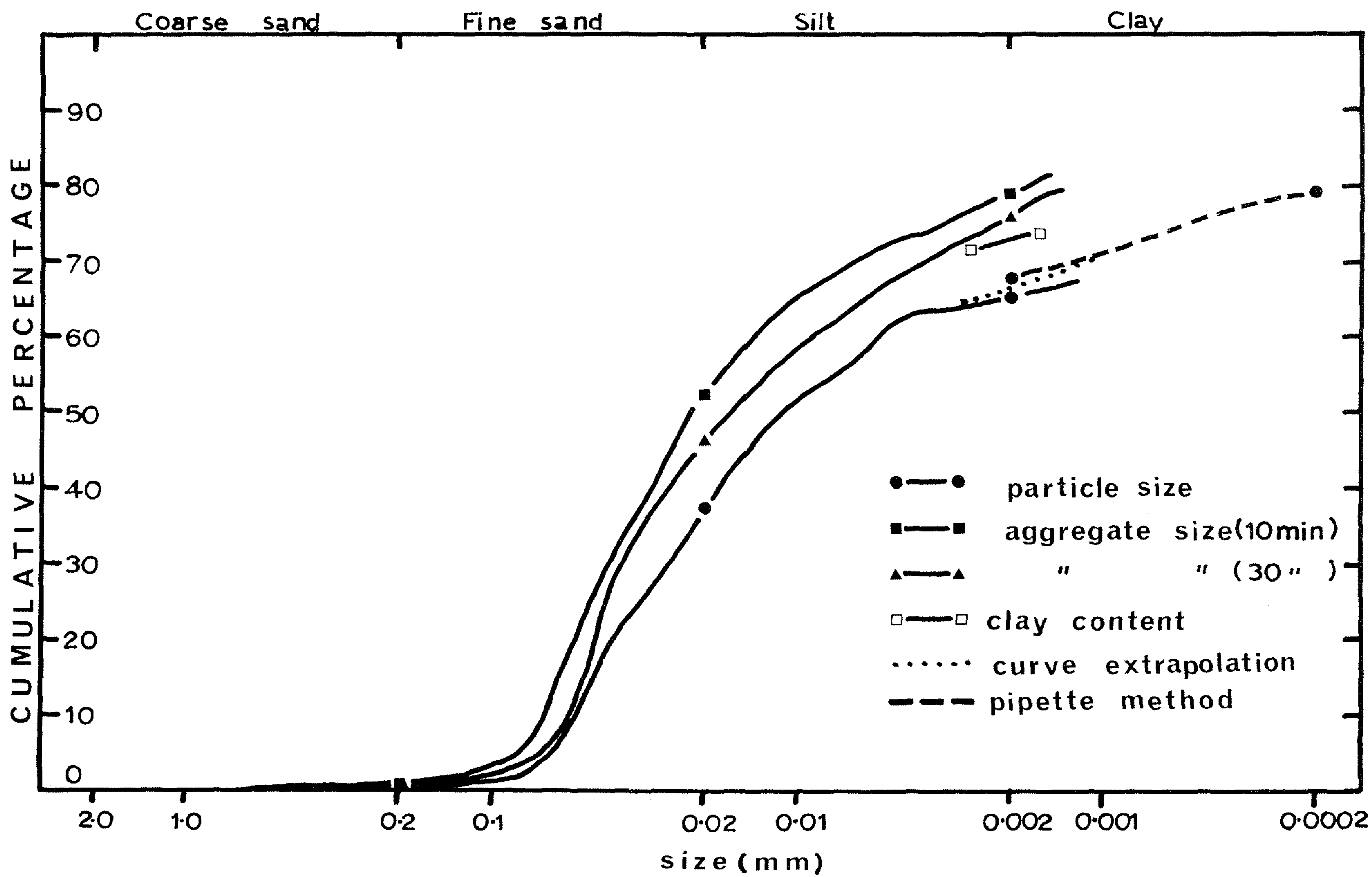
Particle and Aggregate Size Distribution

Fig. 15 Shoulder profile A3 horizon

Particle and Aggregate Size Distribution

Fig. 16 Shoulder profile B1 horizon



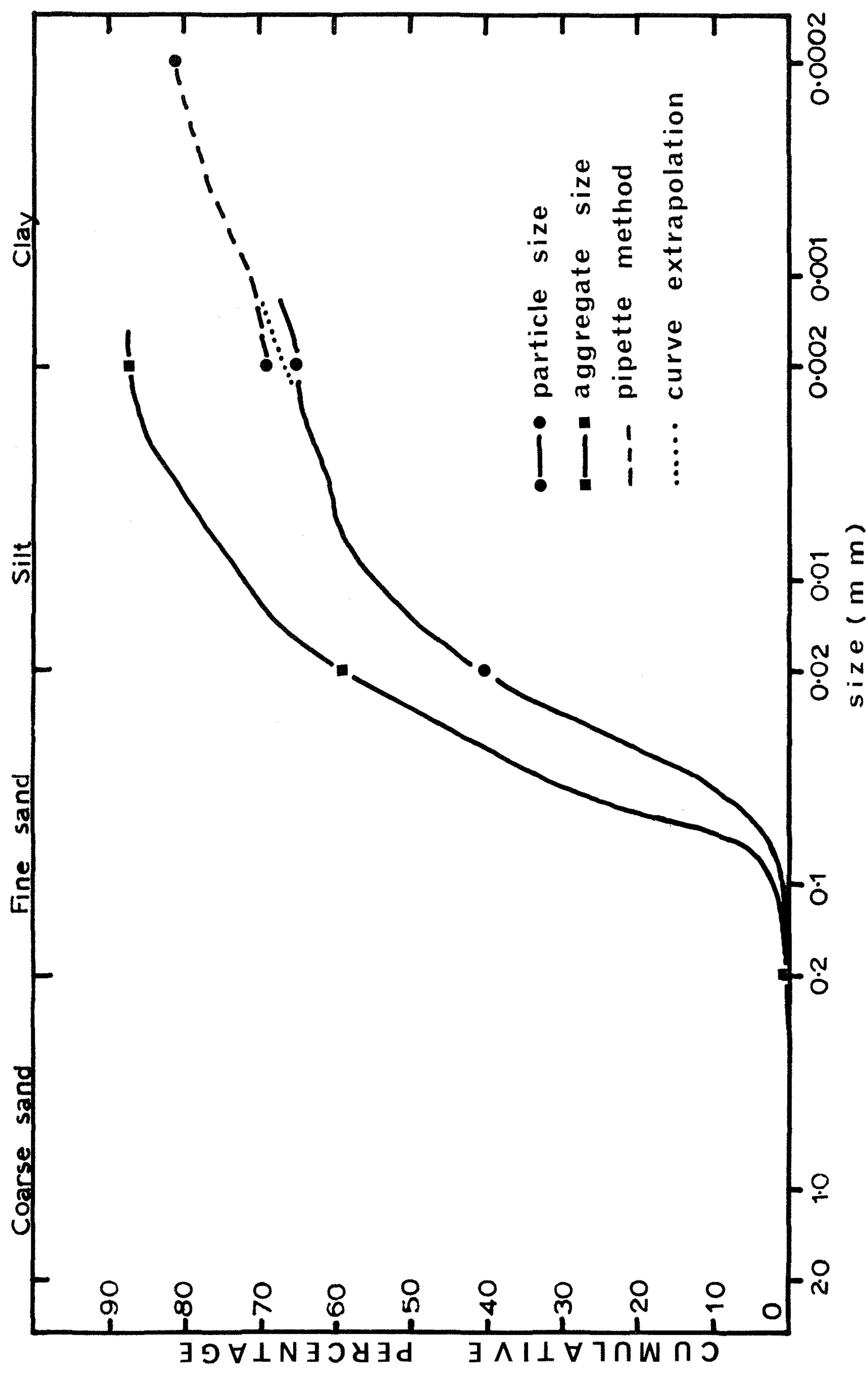


Particle and Aggregate Size Distribution

Fig. 17 Shoulder profile B2 horizon

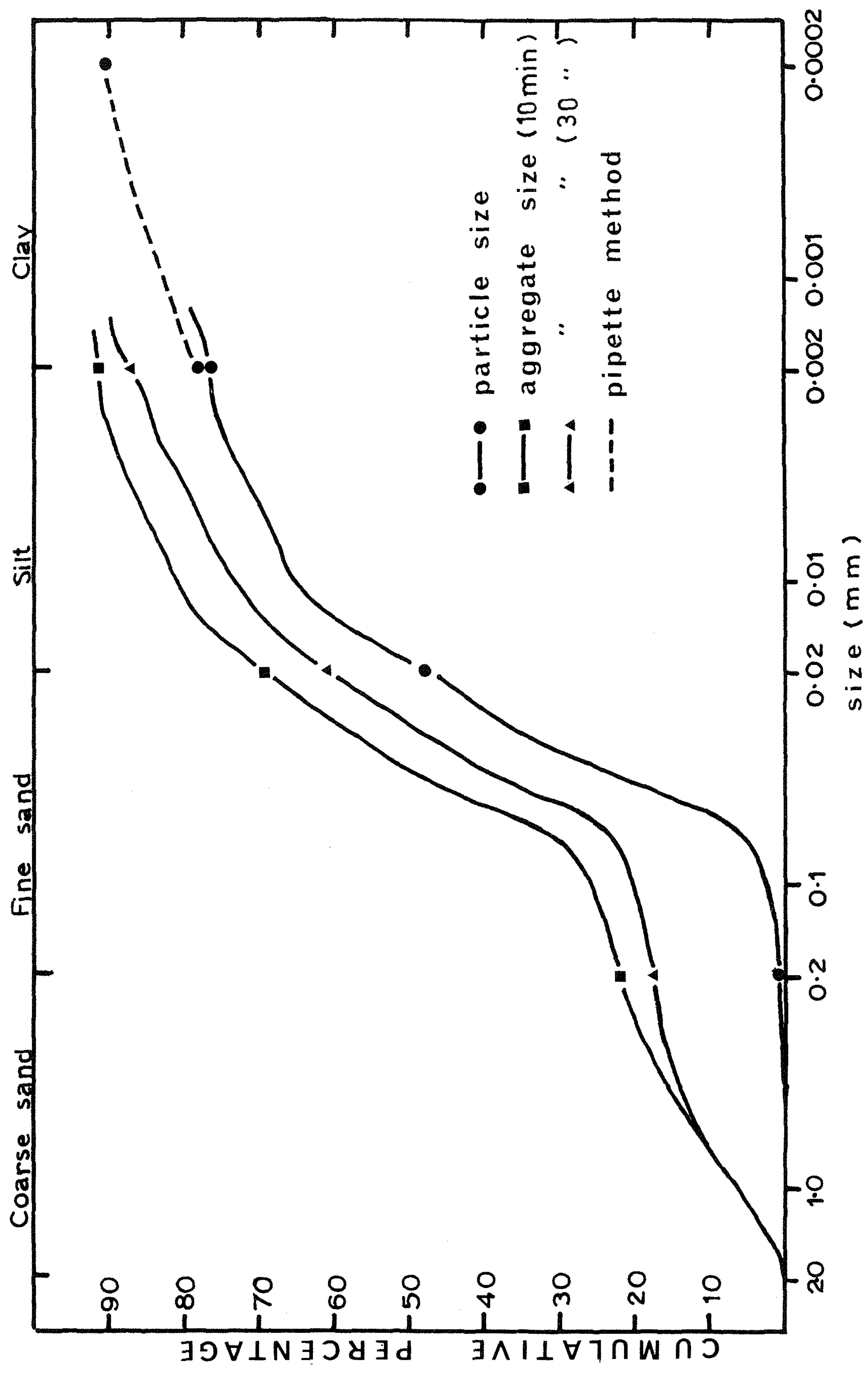
Particle and Aggregate Size Distribution

Fig. 18 Shoulder profile C_x horizon



Particle and Aggregate Size Distribution

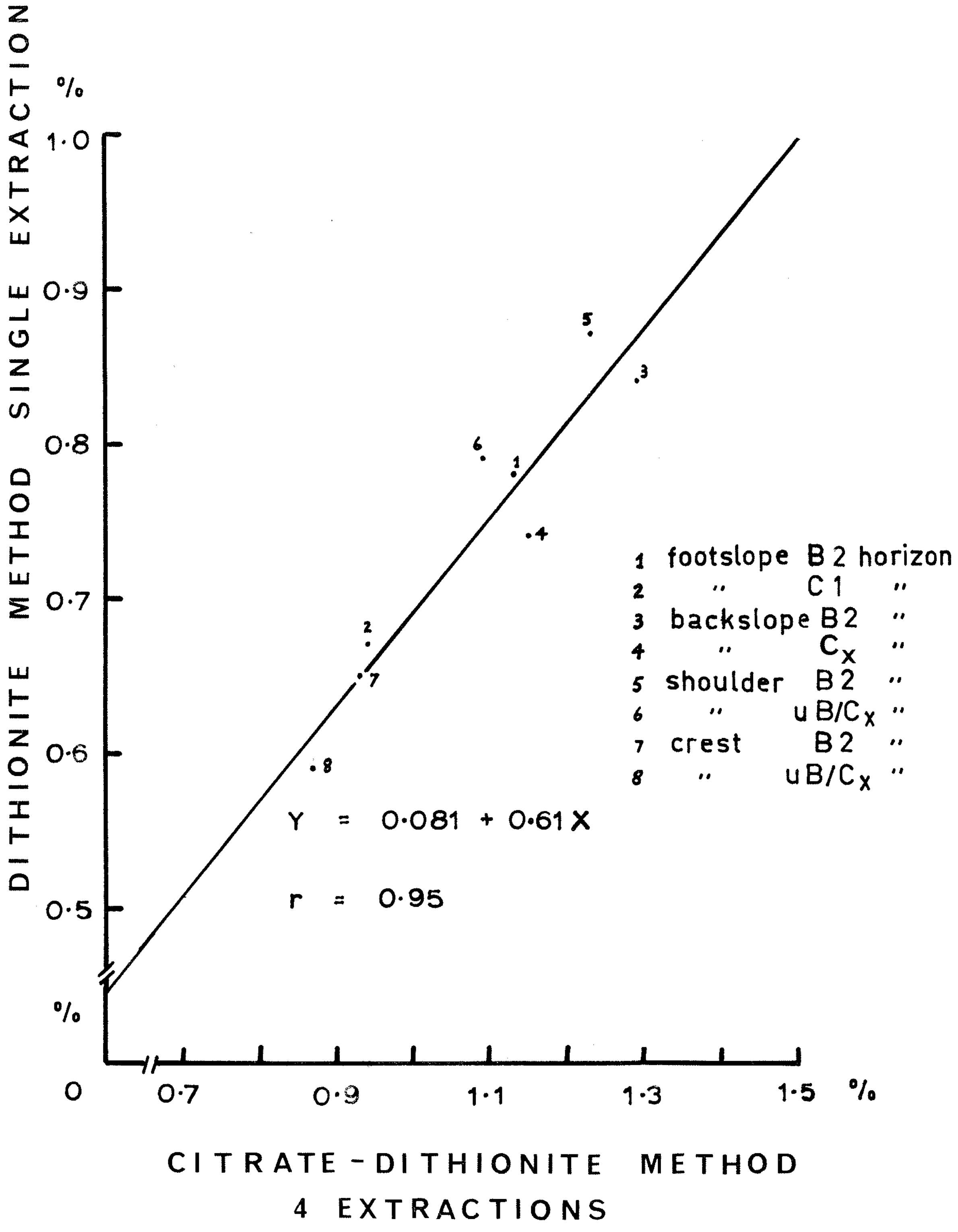
Fig. 19 Shoulder profile $u(B/C)_x$ horizon



APPENDIX D

LINEAR REGRESSION FOR TWO METHODS OF FREE IRON OXIDE DETERMINATION

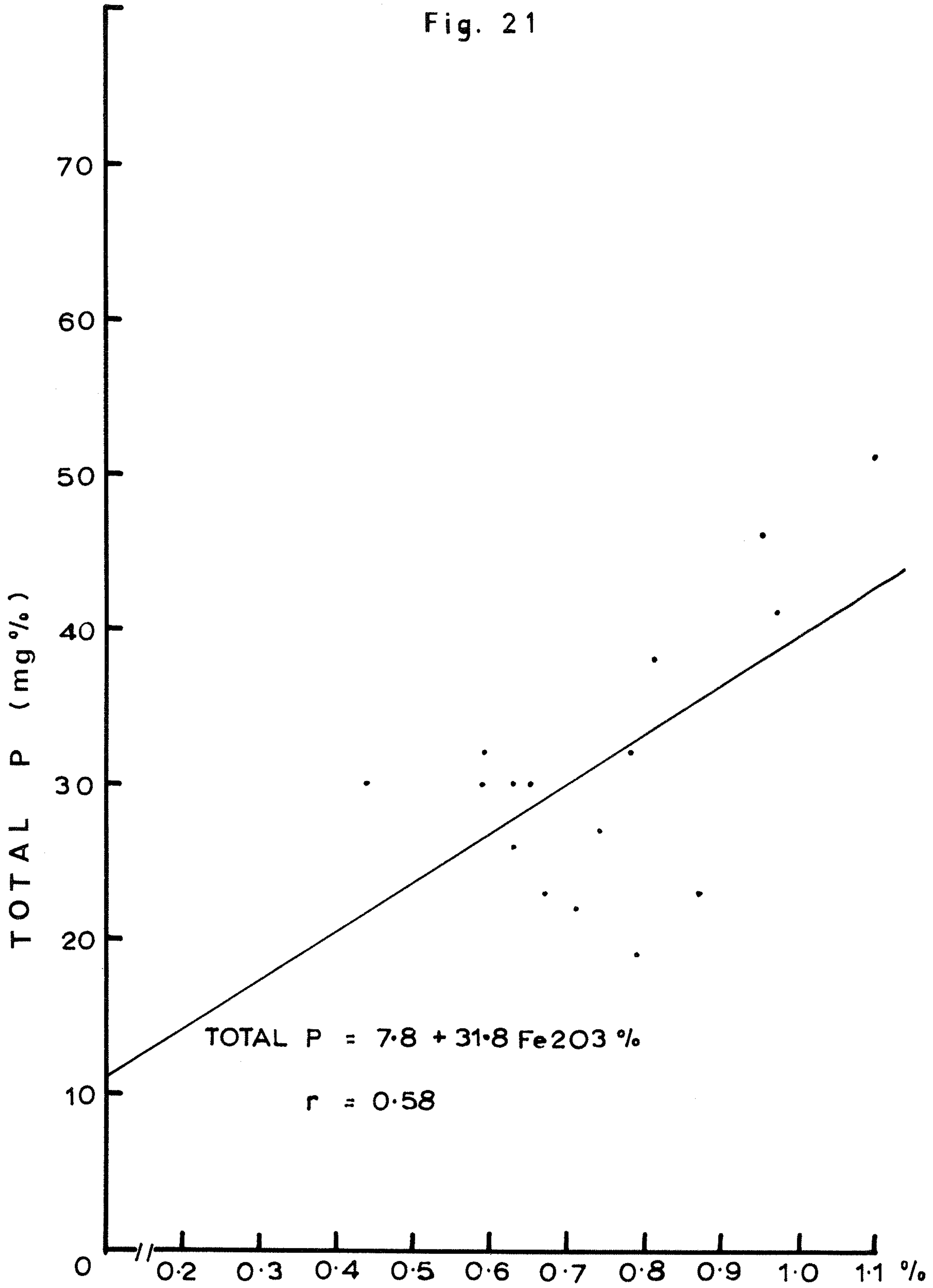
Fig. 20



APPENDIX E

LINEAR REGRESSION TOTAL P (mg%) Vs FREE IRON OXIDES (%) FOR ALL TOPOSEQUENCE B; C; & uB/C HORIZONS

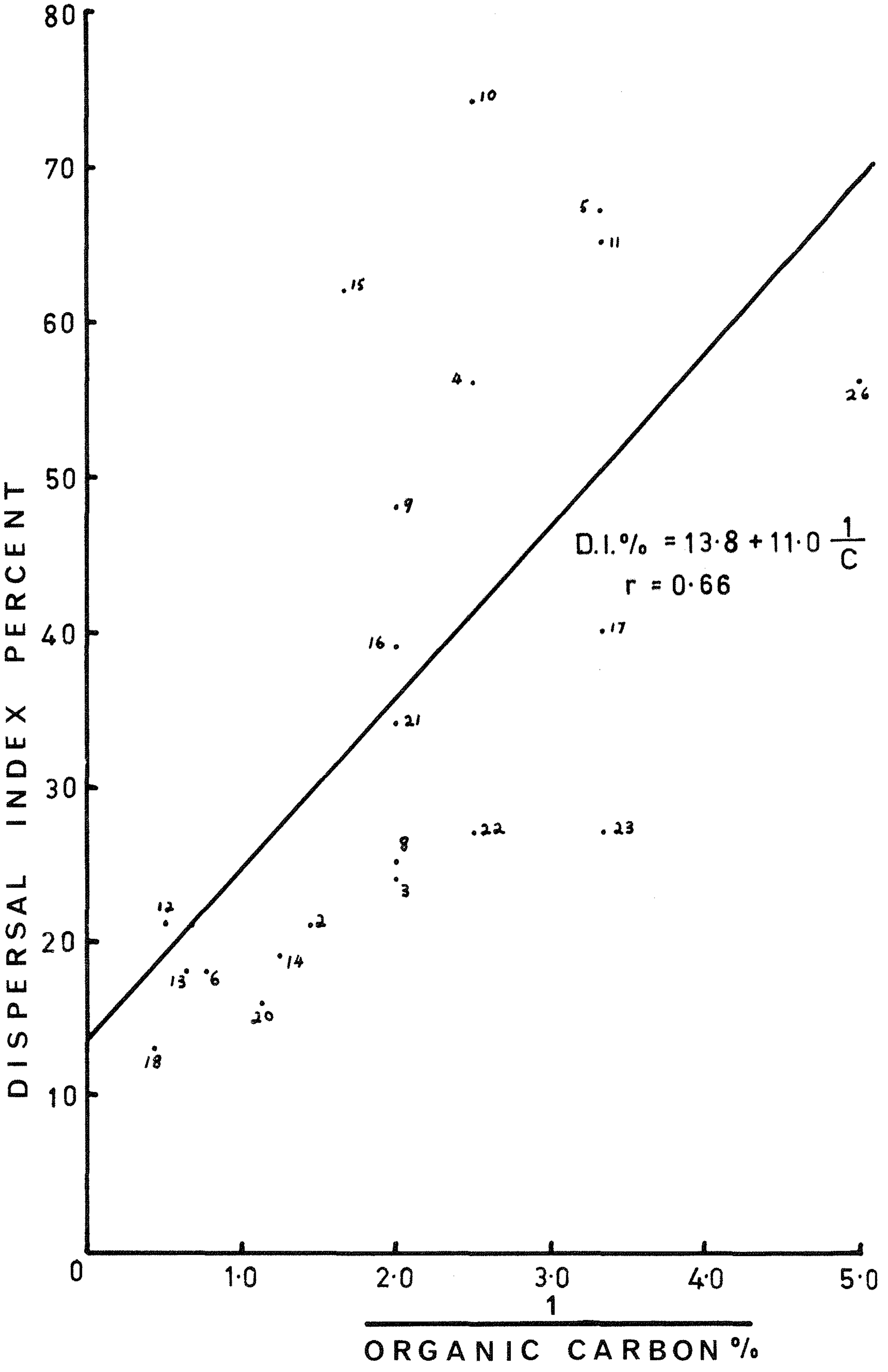
Fig. 21



FREE Fe_2O_3 %

APPENDIX F

Fig. 22 DISPERSAL INDEX, vs RECIPROCAL ORGANIC CARBON



APPENDIX G

PARTICLE AND AGGREGATE SIZE ANALYSES FOR TIMARU AND CLAREMONT SOILS

TEXTURE ANALYSES

PROFILE	HORIZON	Coarse sand 2-0.2mm	Fine sand 0.2-0.02 mm	Silt 0.02-0.002 mm	Clay 0.002 mm
Timaru	A	1	38	38	23
	B_1	1	30	43	26
	B_2	1	33	37	29
	C	1	33	36	30
Claremont	A	1	36	39	24
	B_1	1	36	37	26
	B_2	1	34	34	31
	C	1	36	30	33

AGGREGATE ANALYSES
(10 min shaking)

PROFILE	HORIZON	Coarse sand 2-0.2mm	Fine sand 0.2-0.02 mm	Silt 0.02-0.002 mm	Clay 0.002 mm
Timaru	A	40	49	9	2
	B_1	10	63	23	4
	B_2	6	49	34	11
	C	4	46	36	14
Claremont	A	41	39	19.5	0.5
	B_1	13	59	25	3
	B_2	6	60	29	5
	C	10	54	29	7

APPENDIX H

PROFILE DESCRIPTIONS OF TIMARU AND CLAREMONT SOILS

1. TIMARU SOIL

Soil Type	: Timaru silt loam
Classification	: Moderately enleached gammate pallic soil with strongly developed fragipan from moderately argillised greywacke loess.
Location	: Waitohi, South Canterbury.
Map Sheet	: NZMS1 S102
Grid Reference	: 696756
Topography	: Slope : 12°. Aspect : north. Landform : convex backslope. Elevation : 122 m
Drainage	: Site : medium. Internal : moderately well drained.
Vegetation	: Improved pasture.
Parent Material	: Greywacke loess.

Profile :

A	0-18cms	Brown to dark brown (7.5YR 4/2) silt loam; very friable; weakly to moderately developed fine crumb and medium granular structure; profuse roots; indistinct boundary,
A/B	18-35cm	light brownish grey (10YR 6/2) silt loam; friable; weakly to moderately developed fine nutty structure with many fine worm casts; many roots; indistinct boundary,
B_1	35-50cm	pale brown (10YR 6/3) silt loam; with few/many fine and medium strong brown (7.5YR 5/8) mottles; hard when dry; moderately developed fine nutty structure; few roots; boundary indistinct,
B_2	50-70cm	brown (7.5YR 5/4) heavy silt loam; with yellowish red (5YR 4/8) iron staining lining coarse structures; very hard dry; moderately developed coarse prismatic structure with few dark organic matter stainings and thin discontinuous clayskins lining prismatic structures; few/many roots between peds; few whitish specks inside prismatic structures; indistinct boundary,
C_x	ON	brown (7.5YR 5/4) heavy silt loam with iron staining and dark organic matter staining as in B_2 horizon; very hard dry; moderately developed very coarse prismatic structure with grey gammate veins and iron staining in structural fissures; few, fine distinct yellowish red (5YR 5/8) mottles within coarse prisms; few roots.

2. CLAREMONT SOIL

Soil Type : Claremont silt loam
Classification : Moderately enleached gammate pallic soil with strongly developed fragipan from moderately argillised loess.
Location : Geraldine Downs, South Canterbury.
Map Sheet : NZMS1 S102
Grid Reference : 752892
Topography : Slope : 20^{o}. Aspect : north west. Landform straight upper backslope. Elevation : 152 m
Drainage : Site : medium to rapid.
Internal : moderately well drained.
Vegetation : Improved pasture.
Parent Material : Greywacke loess.

Profile :

A	0-16cm	dark grey (7.5YR 4/1) silt loam; friable; moderately developed fine crumb and nutty structure; many cast granules; many roots; indistinct boundary,
A/B	16-30cm	light yellowish brown (10YR 6/4) silt loam; friable; moderately developed fine nutty structure; many to abundant medium dark grey (10YR 4/1) worm casts with other dark grey organic material with fine nutty structure; many roots; indistinct boundary,
B_1	30-45cm	very pale brown (10YR 7/3 - 7/4) silt loam; few indistinct fine strong brown (7.5YR 5/6) mottles; weakly developed medium blocky structure with primary fine nutty structure; few medium worm casts; many roots; indistinct boundary,
B_2	45-62cm	light yellowish brown (10YR 6/4) heavy silt loam; many fine and medium distinct strong brown (7.5YR 5/6) mottles; weakly to moderately developed fine prismatic structure; thin discontinuous clayskins around peds; few small whitish specks inside prismatic structures; very thin yellowish red (5YR 4/8) iron staining around ped surfaces with thin grey gammate veins in structural fissures; few roots; indistinct boundary,
C_x	ON	strong brown (7.5YR 5/6) clay loam; many to abundant fine and medium distinct yellowish red (5YR 4/8) mottles lining coarse prismatic structures; firm; moderately developed coarse prismatic structure; thick grey gammate veins in structural fissures; few roots.