THE SIGNIFICANCE OF SUBSURFACE WATER AS A GEOMORPHIC AGENT IN AN AREA OF THE GREYWACKE RANGES NEAR WHITEHALL

Undergraduate thesis presented in partial fulfilment of the requirements for the degree of B.A. with Honours in Geography

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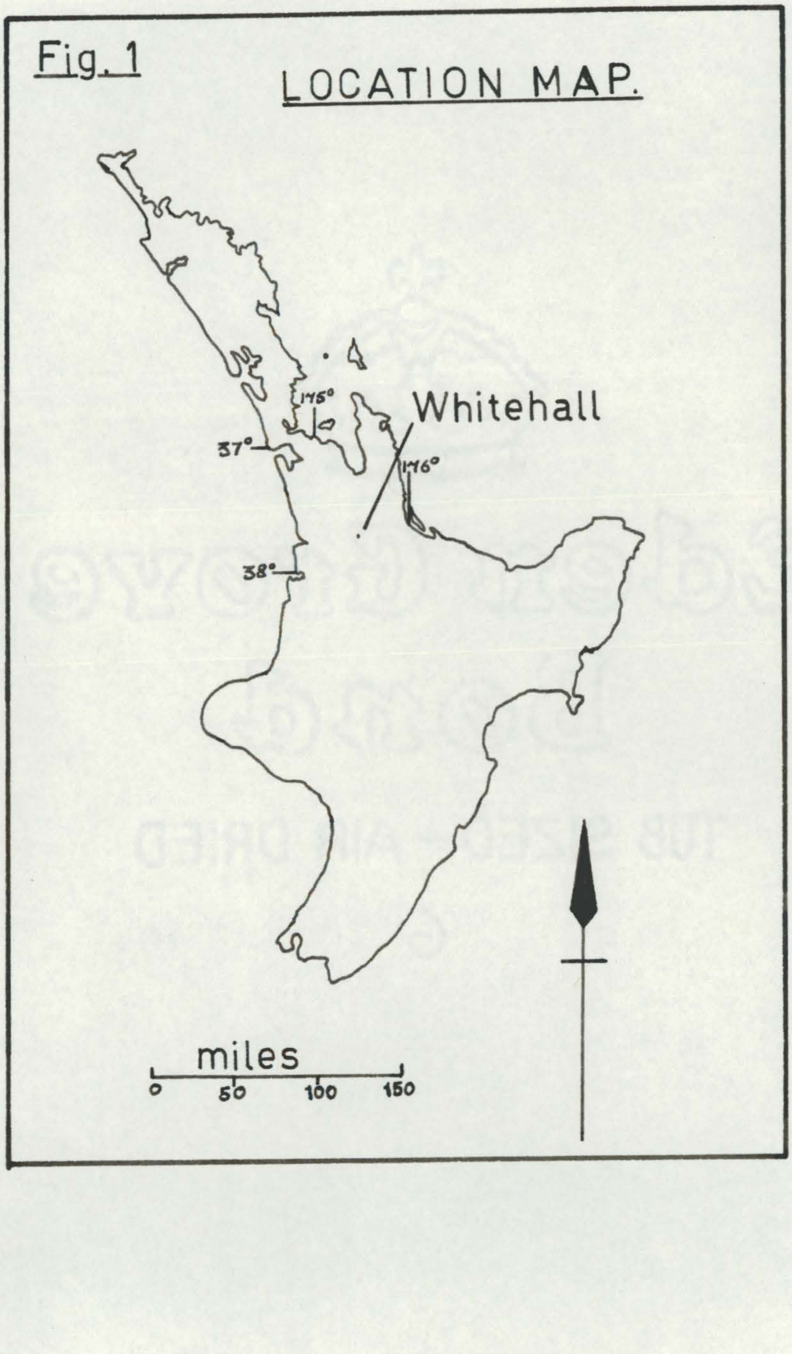
Owing to errata in the draft copy, Figure 4 is also noted as Figure 6, and two figures referred to as Figure 5 are distinguished as 5(a) and 5(b). References to Figures 3, 8 and 9 are incorrect and these figures are not included.

PREFACE

The area chosen for study is situated in the Whitehall district approximately $7\frac{1}{2}$ miles ENE of Cambridge at GR N66/106378 (Figure 1). Recent mass movement features on part of the south and southwest-facing slopes of a valley that is tributary to the Karapiro Stream, and thence the Waikato River, were studied in some detail, but reference is also made to specific features in the area draining to the east. The southwest-facing slopes, with a relative relief of nearly 500 feet, rise to about 1,200 feet a.s.l., where a plateau-like surface dissected by broad mass movement gullies, slopes gradually to the east.

Previous work in Whitehall has consisted of a geological survey by Mead (1938), and more recent surveys for the geological map (Healy, Schofield & Thompson 1964). In a geomorphological study, Selby (1966) dated, and partially explained the mass movement origin of, amphitheatre-like features on the interfluves,[1] as evidence that recent slope denudation has been considerable. (See Lauder 1964). A brief discussion of the genesis of the landforms stresses the importance of mass movements in the formation of the minor valleys and indicates that statements by Cotton (1958a, b; 1962; 1963a, b; 1964) and Mortenson (1959), as to the entirely fluvial origin

Fig. 1



of the feral relief of the greywacke ranges of New Zealand, need to be modified.

Selby (1967a) also broadly classified the major mass movement types according to their form and position on the slopes, described them, and gave a theoretical explanation of possible causes, with emphasis on the effects of high-intensity rainstorms and deforestation. This 1967 study is part of a larger work on the geomorphology of the greywacke ranges in the Waikato, and although much of it is not based on field evidence in Whitehall it is felt that most of the conclusions apply there. The weathering and ash chronology is outlined in some detail in this paper.

This thesis includes a record of the observation of certain geomorphic features on about 400 acres of the greywacke ranges near Whitehall. The basic thesis is that the movement of subsurface water is a major process in the development of these features.[2] Study has been limited to field observations, and only tentative hypotheses are offered. It is not a theoretical study, and only a brief statement of recent landform development and equilibrium theory is presented. In general, the findings support and extend the landform genesis suggested by Selby (1966).

The study is implicitly deductive, with the initial model, the conclusions, or lack of same, of previous workers on similar features and processes, being tested against observed local features. Three of these general conclusions[3] that have particular relevance to this thesis are:

(1) that mass movement increases when forest is replaced by pasture;[4]

(2) that piping does not appear to occur under bush;[5] and

(3) that sliding is the initial movement in rapid mass movements in cohesive materials.[6]

Consequently, the study involved the observation of piping and of larger mass movement features, and was undertaken both on pastured slopes and under bush.

It is concluded that in the study area there is at least as much recent and active mass movement under the native bush as under the pasture, that piping does occur under bush, and that 'water blowouts' flow, rather than slide, upon rupture. Subsurface water movement is of particular importance as an active cause of these features, and their mechanism of development is primarily a function of the interaction between this subsurface water, and the porosity, permeability and strength of the regolith.

In acknowledging the help received from many persons during the preparation of this thesis, special thanks are due to my adviser, Mr M. J. Selby, both for his encouragement and valuable criticism and for the use of his personal library.

I also wish to thank Mr R. J. Blong for many helpful suggestions during the early stages of the study.

Particular thanks are due to my father for permission to study in the area, for making farm equipment available for field work, and for bulldozing the section illustrated in Plate XIII.

Finally, I wish to thank both my parents most sincerely for their patience and unselfish assistance, without which this thesis would not have been possible.

T. I. Oliver

November 1967

Footnotes

(1) Similar features, in the less-weathered and finely shattered schistoze greywackes of the Wellington area, have been attributed to solifluxion processes by Cotton & Te Punga (1955a, b) and Stevens (1957a, b).

(2) Actual processes can be neither seen nor measured, and it is only the results that are observed. However, certain features and resultant forms appear to be directly associated with certain processes, and it is generally these processes to which one refers.

(3) These conclusions tend to be implicit rather than explicit, and generally refer to the particular study area of each worker, without wider application. They are used here as, collectively, they apply to a wide area of New Zealand, and no evidence refuting them has been found in the local literature.

(4) This statement expresses an apparently observed relationship between the amounts of mass movement now occurring under each vegetation type, or an assumed increase where removal of the bush has been complete. Campbell (1945, 1951), O'Byrne (1967), and Selby (1967a), for example, have made explicit statements supporting this conclusion.

(5) Ward (1967 and pers. comm. 1967) has made the only explicit, although guarded, statement of this and it applied to observations in Northland, the Hunua Range, and the Volcanic Plateau. Other New Zealand references to piping do not refer to forested areas, either because of a lack of observation or because no piping was noted in such areas. They are mainly concerned with piping in eolian and alluvial, single-grain deposits, and in some cases (e.g. Blong 1965) are concentrated seepage rather than open pipes. Blong (1965a, b, 1966); Campbell (1945); Cumberland (1947); Cussen (1888); Ferrar (1934); Gibbs (1945); Gilbert (1920); Guthrie-Smith (1926); Henderson & Grange (1926); Wart (1966a, b). Selected non-New Zealand references also supporting the conclusion are: Aitchison et al (1963); Buckman & Cockfield (1950); Bunting (1961); Carroll (1949); Downes (1946); Fletcher & Carroll (1948); Fletcher et al (1954); Hadley & Rolfe (1955); Parker (1963);

Rubey (1928); Woods <u>et al</u> (1964).

(6) This conclusion is not stated explicitly by any particular worker but is arrived at by a process of elimination from the definitions (Sharpe 1938; Varnes 1958) of individual mass movement processes which have an internal mechanism of movement. A primary reason for including it is that there appears to be no evidence to the contrary in the New Zealand literature: Berry & Ruxton (1961); Campbell (1945a, b, 1951); Jackson (1966); O'Byrne (1967); Selby (1966, 1967a); Wright (1965). Non-New Zealand literature also supporting this is extensive, but the following are some select references: Baker (1952); Hennes (1954); Ladd (1935); Newland (1916); Rapp (1961, 1963); Sharpe (1938); Terzaghi (1950); Varnes (1958); and Ward (1945). However, this literature also contains reference to non-sliding processes, which are primarily caused by the nature of the material and its relationship to subsurface water: Ackermann (1948a, b); Eden (1964); Eisenlohr (1952); Hack & Goodlett (1960); Skempton (1953); Yong & Warkentin (1966), and yet, in certain cases, these same properties may result in a pure slide, (Hutchinson 1961).

CHAPTER 1. GEOLOGY, REGOLITH AND ENVIRONMENT

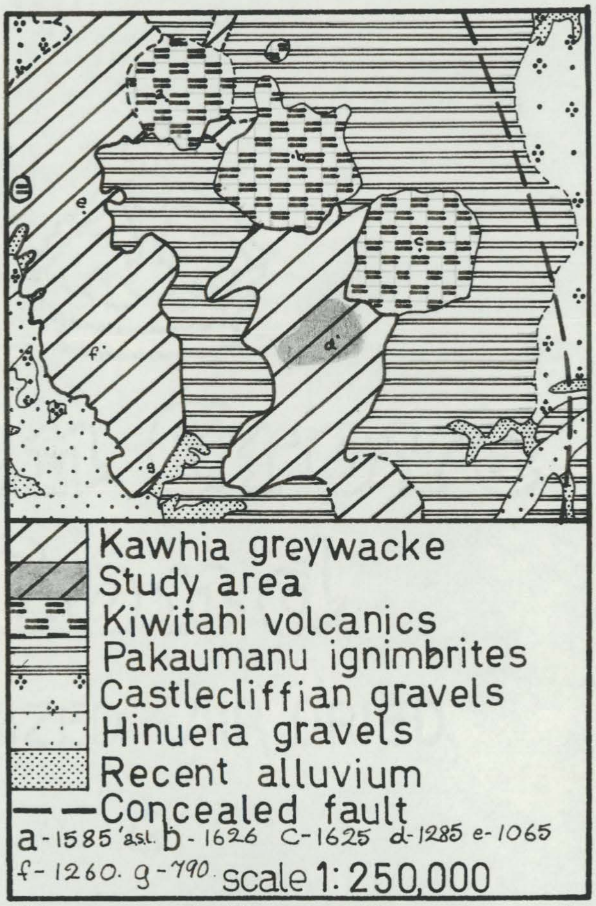
I GEOLOGY

The Whitehall hills are composed of Kawhia Series Jurassic greywacke[1] (Figure 2) (Mead 1938; Healy, Schofield & Thompson 1964) that has been indurated by regional, low-rank metamorphism (Wellman 1951). This greywacke is a marine-deposited, banded siltstone with some rare sandstone and conglomerates (Healy et al. 1964), and it has been intensely fractured by uplift during the Kaikoura orogeny. In the study area it is primarily formed of sub-angular grains of fine-grained andesitic lavas with larger fragments of black argillite (Bartrum, in Mead 1938). In texture these vary from a coarse chipwacke (Schofield 1967) to fine siltwacke (Plate I) over very short distances, apparently as a result of local turbidite bedding.

Thus, the structure of the rocks is complex and, as a result of the induration, intergranular porosity has been lost. Therefore, ground water only occurs in the secondary interstices, but earth movements have opened many joints and fractures, thus giving induced permeability at shallow depths (Collins 1955). This permeability and the close fracture-jointing has been of special importance in aiding subsurface water movement, deep weathering, and the development of clay and manganese

Fig. 2

GEOLOGY of the WHITEHALL AREA



(Healy, Schofield & Thompson.)

cutans (Brewer 1960) (Plate II).

II REGOLITH

1. Weathering Mantle

The greywacke weathering mantle varies in depth. It is assumed to be thickest on the interfluves, thinnest on the upper portions of major, straight slope segments, and thicker again towards the valley floor, where colluvium replaces some of the mantle removed by stream action. However, it is everywhere of considerable depth, and in the upper portion of a typical site consists of red, yellow, and brown material, composed largely of clay minerals, that appears massive when moist. It may not exhibit structures, except for slight variations in colour, on drying, or when mechanically disturbed, but with increasing depth, the influence of the fracture-jointing in maintaining water movement for weathering is more apparent.

At many sites, irrespective of the dominant colouring, which is an indicator of the degree of weathering, there is sand sized material, or even corestones of unweathered rock, towards the centre of the joint-blocks, where water penetration is least (Plate III). Manganese and clay cutans also reduce the entry of water to the joint-blocks. In a meander cutting in the floor of the main valley (GR N66/100376) the material is evenly, but

PLATE I

Unweathered sandwacke and chipwacke on a greywacke boulder that has split along a fracture-joint.

PLATE II

Manganese cutans on interlocking structures of partially weathered greywacke.

PLATE III

Differential insitu weathering of greywacke showing the influence of fracture-jointing in controlling the movement of water through the greywacke.

less intensively weathered, and the particles are virtually all sand sized.

The fracture pattern generally results in large interlocking structures, but towards the surface fissures within these primary structures are opened, increasing water movement and reducing stability (Skempton 1964). This increased seepage results in a tendency to develop planes of seepage and clay translocation, often with thin lenses of intensively gleyed material where suitable subsurface water conditions prevail. The movement of water may also link quite large, manganese coated planes, thereby increasing the potential for sliding by reducing shear strength.

No exposures in the study area exhibit a complete range from weathered to unweathered rock, but in the Whitehall Quarry (GR N66/063352) the weathered mantle is 80 feet thick in places. On a drained slope, as at this location, a definite weathering front is observed, also with yellow and brown staining.

On the basis of Krynine's (1949) association of red beds with warm climates, and Te Punga's (1955) description of red weathering near Wellington as relict from the Mindel-Riss or Riss-Würm interglacial, Selby (1967a) suggested that weathering of the northern greywackes may belong to the same phase. There does not appear to be any evidence contradicting this suggestion, and weathering during at least the past 3,000 years has been much slower.[2]

2. Volcanic Ash Beds and Soils (Plate IV)

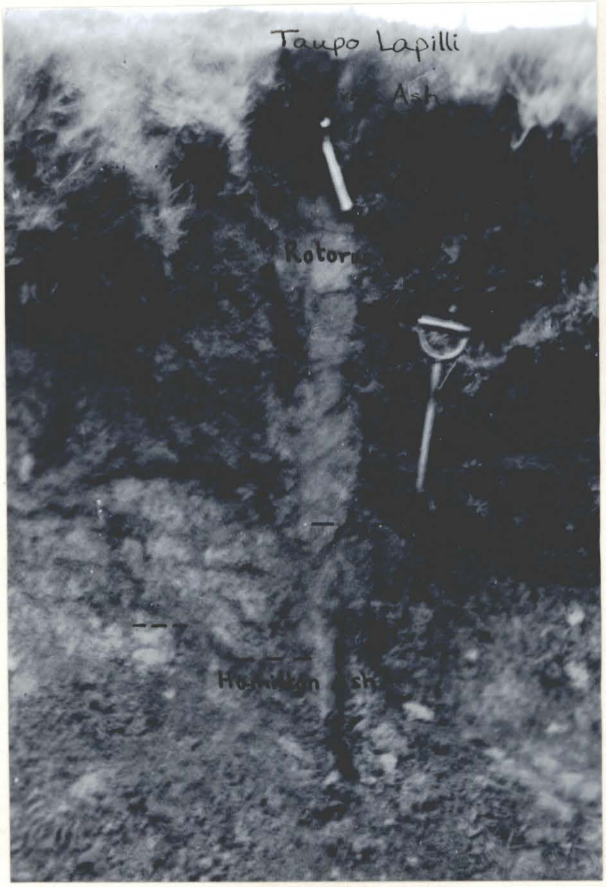
Like the mantle of weathered greywacke beneath them, the thickness of the ash beds depends largely upon their position on the slope. Thus, the broad, gently sloping interfluves have the greatest thickness, the midslopes have generally had much of their cover removed by shallow mass movements, subsurface flow, and surface runoff, and the floors of the gullies and valley contain a predominantly colluvial infill without distinguishable bedding. (Figure 3)

The basal ashes, where present,[3] are part of a group of eight distinguishable members, known collectively as the Hamilton ashes. Kear, Schofield, and Kermode (1964) have placed their age at 75,000 - 125,000 years B.P. They are andesitic and rhyolitic and have weathered to a heavy brown clay, with definite soil formation. Their depth in this district is not great, but elsewhere, as in coastal Bay of Plenty (Pullar 1967), they may exceed 16 feet.

The next ashes are grouped together as the Late Quaternary beds and have four members, (a), (b), (c),

PLATE IV

Airfall ash on an interfluve. (The pecked lines indicate changes in ash type, but only those that have been identified are named.)


Taupo Lapilli
Ash

and (d). (Healy, Vucetich & Pullar 1964)[4] They are much younger than the Hamilton beds, being only 15,000 - 36,000 B.P. The grey banded bed (Vucetich & Pullar 1963), which is a whitish-grey ash that makes a sharp contact with the underlying Hamilton beds, has not yet been identified in the study area, but is most probably represented (Pullar 1967).

The overlying yellow block and white block beds were erupted about 27,000 B.P. Although they have not been positively identified in the study area, a banded bed at GR N66/114372 has been tentatively attributed to these showers (Selby 1966). They also appear to be present at GR N66/115384.

In these sections the next ash bed is unidentified (Selby 1966), but it is brown and easily distinguishable from the younger ashes. This bed could possibly be the three pinkish brown beds (Vucetich & Pullar 1963; Pullar 1967), which were erupted from Tarawera and Taupo 15-20,000 B.P.

The younger ashes of the Tirau group overlie these beds and are represented in considerable depth. The group includes the Taupo, Rotoma, and Rotorua subgroups. Thus, the age of the Tirau ash is unlikely to be older than the Rotorua ash of about 13,000 B.P. (Pullar 1967).

The younger Rotomaash (ca. 8,000 B.P. maximum) is darker in colour, exhibits no shower bedding in this area, and is incorporated in the topsoil. It is loose and friable, but develops weak nutty and blocky structures in the B horizon, and is noticeably less fluffy than the underlying Rotorua ash.

Yellow brown loam soils with grey or brown topsoils (YBL 14, Taylor 1948) develop on these ashes (N.Z. DSIR 1954). The dark A horizon has developed a soft granular, or crumb, structure, and the brown B horizon, which is greasy when moist, develops the nutty and blocky structures noted above. The subsoils, which tend to be yellower in colour, are mainly the very friable Rotorua ash, but may also include some humus-stained Rotoma ash nearer the surface. Upon disturbance, the subsoil breaks down to individual particles very easily, a characteristic which is extremely important in lowering shear strength. Also, the weathered Rotorua ash contains a clay fraction that is high in the greasy, unstable mineral, allophane[5] (Fieldes 1955; Fieldes & Swindale 1954).

Thus, the physical and chemical characteristics of the soils of the area are dependent to a considerable degree upon the nature of the parent material, for the impervious and sticky soils developed on the weathered greywacke and older ashes are in marked contrast with these highly permeable loams, that become slippery on wetting, developed on the Tirau ashes.

The uppermost air-fall bed that has been positively identified in the Whitehall area is the Taupo lapilli member of the Taupo eruption (Selby 1966; 1967a), which has been dated at 1,900± B.P. (Baumgart 1954; Healy, Vucetich & Pullar 1964). The lapilli are generally angular, and greyish in colour. On the interfluves they are generally found only in the surface 1½ - 2", but in the gully floors are mixed with washed colluvium, often to a depth of 12", and where there has been slippage and piping or root channels, the scattered blocks may be found at even greater depths.

The Kaharoa ash (Mt Tarawera, ca. 930 - 70 B.P.) may be present, but the glassy grains observed could well be residuals from weathered Taupo lapilli, which is often glassy in this area.

III CLIMATE AND WEATHER

Selby (1967a) has stated that, climatically, the Whitehall district would be classified as AB'_1ra' under Thornthwaite's 1948 system (Critchfield 1966). Thus, the climate is perhumid (A), mesothermal (B'_1), has no seasonal water deficit (r), and less than 48% of the potential evapo-transpiration is concentrated into the three summer months (a').

However, irregularities of weather (Table 1) are felt to be of greater significance than climatic generalities in the initiation of mass movement, piping, and other forms of denudation in Whitehall. Precipitation is primarily in the form of intense frontal falls followed by heavy showers, and it tends to be more vigorous in winter when the track of the weather systems has moved slightly north of the summer tract and depressions are more frequent (Garnier 1958; de Lisle 1967; Appendix 1). This seasonal shift in latitude of the weather systems also results in more intense anticyclones, and a lower rainfall, during summer. Moreover, much of the rainfall that does occur in summer is of the convectional thunderstorm type, and especially intensive, but relatively infrequent, falls result from the passage of tropical cyclones (Robertson 1963; Table 1, A,B).

Evapotranspiration is highest during the period of low rainfall, and so the soil tends to be dry, and have definite structures with open cracks, when peak intensity falls are experienced. This is felt to be of considerable importance with respect to slope failure, and is discussed in more detail in Chapter 3. Similarly, there is also a tendency for mass movements to occur during periods of intense rainfall in the winter, when the regolith is saturated. Strong gusts of wind at such times are also felt to be significant as a cause of failure in saturated slopes under bush.

TABLE 1. WEATHER AND CLIMATE DATA RELEVANT TO WHITEHALL

A. Rainfall Intensity and Return Period (Robertson 1963)

Station	Return period	Hours duration 1	12	24	48
Ruakura[6]	2 yrs	0.9	2.2	2.7	3.2
	10	1.9	3.8	4.7	5.6
	50	2.8	5.1	6.5	7.7
Karapiro[6]	2	-	-	2.7	-
	20	-	-	5.2	-
Arapuni[6]	2	0.9	2.2	3.0	3.5
	10	1.5	3.5	4.8	5.6
	50	2.0	4.6	6.3	7.5

B. Maximum Recorded Falls (N.Z. Met. Ser. Misc. Pub. 121; Whitehall data)

Station	Minutes 10	20	30	60	Hours 2	6	12	24	48	72
Ruakura	64	88	130	227	241	319	355	524	565	617
Arapuni	63	89	133	174	261	342	421	519	657	699
Whitehall[7]	-	-	-	-	-	-	430	616	880	-

C. Mean Ann. % Frequency Winds - Rukuhia[8] (de Lisle 1967)

Speed	N	S	SW	W	NW
Under 15 mph	7.5	6.2	6.5	12.0	15.0
Over 15 mph	0.5	1.0	2.0	2.3	0.6

IV VEGETATION AND LAND USE

The study area is almost entirely under good quality pasture, with white clover and rye grass predominating, but one face and valley floor have not been cleared, leaving some 40 acres of original bush cover. There is no scrub or open secondary forest in the study area.

The bush consists of mixed evergreen forest (Plate V) dominated by podocarps and hardwoods. There is little totara (Podocarpus totara) and no matai (P. spicatus) was observed. However, there are numerous large rimu (Dacrydium cupressinum) and tawa (Beilschmiedia tawa) trees, some rata (Metrosideros robusta) of widely varying ages, a profusion of shrubs and lianas towards the stream in the valley floor, and pungas (Cyathea ssp.) in gullies in which there is considerable subsurface water.

From field observations, and from their positions on the slopes, it appears that the size and number of the pungas, and the density and luxuriousness of the undergrowth, bear some direct relationship to the amount of moisture available in the soil, but there is no quantitative data to support this contention. The undergrowth and seedlings on the upper slopes have been damaged by stock, but penetration by large animals to the valley floor and into the centre of the bush has been slight.

Although some alteration of the vegetation would have resulted from stock browsing, it is felt that this area of bush, within which a part of the study was conducted, is representative of this type of vegetation

PLATE V

Indigenous forest within which part of the study was conducted.

a

b

cover on the greywacke ranges of the Waikato. Two factors that should be noted though, are the lack of rimu regeneration and the absence of rimus on the lower slopes where much of the tawa is found, and the predominance of tawas among uprooted, mature trees. These are partially explained later, in terms of the regeneration conditions and rooting habits of rimu and tawa (Cameron 1963), with respect to soil moisture and slope stability.

The land under bush is fenced to prevent stock entry, but the remainder of the area is pasture for sheep and store cattle, and has been for approximately 20 years. Prior to this it was covered with fallen logs, scrub and poor grasses for some 50 years. Only small sections have been cultivated by discing, but soil development must be influenced by the superphosphate fertilizer that is applied each autumn and spring. Mob stocking methods are practised and this generally results in an even, high quality pasture, and compaction of the topsoil.

Footnotes

(1) The Manaia Hill Group in the study area is Heterian stage, being differentiated from the younger Ohauan on sparse fossil evidence (Kear & Tolley 1957).

(2) The unweathered corestones exposed during the period of intensive erosion prior to the Taupo eruption (Selby 1966) rarely attain a weathering skin even $\frac{1}{4}$" thick, and any finer than a coarse sandy texture. Vucetich & Pullar (1963), from the degree of weathering of certain ashes, suggest a climate similar to the present for this period.

(3) In the study area, the Hamilton ashes have only been observed around GR N66/115384, but are probably present on the interfluves that have been little disturbed by runoff or mass movement.

(4) The names used to denote the individual Late Quaternary beds are those proposed by Vucetich & Pullar (1963). The grey banded bed corresponds to bed (d) of Healy, Vucetich & Pullar (1964); the yellow block and white block beds to beds (b) and (c), and; the three pinkish brown beds to bed (a).

(5) This aspect is dealt with in considerable detail in Chapter 3. Allophane is the principle constituent of the clay fraction in the rhyolitic ashes in this area, and is formed by the association of the amorphous colloidal hydrous oxides of silica and aluminium released as weathering products. It develops to an increasingly ordered structure. (Fieldes 1955).

(6) These are lowland recording stations to the WNW, SW, and SSW, respectively, of the Whitehall hills. More intense falls with a similar return frequency could probably be expected at Whitehall.

(7) These figures are recorded falls during the passage of Cyclone Dinah, Feb. 1-3 1967. They are for 14, 21, and 48 hours, all involve a gauge-full reading, and are the only figures for less than 24 hours that have been recorded in the area. Twenty-four hour recordings have been made since 1962, during which time there have been 16 falls of 2 - 3", one of 3 - 4" (to 1 June 1962), and two or over 4" (to 1 March 1966, and to 3 Feb. 1967).

(8) A lowland station to the W. of Whitehall, and the figures are based on mean hourly winds at 3-hour intervals. Thus, gusts, which are typical of this area, are not registered and would be considerably higher.

CHAPTER 2. DESCRIPTION OF SOME ACTIVE GEOMORPHIC PROCESSES AND FEATURES AT WHITEHALL

I INTRODUCTION

The establishment of pasture in Whitehall has resulted in a smoothing of relief, where the slopes are less than about 20-25°, and where there is not a surface cover of boulders. The microrelief under the bush, especially on damper and steeper sections of slope, is very rough, and windthrow and mass movements have resulted in considerable mixing of organic debris in the colluvium which mantles the slopes.

Thus, most of the slopes with a pasture cover are a simplification of surface landforms that developed prior to European occupation, and most probably under bush.

In this chapter, the active piping and mass movement features are described, but, except for those that are typical of classificatory examples in the literature (Sharpe 1938; Varnes 1958), discussion of the processes involved in their initiation and development is given in Chapter 3.

Such a division of description and discussion permits the use of a central theme, the movement and action of subsurface water, in the explanation. The use of this theme is based on the assumption that each feature noted expresses the interaction between the regolith and environment, with the movement of subsurface water being a critical factor in causing irreversible rupture.

The piping, much of which channels subsurface water to zones of slope failure, is described first.

II PIPING

1. Introduction

Geologists and other workers in the field of earth science have used a wide variety of terms to describe the processes and results of mechanical eluviation. Cussen (1888) and Gilbert (1920) ascribed funnel-shaped holes in the loose sands of the middle Waikato basin and the Waikato Heads, respectively, to mechanical eluviation, but did not name the process. Some of the terms that have been used are: 'subsurface channels' and 'subsurface drainage' (Aurousseau 1919); 'sub-cutaneous erosion' (Guthrie-Smith 1926, Cumberland 1944); 'gullies formed by sinking of the ground' (Rubey 1928, Buckham & Cockfield 1948); 'rodentless rodent erosion' (Bond 1941); 'tunnel-gully erosion' (Gibbs 1945); 'tunnelling' (Downes 1946); and Campbell (1945) noted the occurrence of 'underrunners'. However, the term 'piping' that is now in general usage in the discussion of the processes of mechanical eluviation has long been used by engineers.

Piping, "the process which produces tubular subsurface drainage channels in insoluble clastic rocks" (Parker _et al_ 1964, p.394), occurs in the relict and reworked mass movements deposits, and in the mantle of weathered greywacke, in Whitehall.

The piping in the study area has been tentatively classified, for the purposes of description and discussion, according to the type of material in which the features have developed. This classification is not entirely satisfactory in that there are conceptual difficulties of using subdivisions based on morphology, which, in most cases, actually reflect differing stages of development in varied materials. Similarly there are difficulties of distinguishing between concentrated seepage and actual pipe development. Furthermore, it is not known if the features noted in the bedded ash really are "the product of the removal of solid clastic rocks on a grain-by-grain basis in suspension in moving water" (Parker _et al_ 1964, p.394) and whether or not drainage is channelled through them in every case. However, the purpose of this classification is for organisation, and it is aimed to illustrate the similarities, rather than the differences, between piping processes under bush and under pasture.

TABLE II CLASSIFICATION OF OBSERVED PIPES AT WHITEHALL

Type No.	Material	Vegetation cover	Description of pipes
1.	Mass movement deposits	Pasture; bush	Seepage lines to large pipes.
a.	Very recent debris - heterogeneous	Bush	Seepage and pipes - along logs.
b.	Stable, dry colluvium	Pasture; bush	Large pipe zones in boulder beds.
c.	Saturated colluvium	Pasture	Boulder bed and base of colluvium.
d.	Recent - pseudopipes	Bush	Channels bridged by debris.
2.	Weathered greywacke	Pasture; bush	Extensive zones of seepage and small pipes between blocks.
3.	Colluvial ash (generally bedded)	Pasture; bush	Holes and cracks of different sizes and from different causes - in friable ash beneath pasture, and in damper, more cohesive colluvium under bush.

2. Piping in Mass Movement Deposits

Introduction

Piping in relict and reworked mass movement deposits is present under both bush and pasture vegetation. The location of a well-developed system of pipes under pasture on the southwest-facing slopes is shown in Figure 4. However, subsurface drainage under the bush has not been mapped because:

(1) The microrelief and the dense mats of supporting tree roots, make piping difficult to locate.

(2) The area of the bush is small and it is situated on a valley-side with a limited catchment area.

(3) Partly as a result of (2) the mass movement deposits are more homogeneous than those downslope from the amphitheatres, thus reducing the potential for piping.

The piping is described in order of increasing development, with examples from under each vegetation cover where relevant. Although very recent features, the 'pseudopipes' are not true pipes and are described last of the Type 1 pipes.

Type 1a Pipes

In the classification, the Type 1a pipes are tabled as those developing in recent mass movement deposits which consist of mixed, heterogeneous materials. As the only recent debris flow in the study area occurred in the

Fig. 4 & 6

DRAINAGE IN HETEROGENEOUS MASS MOVEMENT

DEPOSITS UNDER PASTURE

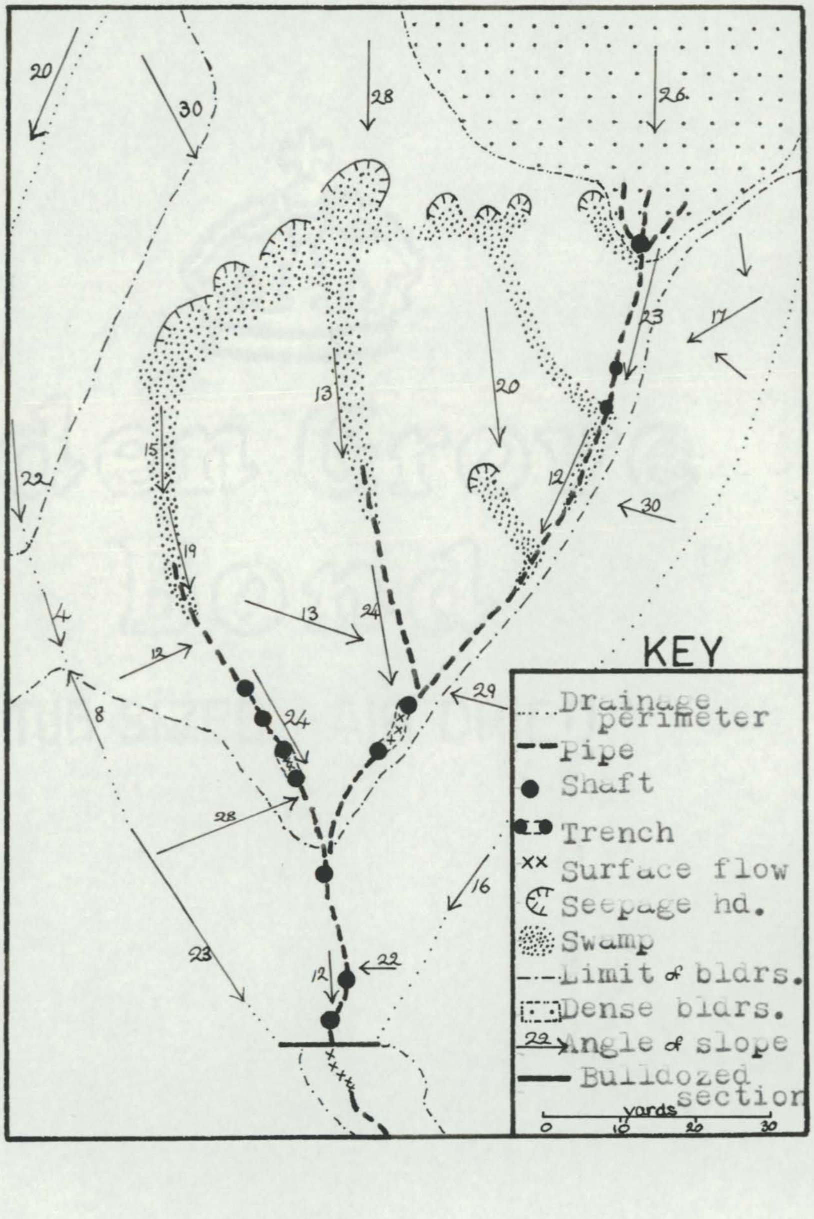


PLATE VI

(a) View from top of headwall of a recent debris slide and flow - probably some backward rotational movement initially.

(b) Dense undergrowth on older deposits at foot of flow.

a

b

bush (GR N66/101376) these pipes are not found under the pasture there. (Plate VI). This flow, the upslope portion of which is covered by a more recent flow of fine, homogeneous colluvium, is estimated at being 10-15 years old.

No pipes were observed in the homogeneous material, although some seepage during settlement undoubtedly occurred, but the absence of surface litter and the presence of numerous small channels and flattened grasses provide evidence of considerable surface wash. In the heterogeneous deposits of fine colluvium and logs there is virtually no surface runoff, but pipes and zones of seepage have developed beneath or beside logs, and at other positions in the colluvium where water is channelled (Plate VII). Several pipes, up to 8" in diameter and of varied section, were observed, but their length and direction is not known.

Type 1b Pipes

A pipe that is larger than those described in the preceding section has developed in a mounded deposit of stabilized, and predominantly fine, colluvium at GR N66/101376. The outlet, with a rectangular section 10" high by 5" (Plate VIII), is above sand-sized, weathered greywacke forming the bank of the stream in the valley floor. The surface depression along the line of the pipe indicates

PLATE VII

Pipes in recent flow deposits:

(a) Beneath log.

(b) In surface colluvium.

PLATE VIII

Pipe in stable colluvium.

(a) Outlet of pipe.

(b) Collapse shaft still partially supported by roots.

PLATE IX

(a) Pipe upslope from collapse shaft.

(b) Dense root mat above pipe.

(c) Tree upslope from shaft and supporting roof of pipe.

a

b

a

b

a

b.

c

subsidence.

At a shaft eight feet from the outlet, some of the material supported by the root network has collapsed, revealing a hole 30" deep and 40" wide, that extends upslope as a pipe (Plate IX). There are no other collapse shafts, and a dense network of roots covers the surface of the ground for a further 50 feet up the slope.

Above this point there is a conspicuous absence of trees or large roots along the line of the pipe (Figure 5), and a collapse trench 40-80" wide and 20-50" deep, extends upslope at 15-35^{o} for about 100 feet. The development of the trench illustrates the importance of tree roots as agents of support, where there are no accumulations of boulders. At the downslope end of the trench, the pipe is 44" wide by 36" high and the base plane slopes at 30-45^{o} for 7 feet to where the pipe is little more than a large crack (Plate X).

The luxuriousness of the vegetation along the trench and its absence along the line of the pipe indicate the efficiency of this subsurface drainage. Although no pipes were observed upslope from the trench, there is no conclusive evidence that they are not present.

The outlet of a second pipe under the bush is at the base of the colluvium in a feature exhibiting characteristics similar to water blowouts. This water blowout has occurred in the backwall of an earlier slide on the surface

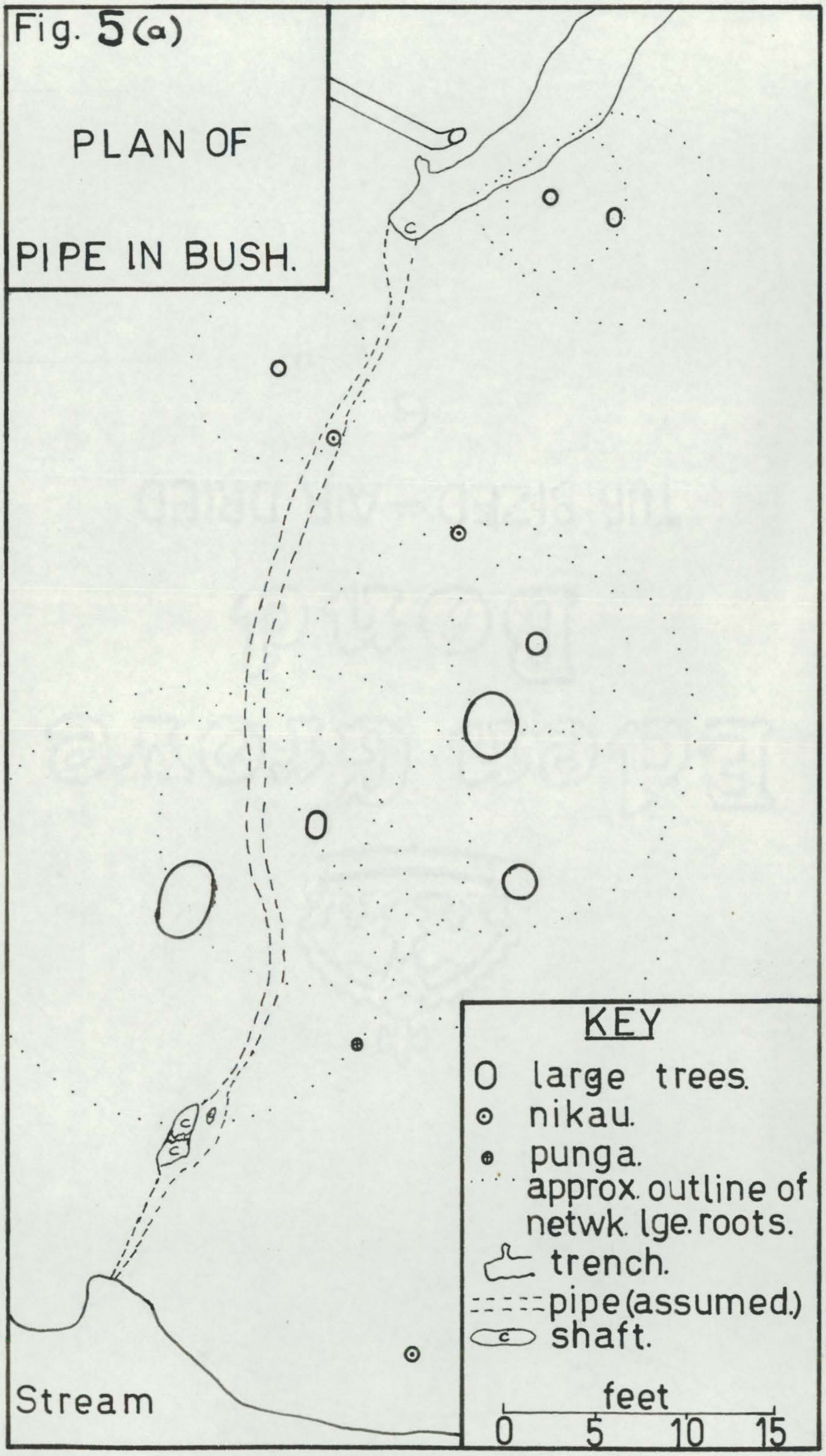


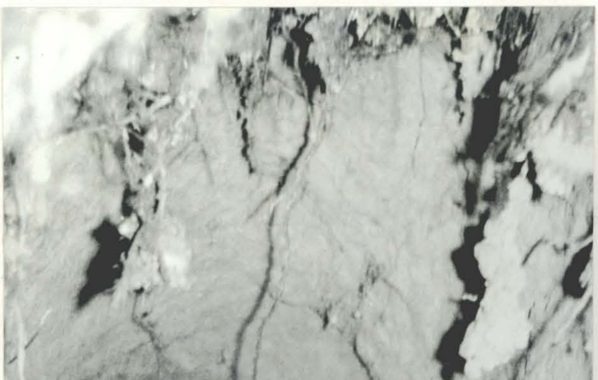
Fig. 5(a)
PLAN OF
PIPE IN BUSH.
Stream
KEY
large trees.
nikau.
punga.
approx. outline of
netwk. lge. roots.
trench.
pipe (assumed.)
shaft.
feet
0
5
10
15

PLATE X

(a) Collapse trench.

(b) Entry to pipe at downslope end of trench.

a



b

of the greywacke, where cracks in the colluvium have been opened by water movement and by the roots of a tree growing directly over the pipe (Plate XI). A channel 6" deep cut in the surface of the greywacke indicates the importance of this pipe as a zone of water flow during rainfall. The pipe extends back into the face as a crack and could not be located further up the slope.[1]

The largest and most fully developed systems of Type 1b pipes have permanent flow and have formed in the deposits infilling the gullies downslope from the amphitheatres on the interfluves (Figure 4). Although there is now a pasture cover on these slopes and most of the collapse shafts are of recent origin, development of the actual pipes occurred beneath a forest cover (Chapter 3, III, 3).

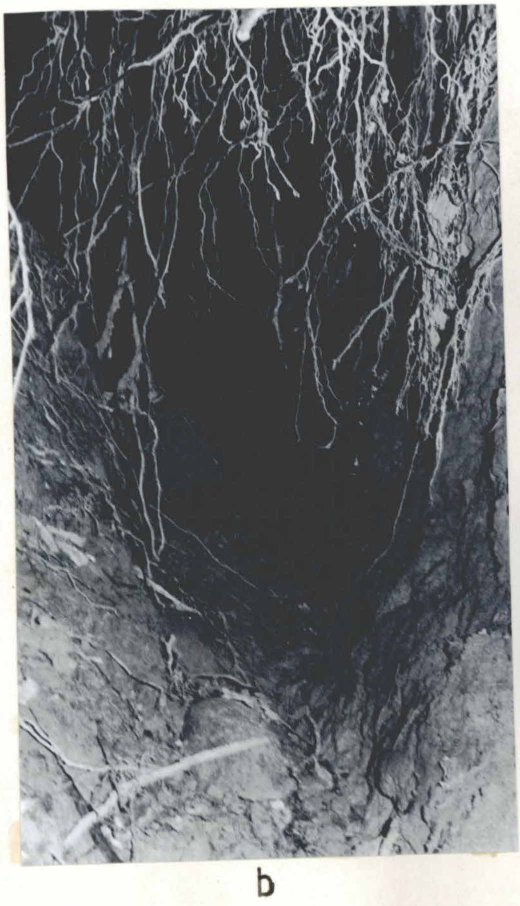
Changes in slope along the floors of these gullies may indicate slump headwalls, but auguring has shown the actual surface expression to be generally the result of deposition lobes of flow material. (See also Lyford, Goodlett, & Coates 1963) Surface wash following deposition, and seepage and subsurface flow along the earlier surface, have resulted in the removal of fines and settling of the deposits, with the result that relatively smooth lines of expected surface drainage overly accumulations of boulders and stones. Flow is along a network of channels that have been maintained at various levels

PLATE XI

(a) Water blowout and slide beneath tree.

(b) and (c) Outlet of pipe and channel on surface of weathered greywacke. Root direction strongly influenced by cracks in colluvium.

a



b

c

through these accumulations of boulders, but during high-intensity rainfalls interstitial space within the beds is sometimes insufficient to channel the total flow and surface flow results (Plate XII).

From the surface these systems of subsurface drainage appear similar to those described elsewhere[2], except for the steeper slopes (up to 25°)[3], but the presence of flow on a number of levels within a channel of stones and boulders, and the development of piping in an area of such high rainfall (mean annual total on 6-year record is 56.0"), are at variance with conclusions derived from the literature.

Vertical collapse shafts (Figure 5), typically circular, broader than they are deep, and with overhanging walls, are common along the lines of the pipes, and appear to occur in all positions except on the steep sections of slope created by deposition lobes (Figure 6). In places, this collapse has created trenches, but these do not open into gullies formed by piping and collapse.

As the form of the piping zones and the nature of the deposition material are felt to provide useful evidence as to their origin and mode of development, a section was bulldozed across one to illustrate the shape of the boulder bed, and its relation to the relatively unwashed colluvium at the foot of the side slopes, and to the surface of the greywacke (Plate XIII).

As is depicted in Plate XIII, the boulder bed is oval

Fig. 5(b) X-SECTION OF COLLAPSE SHAFT

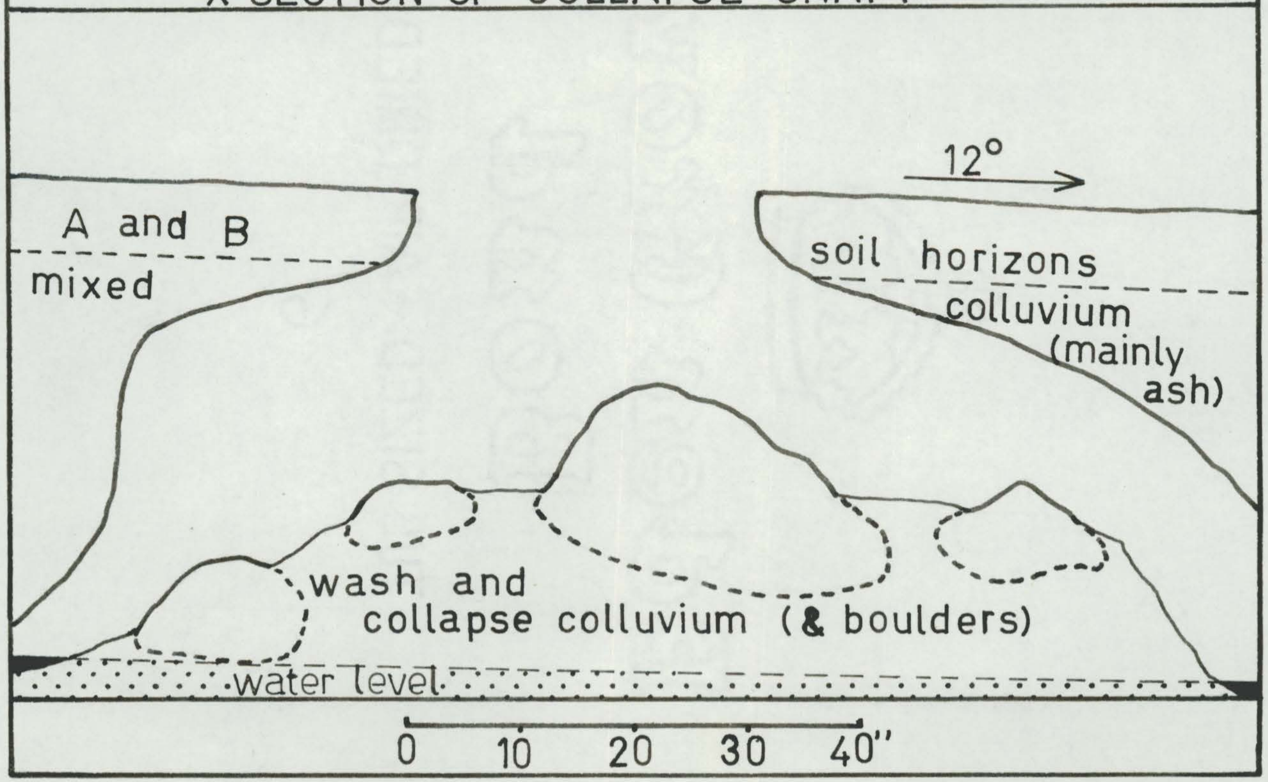


PLATE XII

Pipes and collapse features under pasture.

(a) In flow deposits below amphitheatre - many boulders.

(b) Smooth colluvial slopes with fewer boulders.

(c) (See over page.)
Collapse shafts in area of (a), and in the stream in the valley floor.

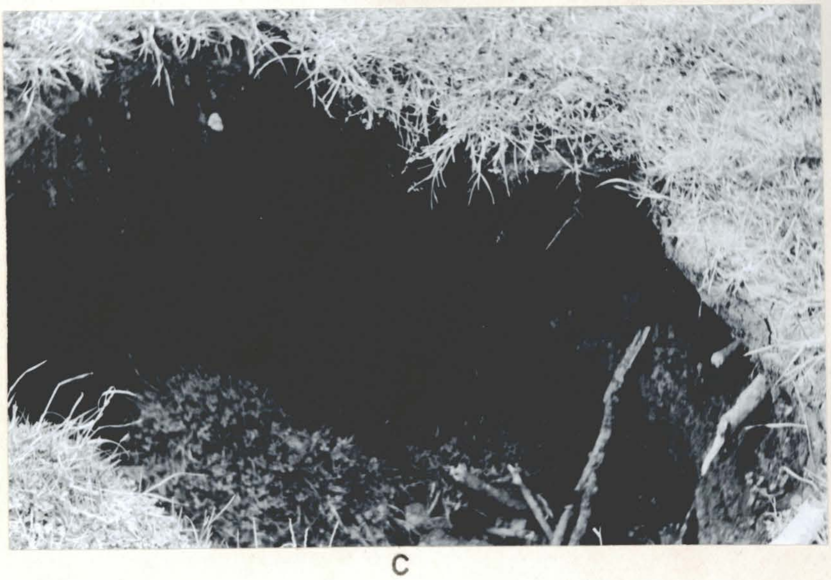
a

a

b

b

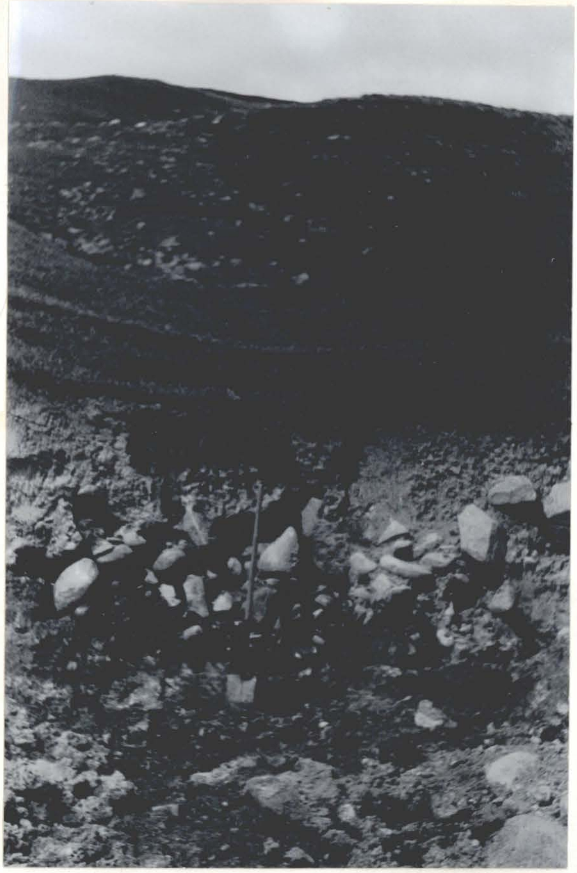
C



C

PLATE XIII

Section through boulder bed at lower extremity of flow deposits. Broad boulder bed with greying of colluvial fines and insitu red weathered greywacke.



a

b

a

b

c

PLATE XIV

(a) Swamp with seepage at various levels, surface flow on the left and an open pipe in the boulder bed, which is visible on the right.

(b) The collapse shaft above the pipe.

(c) Collapse of part of swamp as a result of mechanical eluviation.

in section, with a wide, flat base, and is situated in a depression in the weathered greywacke. The fine sediments and the greywacke at the base of the boulder bed are stained and gleyed, with the limit of gleying being convex outwards from the base of the boulder bed. Flow is at various levels within the bed and much of it is in the form of seepage through the fines between the stones and boulders. Seepage in the greywacke is between the fracture-blocks and in some cases small pipes have developed at similar locations.

Although this section is at the top of a deposition lobe in the narrowest gully, it does illustrate the shape and flow pattern of these subsurface drainage systems (Figure 7).

This piping, which is extremely important in reducing runoff, is slowly regrading the very mixed and mounded flow deposits to a longitudinal profile that is smoother in relation not only to that of the underlying greywacke, which is broken by slump headwalls, but also to the valley side.

Type 1c Pipes

Piping in some low-angle gullies downslope from seepage-heads is similar to that of Type 1b, but is less extensive. The floors are flat in section and are entirely saturated, giving water movement throughout the mass, but

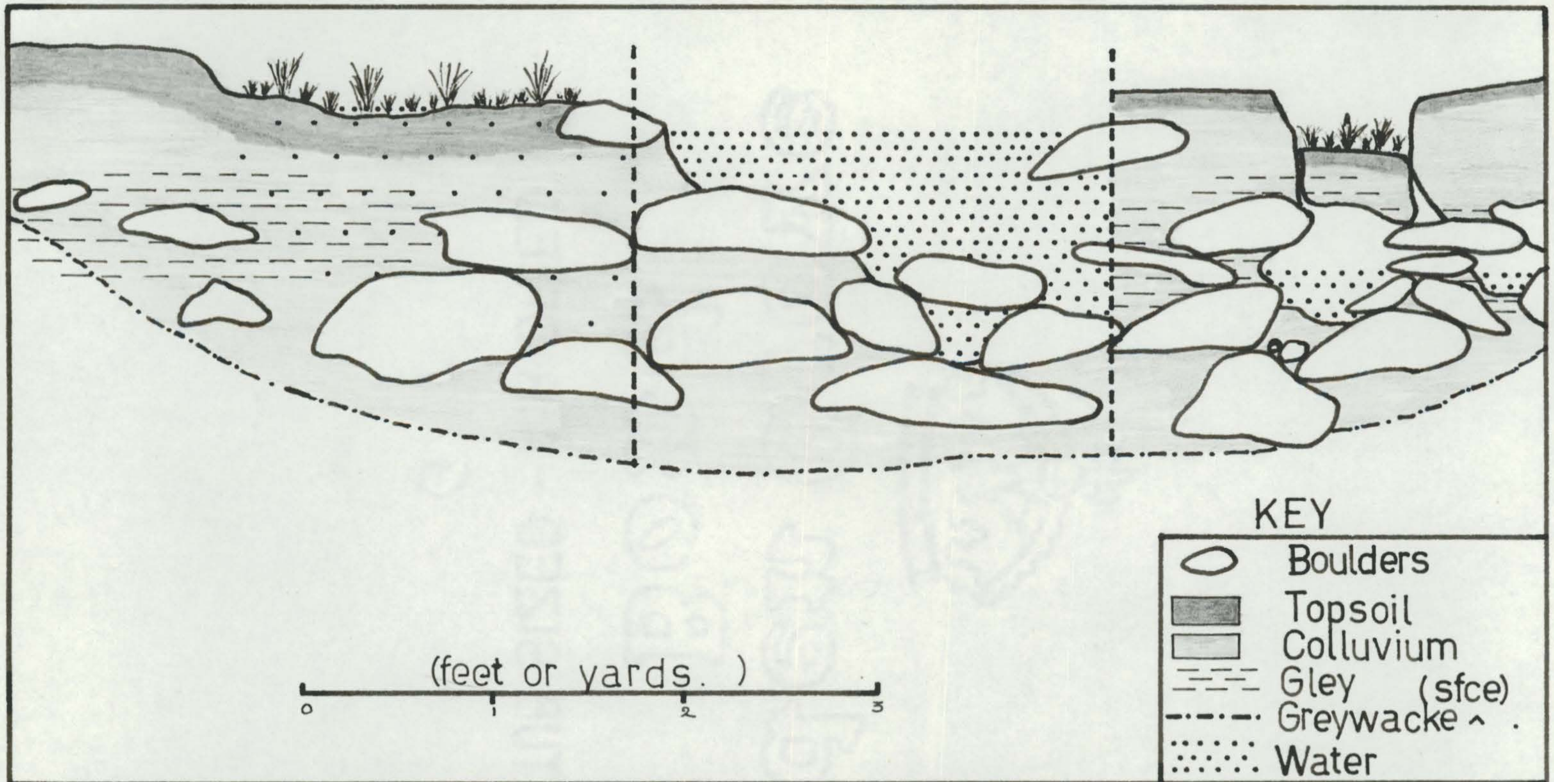


Fig. 7

SECTION THROUGH BOULDER BED

boulder beds are necessary for the development of large channels (Plate XIV).

Saturation appears to be due to the continual seepage, with the low angle of slope of the weathered greywacke creating a ponding effect. On steeper slopes, the break in slope is marked by an increase in the breadth of the swamp, denoting the entry of a seepage line (Figure 8) However, it is not known what influence the increased water supply has in maintaining swamps on steeper slopes.

Type 1d Pipes

Type 1d pipes are 'pseudopipes', a term which has not been observed in the literature, but which is used here to denote subsurface channels produced by processes other than piping.

The pseudopipes in the study area are all small features with a length/depth ratio of less than 1. They occur as small bridges over narrow channels through recent, predominantly fine, mass movement deposits. The pseudopipes developed by one of two processes:

(1) By collapse of a channel wall so that it is supported above the flowing water by its base and the opposite wall, and;

(2) By slump or flow material covering the channel (where there is a tree or similar material to support the overlying colluvium). (Plate XV)

The pseudopipes are relatively temporary features, but the second type is more permanent where the log base

PLATE XV

Pseudopipes caused by:

(a) Windthrow and mass movement;

(b) Collapse of channel wall;

(c) Inlet, and

(d) outlet of pseudopipe caused by mass movement; and

(e) (see over page)
Very recent windthrow.

a

b

c

d

e

is solid and channel migration is slight.

3. Type 2 Seepage and Piping in the Weathered Greywacke

Water movement within the mantle of weathered greywacke, although much less noticeable than that in the overlying colluvium, is along the almost continuous network of intersecting fracture-joints that have been maintained during and by weathering. Most of the movement is in the form of seepage with small pipes having sometimes formed at intersections. These pipes are generally less than $\frac{1}{4}$" diameter, although at seepage heads they have been observed with a diameter of up to $\frac{3}{4}$". Although pipes have been observed in cuttings in the sides of gullies, it is felt that proximity to a free face, or more concentrated flow in the floor of a gully, is necessary for the formation of definite pipes.

In the section at GR N66/105377 (described in Type 1b), (Plate XII) numerous small pipes, and planes of dampness with seepage concentrated into a small zone, are present in the gleyed greywacke beneath, and on either side of, the boulder bed. The upper limit of this water movement was at a lower level than the base of the boulder bed when observations were made during fine weather, but this level may rise when hydrostatic pressures increase during rainfall.

Evidence for this assumed rise in the level of flow, the interconnected network of pipes, and the increase in hydrostatic pressures during rainfall was provided by studying the normally dry backwalls of two slump slides on 25/5/67, following a rainfall of 2" during the preceding 24 hours. Flow from sections of the fracture-joints was considerable and the water from one $\frac{1}{4}$" diameter pipe jetted horizontally for nearly 9".[4] When this pipe and the surrounding zone of concentrated seepage was blocked, flow was immediately observed from pipes and fractures higher up the face. This process was carried out in several positions with a similar result each time. Piping in clay soils generally bears some relation to the surface contour of the ground, but the features described here all follow the line of fractures, resulting in sinuous courses, with the angle of intersection at the face depending on howfar into the slope they are exposed.

Where mass movement colluvium overlies the weathered greywacke, there is often a lens of intensely gleyed clay between them, and this is a major zone of seepage that is very important in reducing shear strength and causing successive failures within earlier mass movement features.

No measurements of soil strength or shearing resistance were made, but a rather crude general impression of strength was gained by pushing a thin stick into the face. Penetration of 4-6" was typical along the fractures from which flow had been observed, and 10-15" along the gleyed lens beneath the colluvium, but only $\frac{1}{4}$-$\frac{1}{2}$" in the actual blocks, thus indicating the importance of water in reducing shear strength.

Under the bush osmotic pressures from tree roots tend to open cracks and joints without breaking the primary structures, and groups of blocks break out together more easily than under pasture. This accentuation of weathering and pedological structures appears to permit increased water movement, and so is important in reducing resistance to shear.

These piping and seepage features have been described in considerable detail for three main reasons:

(1) This type of piping has not been described previously;

(2) Although the pipes and seepage lines are features of microrelief, they appear to extend over virtually the whole of the study area, and;

(3) Water movement at this level is believed to have considerable geomorphic significance in the area studied, in channelling water under considerable hydrostatic pressure from the interfluves towards springs at seepage heads, and in the initiation of slides and slumps at these locations.

4. Type 3 Pipes in the Colluvial Ash

Piping in the colluvial ash has not been studied extensively and the cracks and holes observed may be due to drying and to the decay of logs, respectively, with mechanical eluviation being of little importance in their development. Definite percolines have been observed in the ash, but no channels that could be solely attributed to piping. However, water movement has been significant in enlarging the pipe at GR N66/128391.

This absence of pipes may be the result of insufficient observations, of almost unconfined flow through the loose Rotorua ash, or of the absence of bedded ash in the gullies, where concentrations of subsurface water above the greywacke are greatest.

Although not occurring solely in colluvial ash, another system of pipes is present under the bush. Free spaces occur around many roots and it is possible that wetting and drying cycles, associated with osmotic pressures and the swaying action of trees, creates open channels that are enlarged by water movement. Interception loss is not recorded in surface runoff, and it is felt that, although infiltration rates are high under bush, (Campbell 1945, Selby 1967a) the continuation of stemflow and some of the surface runoff directly down these root channels may be even more significant in the rapid movement of water to the major zones of flow within the regolith.

5. Summary

Piping in the study area is broadly classified as-according to the material in which the features have developed, and pipes under both pasture and bush are described.

The major zones of piping are in boulder beds in the stabilized flow deposits at the toe of large slumps. These pipes developed in heterogeneous materials, flow at various levels, and are dependent on the skeletal structure of the boulders or the support of tree roots, for their maintenance. Similar piping is also found in some swamps, and pseudopipes may develop through the bridging of channels in colluvium.

Well-developed and interconnected systems of small pipes and seepage lines occur in the fracture-joints that have been maintained in the greywacke during weathering.

Various other holes and pipes are found in the colluvial ash, and it is felt that the free space around tree roots may be significant in channelling water to the lower colluvium and greywacke, but this has not been tested.

III RECENT MASS MOVEMENTS

1. Introduction

Mass movements may be defined as the downslope movement, en masse and in linear or sheet form, of weathered or unweathered surface materials. All denudation processes are closely interrelated and the material moving downslope ranges from almost pure water through to debris with virtually no liquid content, but possibly fluidized by the content of interstitial air, through to almost pure ice. As the water content decreases, the mass's viscosity increases, and with a uniform material the slope necessary for movement also increases. The coarseness of the material being moved is also graded, as in the increasing proportion of fines encountered in a range from rockfalls through debris slides to soil creep.

All mass movements are discontinuous movements of material. Thus, they all require a critical shear stress to shear strength ratio to be reached for initiation of such movement. Once static friction has been broken, the forces that caused rupture are sufficient to maintain movement until shear strength again exceeds shear stress. This is generally achieved by a reduction in the angle of slope, reduction in buoyancy through the loss of moisture, or stresses at different points on a block cancelling each other.

High-intensity rainfalls, and associated subsurface water movement with changes in soil pore-water pressures and physical properties, are felt to be of prime importance in initiating slope failure and maintaining downslope movement of dislodged material, in areas of temperate humid climate (Chapter 4, III).

Many classifications of mass movements have been proposed, but it is thought that a hypothetical positioning of Varnes' (1958, Plate 1) classification within Sharpe's (1938) scheme, and an expansion of some of the cold climate forms as provided by Rapp (1961), give the most suitable and complete classification that can be obtained at present. All the Whitehall features can be classified within Varnes' framework, with the water blowouts being included as 'all-unconsolidated-wet-flow of mostly plastic materials'.[5]

Most of the recent mass movements in the study area are similar to type examples described and explained by Sharpe and Varnes, and are not described in detail. The mass movements all occur within the regolith, which consists mainly of clay, silt and sand-sized material with some boulders, logs and tree roots, and subsurface water is an important factor in their initiation and in influencing the mode of movement. The individual movements may be in the form of slumping, sliding, or flowing, or combinations of these, depending on the angle of the plane at the base of the movement, the amount and concentration of the contained water, and the rate of change of water pressures. In the features studied the flows ranged in fluidity from fairly viscous earth flows, through mudflows, to the water blowouts. All the initial movements were 'very rapid' to 'extremely rapid', but the settling of the deposits involved 'moderate' to 'very rapid' movement.[6]

The term 'water blowout' has been used several times in this thesis and, as certain of these features are described in this chapter, a short explanation is necessary. The term has not been used in the New Zealand literature on mass movements, and the writer has found only two references to it in the literature from other countries.

The first use of the term 'blowout' was by Eisenlohr (1952, p.77) to name large holes that developed at a similar level along a valley-side in Pennsylvania during exceptionally intense rainfall. The soil from these holes had flowed to the floor of the valley without damaging the surface of the ground. The cause was attributed to a great increase in hydrostatic pressure, owing to the very heavy rainfall, and subsequent failure at the weakest points on the slope. They occurred where a plane of shattered rock created a perched water table. When the pore-water pressures at the surface of the soil became critical, slope failure, in the form of rupture of the sod cover and outflow of the underlying material, resulted. It is felt that these ruptures acted as safety valves and prevented the movement of larger areas of slopes.

The second reference to similar features was made by Hack & Goodlett (1960, p.45). They proposed the term 'water blowout' to prevent confusion with blowouts of eolian origin, and use of this term is supported by the writer. The water blowouts described were semi-circular holes, about 50 feet in diameter, in the debris mantle. They occurred along the line of an impervious diabase sill where hydrostatic pressures increased through water concentration at one point, as a result of intersecting fractures, during high-intensity rainfall.[7] The downslope movement of the material was consistent with that described by Eisenlohr, being "either explosive or sufficiently fluid so that the soil mantle was not destroyed." (Hack & Goodlett 1960, p.47). The Whitehall features are smaller than these and the rate of development ranged from collapse and saturated flow to explosive rupture.

In the following sections the mass movements are subdivided into those located at seepage heads and those at locations without a permanent, subsurface supply of water.

2. Recent Mass Movements Located at Seepage Heads

The mass movement features located at seepage heads are noted in order of decreasing static friction, which, in the materials involved, appears to be inversely proportional to the water content of the mass. Seepage heads are, by description (Selby 1967a, p.51), "small hollows, usually with terracetted backwalls, from which originate swampy channels infilled with fine sediment." They appear to progress upslope from the floor of the valley by mass movements in the backwalls during periods of intense

PLATE XVI

(a) Well-developed network of swamps and seepage heads, which are sapping upslope from the central foreground.

(b) Slide at seepage head - hammer marks level of seepage.

(continued following page)

a

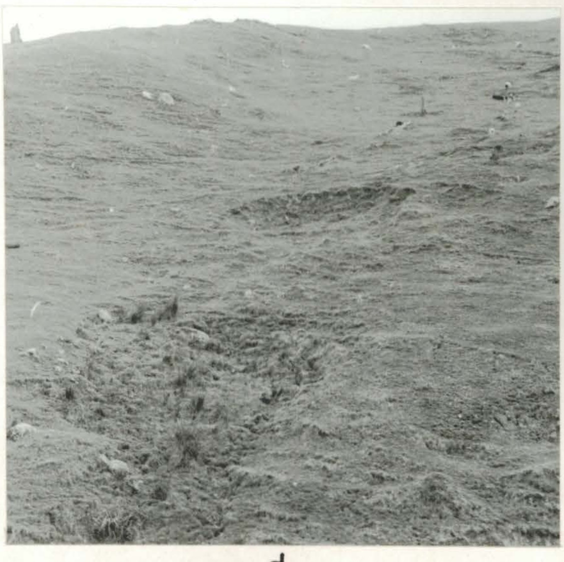
b

PLATE XVI

(c) Slump at seepage head.

(d) Scar above seepage head - possibly caused by the formation of a water blowout during high-intensity rainfall.

c



d

rainfall.

Failure by slumping, sliding, and flowing is more common at seepage heads (Plate XVI) than at other locations in the study area, and generally involves frequent small mass movements with a vertical displacement of less than 30 feet and a horizontal movement of up to 100 feet. Sliding along a 20-40° plane on a lens of gleyed material or directly on the surface of the greywacke is the usual initial movement, degenerating to flow through loss of cohesion upon disturbance of the mass, and when some of the deposits remain on the slip plane. However, small slumps do occur under both pasture and forest. The influence of the vegetation on the incidence and form of these mass movements at seepage heads does not appear to be great. However, there is a tendency for movements, subsequent to any given failure, to continue for longer periods under bush than under pasture, where stock action smooths the microrelief and where drying out and vegetation growth are more rapid. Also, cohesive blocks tend to be larger under the bush, when a tree moves with the slump or slide, but where the water content is high and interparticle contact reduced, the absence of a turf cover often results in structural collapse of the entire mass (Plate XVII).

PLATE XVII

Complete structural collapse of saturated flow material under bush, with the punga roots maintaining a cohesive block of material that slid downslope without rotation.

PLATE XVIII

Water blowout under bush. Complete structural collapse and saturated flow rather than explosive rupture.

The break in slope, the high-intensity rainfall, and the continual subsurface supply of water are felt to be the most important causes of these slumps, slides and flows. The significance of these factors is indicated by the tendency for mass movements, at positions other than seepage heads, to occur at a break in slope and during high-intensity rainfall (Selby 1967a, b), but to occur less frequently than similar movements where there is continual seepage. The break in slope brings the flow net closer to the surface and increases the effective shear stress weight of the mass, the high-intensity rainfall gives rapid increases in hydrostatic pressures, and the continual water supply results in a lower shear strength through reducing cohesion.

The water blowouts involve more complete alteration of the mass upon rupture than do those movements described above. Under the bush, structural collapse of an entirely saturated mass occurs, but flow appears to be for only short distances, and it is felt that normal slides and flows may occur, without the dense network of fine tree roots and the concentrated subsurface flow that were present in each example studied (Plate XVIII).

A water blowout under pasture occurred in the backwall of a seepage head at GR N66/128391 during the high-intensity rainfall of the night of 2-3 February 1967 (Plate XIX). A dry pipe, in the form of a large crack, extends into the face. This crack in the colluvial ash is widest at its base on the surface of the weathered greywacke. The feature has been classified as a water blowout because of the rapidity of flow of the fine, saturated material. The mud flowed rapidly over the 6° surface of the swamp for at least 100 yards, forming a levée (Sharp 1942) 2-4 feet above the level of the swamp, on the outside of a curve in the direction of flow, 40-60 yards below the blowout scar.

This upslope progression of seepage heads by these mass movements appears to be most important method of gully development that is operating at present, and has operated in the immediate past, in the study area.

3. Recent Mass Movements at Locations other than Seepage Heads

Recent mass movements at seepage heads under bush are very similar to those at seepage heads under pasture, but there are some striking differences between those under the different vegetation covers on the drier slopes. Generally, the causes and types of movements are similar to those at seepage heads, and in the one slump and flow under bush that was observed, and was much larger than any of the same type under pasture, seepage may have been more important than surface features indicated, because the

PLATE XIX

Water blowout at seepage head. Hammer indicates level of permanent seepage, below the pipe in the colluvial ash. The knife in the left foreground indicates the entry of another line of seepage.

movement was deep and occurred on a large dry slope.

The most significant difference is the absence of shallow midslope debris slides and water blowouts under bush. Selby (1967a, b) has emphasised the extent, and frequency of occurrence, of shallow debris slides on drier midslopes during high-intensity rainfalls, and although this type of movement, which was common in the greywacke ranges to the north of Whitehall, did not occur in the study area during the 1966 and 1967 summer storms, grass-covered scars on disced slopes indicate that such slides have been numerous since land development. However, similar recent scars were not observed under the bush although breaks in slope may be evidence of older slides. The only features observed that are at all similar are the hollows and mounds from windthrow.[8]

This difference between the frequency of debris slides under and on slopes with a pasture cover, and the absence of explosive water blowouts under bush, is thought to be due largely to the changes in soil properties that follow the removal of the forest cover, but the small size of the study area may also be significant. Some of the erosion-inhibiting effects which forest have on soils are: tree roots keep the water table lower than do grasses, thus reducing loss of cohesion, and they also give structural strength to resist soil movement and fluvial erosion; forest soils are less compacted, have more macropores, and have a greater content of binding humus than those under

PLATE XX

Mass movements beside road. In each case the movement involved sliding with some rotation and, in (a), collapse as well.

a

b

pasture; as forest soils do not undergo as great a volume change as grassland soils, drying cracks are negligible; and, interception loss reduces the rapidity with which pore-water pressures rise, and the litter layer reduces runoff and stream erosion (Selby 1967a, p.53).

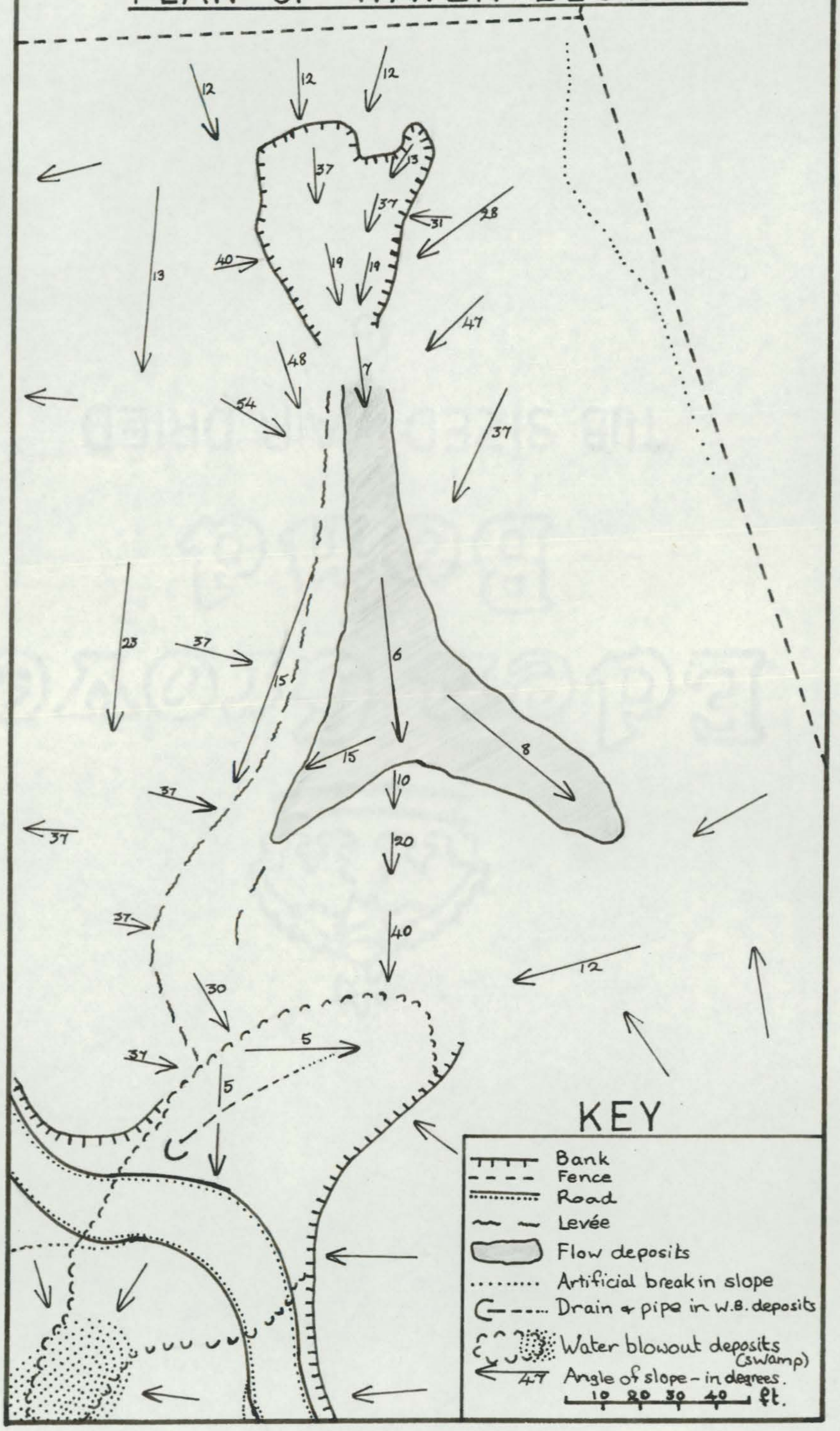
The midslope slumps and slides that did occur during Cyclone Dinah are all on a slope above a road, where undercutting had reduced stability, and are opposite the two slides in the seepage heads at GR N66/111373. The major slide involved the renewed movement of the colluvium from a previous failure, and was along a lens of gleyed clay on the 35^{o} surface of the underlying greywacke. Following the removal of support by the slide and rapid drawdown of water contained in the ash, some of the colluvium forming the backwall slumped onto the slide material (Plate XX).

The most interesting features, though, are the water blowouts that occurred during the night of 2-3 February 1967[9], when rainfall was most intense (Table 1B). They are both at a similar level near the top of headwalls of dry gullies, where the weathered greywacke is nearest the surface of the ground.

In water blowout A (Plate XXI), the ash flowed as a thin liquid to a ponding area formed by the road. The only material remaining on the slope was some of the

Fig. 10

PLAN OF WATER BLOWOUT.



collapsed turf and two small levées 3-6 feet apart, marking the edge of the flow. A detailed plan of this feature is shown in Figure 10, and the shape of the deposits illustrates the very different type of flow that occurred when material, under low pressure, collapsed from the side of the scar during rainfall on 2 March 1967 (0.9") and removed the sods from the slip plane.

Water blowout B (Plate XXI) exhibited similar characteristics to example A, but is noted here because it occurred on one side of a curved tension fracture marking an incipient slump. This movement, combined with concentrated hydrostatic pressure, possibly ruptured the sod cover and resulted in the water blowout. The rupture may have reduced shear stresses in the remainder of the mass, thereby creating the safety-valve effect postulated by Eisenlohr (1952, p.78).

The final example of a recent mass movement was not studied until after the deposits had dried out and been mixed by stock action, and so the order of rupture could not be ascertained. However, the movement (GR N66/129389) involved a slump, at least one slide, and a water blowout. The slide developed into an earth flow, resulting in mounded deposits downslope from the scar. The water blowout occurred from an almost vertical slip plane on the greywacke, at a break in slope in the floor of the gully. The fine colluvial material flowed 400-500 feet to the

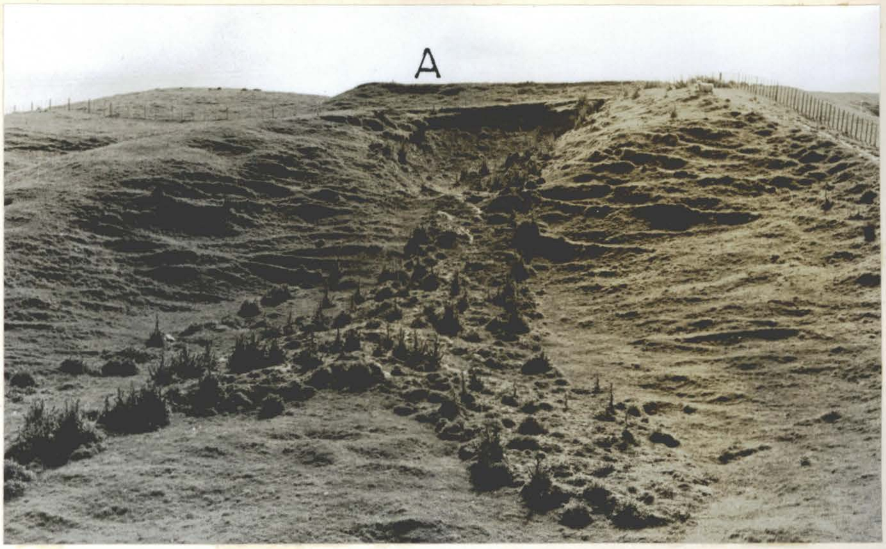
PLATE XXI

Water blowout A showing:

(a) deposits from flow in March;

(b) shape of scar and slip plane; and

(c) direction of flow.



a

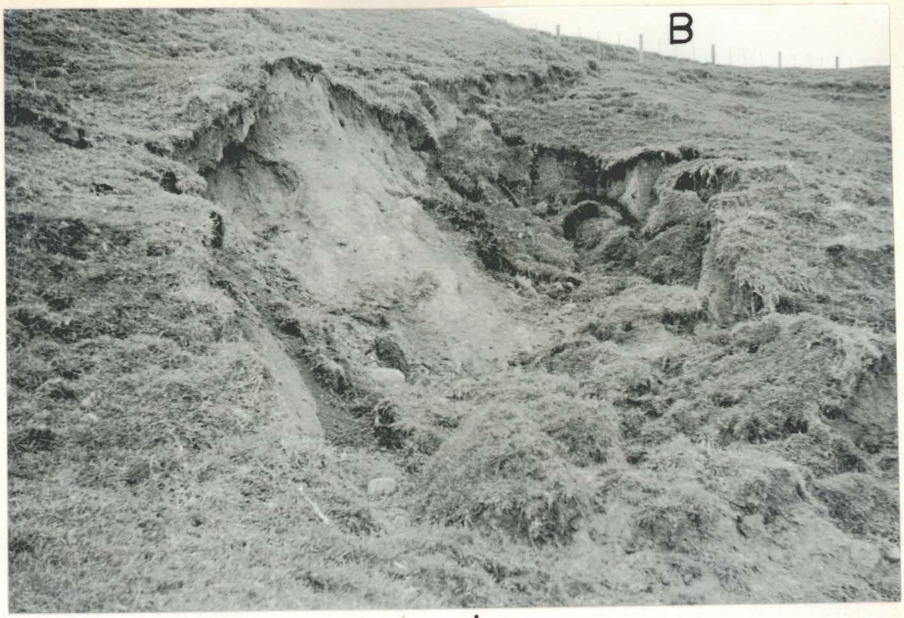

b


c

PLATE XXI (cont.)

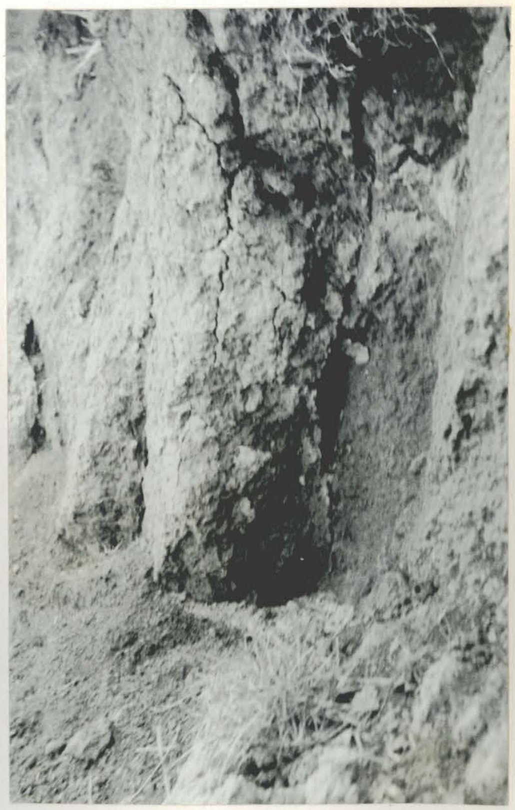
(d) Water blowout B.

(e) and (f) Cracks and holes in the Rotorua ash.



d

e



f

PLATE XXII

Compound mass movement involving slump, slide, earthflow and water blowout movements. Note hollows in gully floor - possibly caused by piping and collapse, or water blowouts.

main swamp. A levée formed up to four feet above the general level of the flow and although some of the earth was trapped behind a log, most of it flowed over this obstacle and for a further 100-200 feet (Plate XXII).

4. Summary

Recent mass movements in the study area occurred during the high-intensity rainfall associated with the passage of Cyclone Dinah, and during the winter. All the features observed are discrete examples within a continuum of processes, in which the water content of the regolith materials, by controlling the static friction of the mass, is largely responsible for the type of failure that occurs.

The importance of the subsurface water supply is also indicated by the similarity between the type and frequency and type of mass movements on the drier midslopes, where the soil-water relationships differ considerably between forested slopes and those with a pasture cover.

Footnotes

(1) A similar feature was observed at a seepage head under pasture at GR N66/128391 and is discussed in the section on water blowouts. Another under the bush is only a crack, but also has concentrated seepage.

(2) An extensive survey of the literature dealing with piping was made, and the various papers are noted in the list of references.

(3) This figure refers to the angle of surface slope. However, the pipes beneath the steeper sections of slope, which are, essentially, depositional features of microrelief, are thought to be at a lesser angle, although this could not be measured.

(4) Local farmers have observed water fountaining up to about 18" into the air at some seepage heads after periods of very intense rainfall, especially following rainfall to wet the ground and recharge the flow net.

(5) A specialised classification based on the type of movement resulting from different water contents was proposed by Terzaghi (1925, in Ladd 1935, p. 1097) and most of the recent flow features at Whitehall would be included in Order B (plastic movements partly or entirely without static friction), Group V (flows resulting from hydrostatic overload in the contained water called forth by overload - usually along joints and lines of seepage.) However, this is not in general use, and subclassification would involve the use of terminology from Sharpe (1938) and the ordering provided by Varnes (1958).

(6) These rates of movement are according to the scale of the U.S. Highways Research Board (Eckel 1958, Plate 1).

(7) The rainfall was not recorded but the authors believe it to have been as high as 30" in 4½ hours (Hack & Goodlett 1960, p.43).

(8) Windthrow (Lutz 1940, p.1) refers to the uprooting of trees where wind is the major immediate cause. All the recent examples of windthrow in the study area involved Tawa trees, which have a tight, shallow network of roots.

(9) The road was clear at 9.30 p.m., 2 February, but was blocked by saturated flow material the following morning.

CHAPTER 3. DISCUSSION OF THE MASS MOVEMENT AND PIPING PROCESSES IN WHITEHALL AND THE SIGNIFICANCE OF SUBSURFACE WATER MOVEMENT

I INTRODUCTION

The active and recent mass movement features in the study area have been described, and in some cases explained, but the more general nature of the processes involved has not been discussed. All these features appear to be discrete examples within a continuum of processes, from eluviation by solution, which is nearly continuous, to non-periodic slides and slumps involving little loss of structure within the moving mass.

Discussion is concentrated on the development of pipes in heterogeneous colluvial deposits, the origin and influence of the microrelief under bush, and the causes and mechanics of water blowout development. Some of the differences between the scale and rates of processes under bush and under pasture are explained in terms of the nature of the regolith materials, and the effects of the different vegetation types on their physical properties, in relation to specific examples.

II PIPING IN WEATHERED GREYWACKE

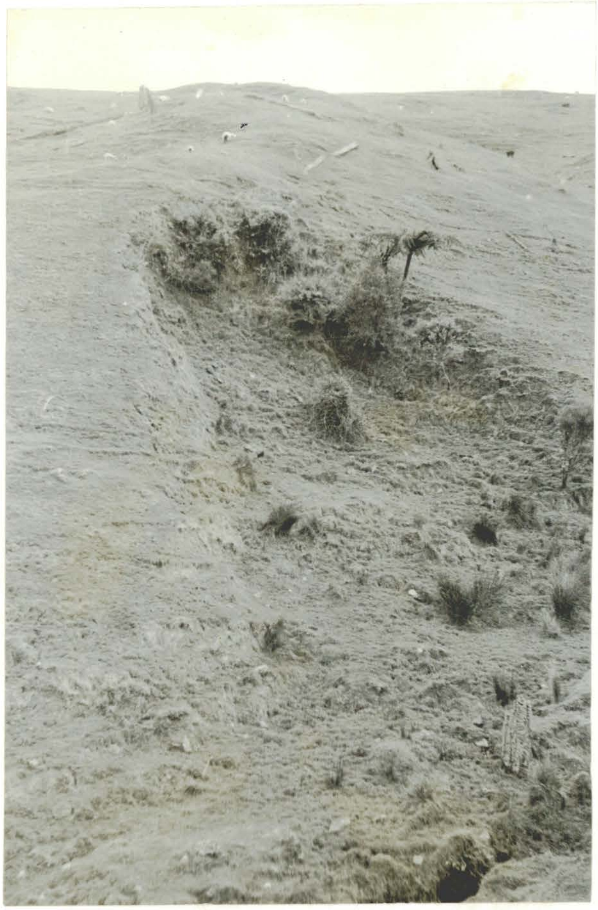
In the piping in the greywacke, water movement is controlled by the fracture-jointing, and on the lower slopes at least, is felt to be flowing from the base of the weathering mantle or actually from a net within the base rock. Water flow through the fractures in the base rock is considerable (Collins 1955; site at GR N66/063352) and has probably been maintained in the same positions during weathering.[1] The pipes are small and have involved the removal of only individual particles or clay gels. Movement is generally in the form of concentrated seepage through lenses of a saturated matrix, and pipes may only develop close to a free face in the greywacke or where movement has resulted in minute crush zones along intersecting fractures. The removal of minerals in solution during weathering may also have enlarged these secondary interstices.

The presence of gleyed and clay slip planes on the surface of the greywacke indicates that very little of the water percolating through the colluvium penetrates the material that has been weathered in situ.[2] In fact, below some breaks in slope, the movement at this level is increased by water emerging under hydrostatic pressure from the greywacke.

It is concluded, therefore, that the subsurface water content of the greywacke is supplied almost completely from the broad interfluves. It is also possible that the development of deep percolines (Bunting 1961) on the interfluves may concentrate the entry of water

PLATE XXIII

Slide scar and maintenance as seepage head. (Not related to general pattern of surface drainage.)



to the greywacke and influence the location of seepage heads, as the location of these features is not always related to the contour of the surface drainage (Plate XXIII). Following initiation, this position is also maintained by the increased intake area (Terzaghi & Peck 1948; Parker 1964). This results from an effectively greater hydraulic gradient, caused by a reduction in the resistive distance, which raises the hydrostatic pressure at the outlet of flow and effectively reduces it along the same contour.

III PIPING IN COLLUVIAL DEPOSITS AT WHITEHALL

1. Introduction

The movement of subsurface water and the development of pipes within the colluvium are responses to controls that differ somewhat from those operating in the weathered greywacke. The colluvial material is mixed, is less cohesive than the greywacke, and has been made more permeable by transport. Pedological structures, especially where these are influenced by root growth, do influence percolation, but material from the faces and edges of blocks is susceptible to removal in suspension. Mechanical eluviation appears to be even more rapid when the mass is still unstable following slope failure, and when it is composed of heterogeneous materials. Following mass movement flow, the contained water seeps from much of the toe, but, depending on the nature of the underlying material, may be concentrated above it or be absent along that plane.

In the study area piping and seepage do not appear to develop once flows of homogeneous materials have stabilised, except where the material is deposited on top of a swamp. However, with heterogeneous materials, piping on quite a large scale develops through mechanical eluviation. Depending upon the resistance to decay of materials providing the structural support of the walls and roof of each pipe, these networks may be temporary or fairly permanent. Thus, the examples of piping under the bush, although developing in a manner similar to that in which the systems observed under pasture developed, appear to be less permanent than the latter because support is provided almost entirely by logs and roots and collapse occurs on their decay (Plates X, XII, XXIV).

In order to understand the processes involved in the development of the systems of pipes at Whitehall, a discussion of the general mechanics of piping and the conditions necessary for its development follows.

2. The Mechanics of Piping and Conditions Necessary for its Development

Chemical eluviation involves the removal of material

PLATE XXIV

Pipe development in fine colluvium, and collapse upon loss of timber supports.

(a) Inlet to one shaft.

(b) Outlet of same shaft.

(b) View of upslope side of shaft and logs above it. (Narrow shaft, 8 - 10 feet deep, between logs.)

a

b

c

in solution, mechanical eluviation the removal of particles in suspension, and in mass movements subsurface water increases sheer stresses, reduces sheer strength, and acts as an agent of buoyancy and dispersion, either along a slip plane or in a zone of distributed shear. Thus, concentrated seepage may result in the failure of a clay particle and its removal in suspension. With increasing concentrations of water small voids may be linked, thus creating a subsurface channel, which would enlarge through the scouring and backtrickling (Gibbs 1945, p.144; Blong 1966) that accompany turbid flow in bedded materials. With the creation of a definite pipe micromass movements become important in its enlargement, and then larger slumps and collapse may occur.

Piping is most common in areas of loose sand and silt where large hydraulic head differentials have been created over short distances (Parker 1964). This hydraulic head generally results from artificial factors such as irrigation or dam construction, but very high-intensity rainfall or a landslide blocking a valley can have the same effect. Concentrated seepage, caused by this hydraulic head, may result in the removal of grains "in suspension through the more permeable parts of a permeable formation" (Parker 1964, p.103) resulting in boiling at the surface (Sowers & Sowers 1961) and entrainment that increases in rapidity with the greater effective hydraulic gradient, from a decrease in the seepage distance, and with the increased size of the flow net. The volume of flow in such pipes is large, and they are generally a temporary feature. Upon collapse, surface stream flow is again dominant.

The type of piping just described is an extreme form, but it serves to illustrate the conditions necessary for the initiation of pipes, and indicates the development of the process. Fletcher, Harris, Peterson, and Chandler (1954, p.258) stated these necessary conditions as follows:

> "(1) There must be a source of water, (2) surface infiltration rate must exceed permeability rate of some subsoil layer, (3) there must be an erodible layer just above the retarding layer, (4) water above the retarding layer must have a hydraulic gradient to make it flow, and (5) there must be an outlet for the lateral flow."

The above example supports these conditions except for the requirements of a retarding layer. The presence of a retarding layer may control seepage and pipe development, but it is not necessary (Parker 1964) as the hydraulic gradient above the base level may be sufficient to initiate piping in the presence of the other necessary conditions.

In locations where the creation of the conditions necessary and sufficient for piping is less sudden, the water supply, in the form of high-intensity rainfall, springs, or irrigation can be the critical factor. In such cases, development occurs more slowly, and boiling is generally not apparent. Wetting and drying cycles may also be important in permitting the entry of water to the subsoil (Aurousseau 1919; Gibbs 1945; Ward 1966a, b), and deflocculation and dispersion are important factors in the development of piping in clay soils (Aitchison, Ingles, Wood 1963; Cumberland 1944; Downes 1946; Emerson 1960; Ward 1966a, b, 1967; Wood, Aitchison, Ingles 1964). On the basis of this discussion it is possible to present an hypothesis explaining the development of pipes in mass movement deposits in Whitehall.

3. Genesis of the Pipes

During the pre-Taupo eruption period of intense erosion at Whitehall, massive slumps occurred in the deep regolith on the edges of the broad interfluves (Selby 1966). The material from these deep-seated movements, containing large amounts of unweathered greywacke boulders, slipped and flowed down the sides of the valleys (Plate XXV; Figure 4) in a series of lobes, and probably with intermittent, pulsatory movements. It is also probable that the floors of the gullies in which most of the material was deposited already contained accumulations of boulders and colluvial fines from earlier movements or stream erosion. The presence of a forest cover at

PLATE XXV

Amphitheatres and deposits. Note that the deposits infilling the head of the centre gully in (a) is where the best development system of pipes is located.

a

b

c

a

b

PLATE XXVI

(a) A line of seepage heads at a similar level in the deposits infilling the head of the gully below the central amphitheatre in Plate XXV(a).

(b) A single seepage head in massive flow deposits.

this time is not certain but is assumed, as climatic conditions were similar to, or warmer than, those at present (Vucetich & Pullar 1963).

It is felt that seepage from within the heterogeneous flow material of fines, boulders and trees, would have been considerable, especially if the slumps were associated with high-intensity rainfall, as was suggested by Selby (1966). Furthermore, the line of springs at the heads of the infilled gullies, but below the present level of the floors of the amphitheatres, possibly mark relict seepage heads (Plate XXVI). If this is so, there would also have been considerable movement of water directly beneath the deposition material.

In these deposits, seepage tends to concentrate on or around impervious logs, and rocks, thus creating channel flow against a retarding layer. This subsurface flow would result in the eluviation of considerable amounts of fines from the unconsolidated mass. With increasing development and coalescence of the pipes, and the decay of logs, the deposits tend to move downslope and towards the floor of the gully. These fines infilled the gullies further downslope and covered many exposed boulders. Some of the surface runoff, which washed fines from the amphitheatres and the debris, would also have percolated through to the zones of subsurface flow and increased the rate of eluviation of fines.

Development has been such that today the major zones of seepage and piping, which are maintained as subsurface flow by the skeleton-like accumulations of boulders supporting the overlying colluvial fines, are indicated by surface depressions. Under bush the tree roots support the roofs of pipes in the absence of boulders, but the removal of these roots, whether locally or over a wide area, soon results in collapse, and entrenched surface flow. This process of collapse may account for several very narrow gullies observed under pasture in the study area, and may be significant in gully development (Plate XXVII).

In all the examples observed, the boulder bed is in a shallow depression in the weathered greywacke, and has fine colluvial infill through it, on either side, and in most places forming a surface cover as well (Plate XIII). Flow is generally near the middle of the bed with seepage at lower levels in the colluvium, and also beneath the impervious surface of the weathered greywacke. Where ponding occurs with a continual water supply, swamp results, and on some steep slopes the seepage occurs through the interstistial fines (Plate XXVIII).

In summary, then, it is felt that the network of pipes in the colluvial infill in the gullies on the valley sides have developed through the eluviation of fines and decayed organic matter by subsurface flow. This has

PLATE XXVII

Gully formation, possibly due to collapse in (a) and (b)

(c) Collapse hollow in the foreground with the man standing at the head of a mass movement gully.

a

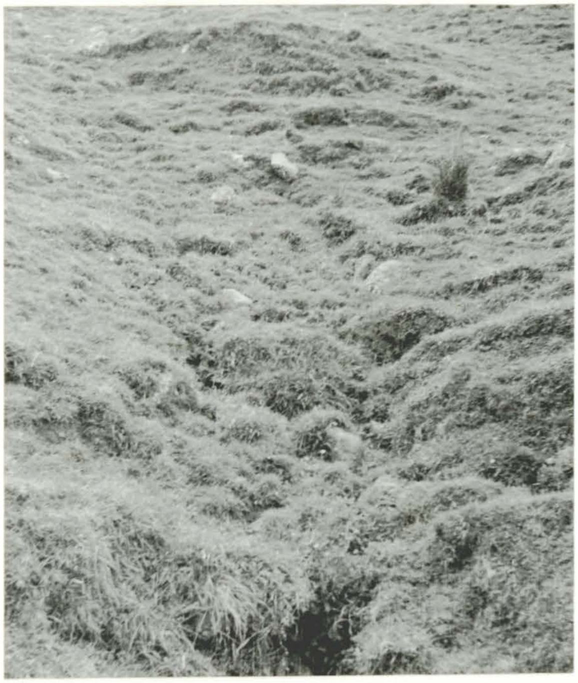
b

c

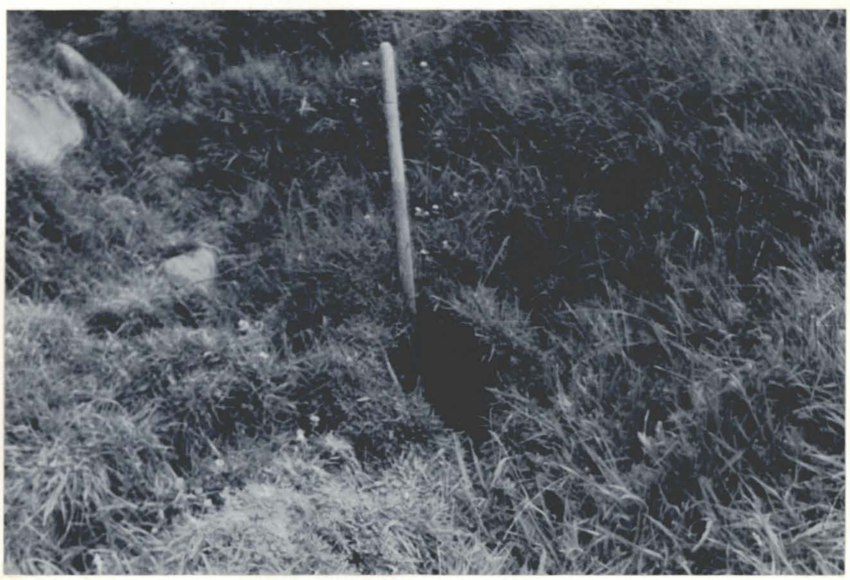
PLATE XXVIII

(a) Seepage through the colluvial fines between boulders on a 23 degree slope. Note the subsidence along the line of seepage. This feature is swampy, following prolonged rainfall, but generally the surface is dry.

(b) Swamp at low angle of slope with subsurface stream flow in a network of pipes between boulders.



a



b

resulted in a decrease in the volume of the flow deposits, and the accumulation of boulders in the channel floor. These boulders are resistent to erosion and maintain pipes, through supporting the overlying colluvium. Collapse is more rapid under pasture than under bush, and in time, the overlying colluvium may be removed to leave open streams in boulder beds, similar to those in the floor of the main valley (Plate XXIX).

IV SLUMPS, SLIDES, DEBRIS FLOWS AND WINDTHROW

The causes of slumps, slides and debris flows, and the mechanics of their initiation and development, have been dealt with in detail by Sharpe (1938), Terzaghi (1950), Skempton (1953) and Varnes (1958). As the recent features of these types in the Whitehall area are similar to the type examples discussed by these authors, only a short explanation of the possible causes and mechanics involved is given in Chapter 2. In the introduction to this chapter, the influence of subsurface water is further discussed, and the conclusion reached that in the study area the mechanics of slumps, slides, and flows are largely the result of the permeability and porosity of the regolith materials and the nature and size of the subsurface water supply. Thus, slumps and slides fail along a plane of shear, while flows, involving an almost complete loss of structure and static friction upon loss

PLATE XXIX

(a) Stream, showing boulders, swamp and subsurface flow. (See fig. 7)

(b) Pipe cutting off a meander in the stream in the bush.

a

b

of cohesion through the separation of particles by water, undergo distributed shear. They occur most commonly at locations with a permanent subsurface supply of water, and where high-intensity rainstorms occur with an already saturated regolith. This indicates the importance of hydrostatic pressures and their influence in rapidly increasing pore-water pressures, and thus in reducing cohesion throughout a potentially unstable mass (Taylor 1948). It is not proposed to elaborate on these statements in this thesis.

However, as one of the aims of this study is to assess slope failures under bush, a short note on the relationship between small mass movements and the uprooting of mature trees is felt to be necessary, with a wider explanation of the microrelief found under forest.

1. Microrelief under the Bush

The intensity of the microrelief under the bush has been stressed already. There are several possible explanations for such intensity, and it is thought, although no detailed study has been undertaken, that they may all contribute to some extent. The bush is on a south-facing slope, and this aspect on pastured slopes often results in considerable terracette formation, and small mass movements is probably due primarily to the moister conditions prevailing on south-facing slopes (Plate XXX). The

PLATE XXX

Micro relief on south-facing slopes. (Note that these slopes are steeper than most of those facing north and the angle of slope, which, however, may be influenced by the aspect, is thought to be more directly important as a control of micro relief.

effect of aspect in increasing dampness would be reduced by the bush cover, but it may be significant.

A second factor is the different rooting systems of different types of trees. Butuzova (1962) found that mature pines with a deep tap root, and many thick roots, develop butt hillocks, and that spruce trees, which have a small, saucer-shaped root system, develop a podzolic A_2 horizon beneath them, but no mounds. In the study area, tawa and rimu appear to be co-dominants and the conspicuous regeneration of the former, and the lack of rimu seedlings, has been noted. Mature rimu trees have a very dense and extensive, platelike system of lateral roots about twice the radius of the crown, and massive central sinkers. The rooting system of mature tawas, however, is compact and shallow to about half the radius of the crown, and has no tap root (Cameron 1963). A further significant factor in the growth patterns of these trees is that rimu regeneration is greatest on fallen logs, with considerable sunlight, whereas tawas regenerate on the soil, under a dense canopy (Cameron 1963). Mounding was observed at the base of trees, and, although this is due in some cases to mass movements and surface wash, it is thought to be generally the result of growth patterns. This form of microrelief appears to be greatest under mature rata trees in the study area (Plate XXXI).

PLATE XXXI

Micro relief at the base of trees.

(a) Rata butt hillock.

(b) Wash material on upslope side of a rata root.

(c) Mass movement deposits mounded against a tawa tree.

(d) Piping beneath the tree in (c), with the hammer resting on fluvially deposited sand.

a

b

c

d

However, the main cause of microrelief under the bush at Whitehall is the windthrow of mature trees. During high-intensity rainstorms and associated wind gusts uprooting is quite common on the lower and steeper slopes, and is almost entirely restricted to tawa trees (and pungas). This is thought to be largely a result of the small, shallow rooting system of tawa trees, and the saturation of colluvium overlying the more massive greywacke in the weathering mantle. Rimu, and other deeprooting trees are probably anchored into the greywacke, and are rarely uprooted, although they are taller and are in more exposed locations (Plate XXXII). The trees generally fall downslope, creating long, narrow mounds with almost vertical walls, which are perpendicular to the pit they created. With decay of the supporting roots the mound is lowered and rounded to form a dome that is oval or circular in shape, downslope from the pit. When all remains of the tree have been removed, these features closely resemble the scars and deposits of small slumps or slides (Plate XXXIII).

As windthrow is much more common than recent, shallow, midslope slides in the study area, it is thought that the former process may explain much of the microrelief,[3] and especially the small breaks in slope which were noted earlier. They do not explain the larger scars and deposits, and these are the result of earlier mass

PLATE XXXII

Illustrations of the height and location of rimu trees in relation to other species in the bush.

a

b

PLATE XXXIII

Windthrow mounds; depicted in order of decreasing relief. In photos (c) and (d) the pungas and change in slope indicate the amount that the mounds have been flattened.


a


b


c


d

movements. Windthrow is also significant in creating conditions favourable for the establishment and development of forest trees, by mixing organic matter and the soil horizons, by increasing both the macro-pore space and the non-capillary micro-pore space, and thus the permeability and porosity of the deposits, and by raising the heavy minerals[4] to the surface (Lutz 1940). Windthrow also produces "local differences in the depth to the water table - differences that may be significant in determining the relative abundance of species in a given area". (Denny & Goodlett 1956, p.60).

As a cause of mass movements at seepage heads, or other locations where subsurface water movement has reduced strength along planes of shear, the influence of wind action, and the uprooting of trees is less clear than in the creation of windthrow mounds. When these movements occur the soil is saturated, and the swaying action of trees weighted by interception loss is important in opening structural planes and, thus, in altering the pressure and movement of subsurface water. This is especially important where the base of the root system is near the impervious surface of the cohesive, weathered greywacke. If this lever action opens pipes or lines of seepage under considerable hydrostatic head, a drawdown effect may be expected to result, further reducing stability.

It is felt to be significant that whereas windthrow on ridges and midslopes is generally not associated with mass movements, the same process in zones of continual water movement is usually accompanied by the failure of at least a small mass of saturated material (Plate XXXIV). The increased water movement and hydrostatic pressures are felt to be significant causes in this accompanying slope failure. Where uprooting precedes failure, the lever action of the falling tree and its impact may induce movement of the larger mass. In such cases the regolith material is well mixed along the trunk or through the crown of the tree. However, in other cases, the nature of the regolith materials, the subsurface water, and the root structure and swaying action of the tree involved, results in more general slope failure preceding the actual uprooting of the tree. Unless the mass movement is large, the tree tends to lie on the surface of the slide or flow deposits.

The direct results of these basic processes of wind and water movement accentuate each other, and though, in some cases, one may be obviously dominant, it is generally their interaction that results in a combined failure, and only the immediate cause of rupture can be attributed to any one process.

PLATE XXXIV

(a) Slide combined with windthrow at a seepage head. (The tree involved is to the left of the photograph.)

(b) Windthrow on a dry section of slope, without any accompanying mass movement.

a

b

V WATER BLOWOUTS

The origin and use of the term 'water blowout' is noted in the introduction to Chapter 2, III, with a discussion of the causes and mechanics involved in the development of these features. The most important conditions necessary for their development appear to be a rapid and very large increase in hydrostatic pressures, and regolith materials that permit these pressure increases but undergo a localised and explosive type of rupture and flow of the subsoil when they become critical. Several features exhibiting the characteristics of water blowouts were observed at Whitehall following Cyclone Dinah and these are described in Chapter 2, III, 2 & 3. Depending on the properties of the regolith materials, and the nature of the water movement and increases in hydrostatic pressures in each example, the development of these features ranged from explosive bursting under the pasture, to very rapid and fluid mudflow in one example under the bush. Complete structural collapse and loss of static friction within the flow material is essential. The large amounts of interstitial water in comparatively light and friable materials create a buoyancy effect similar to that of fluidization with entrapped air in large rockfalls, which "permits high speed movement of the fall as a flood of unsorted rock fragments over irregular ground and obstacles" (Kent 1966, p.79). The following explanation refers specifically to the three explosive water blowouts on the pastured slopes, and then reference is made to the less extreme development of those under the bush in an attempt to account for these differences between them. In all cases the proximity of the weathered greywacke to the surface and the flow of material along it indicates its effect as a perched water table.

Rainfall at the time these water blowouts developed was the most intense recorded in the area (Table 1B) and thus, would be expected to raise hydrostatic pressures rapidly. In the seepage head example the pipe and cracks would permit the rapid subsurface flow necessary to achieve this, but unless there were large cracks through the topsoil, it is difficult to explain the entry of the large amounts of water necessary for the development of such features in the midslope examples. However, if such cracks were present, and it is thought that they must have been, the flow into the extremely porous, allophanic ash would have been very great because the location receives the runoff from about four acres of the compacted and sloping toe of an airstrip.

In all cases water movement through the fluffy Rotorua ash is virtually unrestricted, and it probably concentrated in depressions along the surface of the weathered greywacke. However, it is felt that the pressures required for the development of water blowouts would not have built up under the rainfall and conditions of water entry experienced without the presence of a restricted outlet. In the case of the seepage head example, this increase is difficult to account for, as it appears to have occurred on a free face. However, the outlet of the pipe may have been blocked by a small slide or the collapse of some of the overlying material. The pastured topsoil, with porosity reduced by drying subsequent to animal treading under wet conditions (Gradwell 1960), is felt to have effectively blocked the outlet of flow in the other examples.

The influence of the drying out of the soil in these slope failures cannot be stated in absolute terms, but cracking is felt to be extremely important. During a rainstorm of only slightly less intensity in March 1966, the moisture content of the soil is the only factor known to have differed significantly from the conditions in February 1967, yet slight sliding at some seepage heads was the only mass movement that occurred. Prior to the 1966 storm the soil had been saturated by 2" of rain over a period of six days, but in 1967 there was no recorded rainfall over the two weeks preceding Cyclone Dinah. Although water movement through the Rotorua ash is virtually unrestricted, the findings of Horton and Hawkins (1965, pp.377-8) that percolation "is accomplished throughout most of the flow path by downward displacement of water previously retained by the soil at field capacity . . . even with abnormally large amounts of rain", indicate that cracks through the topsoil may be necessary to create sufficiently rapid entry of water to cause water blowouts. The findings also indicate the importance of a critical rainfall intensity in causing slope failure, through permitting increased water movement through the macro-pores to a zone of shear.

The moisture content of the regolith under the bush, the remoulded nature of the colluvium, the presence of root channels, and the absence of a tight pasture cover are felt to have permitted more general rupture at lower hydrostatic pressures, and with slower and less liquid flow and, thus, to be largely responsible for the different form of the water blowouts under this vegetation cover.

The third important factor is the nature of the subsoil. It consists almost entirely of Rotorua ash and is extremely light and fluffy. With moderate weathering there is a 20-30% clay content,[5] which is composed almost entirely of allophane (Fieldes 1962). Allophane is a finely divided, amorphous mineral (Gradwell 1955) with a "structure consisting of hydrous alumina octahedra randomly cross-linked by silica tetrahedra tending to regroup to a [more ordered] kaolin structure". (Fieldes, Walker, Williams 1956, p.38). The water-holding ability of allophanes, their tendency to aggregate with organic compounds, and other physical properties may be important in the type of failure that occurred.

In the allophane there is no appreciable internal surface (Gradwell & Birrell 1954) but water is held there in single layers (Fieldes 1957) in a quasi-crystalline form (Sears 1960; Yong & Warkentin 1966). However, physical absorption of cations is strong (Birrell & Gradwell 1956) and gives rise to abnormally high surface area values of water in hydration shells (Birrell 1966). This is of importance because allophane, by virtue of its extremely small particle size and large surface area, has a high liquid limit, but airdrying results in the aggregation offine particles and the liquid limit may fall by 50% (Gradwell & Birrell 1954). The allophane may be expected to have had a considerable effect on the whole subsoil in the zone of the water blowouts.

The allophane behaves as a slowly reversible gel of high water content and, with the high void ratio, is fairly sensitive (Gradwell & Birrell 1954; Skempton 1953; Yong & Warkentin 1966). The formation of aggregates results from "stronger cohesive forces between particles within the aggregate than between aggregates" and polar organic compounds, of which there are considerable amounts in the allophane, "form physiochemical bonds with the surface active clays which prevent breakdown of the aggregates on wetting" (Martin <u>et al</u> 1955, pp.11 & 28; Hutcheon 1942). The tendency to aggregation is high with allophanes, resulting in non-sticky silt and even sand-sized particles and the underestimation of the clay content of the soil (Birrell 1966). This underestimation could well aid in the explanation of the fluffiness of the subsoil where the water blowouts occurred, and, if underestimation is the case, then the influences of surface water absorption and the active fraction would become even more important, as a result of the increase in small particles (Fieldes 1962).

Initially, the allophane hydrogels contain much water, preventing shrinkage and further development (Fieldes 1966), but air-drying and increased cross-linking result in more compact xerogels. The process is irreversible and it is the allophane xerogels which give these soils their friable feel (Fieldes 1962; Fieldes & Furkert 1966), as well as the influence of the high void ratio from aggregation and the airfall origin. However, acidity, which is highest with moderate weathering (Birrell 1962), as in the Rotorua ash in Whitehall, encourages the persistence of hydrogels (Fieldes 1962). Further evidence supporting this discussion is that the moisture and compaction characteristics of the materials indicate the liability to failure of the finer textural members of the rhyolitic volcanic ash deposits (Birrell

1952, 1956). Thus, the overburden and compaction from the airstrip may also have been directly important in increasing shear stress.

The higher moisture content of the percolines most probably results in the maintenance of hydrogels, and more rapid flow of moisture, and because of this and the link to the surface by the flow pattern of the upper horizons (Van't Woudt 1954; Leatherwood & Peterson 1954), it is postulated that rupture and flow first developed along these lines of movement. It is also felt that soil moisture flow induced by thermal gradients prior to saturation, as discussed by Gurr, Marshall and Hutton (1952) and Hutcheon (1956), would have been negligible, and certainly would have been insignificant as a cause of the water blowouts.

The chief conclusion drawn from this discussion is that the ash at the site of the blowouts is potentially unstable, and would, upon disturbance while saturated, undergo almost complete structural collapse and rheotropic alteration, with the net loss in volume releasing internal energy (Hutchinson 1961). The nature of the deposits is felt to support this conclusion.

The incipient slump influenced the exact location of the smaller of the two midslope water blowouts, and the centre of the other is felt to mark a percoline. The percoline and subsurface storm flow pattern may be expected to have reduced shear strength near the surface and when the water pressure in the continuous, loose layer of the ash reached a critical level, rupture occurred there. Rupture in this type of material "immediately raises the water pressure . . . at the point in question, and reduces the strength . . . in this place to zero. As a result, the stress increases in the adjacent parts of the . . . layer, and the high water pressure is also transmitted to these parts". (Kjellman 1955, p.169). This is the type of rupture and outflow that is believed to have occurred, being more explosive in some cases than in others. Expressed slightly differently, the mechanics of this failure involved rupture, followed by almost instantaneous boiling and entrainment until stability was re-established with the loss of hydrostatic head, and collapse of the overlying turf and sections of the side walls.

Thus, these water blowouts are, in effect, very short sections of pipe that undergo complete development from a stable slope to an open gully almost instantaneously. They form the intermediate, or linking, case in the range of piping and mass movement processes.

VI SUMMARY

The individual mass movement and piping processes discussed occur within a continuum of denudation processes, from solution to slumping to windthrow. Piping within the weathered greywacke and the overlying colluvium has been described and discussed, as have the more discrete mass movement processes, with respect to the materials involved, the causes and mechanics of development, and the significance of subsurface water in causing individual failures.

Footnotes

(1) The settlement of sand-sized and little-weathered material in troughs supplied these springs emerging from the greywacke indicates the depth of flow, the importance of mechanical eluviation, and a source of some of the colluvial infill in the gully floors.

(2) No infiltration tests were conducted, but even in the more permeable horizon of a soil developed from greywacke, infiltration is in the order of only 0.09 cm/hr (MacDonald 1961).

(3) The conclusion that windthrow is an important cause of microrelief in forested areas is supported by the findings of Lutz 1940, and Denny & Goodlett 1956, in the U.S.A.

(4) The heavy minerals (sp.g. greater than 2.68) which weather fairly rapidly and are important sources of nutrient elements, generally increase with depth in forest soils (Lutz 1940).

(5) This clay content may be an underestimation in many cases (Birrell 1966).

CHAPTER 4. GENERAL SUMMARY AND CONCLUSION

I SUMMARY AND CONCLUSION OF THE ACTIVE PIPING AND MASS MOVEMENT PROCESSES IN WHITEHALL

It has been stressed throughout this thesis that all mass movement and piping processes operate within a continuum of denudation processes, and that any particular feature is the expression of a critical relation between sheer strength and sheer stress in the materials involved. Generally the elastic properties of earth materials are such that temporary remoulding occurs almost unnoticed, but the attainment of this critical relationship produces failure out of all proportion to the reduction in the ratio between sheer stress and sheer strength that is necessary for the initiation of movement.

Seepage and piping in the weathered greywacke is primarily controlled by the fracture-jointing in the base rock. The fracture-jointing was caused by uplift and was maintained during weathering by water movement and the development of cutans on the faces and edges of blocks.

In the colluvium, the piping is generally related to the previous surface drainage pattern. It is best developed in heterogeneous materials, and probably originated under a forest cover. Without the accumulations of stones and boulders from the massive slumps and flows on the edges of the interfluves, these pipes collapse upon decay of the supporting roots and logs. Even with the boulder beds the development is towards further collapse, through the eluviation of fines, and the re-establishment of surface drainage.

Slumps, slides, and flows are most common at seepage heads, indicating the importance of the piezometric head and the movement of subsurface water in lowering the sheer strength of the regolith, through reducing the effective weight and interparticle contact of the materials at these locations. This is also noted by the empirical Coulomb-Terzaghi formula, which is considered as the fundamental relation of soils mechanics.[1]

The lever action of swaying trees is important in creating critical shear stress: shear strength ratios at seepage heads, and at drier locations windthrow is an important process in the creation of microrelief, and in the regeneration pattern of the bush.

Water blowouts are slope failures with a mass movement form that develop by failure involving almost instantaneous piping and structural collapse. The more explosive water blowouts develop where there is a rapid increase in hydrostatic pressures, localised rupture, and an easily eroded subsoil. In the study area, the factors creating these necessary conditions appear to be: extremely high-intensity rainfall following drying of the soil; entry of water to the loose and fluffy, allophanic Rotorua ash, which has physical properties making it especially liable to failures of this type; concentrated water flow on the surface of the greywacke, and; a dense pasture cover to permit the buildup of pressures necessary for explosive rupture upon the attainment of a critical shear stress to shear strength ratio.

Under forest cover the development of mass movements with the characteristics of water blowouts are less extreme, and are in the form of highly saturated flows. This results from the effects of the bush in ameliorating rainfall intensity, maintaining the water table at a lower level than under pasture, preventing drying out of the soil and maintaining strong aggregates, and in permitting rupture of the surface at lower pressures in the absence of a dense, binding mat of grass roots. In the study area all the bush is on colluvium, which is less susceptible to rapid piping and flow-type failure than is the loose, airfall Rotorua ash.

The major effect on mass movement of the removal of forest cover, and the resultant changes in the physical properties of the soils, is to be seen in the absence of windthrow mounds and their replacement by shallow slides and slumps which are not common under the bush. Water blowouts appear to have a more extreme form under pasture, but at seepage heads, where there is a continual subsurface supply of water and where mass movements most commonly occur, the type and size of failure varies within similar limits under either vegetation cover.

Field evidence indicates that the three conclusions stated in the preface to this thesis do not apply to Whitehall. There is at least as much recent and active mass movement under the native bush as on the pastured slopes; piping does occur under the bush, and water blowouts, which are classified as mass movements, flow, rather than slide, upon rupture.

However, it is stressed that these conclusions apply only to the study area and should not be extended without more widespread field observation. Most geomorphological study in New Zealand has been undertaken under pasture with virtually the complete absence of even cursory studies under bush. Also, analyses of mass movement features are often conducted long after their occurrence and so the importance of subsurface moisture and the nature of the deposits as clues and mechanism of movement are not realized. Thus, it would appear that the conclusions in the preface, far from being based on erroneous observation and analysis, are primarily the result of insufficient field work under varied climatic, vegetational, lithological, and structural conditions.

There is a very definite lack of quantitative and advanced study on the importance of subsurface water as a geomorphic agent, and the nature of its different processes under a variety of conditions. This may be due to a failure to recognise its importance, and to the difficulties of observation and measurement beneath the surface of the ground, and the necessity of conducting detailed investigations of the properties of the clay fraction and their influence on the regolith.

II GENESIS OF THE LANDFORMS

> Selby (1966, p.41) "assumed that the main valley has been cut by a stream which may have been assisted by mass movement. The minor valleys show virtually no sign of stream erosion and are thought to have been formed by mass movements. The present land surface indicates that this is of two main types. On many of the steep slopes large debris slides with no rotational movement occur. . . . The second type of mass movement is a slump. . . . Evidence of the rotational movement is present in the forms of the mounds of boulders and ash in the amphitheatres. . . . The floors of the minor valleys are infilled with redeposited fine ash and weathered greywacke, which has been washed out of the mass movement debris."

The present study supports this suggested genesis and provides further explanation of the development of the long, narrow gullies, some of which were infilled by the large debris slides and slumps that formed the amphitheatre-like features on the steep slopes and at the

PLATE XXXV

(a), (b) and (c) illustrate a variety of gully forms that are found in the study area.

a

b

c

e

d

f

g

h

PLATE XXXV (cont.)

(d) A fairly steep-sided gully caused by mass movement. Seepage is present immediately below the surface of the mounded deposits in the foreground.

(e) and (f) illustrate a similar gully under pasture. This gully developed under bush but has been smoothed by discing and stock trampling. Seepage is present at the break in slope in the middle background.

(g) and (h) show similar, but shallower, gullies under bush and with a pasture cover.

edges of the interfluves. Observations of numerous gullies at various stages of development has led to the conclusion that they formed under forest, and that small mass movements at the outlet of zones of continual, or intermittent, concentrated seepage have been the chief agent in their development (Plate XXXV). Many incipient and well-formed gullies under bush and under pasture continue to develop by these processes at present.

A very good example of this type of gully development is found at GR N66/100377. The flow and wash deposits at the mouth of the gully are almost level, but form a bank at the stream, and the surface flow is only slightly incised (Plate XXXVI). Further up the gully the walls have been steepened by mass movements and the floor is very rough, with a deeply incised channel in the predominantly fine, colluvium. Numerous small mass movement features are found along this channel, with pseudo-pipes, seepage along logs, and small waterfalls as well (Plate XXXVII). About 150 yards upslope from the gully mouth is a small, but deep, amphitheatre caused by mass movements, and five major lines of seepage, three of them in gullies, enter this feature (Plate XXXVIII). With continued development these gullies may coalesce and create a much larger amphitheatre. One of the gullies appears to be fairly stable at present, another has a water blowout, or thin liquid flow, at its head, and the

PLATE XXXVI

The lower section of a mass movement gully under bush.

(a) Flat floor at the mouth of the gully, with incising channel.

(b) Vertical bank where the floor of the gully intersects the stream in the valley floor. The dense mat of tree roots reduces erosion, but collapse of sections of the bank is common.

a

b

PLATE XXXVII

Micro relief features in the middle section of the gully.

(a) Deep, narrow channel.

(b) Similar to (a), but channel almost covered by colluvium and vegetation at the surface of the flow deposits.

(c) A small waterfall, illustrating the importance of logs and boulders in influencing water movement in gullies of this type.

(d) The knife is in a log with seepage and gleying around it. This water movement had caused a small slump, which revealed the lens of gleyed clay and the pipe along the log.

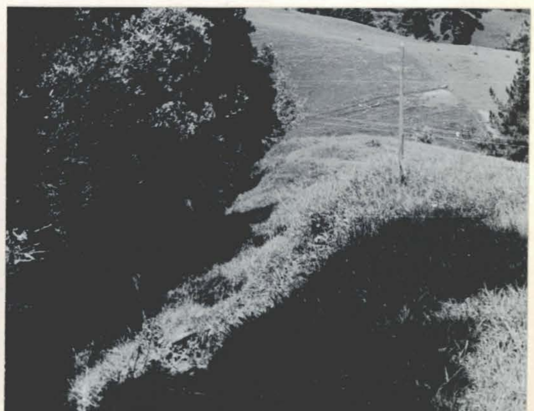
(e) The shape of the gully wall, and the sharp break in slope at the upper limit of mass movement.


a


b

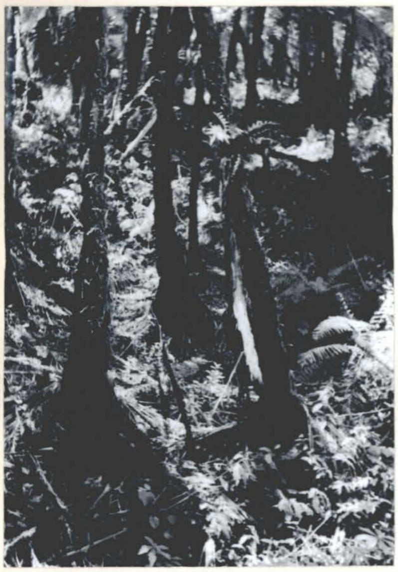

c


d


e

a b

d



c

e

PLATE XXXVIII

(a) through to (d) illustrate the shape of the deep amphitheatre at the head of the gully. (The shadows indicate the angle of each photo in relation to a single datum.)

(e) depicts the back wall of a slump or slide near the amphitheatre, and it illustrates the shape of the amphitheatre more clearly with less obstruction from trees.

third appears to be developing by piping, collapse, and small slumps and slides (Plate XXXIX). In each case, the movement of subsurface water has been of great importance in influencing the form and scale of development.

The importance of concentrated subsurface flow is evidenced by the large number of mass movements occurring at gully heads, where there are either springs or percolines. Geomorphic processes, but especially land development, have smoothed the outline of these gullies and, with surface wash, have infilled the floors with fine material. At seepage heads, mass movement material settles and forms shallow swamps.

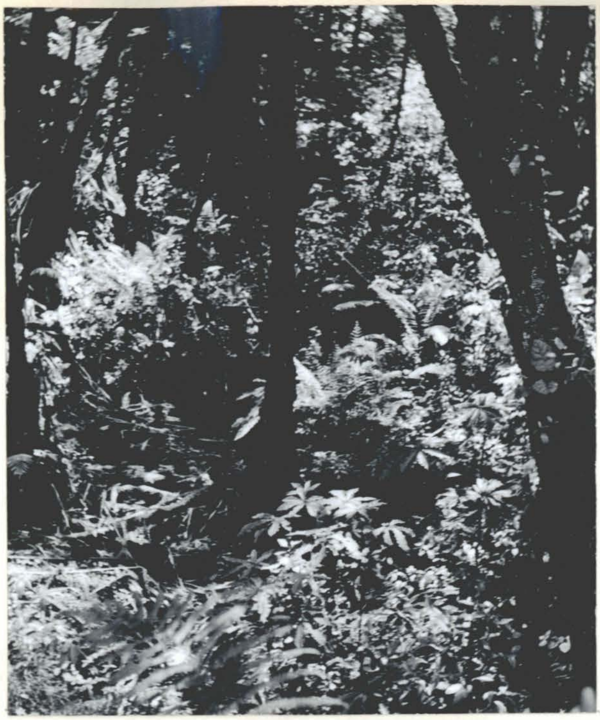
Many of these gullies are developing upslope along the floors of large debris slides and slumps[2] that do not have surface flow. Others are forming on long slopes which show no evidence of large-scale mass movements. However, in every case, subsurface water flow appears to be present during the occurrence of the mass movements that create these gully forms.

The different stages of development of these gullies, and the nature of the processes operating at present, provide considerable evidence in support of Selby's conclusion, which is based primarily on the presence of these gullies, and on the form of the amphitheatres, (which Cotton & Te Punga [1955a, b] and Stevens [1957a, b]

PLATE XXXIX

Plate XXXIX depicts the form of the three gullies upslope from the amphitheatre, and it also indicates the method of development of each.

(a), (b) and (c) show a gully that is stable at present, but has developed by small mass movements which have been sufficiently fluid not to remove some of the pungas in the floor of the gully.


a


b


c

PLATE XXXIX (cont.)

(d) illustrates a water blowout at the head of the second gully. This water blowout has truncated the boulder bed (e) of the original line of the gully.

d

e

PLATE XXXIX (cont.)

(f), (g) and (h) are photographs of the third gully.

(f) depicts a pipe and a small slide.

(g) is of a windthrow mound at a small seepage head a little further up the slope.

(h) is just upslope from the seepage head and appears to be a collapse hollow. (It is assumed that worms of the size shown in (h) may play a significant part in promoting rapid drainage, and hence eluviation, from such hollows.)


f


g


h

actually attributed to solifluxion processes in the Wellington area). Selby concluded that "Cotton's statement, 'Relief of fine texture due to sculpture by streams of running water is characteristic of New Zealand' (1958a, p.187) has to be modified to include mass movement. Lauder's suggestion that . . . 'there has been only moderate modification of our landscape in the last 10,000 or even 100,000 years' . . . likewise has to be modified. . . . The outstanding feature of the northern greywacke ranges is the incompetence of contemporary stream erosion and the significance of mass movement." (Selby 1966, p.43)

III EQUILIBRIUM THEORY AND WHITEHALL LANDFORMS

Equilibrium theory does not explain the origin of the Whitehall landforms, but it does aid in providing a framework for viewing and understanding them. In the equilibrium concept the entire topography is a single system, but individual segments may undergo discrete adjustment to local changes in energy input. Thus, in every area at any particular time there are some features that are in equilibrium and others that are not (Schumm & Lichty 1965). In an area such as that being studied, where mass movement is the primary agent of landform sculpture, slope stability indicates a steady state. Thus, the amphitheatres are now stable, and achieve stability for the interfluves between them, but discrete segments of the valley-side slopes still fail during rainfall intensities with a fairly short return period.

This readjustment involves the concept of interdependence of all parts of the landscape and environment, that was expressed by G. K. Gilbert (1877). Melton (1957, 1960) and others (e.g. Selby 1967a) have also stressed this interdependence of variables in the landscape, with land-surface morphology at any given time being an expression of their total interaction, and oppose any single-cause explanation of landform features. When there is a change in the flow of materials into the open system of the landscape this interaction of variables is also altered and causes readjustment to take place (Strahler 1950), but there is no particular cycle or succession of changes through which the forms inevitably evolve (Hack 1965).

However, even with the attainment of a condition of dynamic equilibrium, the system is one of work and through-put of energy, and can never achieve the static condition of maximum entropy (Leopold and Langbein 1962) that appears to be implicit in the closed system framework of Davisian geomorphology.

The influence of lithology and structure on land-form development is well-known (Jackson 1966; Melton 1957; Russell 1959; White 1949), for "the form produced by a given process acting on any given rock is maintained as erosion proceeds." (Hack 1966, p.6). In the Whitehall area recent uplift of the hard basal greywacke has resulted in the maintenance of broad, rounded interfluves and moderately steep slopes with incising streams in the main valleys. Valley-side gullies are formed entirely within the regolith and as mass movement is the chief process in their development and is still active, this is felt to indicate an imbalance in the system. Without such an imbalance the steady state "manifests itself in the development of certain topographic form characteristics which achieve a time-independent condition. . . . Erosional and transportational processes meanwhile produce a steady flow . . . of water and waste from and through the landform system". (Strahler 1950, p.676). "As the landmass is reduced, both slopes and stream gradients are reduced, being slowly and continuously regraded to maintain approximate equilibrium." (Strahler 1950, pp.810-11) and this is accompanied by a reduction in the rate of weathering and denudation "because of the lesser potential energy available in any part of the system" (Hack 1965, p.8). However, there is no evidence that this graded development is occurring in Whitehall.

This imbalance in the expression of the interaction between landforms and environment in the Whitehall area is felt to be due to changed sets of conditions caused by the recent and rapid uplift, the depth of weathering, the deposition of ashes resulting in overburden compaction and a regolith with varied physical properties, and by the occurrence of high-intensity rainfalls. Of these changes the last is undoubtedly the most important in causing mass movements in Whitehall. The first three are slow processes and this is significant because earth materials all have a certain elasticity (Holmes 1965; Strahler 1952) and may adjust to slow changes without failure, but high-intensity rainfall creates very altered conditions instantaneously, in geologic time, and rupture, which is irreversible, generally results. The mass movements that occurred in the study area during Cyclone Dinah (1967) exemplify the importance of high-intensity rainfalls in creating a critical relationship between shear stresses and shear strengh, especially when the ratio has already been reduced by other factors. The effects of high-intensity rainfall in causing widespread slope failure have, during recent years, been emphasised by several writers (Wolman & Miller 1960; Blong 1965; Bunting 1964; Elder 1963; Grant 1965; Jackson 1966; Scott 1963; Selby 1966, 1967a, b). Once rupture has occurred smaller failures continue to occur within most features as a result of the oversteepened walls and, in the Whitehall area, the supply of concentrated seepage to reduce cohesion and effective weight of the material. One result of this tendency is that gullying tends to continue at various levels within any one feature, and this is very unlike the regular type of slope retreat by gullying that Beaty (1959) postulated. This is also clearly illustrated in the series of slumps and slides occurring within each other on the end faces of many spurs, truncated by active stream erosion, in the Tertiary banded mudstones and siltstones in parts of the Gisborne-Wairoa area.

With the reduction in potential energy that is concurrent with development towards a steady state, the forces required to initiate failure on any particular slope facet will tend to increase. However, in the open system of the landscape, this simple closed system case is complicated by the input of energy and material from higher up the valley sides, as, for example, with the outflow from the amphitheatres and other mass movements. Thus, although many of the slopes appeared to be approaching a steady state, mass movements have occurred frequently during high-intensity rainfalls following the removal of the bush.

At present, the study area is a landscape with stable interfluves, less stable valley sides under pasture where shallow slide planes develop, and potential instability at the outlet of zones of concentrated seepage, with mass movements tending to concentrate in the scars or deposits of earlier slope failures.

IV GENERAL CONCLUSION

The geomorphic processes and features described and discussed in this thesis all appear to be discrete examples within a continuum of denudation processes, from the continuous, or nearly continuous, eluviation by solution of certain minerals, to non-periodic slides and slumps involving little loss of structure within the moving mass. Windthrow provides an intermediate type of process linking eolian and mass movement processes, and water blowouts appear to link mass movement and piping processes. These processes are acting entirely within the regolith, which consists mainly of silt and clay-sized material, and contains some undecayed organic matter and corestones of unweathered greywacke.

Throughout this range of geomorphic processes noted in Whitehall, the chief variation appears to be in the void ratio and water content of the mass, and the nature of the water movement. These factors are strongly influenced by the permeability, porosity, and stability of the materials at different levels within the regolith, by the depth of the water table, and by the size and availability of the potential water supply.

The basic processes of geomorphic development in the study area are the weathering of the regolith and the subsurface movement of water under gravity. Under certain conditions the interaction of these processes becomes critical and failure of part of the regolith occurs. Subsurface water, through increasing shear stresses and reducing shear strength within the mass of the weathered material, is extremely important in creating these critical conditions. The individual piping and mass movement processes described and discussed are distinguished largely from the form of this failure and the nature of the subsequent movements, which are generally indicated by the shape of the scar and the shape and content of the resultant deposits. These processes are primarily responsible for the valley side morphology in the study area, and surface flow appears to be relatively ineffective as an agent of erosion on these slopes.

The final conclusion drawn from this brief and superficial study requires much substantiation by: detailed investigations of the flow nets in and beneath the regolith in relation to rainfall intensity and previous dryness; testing of the physical properties of the regolith materials in different stages of remoulding and at different moisture contents; studies of the relationships between soil moisture and soil strength under different vegetation covers and at different degrees of compaction, and; by multivariate analyses to establish the presence or absence of a significant correlation between rainfall intensity, the length and angle of slope, hydrostatic pressures, and the frequency and magnitude of various mass movement processes. However, initial findings in the study area indicate that the influence of subsurface water on slope stability is such that not only is the statement in the U.S. Bureau of Public Roads' handbook of Landslide Investigations (p.19) that "Groundwater . . . is the most important contributory cause of landslides" conclusively supported by this thesis, but that subsurface water is a major agent of landform development in the ash-mantled greywacke ranges at Whitehall.

Footnotes

(1) The formula is: $s = c\ (O - hw) \tan \varnothing$ where: s is equivalent to shearing strength; c to cohesion of soil particles; O to the pressure normal to the shear plane; hw to the hydrostatic head of pore-water; and $\varnothing$ to the angle of internal friction.

(2) All the amphitheatres that were investigated occurred between the Rotoma and Taupo eruptions, as the pre-Taupo ashes are mixed with weathered greywacke, but the Taupo lapilli overlies the features in a thin layer. This indicates a period of very intensive erosion, and high-intensity rainfall is suggested as a probable cause. (Selby 1966).

APPENDIX : WHITEHALL RAINFALL DATA, 1962 - 1967

The following table is based on local records and it should be noted that the number of raindays is only the number of days on which rainfall was recorded, and thus would not include days on which there was only a light shower, although an automatic recorder would have registered these falls. However, the table is presented to show the variability of the rainfall, both in total and intensity, and this is clearly illustrated.

Year, month	Total fall	Recorded raindays	Greatest 24 hour fall
1962			
March	7.68	7	2.50 ins
April	4.97	4	2.33
May	6.58	6	2.25
June	7.14	6	2.43
July	5.31	6	1.71
August	6.12	8	1.44
September	3.34	5	1.22
October	9.11	9	2.00
November	7.23	10	1.57
December	6.24	9	1.63
1962, Total (M.-D.)	62.58	70	2.50
1963			
January	2.40	-	-
February	2.96	6	1.06
March	2.40	6	1.20
April	1.48	6	0.47
May	4.04	7	1.20
June	5.47	11	1-1.05
July	9.55	12	1.40
August	3.61	7	1.28
September	3.43	5	1.07
October	1.58	4	0.69
November	3.14	7	0.75
December	3.05	8	1.30
1963, Total	44.82	79	1.40

Year, month	Total fall	Recorded raindays	Greatest 24 hour fall
1964			
January	2.47	-	-
February	1.44	2	1.34
March	5.43	11	1.93
April	1.85	2	1.30
May	6.26	13	1.43
June	6.10	12	1.50
July	6.65	20	0.90
August	5.80	14	1.15
September	6.10	14	1.20
October	6.03	14	0.96
November	2.29	10	0.59
December	3.37	7	1.61
1964, Total	55.67	119	1.93
1965			
January	4.08	5	2.07
February	6.71	9	2.40
March	4.96	9	2.15
April	3.76	6	2.30
May	6.15	7	1.73
June	3.92	6	1.80
July	6.04	10	1.13
August	6.77	10	1.98
September	1.63	6	0.53
October	2.99	7	1.55
November	3.66	8	0.90
December	3.20	8	1.26
1965, Total	53.87	91	2.40
1966			
January	7.25	-	-
February	3.48	7	1.40
March	7.73	10	4.02
April	4.89	6	1.51
May	3.40	5	2.90
June	5.93	8	2.55
July	5.88	8	1.45
August	4.71	7	2.00
September	5.00	9	2.07
October	1.58	4	1.00
November	5.58	9	1-1.75
December	4.59	8	1.44
1966, Total	60.10	81	4.02

Year, month	Total fall	Recorded raindays	Greatest 24 hour fall
1967			
January	4.08	8	-
February	9.84	6	6.16 (21 hrs)
March	6.39	5	2.65
April	1.47	5	0.53
May	5.87	7	2.00
June	1.04	6	0.61
July	3.58	6	1.18
August	7.68	12	1.40
September	3.24	6	1.00
October	1.56	9	0.26
1967, Total (Jan.-Oct.)	44.75	70	6.16

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