

**EFFECTS OF BASEMENT LITHOLOGY, REGOLITH,  
AND SLOPE ON LANDSLIDE POTENTIAL,  
OTAGO PENINSULA, NEW ZEALAND**

**By D.M. LESLIE**

Soil Bureau, Department of Scientific  
and Industrial Research, Dunedin

**NEW ZEALAND SOIL BUREAU SCIENTIFIC REPORT 12**

**DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH, N.Z.**

**1974**

Bibliographic Reference:

LESLIE, D.M. 1974: Effects of basement lithology, regolith and slopes on landslide potential, Otago Peninsula, New Zealand. New Zealand Soil Bureau Scientific Report 12. 25 p.

LESLIE, D.M. 1974: Landslide potential on Otago Peninsula, New Zealand. Scale 1:31,680 (1 inch to 40 chains). New Zealand Soil Bureau Map 135, part New Zealand Soil Bureau Scientific Report 12.



## CONTENTS

Summary	5
Introduction	7
Landslide Classification and Distribution	8
Causal Factors of Landslides and Slope Development	9
Basement lithology as a factor in landslide occurrence	9
The regolith as a factor in landslide occurrence	12
Slope as a factor in landslide occurrence	17
Contributory Factors	17
Classification of Landslide Potential	19
Conclusions	23
Acknowledgments	24
References	25

## LIST OF FIGURES

- Figure 1. Location map.
- Figure 2. Successive generations of landslides - Allans Beach Road. Debris avalanche (with levees) (A) developed from a debris slide (B); older and quasi-stable debris slides (C); debris flow with actively eroding scarp (D); remnant levee (E) of old debris avalanche (F).
- Figure 3. Left flank scarp of slump, adjacent to Papanui inlet. The regolith is deep primary loess (fragipan A) overlying basaltic agglomerate. Arrows locate striations that indicate movement direction. Landslide debris in the foreground is rotated back toward the slump crown.
- Figure 4. Debris avalanche (A) near Peggy's Hill. Flow debris (B) extended 200 m down valley. Arrows locate tension cracks. Potential landslide zones (C) and old landslide debris accumulations (D) are shown.
- Figure 5. Extensive landsliding near Portobello township. Arrows locate tension cracks of potential landslide zones. Debris flow (A) developing from debris slide (B). Older landslide debris (C) is shown. Crosses indicate logs of the original indigenous forest.
- Figure 6. The relationship of basement lithology to landslide type and distribution.
- Figure 7. Weathered anorthoclase trachyte saprolite and soil formed on it.
- Figure 8. Weathered basaltic agglomerate saprolite.
- Figure 9. Shallow loess/volcanic solifluction material (A) overlying weakly weathered basalt saprolite (B).
- Figure 10. Weathered theralite saprolite showing close jointing and core stones and soil formed on it.
- Figure 11. The relationship of regolith type to landslide type and distribution.
- Figure 12. Primary loess showing a well developed pedologically modified (A) and unmodified (B) fragipan, prismatic structure and "vertical cracks" or "gammations" (C).
- Figure 13. Loess colluvium (A) overlying weakly weathered phonolite (B).
- Figure 14. Deep solifluction debris near Glenfalloch.
- Figure 15. Relict cryoplanation surfaces with boulder fields near Highcliff.
- Figure 16, 17, 18. Typical longitudinal slope profiles showing the relationship between basement lithology, regolith type and slope.
- Figure 19. The relationship of slope to landslide type and distribution.
- (back pocket) Classification for landslide probability potential (New Zealand Soil Bureau Map 135).

## SUMMARY

Landsliding on the Otago Peninsula is a significant soil-forming process, which accounts in part for the intricate soil mosaic and has particular relevance to all forms of land use planning. The paper outlines the incidence of landsliding, classifies the various landslide types, and assesses their distribution pattern in relation to the three most important causal factors (basement lithology, regolith, and slope) that influence the degree of instability on natural slopes. A classification of landslide potential is presented based on an evaluation of these causal factors.

The study is relevant to theories of slope development in regions where slope processes under a temperate climate are superimposed on a landscape in which many relict Quaternary features are preserved.

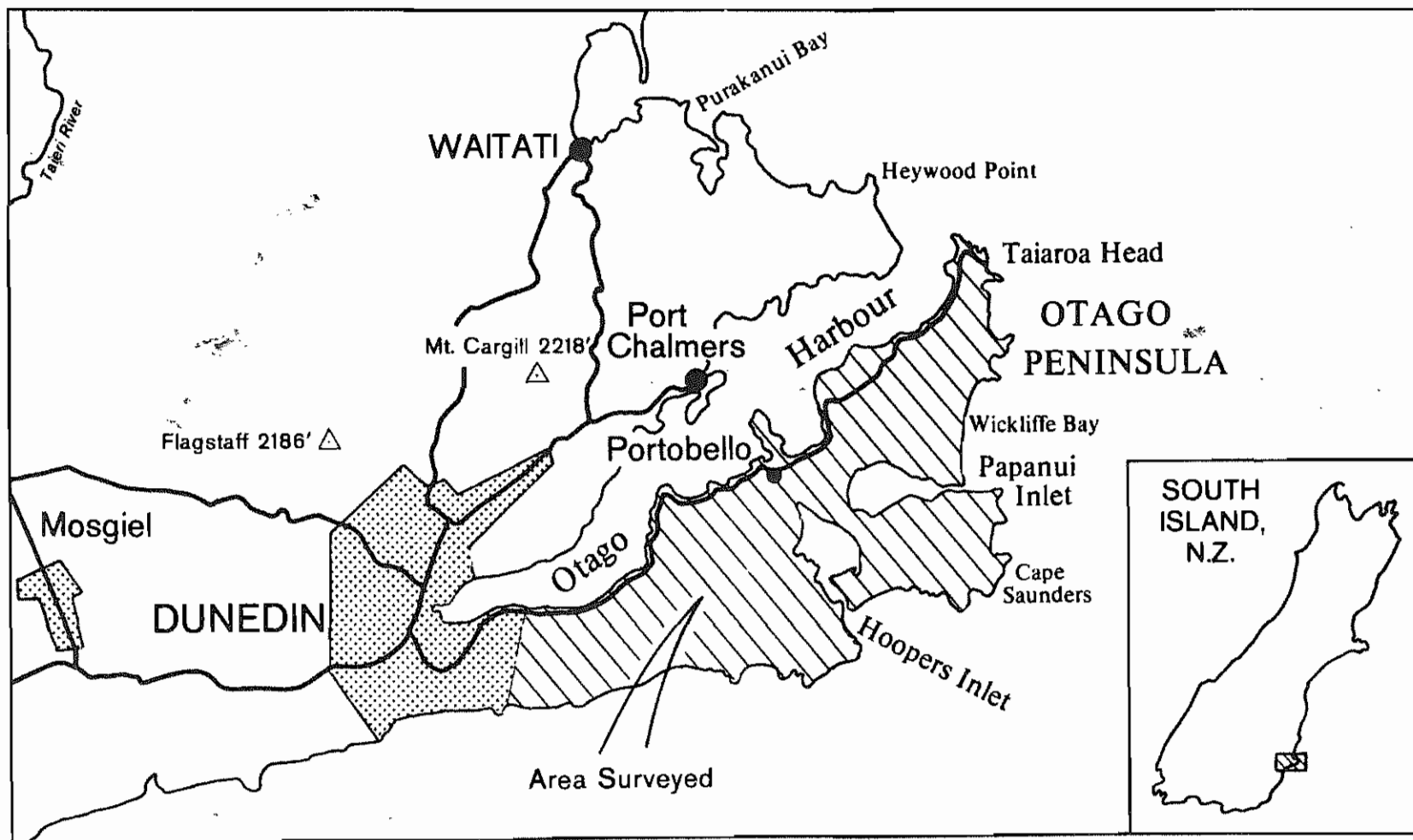


FIG. 1. Locality map.

## INTRODUCTION

A soil survey of the Otago Peninsula, New Zealand (Fig. 1) was completed at a scale of 1:15,840 in 1971 (Leslie, in press (a)). It became apparent during the course of the field work that landslide and related phenomena were recent soil-forming processes of some significance. This study was initiated to understand more fully the principal causal factors in landslide genesis.

For the purpose of this study nomenclature and definition of landslides follows Varnes (1958) who defined the term 'landslide' as a phenomenon that includes all 'downward and outward movement of slope-forming materials composed of natural rock, soils, artificial fills, or combinations of these materials.' Movement may involve falling, sliding, or flowing, or their combinations.

Based on movement type, Varnes classified landslides in four broad groups:

1. Falls - where the dislodged material, whether soil or rock, moves almost entirely through the air.
2. Slides - where movement is initiated by finite shear failure along one surface. Two subgroups are differentiated according to mechanics of movement: those in which the moving mass is not greatly deformed, e.g. slumps, and those in which the material in motion is greatly deformed or consists of many semi-independent units, e.g. debris slides.
3. Flows - where the movement within the displaced mass is such that the form taken by the moving material resembles those of viscous fluids, e.g. debris avalanches and debris flows.

The gradation from debris slide through debris avalanche to debris flow reflects, in part, increasing wetness.

4. Complex landslides - include moving masses that display elements of both flowing and sliding.

Figures 2, 3, 4 and 5 show examples of these four groups of landslides that occur on Otago Peninsula.

Contemporary environmental, or other, factors that trigger off landslides, landslide morphometry and mechanics of movement within individual landslides, are described elsewhere (Crozier 1968, 1969a, 1969b) and are not discussed in this paper.

## LANDSLIDE CLASSIFICATION AND DISTRIBUTION

Table 1 is a classification (after Varnes) of landslides, showing only those movement forms mapped and described on the Otago Peninsula. The more subtle and small scale forms of mass movement, e.g. soil creep, soil slip and soil flow, were not mapped but their field relationship to regolith, basement lithology and slope were noted and incorporated in the section classifying landslide potential.

Table 1 classifies landslides of the Otago Peninsula into seven types. Two types, soil fall and rock fall, occur along coastlines subjected to intensive marine corrosion and, as their distribution is sinuous and narrow, only zones of occurrence are delimited.

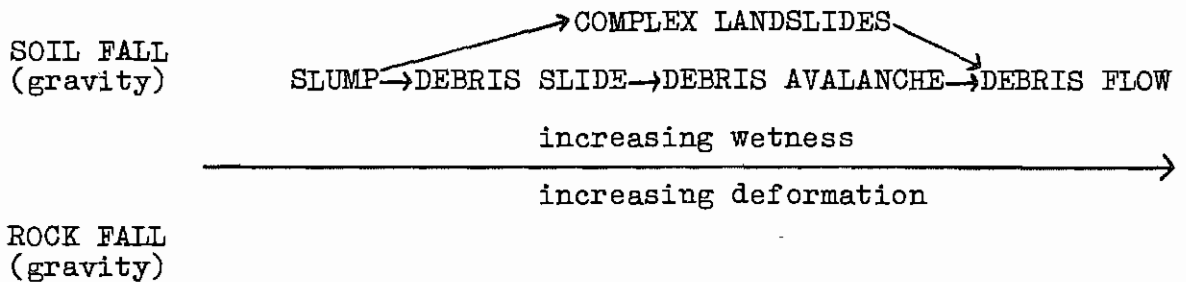


TABLE 1. LANDSLIDE CLASSIFICATION (after Varnes 1958)

A total of 504 large landslides were individually described in the survey and their order of frequency is as follows: debris avalanches, 415 (82%); debris slides, 44 (9%); debris flows, 29 (6%); slumps, 10 (2%); complex landslides, 6 (1%) (Table 2). Landslides displaying rotational movement and slight deformation, i.e. slumps and complex landslides, comprise only 3% and slides and all flows showing deformation, although of variable viscosity, are the predominate (97%) landslide type.

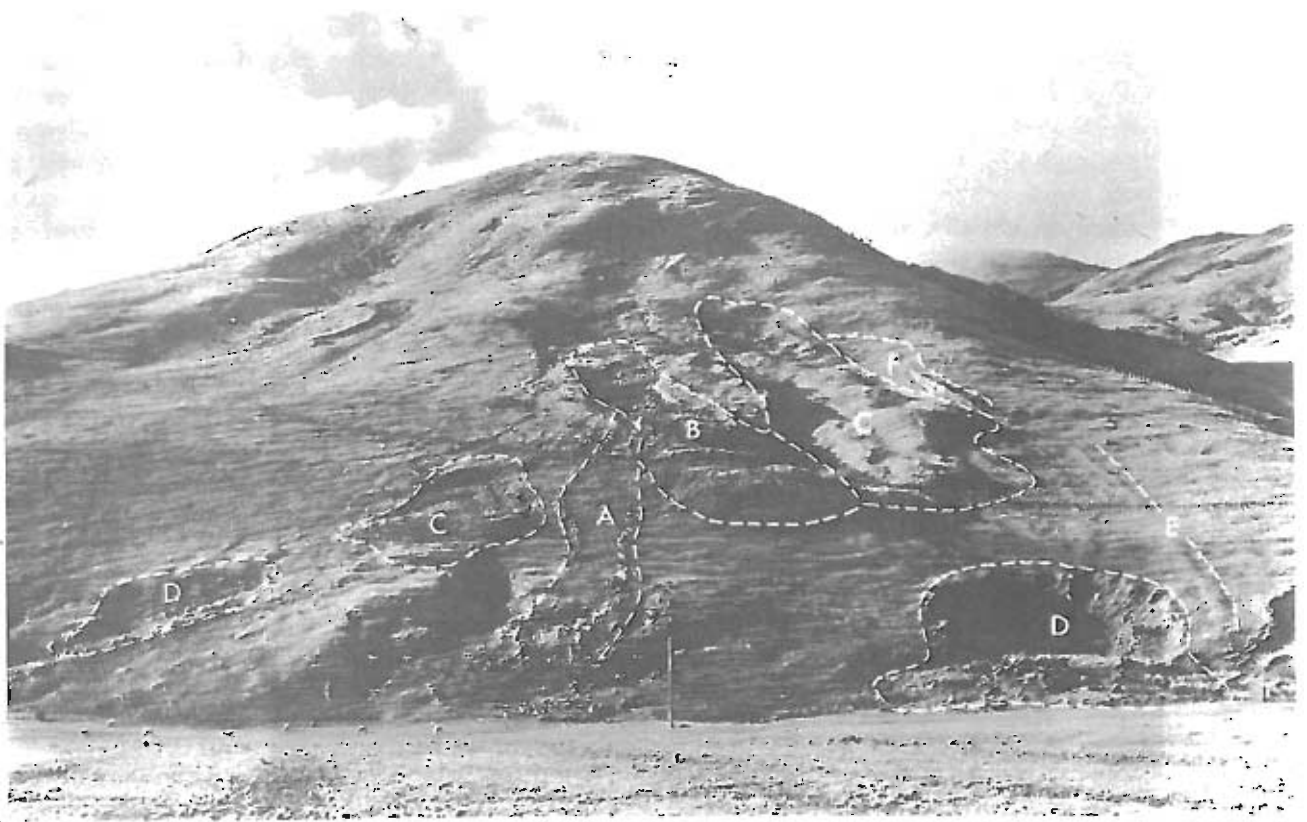


Fig.2 (Top). Successive generations of landslides-Allans Beach Road. Debris avalanche (with levees) (A) developed from a debris slide (B); older and quasi-stable debris slides (C); debris flow with actively eroding scarp (D); remnant levee (E) of old debris avalanche (F).

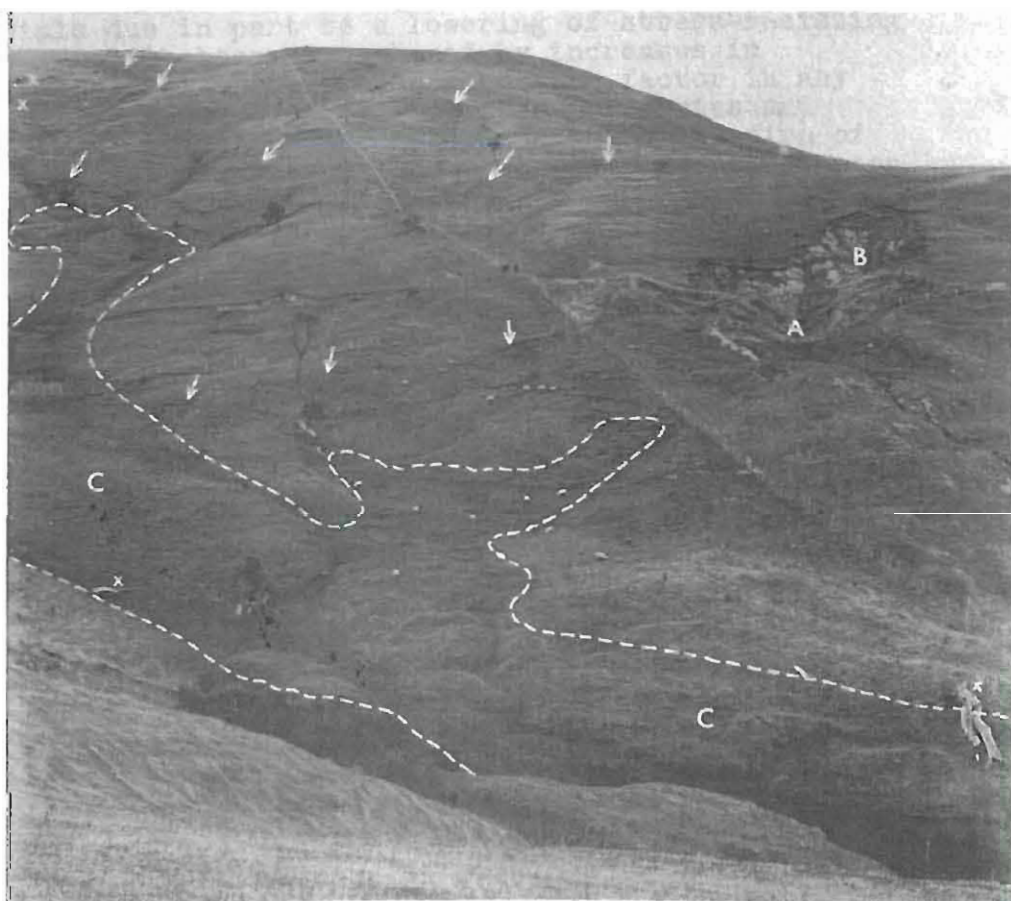
Fig.3 (Lower). Left flank scarp of slump, adjacent to Papanui inlet. The regolith is deep primary loess (fragipan A) overlying basaltic agglomerate. Arrows locate striations that indicate movement direction. Landslide debris in the foreground is rotated back toward the slump crown.

Photos: W.F.Rennie

Fig.4  
 Debris avalanche (A)  
 near Peggy's Hill.  
 Flow debris (B) ex-  
 tended 200 m down  
 valley.  
 Arrows locate tension  
 cracks.  
 Potential landslide  
 zones (C) and old  
 landslide debris  
 accumulations (D) are  
 shown.



Fig.5  
 Extensive landsliding  
 near Portobello  
 township. Arrows  
 locate tension cracks  
 of potential landslide  
 zones.  
 Debris flow (A)  
 developing from debris  
 slide (B). Older  
 landslide debris (C)  
 is shown. Crosses  
 indicate logs of the  
 original indigenous  
 forest.



## CAUSAL FACTORS OF LANDSLIDES AND SLOPE DEVELOPMENT

Slope stability is dependent on a balance between forces. In the main, slope failure occurs when the shear force along a surface of potential failure exceeds the shear strength of the materials at the material interface. Pore water pressure is the prime factor influencing shear strength. However, the subject of this paper is not contributory factors but rather the inherent elements of the landscape that are responsible for a higher incidence of landsliding in some areas than in others. Thus analysis is centred on material shear strength and shear stress within a potentially unstable zone. Variations in basement lithology and the constitution of the derived regolith are fundamental to material strength, while slope geometry has significance both to shear strength and, through gravity, to stress conditions within the regolith.

It is apparent that there is a higher incidence of landsliding in cohesive materials due in part to a lowering of stress-resisting properties as the regolith becomes weakened by increases in moisture. Soil drainage is therefore an important factor in any discussion of landslide genesis. Soil moisture properties and internal drainage behaviour are considered with the discussion of the principal causal factors, rather than separately for the reason that slope, basement lithology and regolith factors all influence soil drainage to a greater or lesser degree.

Thus basement lithology, regolith, and slope are the key causal factors in landslide genesis. Table 2 tabulates the relationship these three factors have with landslide type.

### 1. Basement lithology as a factor in landslide occurrence

Slope form is not determined by any one factor, but rather by a complexity of factors of which basement lithology is one. The stratigraphic position of different lithologies (rock types) and

LANDSLIDE TYPE	NUMBER		BASEMENT LITHOLOGY					REGOLITH						SLOPE			TOTAL	
			TOTAL	SAND, ALLUVIUM, ETC.	TERTIARY ROCKS	FLOW ROCKS	PYROCLASTIC ROCKS	DEEP LOESS (>90 cm)	MODERATELY DEEP LOESS (45-90 cm)	LOESS COLLUVIUM	UNDIFFERENTIATED MIXTURES OF LOESS AND VOLCANIC WEA- THERING PRODUCTS	CRYOPLANATION SURFACE	HOLOCENE SAND AND ALLUVIUM	TOTAL	<12°	12-28°		>28°
DEBRIS SLIDE	44	9	23	18	3	-	44	8	1	18	14	-	3	44	2	42	-	44
DEBRIS AVALANCHE	415	82	241	171	3	-	415	13	16	106	280	-	-	415	9	404	2	415
DEBRIS FLOW	29	6	24	5	-	-	29	-	2	10	17	-	-	29	-	29	-	29
SLUMP	10	2	6	4	-	-	10	6	2	2	-	-	-	10	-	10	-	10
COMPLEX LANDSLIDE	6	1	3	3	-	-	6	-	1	3	2	-	-	6	1	5	-	6
TOTAL	504		297	201	6	-	504	27	22	139	313	-	3	504	12	490	2	504
LANDSLIDE (%)		100	59	40	1	-	100	5	4	28	62	-	1	100	2	97	1	100
UNIT AREA (%)			26.8	62.8	0.4	10.0	100	14.3	3.9	12.2	47.4	4.8	17.4	100	40.4	58.7	0.9	100

TABLE 2. NUMBER OF LANDSLIDES OF VARIOUS TYPES (after Varnes, 1958)  
ACCORDING TO BASEMENT LITHOLOGY, REGOLITH, AND SLOPE FACTORS

the relative susceptibility of each to weathering ultimately determines slope form, although processes operative under the different climates of the late Pleistocene to Holocene period have had significant modifying influence. Thus, weathering of a particular rock is influenced not only by its inherent physical properties but also by its structural and stratigraphic relationship to other rocks.

Fig. 6 relates each landslide type to the main lithological units, differentiated on the basis of mode of emplacement and relative erodibility.

It is apparent that the pyroclastic rocks, tuffaceous anorthoclase trachyte (Fig. 7) and basaltic agglomerate (Fig. 8) (Benson, 1968), relate closely to the incidence of landsliding with 59% of all movements being initiated in areas of pyroclastic rocks (Table 2). Landslides in areas of flow rocks, mainly basalts and phonolites (Benson, 1968), are of lesser significance, and where these rocks occur landsliding is explicable in terms of regolith constitution rather than basement lithology.

The pyroclastic rocks are strongly weathered, and the trachyte is both strongly and deeply weathered. Comprising consolidated angular fragments of ejecta material (4-32 mm) they are porous, permeable and very susceptible to chemical and mechanical disintegration to some depth. Depth of weathering is in part governed by ground water levels which are deep because of the high porosity and permeability, of the pyroclastic rocks. The saprolite zone of the pyroclastic rocks is an incoherent mass, and although having a rock-like appearance has low shear strength, cohesion and weight. It is also subject to considerable volume change as the degree of water saturation changes.

The fine grained flow rocks are dense and have very low porosity and permeability. The basalts which exhibit columnar jointing do allow considerable water penetration along natural fissures yet the rock itself is quite impervious (Fig. 9). Weathering in the flow rocks is concentrated along the joint planes, and at an advanced stage is recognised by spheroidal weathering, i.e. core stones surrounded by alteration products of clay and iron oxides that formed along the joint planes (Fig. 10). Indications are that periglacial stripping removed saprolite from all rocks, both flow and pyroclastic, exposed to denudation, and that the deep weathering of the pyroclastic rocks relative to that of the flow rocks is a reflection of the difference in susceptibility to weathering of the two rock types.

Chemical alteration in the pyroclastic rocks has produced clays that are predominantly of the swelling type, e.g. montmorillonite and vermiculite from the weathering of basalt (Swindale, 1966), and halloysite and montmorillonite from trachyte (Leslie, in press b). Hydration, and desiccation of the clays lead respectively to compression and tension forces being set up within the materials. This combined with changes due to weathering and other physico-chemical reactions upsets the delicate balance of shear strength and shear stress. These clays have moderate porosity (45%) but because of hydration exhibit very low permeability, creating an impermeable barrier to water penetration at the soil/

saprolite interface. This situation induces high shear stress conditions and increases the probability of failure on this plane.

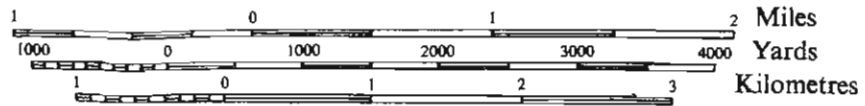
The stratigraphic position of the pyroclastic rocks is of some significance in relation to slope development and overall form of the land surface. The stable flow rocks post-date pyroclastic eruptions and are, in the main, stratigraphically superior to the latter (Benson, 1968). Competent cap rock effectively reduces interfluvial retreat relative to that occurring in the underlying pyroclastic rocks which can be readily worn back by marine erosion and slope-eroding processes. These processes result in over-steepening, increases in gravity forces and the induction of high stress conditions by removal of lateral support. Reference to Fig. 6 shows the high susceptibility of the pyroclastic rocks to marine corrasion, for wherever these crop out at sea level, the coastline is strongly indented, e.g. Papanui and Hoopers Inlets. Conversely where competent flow rocks crop out at sea level a steep cliffed headland with free fall faces develops, e.g. Cape Saunders, Taiaroa Head.






## 2. The regolith as a factor in landslide occurrence

Table 2 relates landslide type to the five deposits and one erosion surface which are regarded as regolith types and differentiated as such in Fig. 11. These are as follows: deep loess (greater than 90 cm); moderately deep loess (45-90 cm); loess colluvium; undifferentiated mixtures of loess and volcanic weathering products as colluvium or solifluction; areas of Holocene sand and alluvium; cryoplanation surfaces with volcanic saprolite. From Table 2 it is apparent that 62% of landslides occur in the loess and volcanic weathering product mixtures and 28% in loess colluvium. Thus, 90% of all mapped landslides occur within slope deposits of weathering products that have already experienced slope transport by different processes. No landslides were initiated in the areas of relict cryoplanation surfaces.

The following discussion describes each regolith type and evaluates the effect different regolith properties have in influencing the balance between material shear strength and the shear stress forces operating within these materials under variable soil moisture conditions.

Scale 1 : 50,000



-  Anorthoclase trachyte
-  Basaltic agglomerate
-  Tertiary sediments
-  Volcanic flow rocks
-  Holocene sand, etc.

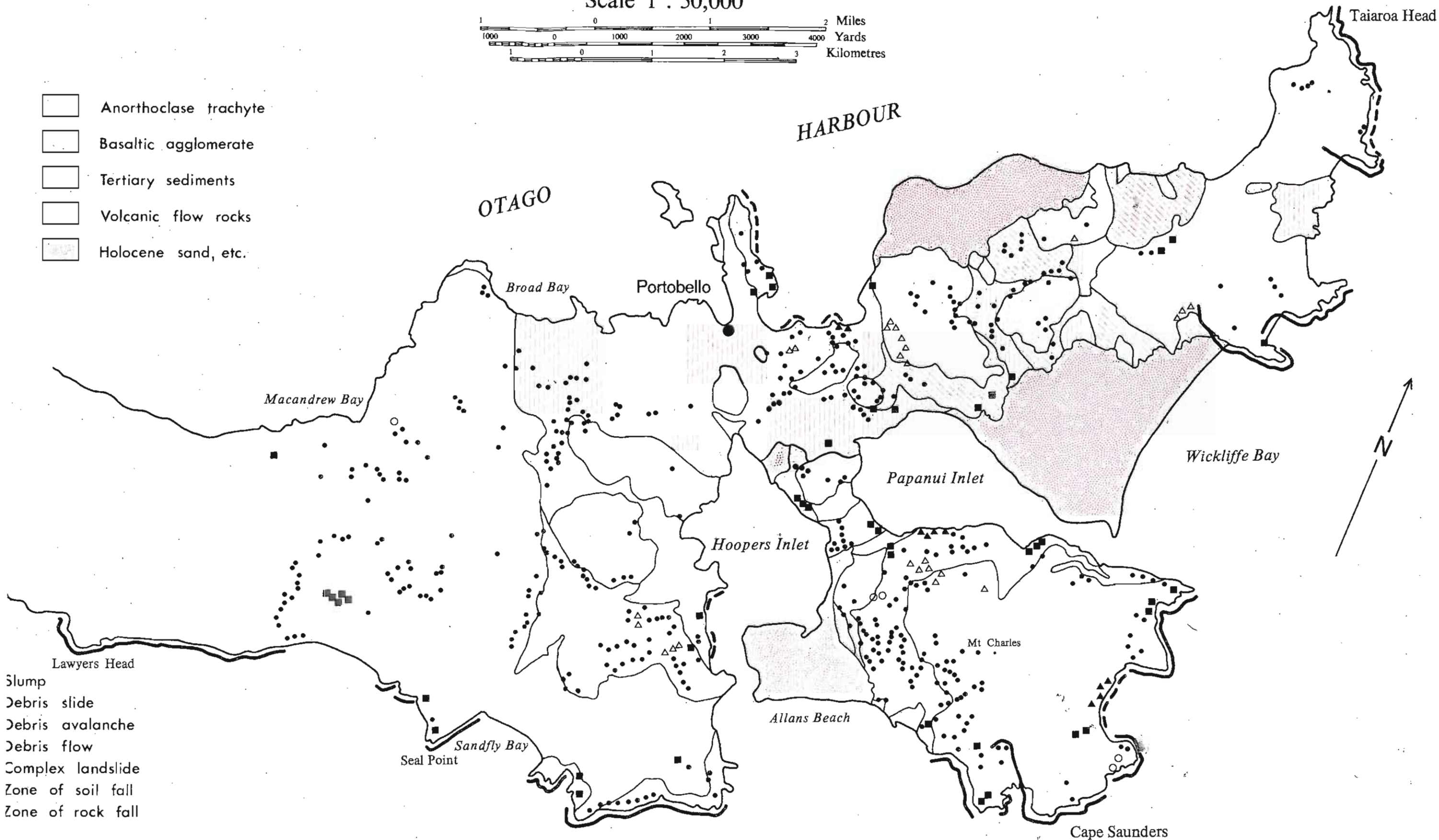
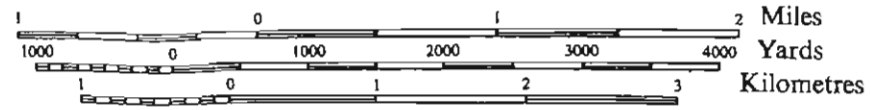








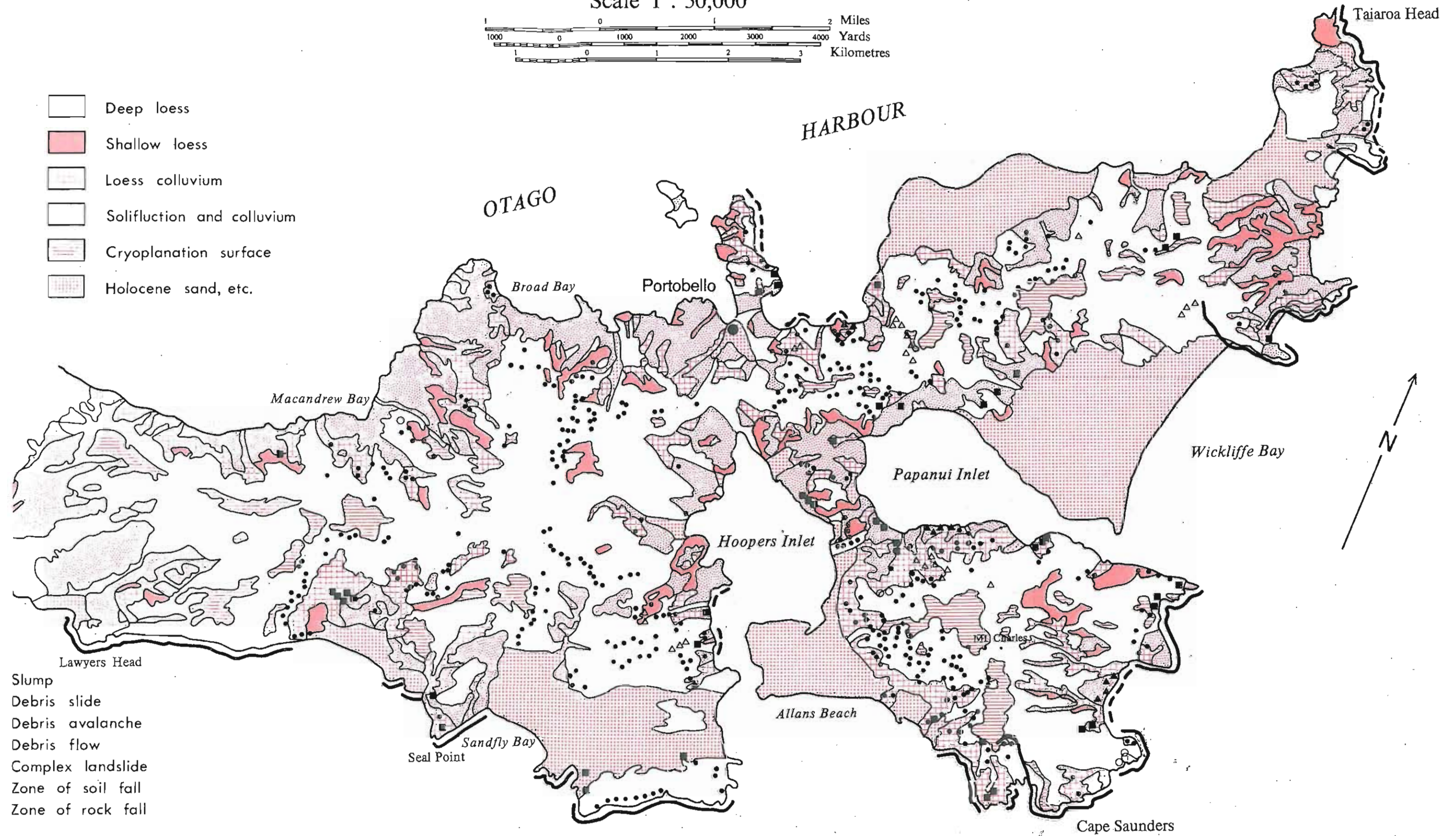
Figure 6. The relationship of basement lithology to landslide type and distribution

Drawn by W.F. Rennie and D.C. Barthow

Scale 1 : 50,000



-  Deep loess
-  Shallow loess
-  Loess colluvium
-  Solifluction and colluvium
-  Cryoplanation surface
-  Holocene sand, etc.



- Slump
- Debris slide
- Debris avalanche
- Debris flow
- Complex landslide
- Zone of soil fall
- Zone of rock fall

Figure 11. The relationship of regolith type to landslide type and distribution

Drawn by W.F. Rennie and D.C. Barthow

## Deep Loess (> 90 cm)

This unit comprises in situ aeolian silts (primary loess) and fine sands that were blown and saltated respectively from harbour inlets and near-shore coastal zones during periods of eustatic low sea levels. The loess is thickest nearest the source area and becomes progressively thinner with distance from source and with increasing elevation. A feature of loess deposition is its ability to smooth out the irregularities on the predepositional surface, and the prevalence of filled fossil gullies are a manifestation of this process of smoothing. A significant number of coastal loess sections show a vertical textural gradient from sand at the base to silt near the surface of the loess layer, probably indicative of source area textural changes or increasing distance from source related to a slow progressive lowering of sea level.

Soils developed on the loess deposits display dominant morphological features of the intergrades between yellow-grey earths and yellow-brown earths. The loess is well-sorted material with a dominance of particles in the 0.05 to 0.002 mm fraction, a well-developed fragipan (pan A) developed in the absence of biotic activity and below the optimum moisture necessary for mineral weathering and therefore soil development (Mr J.G. Bruce, pers. comm.), and a 'modified fragipan' (pan B), i.e. modification of pan A by pedological processes (Mr J.G. Bruce, pers. comm.) (Fig. 12). It also shows net gammadation, the dominant vertical gammadations following vertical fissures in the loess, and layering of clay minerals along fissures and gammate zones. The position of fragipans within the loess mantle have considerable influence on the permeability of the loess. Both fragipans are compact with very firm consistence, have low apparent macroporosity and high dry bulk density (Birrell and Packard, 1953). On closer inspection the macropores of the modified fragipan have cemented walls that enhance material shear strength but reduce permeability. The underlying fragipan (pan A) lacks cementation and so retains its permeability but 'slakes' when moistened (Mr J.G. Bruce, pers. comm.) and its material shear strength is reduced.

Under the present climate, loess soils have developed under conditions of summer drying and winter wetting. Deep vertical cracks in the regolith markedly reduce shear resistance along the length of the crack. Near maximum soil water conditions hydrate the clay minerals concentrated along gammadations and other vertical cracks and induces swelling that effectively seals off the fragipan to downward percolating soil water. With continued precipitation, the regolith water storage is confined to that zone immediately above the 'modified' fragipan so that field capacity conditions are thought to be reached earlier in that zone than in free draining regoliths such as mixtures of loess and volcanic weathering products. Following saturation, lateral soil-water movement under gravity in this zone becomes significant in causing shear failure, firstly, as an in situ load factor and secondly by increasing

run-off, thereby diverting precipitation to other areas of potential instability. The load factor, combined with a high bulk density induces high shear stress conditions at the volcanic saprolite interface and markedly increases probability of failure if the underlying volcanic material is of low shear strength, e.g. a pyroclastic rock.

### Moderately Deep Loess (45-90cm)

Moderately deep regoliths of primary loess (45-90 cm) possess many characteristics of deep primary loess, but in general the development of the fragipan and related morphological features are less well expressed. Because of shallowness, the load factor is not as critical. However, loading is reduced by increased gravity effectiveness because in most situations moderately deep loess occurs on steeper topography than does deep loess.

In terms of material strength, moderately deep loess behaves similarly to deep loess and its potential to fail is governed by the strength of the underlying saprolite and by the slope.

### Loess Colluvium

Loess colluvium is a regolith of variable depth comprising predominantly reworked loess, i.e. secondary loess. Although essentially of quartzofeldspathic silts, it may contain up to 10% weathered volcanic material of clay, silt, and sand fractions.

The loess colluvium has a similar pattern (Fig. 11) of distribution in relation to source areas as that for loess, though it is further from the source and of wider areal extent. It may be found on side slopes of broad loess ridges, on steeper topography upslope of primary loess, in heads of long gullies the original base levels of which adjoined that of a lower sea level, and in fossil gullies.

Loess colluvium lacks the compaction of primary loess, has lower bulk density and rarely has a fragipan. Morphologically, it is moderately compact with higher porosity than loess, and because of a coarse blocky structure it has high permeability (Fig. 13).

Regolith disturbance has mixed the parent materials and this, more than any other factor, has created areas with variable soil moisture retention and variable strength. In general, loess colluvium is of low to moderate shear strength.

Fig.12. Primary loess showing a well developed pedologically modified (A) and unmodified (B) fragipan, prismatic structure and "vertical cracks" or "gammations" (C).



Fig. 13. Loess colluvium (A) overlying weakly weathered phonolite (B). Photos:W.F.Rennie



## Undifferentiated Mixtures of Loess and Volcanic Weathering Products

This unit is the most complex, variable in its properties, and extensive of the regolith types. It comprises all mixtures of loess and volcanic weathering products whether developed under the present climate and manifest as slope colluvium, or as relict Quaternary erosion deposits interpreted as solifluction deposits.

The colluvium develops mid-slope between the aeolian (loess) footslope and the convex upper backslope of solifluction (Fig. 18). Generally, the regolith is thin (1.5 m), but it thickens as the ratio of loess to volcanic material increases. Slope gradient and position, weak compaction, and the fact that this unit is essentially an accumulation zone both for run-off and slope detritus, contribute to a reduction of shear strength. Materials themselves are variable in their properties, but it is the percentage clay (derived from volcanic weathering products) that most influences material strength and therefore the degree of stability. These clays have a high void ratio (cf. silt), low internal friction, and low permeability and cohesion when dry. The cohesion and shear strength decrease as the moisture content increases. Mixtures of the weathering products from pyroclastic rocks usually overlie a pyroclastic saprolite and it is this situation that has the greatest potential for failure. Regoliths from flow rock material are also of low strength, but they are stronger than those from pyroclastics. Landslides in colluvial materials mapped in this survey are shallow and principally of the debris avalanche type.

Loess and volcanic weathering product solifluction occurs as a convex lobe on the upper backslope of the high hills below zones of relict cryoplanation. The materials comprise volcanic stones and boulders (core stones from interglacial weathering) set in a matrix of silty clay derived from loess (deposition of which was contemporaneous with solifluction) and volcanic weathering products (Fig. 14). The volcanic materials relate closely to the lithology of the local cap rock. There is a wide variability in the thickness of the unit, e.g. 6 m in the fossil gully situation; 60 cm at the distal end of the lobe (Fig. 9), but overall the deposit averages 2.5 m in thickness.

Removal of saprolite materials from summit areas by cryoplanation and deposition of the former on the upper backslope has increased steepness in the zone and materially affected the entire slope profile. Landslides occurring in solifluction deposits are deeper than those in the colluvium and this is related more to the depth of regolith than to any other factor. As with the colluvium, the effect of excess water and the materials above the saprolite is to reduce shear strength. In most situations the solifluction regolith has a well defined surface of potential failure or zone of low shear strength. This may be either a lithological discontinuity, a paleosol on volcanic saprolite, a stone line, or a shaved surface.

### Cryoplanation Surface (Volcanic Saprolite)

This regolith unit is not important in terms of landslide potential but is described here to complete the discussion of regolith types. It has restricted areal distribution, occurring in the upland summit zones (Fig. 15) that experienced cryoplanation during the late Pleistocene. Morphologically, the unit has a flat surface with areas of core stone accumulation. The core stones are remnants of deep interglacial weathering, the weathering products of which are removed by erosion under periglacial climate and redeposited downslope as solifluction. The profile is thin (30-80 cm), and the regolith, comprising volcanic saprolite without loess possesses excellent cohesion and strength.

### Holocene Sand and Alluvium

These areas comprise 1721 ha (4250 ac.) or 18.5% of the total Otago Peninsula area. As they display no landslide potential, they are not included in this study. However a full description of the Holocene surfaces and deposits is made elsewhere (Leslie, in press c).

Discussion has centred on the important physical properties, of the regolith types as they relate to landsliding, and has shown, without accounting for, their distribution. Each regolith type was differentiated and described as a unit that developed in response to slope processes operating under distinctive and different climates and regolith polygenesis and lithological discontinuities are used as evidence for climatic change. Environmental reconstruction and an appreciation of multi-cyclic slope change is fundamental to any explanation of why landslides are peculiar to a particular element in the landscape. Figs. 16, 17, and 18 go some way to summarise the phenomena. Three typical longitudinal slope profiles, each of which is representative of the range of situations encountered in the study area, are presented to show the relationship between slope and basement lithology, regolith type, and position



Fig.14.  
Deep solifluction  
debris near  
Glenfalloch.

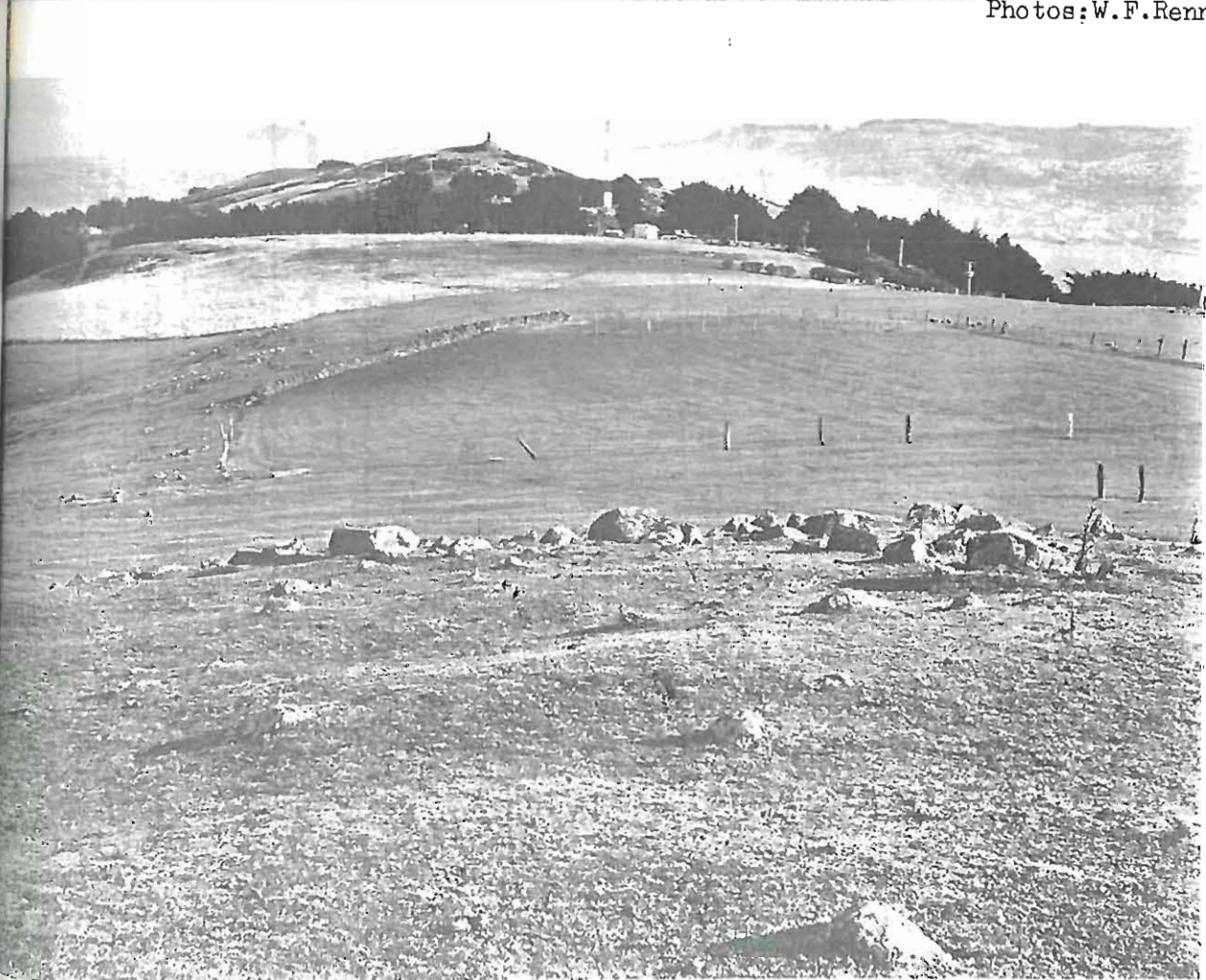


Fig.15. Relict  
cryoplanation sur-  
faces with boulder  
fields near  
Highcliff.

Photos:W.F.Rennie

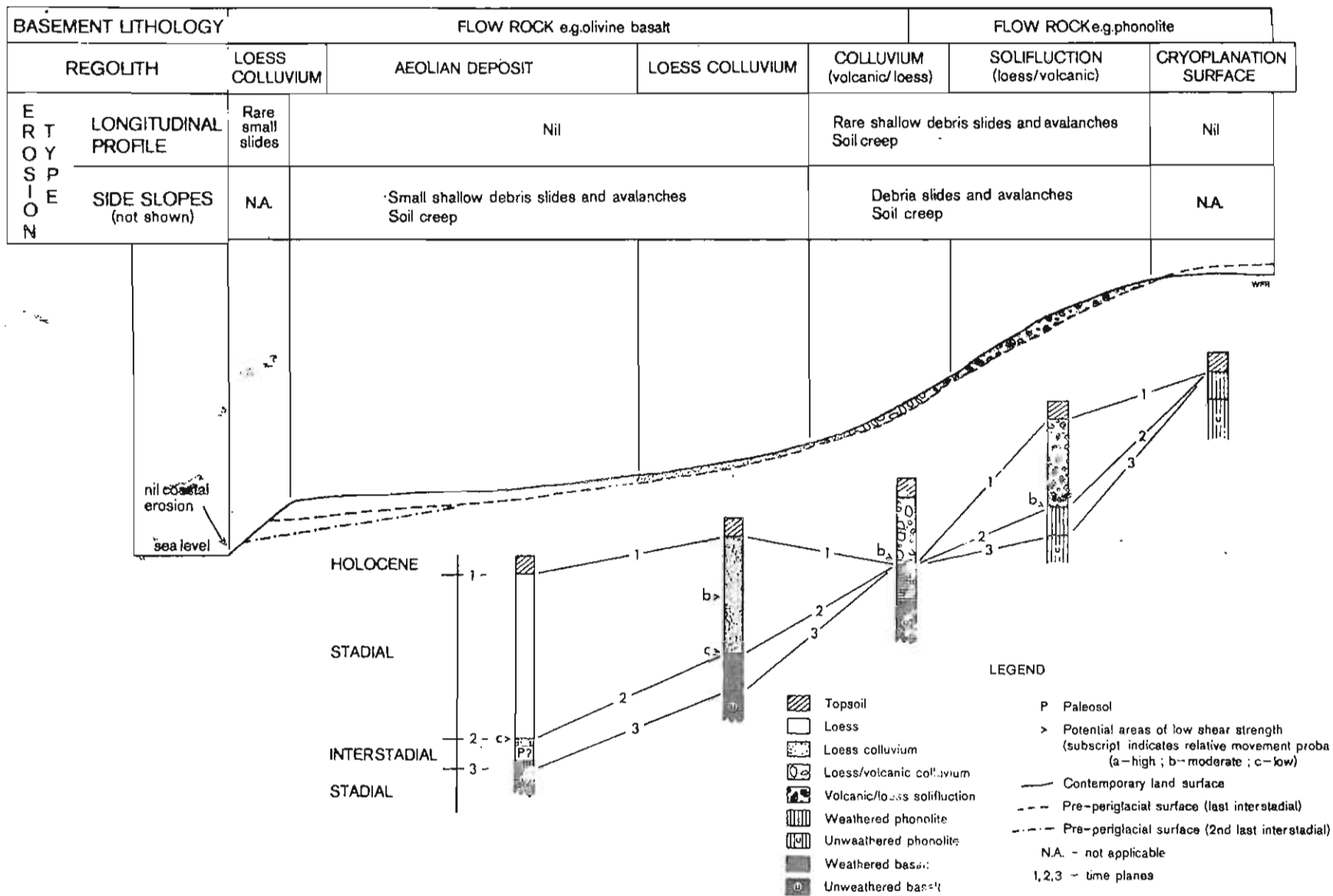


Fig. 16. Typical longitudinal slope profiles showing the relationship between basement lithology, regolith type and slope

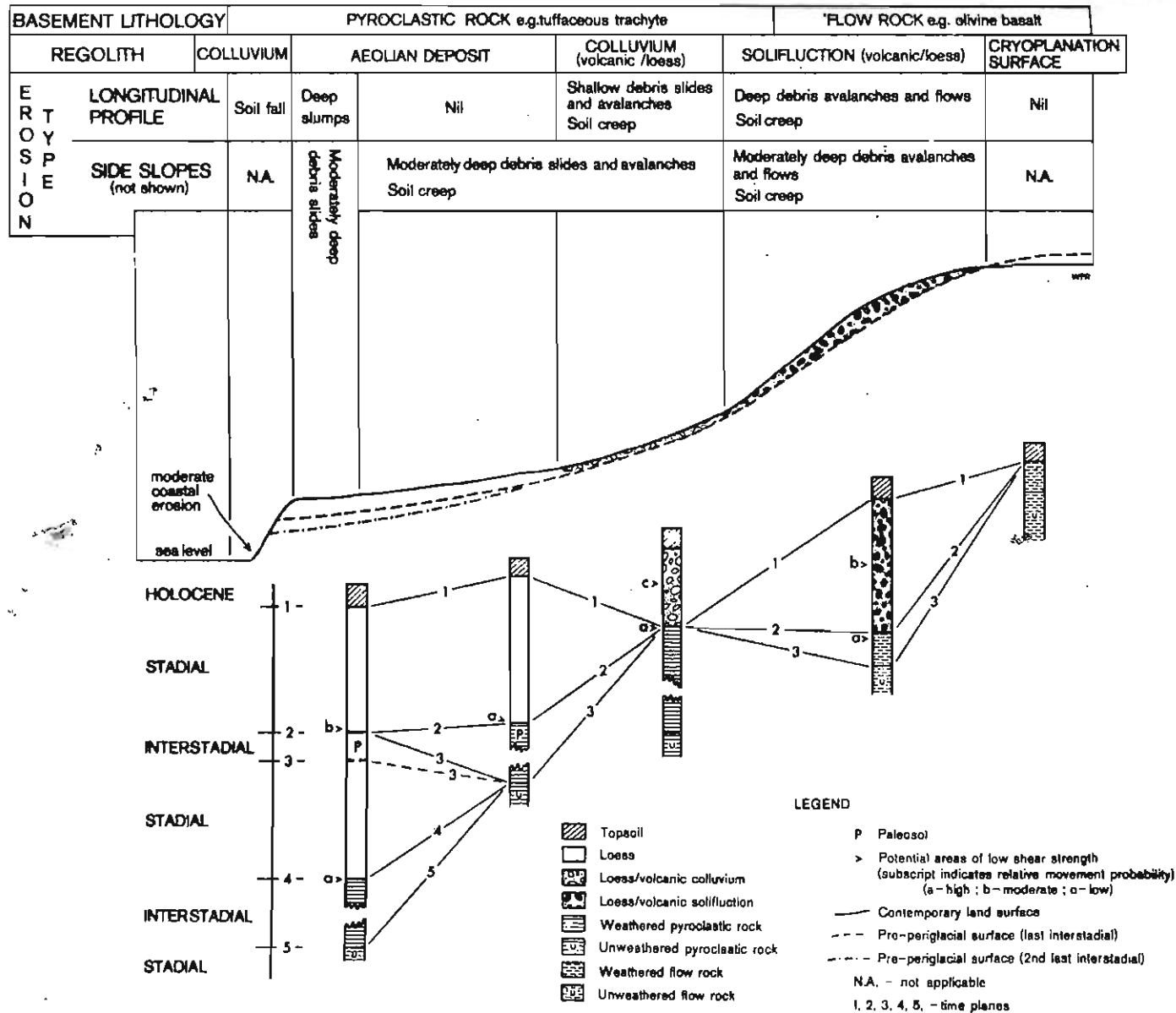


Fig. 17. Typical longitudinal slope profiles showing the relationship between basement lithology, regolith type and slope

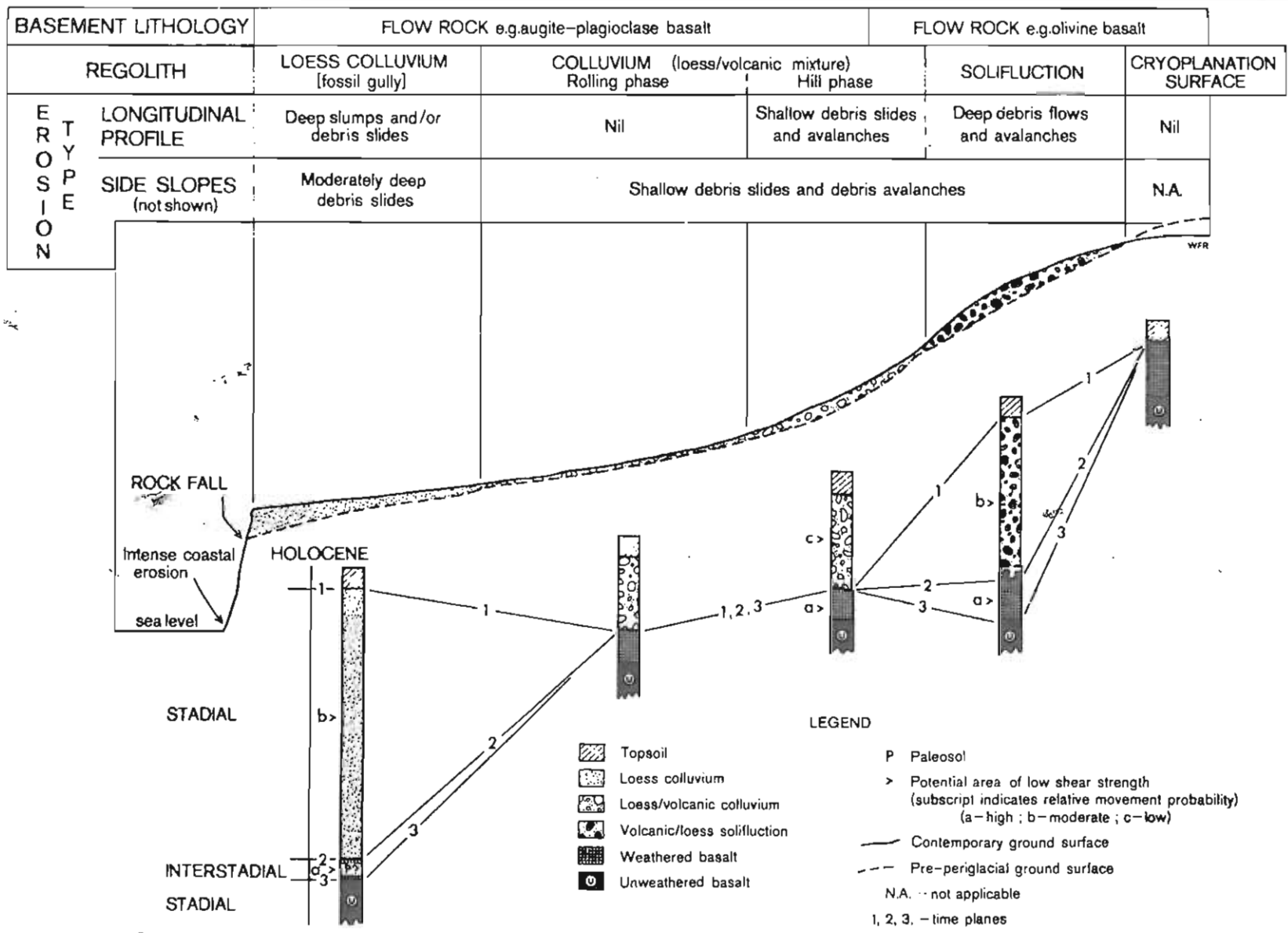


Fig. 18. Typical longitudinal slope profiles showing the relationship between basement lithology, regolith type and slope

on slope of a particular regolith type. They also indicate the influence the various landform units have on the landslide type and frequency, both on the longitudinal profile and on the side slopes. Associated with the profiles are a series of stratigraphic columns designed to show stratigraphy, lithological discontinuities, paleosols, the relative age relationships of the materials (with tentative correlation to the Quaternary stratigraphic column), and potential failure zones.

### 3. Slope as a factor in landslide occurrence

Fig. 19 shows the broad slope categories of 0-12°; 12-28°, and 28°. With the 504 landslide occurrences superimposed over these slope categories it is apparent that a strong relationship between slopes 12-28° and landsliding exists. Reference to Table 2 shows that 97% of all landslides occur in this slope range, and confirms gravity as an important causal factor in landslide genesis.

## CONTRIBUTORY FACTORS

It has been shown in this survey that certain elements of the landscape are naturally unstable irrespective of human influences. However, human activities in zones of potential instability have undoubtedly activated landsliding. Landsliding is considered to have been significant immediately following the last stadial period but to have diminished as slopes attained equilibrium grade, and virtually ceased with the establishment of the dicotylous-podocarp climax vegetation. Crozier (1969a, 1969b) attributes the progressive development of unstable land in Eastern Otago over the last 120 years to conversion of forest to grassland by Europeans. Slope equilibrium that existed under indigenous forest cover was lost by forest clearance and this increased the probability of failure on hill slopes and those areas that have inherent natural instability. The present instability is considered to be an evolutionary stage in slope development whereby the land surface gradient by under-

steepening progresses toward an equilibrium under a grassland cover. Gray (1970), in his review of literature pertaining to forest clearance in relation to landsliding, notes that forest cover induces greater slope stability through "mechanical reinforcement from the root system and modification of the hydrologic regime in the soil mantle". Crozier (1968) observed that phases of landslide activity are closely associated with storms of low frequency, large area, long duration, and low intensity.

A grassland vegetation cover has markedly lessened transpiration effectiveness, reduced soil hydrologic activity because of a shallower rooting system, and reduced rainfall interception effectiveness compared with the former forest cover. For these reasons it can be predicted that maximum soil-water levels are approached or attained more often under grass than under forest. Also, under grassland cover, in the absence of the mechanical strength afforded by a woody root system, gravity effectiveness assumes significance in geologically unstable hill areas.

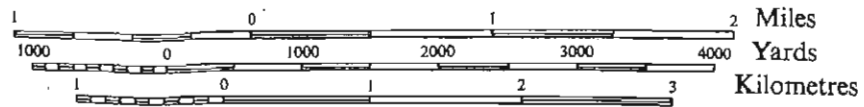
The stabilisation of potential or active landslide areas is a problem that confronts both agriculturalists and engineers. The application of preventive and corrective measures is necessary, but in most places where the existing land use is semi-intensive pastoral effective measures will be uneconomic.

It could be argued that deciduous trees (willows, poplars) with their high transpiration capability, large water consumption potential, and woody root system would enhance slope stability. However, deciduous species have no foliage in winter when their water-using ability is most required, and stabilisation by their rooting systems applies only to areas of shallow landslides and subtle forms of mass movement such as soil creep.

Undoubtedly, the planting of an evergreen crop, e.g. conifers, would go further than any other measure using vegetation toward achieving stability. But this would necessitate a change in existing land use policy as to be effective almost the entire area would require planting.

In the absence of vegetation and major engineering structures, well designed surface and subsurface drainage is the only effective method of controlling slope instability.

Scale 1 : 50,000



SLOPE

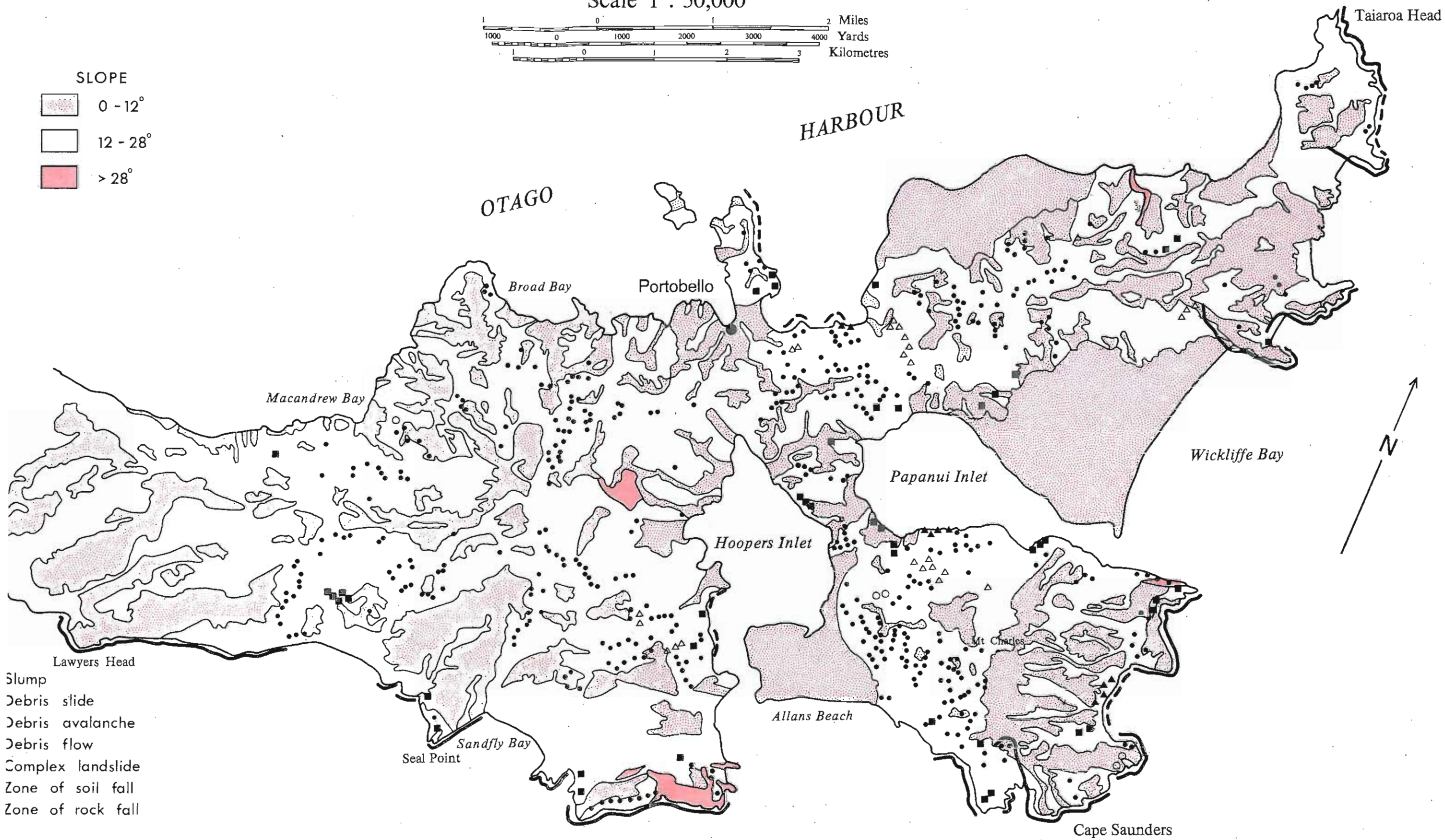
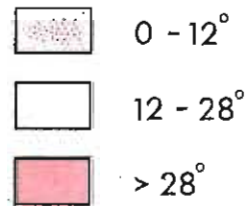


Figure 19. The relationship of slope to landslide type and distribution

Drawn by W.F. Rennie and D.C. Barthow

## CLASSIFICATION OF LANDSLIDE POTENTIAL

The relative inherent shear strength of the various regolith and basement lithologic materials was gauged by qualitative estimation of their physical and chemical properties. Material shear strength, the stratigraphic position of one material relative to another, and the incorporation of the slope or gravity factor into the assessment of potential instability allows classification of the majority of situations. Where quantitative data is absent, prediction of material behaviour under high stress conditions can be gauged by field observations from those areas of the landscape that display a high incidence of landsliding.

The classification is therefore a grouping of like situations possessing inherently similar potential for failure. The relative increasing order of risk assumes behaviour probability under the impress of the same contributing factors. Contributing factors can be one or more events or combinations of events that induce failure by an increase in shear stress, e.g. addition of water to a slope.

### CLASS 1 VERY SLIGHT RISK

Situations in which materials of high shear strength overlie similar strength materials, on flat to gently undulating slopes, with no apparent surface or zone of potential failure.

- deep (greater than 90 cm) and moderately deep (45-90 cm) primary loess on gentle slopes (less than 12°) overlying flow rocks.
- shallow (less than 45 cm) volcanic regolith developed through in situ chemical weathering of flow rocks on flat relict cryoplanation surfaces.

## CLASS 2 SLIGHT RISK

Situations in which materials of high shear strength overlie similar strength materials, on rolling to strongly rolling slopes, with an ill-defined surface or zone of potential failure;

Situations in which materials of high and moderate shear strength overlie low shear strength materials on flat or gently undulating slopes; material discontinuity is a well defined surface of potential failure but the more gentle slope tends to compensate for this:

- deep and moderately deep primary loess on hill slopes overlying flow rocks.
- moderately deep volcanic colluvium on hill slopes adjacent to and downslope from cryoplanation surfaces.
- loess colluvium, and loess/volcanic colluvium on gentle slopes overlying stable flow rocks.
- deep and moderately deep primary loess on gentle slopes overlying pyroclastic rocks.

## CLASS 3 MODERATE RISK

Situations in which materials of high shear strength overlie materials of low shear strength, on rolling slopes, with a well defined surface of potential failure at the material interface;

Situations in which materials of low and moderate shear strength overlie high shear strength materials, on rolling and strongly rolling slopes, with an ill-defined surface of potential failure; failure occurs primarily within the low and moderate shear strength regolith;

Situations in which materials of moderate shear strength overlie low shear strength materials, on flat or undulating slopes, with a well defined surface of potential failure:

- deep and moderately deep primary loess on hillslopes overlying pyroclastic rocks.
- loess colluvium on hillslopes overlying flow rocks.
- volcanic/loess colluvium on hillslopes overlying non-vesicular flow rocks.
- loess colluvium on gentle slopes overlying pyroclastic rocks.

### CLASS 4 SEVERE RISK

Situations in which materials of low or moderate shear strength overlie materials of high shear strength, with a well defined surface of potential failure, on gently undulating to rolling slopes that are subject to removal of lateral support or of material from the toe of the slope;

Situations in which materials of moderate shear strength overlie materials of low shear strength, on rolling to strongly rolling slopes, with a well defined surface of potential failure at the material interface; failure can occur within the overlying moderate shear strength materials;

Situations in which materials of low shear strength overlie similar strength materials, on flat or undulating slopes, with a well defined surface of potential failure at the material interface:

- deep and moderately deep primary loess, loess/volcanic colluvium, and loess colluvium overlying stable flow rocks that are subject to marine or fluvial erosion or human removal of underlying support.
- loess colluvium on hillslopes overlying pyroclastic rocks.
- loess colluvium on hillslopes infilling valley-heads or occurring in fossil gullies.
- loess/volcanic colluvium or solifluction on gentle slopes overlying pyroclastic rocks.
- loess/volcanic colluvium or solifluction on hillslopes overlying vesicular flow rocks.

### CLASS 5 VERY SEVERE RISK

Situations in which materials of low, moderate or high shear strength overlie materials of low shear strength with a well defined surface of potential failure, on strongly rolling slopes that are subject to removal of lateral support or of material from the toe of the slope;

Situations in which materials of low shear strength overlie similar strength materials, on strongly rolling slopes, with a well defined surface of potential failure:

- deep and shallow loess, loess colluvium, and loess/volcanic colluvium overlying pyroclastic rocks that are subject to marine or fluvial erosion or human removal of underlying support.
- volcanic/loess colluvium on hillslopes overlying pyroclastic rocks.

## AREAL DISTRIBUTION OF RISK CLASSES

New Zealand Soil Bureau Map 135 (in back pocket) shows in map form the areal distribution of the 5 risk classes of landslide potential. The location of the 504 landslides analysed in this report are also included for comparative purposes. The following data shows the percentage of each risk class:

Class 0 - no risk	18.5%	(4,250 ac.)	1721 ha
Class 1 - very slight risk	11.1%	(2,550 ac.)	1032 ha
Class 2 - slight risk	20.2%	(4,650 ac.)	1883 ha
Class 3 - moderate risk	11.5%	(2,650 ac.)	1073 ha
Class 4 - severe risk	28.7%	(6,600 ac.)	2673 ha
Class 5 - very severe risk	10.0%	(2,300 ac.)	931 ha
Total	100%	(23,000 ac.)	9313 ha

From this list it is apparent that approximately 50.0% or 4677 hectares (11,550 acres) of the Otago Peninsula hill country has moderate to very severe potential to landsliding. The area of Holocene sand dunes and recent alluvium have no risk and comprise 1721 hectares (4,250 acres) or 18.5% of the total land area of the Otago Peninsula.

## CONCLUSIONS

This study was designed to measure the distribution and intensity of landslide phenomena on the Otago Peninsula, to analyse relationships that exist between landslide occurrence and causal factors, and to classify the area into classes of relative landslide potential. It was expected that this basic information would provide guidelines to planning authorities, engineers, and soil conservators in the formulation of methods for corrective and preventive stabilisation not only to the study area but also to other parts of coastal Otago with similar soils, landforms, etc.

It is concluded that:

1. Debris avalanches are the commonest landslide type (82%, Table 2) and this indicates the wet-flow nature of earth movements in the study area.
2. A significant relationship exists between landslide occurrence and the distribution of pyroclastic rocks (occurring over about 27% of the area), as 59% of all landslides occurred on this rock type.
3. 90% of landslides occur in colluvial or solifluction deposits, i.e. material that has previously experienced slope transport. In comparison, loess and relict cryoplanation surfaces are stable regolith types.
4. 97% of landslides develop on slopes 12-28°, pointing to the importance of gravity as a causal factor.
5. A marked increase in landslide frequency has accompanied the conversion of indigenous forest to grassland in the last 120 years. This conversion has markedly altered the hydrologic regime of the regolith and altered the balance between shear strength and shear stresses.
6. Classification of the area in terms of its potential to fail under the impress of the same contributory factors indicated that approximately 50% of the Otago Peninsula has a moderate, severe, or very severe potential to landsliding.

### LEGEND

#### CLASSIFICATION OF LANDSLIDE POTENTIAL

##### CLASS 1-VERY SLIGHT RISK

Situations in which materials of high shear strength overlie similar strength materials, on flat to gently undulating slopes, with no apparent surface or zone of potential failure.

##### CLASS 2-SLIGHT RISK

Situations in which materials of high shear strength overlie similar strength materials, on rolling to strongly rolling slopes, with an ill-defined surface or zone of potential failure.

Situations in which materials of high and moderate shear strength overlie low shear strength materials, on flat or gently undulating slopes; material discontinuity is a well defined surface of potential failure but the more gentle slope tends to compensate for this.

##### CLASS 3-MODERATE RISK

Situations in which materials of high shear strength overlie materials of low shear strength, on rolling slopes, with a well defined surface of potential failure at the material interface.

Situations in which materials of low and moderate shear strength overlie high shear strength materials, on rolling and strongly rolling slopes, with an ill-defined surface of potential failure; failure occurs primarily within the low and moderate shear strength regolith.

Situations in which materials of moderate shear strength overlie low shear strength materials, on flat or undulating slopes, with a well defined surface of potential failure.

##### CLASS 4-SEVERE RISK

Situations in which materials of low or moderate shear strength overlie materials of high shear strength with a well defined surface of potential failure, on gently undulating to rolling slopes that are subject to removal of lateral support or of material from the toe of the slope.

Situations in which materials of moderate shear strength overlie materials of low shear strength, on rolling to strongly rolling slopes, with a well defined surface of potential failure at the material interface; failure can occur within the overlying moderate shear strength materials.

Situations in which low shear strength overlie similar strength materials, on flat or undulating slopes, with a well defined surface of potential failure at the material interface.

##### CLASS 5-VERY SEVERE RISK

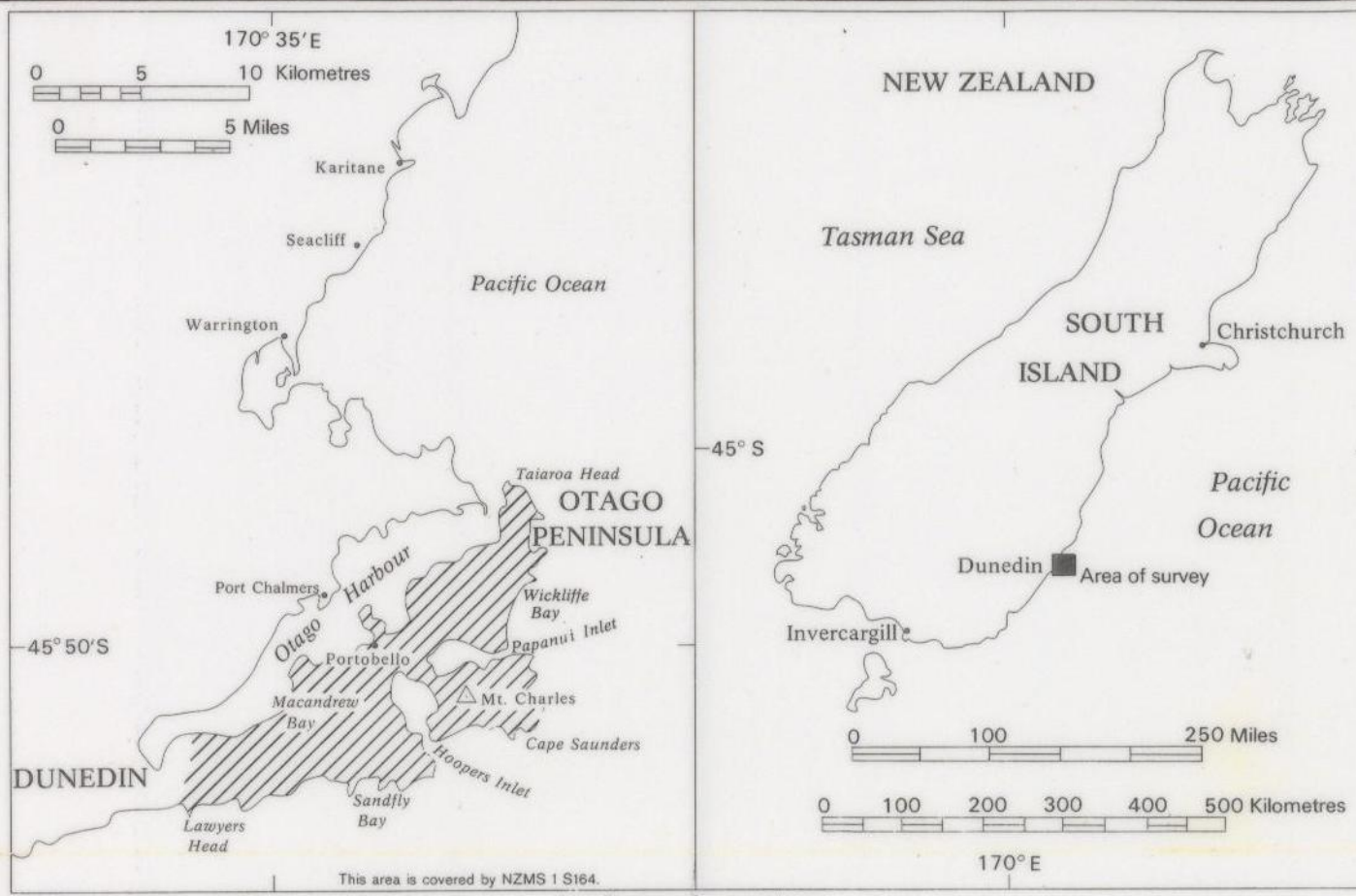
Situations in which materials of low, moderate or high shear strength overlie materials of low shear strength, with a well defined surface of potential failure on strongly rolling slopes that are subject to removal of lateral support or of material from the toe of the slope.

Situations in which materials of low shear strength overlie similar strength materials, on strongly rolling slopes, with a well defined surface of potential failure.

#### COASTAL SANDS, ALLUVIUM OR ESTUARINE SILTS

#### REFERENCE

- Road
- Stream
- ▲ Trig Station (height in metres)



Survey by D.M. Leslie, Soil Bureau, Department of Scientific and Industrial Research, Dunedin, 1972.  
 Base data from Lands and Survey Department, Wellington, New Zealand, 1974.  
 Published by Department of Scientific and Industrial Research, Wellington, New Zealand, 1974.  
**BIBLIOGRAPHIC REFERENCE:**  
 LESLIE, D.M. 1974. Landslide Potential on Otago Peninsula, New Zealand. Scale 1:31,680  
 To accompany New Zealand Soil Bureau Scientific Report 12.

