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RECORD 1984/44

SLOPE STABILITY AND ITS CONSTRAINTS ON CLOSER SETTLEMENT IN THE FOOTHILLS OF THE TOOWOOMBA RANGE, GATTON SHIRE

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CONTENTS

SUMMARY

Landslides on the lower slopes of the Toowoomba range have been examined to assess the dangers they present for future closer settlement, and to provide appropriate advice to the Gatton Shire Council.

The landslides occur predominantly in unconsolidated colluvial (hillslope) debris on slopes underlain by basalt lavas, and in colluvium and weathered rock on slopes formed by the interbedded sediments of the Marburg Formation. Besides being common on the steeper slopes, the landslides also affect flat to gently sloping benches on the flanks of ridges, particularly benches developed on interbedded shale or siltstone. There, the slides may occur in the weathered soft shale bedrock, and affect considerable areas.

The prime cause of the landslides appears to be the removal of forest cover since European settlement, which has reduced mechanical support for the slopes, and allowed groundwater pressures to rise to critical levels.

Thirteen stability zones have been delineated by relating known landslide occurrences to combinations of topographic, geological and groundwater conditions. Recommendations are given on the suitability of the zones for closer settlement, and on precautions needed for subdivision and building within them. In zones where some settlement is possible, but unstable or suspect areas are present within them, further study is needed prior to subdivision or buidling to allow safe subdivision layouts to be designed.

Keywords: Landslides; slope stability; land use planning; Toowoomba-Gatton.

INTRODUCTION

The escarpment loosely known as the Toowoomba range, forming the eastern edge of the Darling Downs and the western margin of the Lockyer Valley, is developed on a series of basalt lavas of Tertiary age. Along its eastern foothills, steep easterly-trending ridges and valleys have been eroded in both the basalts and the underlying older sedimentary rocks of the Marburg Formation.

Landslide problems have been reported in the basalt terrain on the eastern edge of Toowoomba, and extensive slope instability is well known on the Marburg Formation in the Lockyer Valley.

In recent years, the existence of several roads down the escarpment has encouraged the development of rural residential settlement in the foothills zone, catering for Toowoomba residents who desire a rural atmosphere within commuting distance of the city. The Gatton Shire Council is concerned, however, about the risks posed to building in this area by slope instability, and has commenced a development control plan to examine this and other constraints on closer settlement in the area.

The Shire Council has requested the Geological Survey of Queensland to undertake a slope stability study of the foothills zone to allow geological factors to be taken into account in the development control plan.

This resulting report is designed to provide advice to both the Council and the general public. The study has considered the topographical, geological, and hydrogeological controls of landslides in the foothills zone, and delineated, at district scale, various types of landslide-prone land. It is intended to provide a background against which future land-use decisions can be made, as well as guidelines for more detailed studies of particular areas. The study area includes the lower part of the escarpment itself, and the upper sections of the valleys of Stockyard, Flagstone, Monkey Water Holes, Puzzling, Gatton, Little Oaky, Rocky and Murphys Creeks, together with their intervening ridges (Fig. 1). Other valleys further east in the Lockyer Valley, which have significant landslide problems, are not covered because of their greater distance from Toowoomba. A small section of the crest of the escarpment south of Toowoomba, which lies in the Gatton Shire, has been included for the sake of completeness. The crest of the escarpment within Toowoomba City has been assessed previously (Holmes, 1981).

Previous investigations

The landslide problems on the eastern edge of the Toowoomba escarpment have been studied by Hughes (1974), and by Holmes (1981) who has zoned the land into several stability categories. Ciesiolka (1974) studied landslides in the adjacent Murphys Creek valley.

In the Lockyer Valley, widespread land degradation problems, including landslides, have been discussed by Shaw (1979). Zahawi & Trezise (1981) and Zahawi(1983a) investigated several landslides in detail, including some in the study area, to determine reasons for failure. Zahawi (1983b) has also divided land within the Lockyer Valley into several regional slope-stability categories, to assist rural land management. Brown & Partners (1983) have reported on a number of proposed subdivisions for landowners in the Flagstone Creek area.

The general regional geology of the study area has been investigated by numerous workers to whom reference is made in the following chapters.

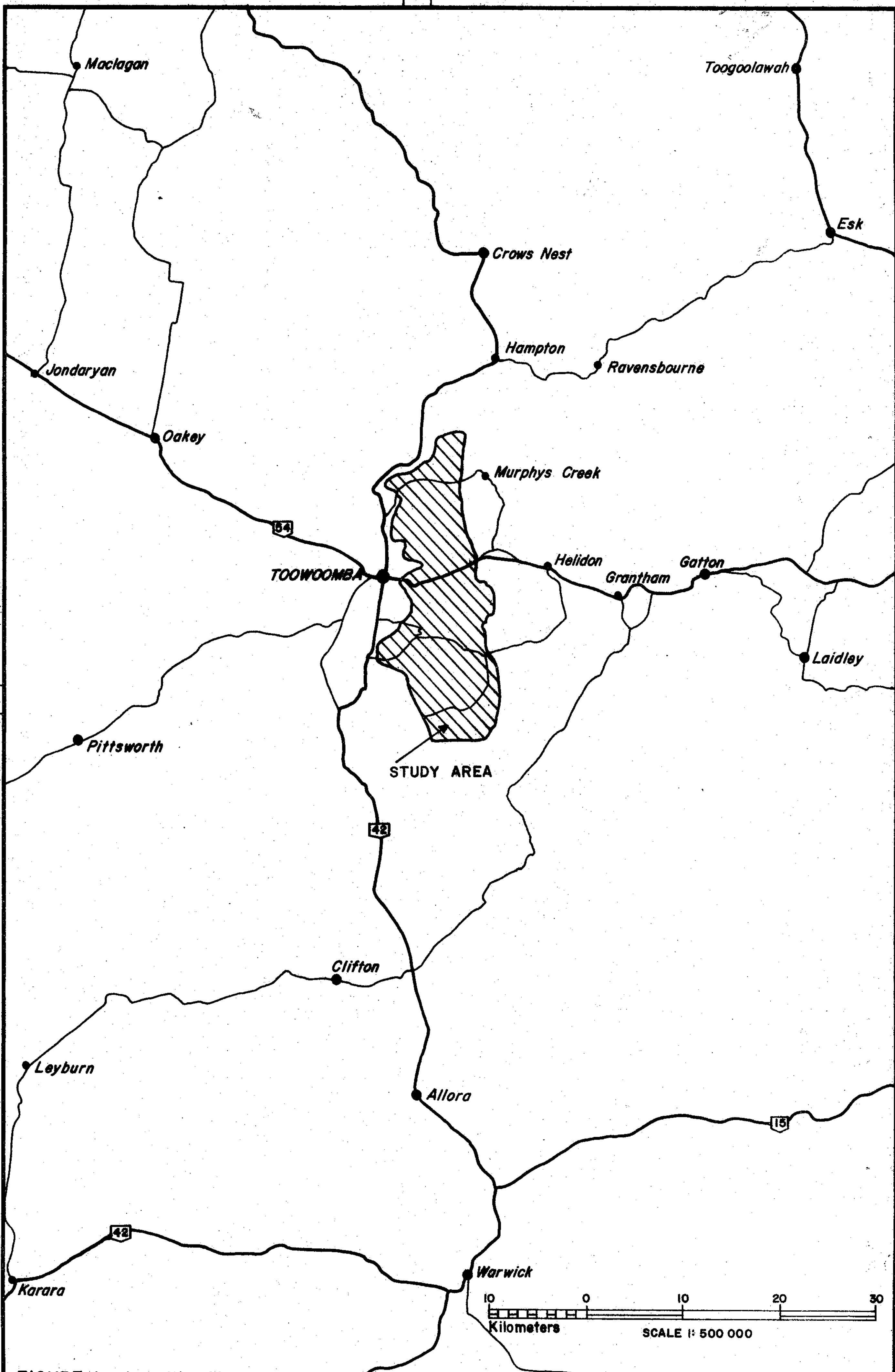

FIGURE 1: Locality Map

Methods of investigation

A scale of 1:25 000 was adopted for the survey as this was the most detailed for which contoured topographic maps were available for most of the area. Unfortunately, topographic map coverage of the area has not been systematic, and the map compiled for this report is a mosaic derived from published and unpublished 1:25 000 maps, a reduction of the 1:15 000 Toowoomba City map, and an enlargement of sections of the 1:100 000 maps. The 1:25 000 scale is also convenient for covering a district study in a reasonable time.

To provide an accurate geological base at this scale, considerable refinement of previous geological mapping was necessary. Field traversing based on prior airphoto interpretation concentrated on a delineation of the limits of the basalt, and on loose hillslope debris (colluvium) derived from both basalt and sandstone/shale material.

The most useful airphotos were found to be the 1974 Southern Moreton District Flood set (about 1:25 000 scale), which were flown in colour shortly after the heavy rainfall of January 1974, when landslide scars were still fresh. Other photos used were the Helidon 1976 set, and the Esk 1982 set for the northern part of the area (both about 1:25 000 scale).

During the field traversing, landslides suspected from the airphoto interpretation were confirmed, and any additional slides, possible slides, or suspect areas were plotted. It was found that slides could often be better recognised from a distance (say from an opposite hillside) than on the particular hillside itself, due to limited visibility amongst grass and weeds, and undulations on the hill. Thus not all slides were inspected on the ground, but all hillsides were scanned, and identified landslides were plotted on the airphotos. Consequently, it is not claimed that each and every slide has been recorded, but it is considered that all of significant size have been observed to determine the pattern of activity.

All landslides identified were plotted on both the geological map (Map 1) and the stability zoning map (Map 2). The topographic and geological pattern that became evident during the study allowed generalizations to be made regarding the stability of certain zones. These are shown on Map 2. The significance of these zones is discussed below.

Detailed investigations of individual slides, soil testing or stability calculations were not carried out as they were not considered appropriate for a broad-scale survey such as this.

Acknowledgements

The assistance of the Division of Land Utilization, Department of Primary Industry in loaning a set of the 1974 Southern Moreton District Flood colour airphotos is appreciated.

TOPOGRAPHY AND ITS DEVELOPMENT

The basalt highlands of the Great Dividing Range once extended considerably further eastwards than Toowoomba, and the present topography has resulted from the erosion of this terrain and the underlying rocks by the tributaries of Lockyer Creek. The main upper escarpment of the Toowoomba range, which at a regional scale forms a semi-circle around the periphery of the Lockyer catchment between the Mistake Mountains and Mount Perseverence, has formed by westward scarp retreat, promoted by headwater erosion of the various tributaries. This process is continuing.

As the scarp retreated, prominent east-trending ridges were left between the major stream valleys; towards the west they remain at a similar height to the summit of the range and are still capped by basalt, but they fall gradually eastwards where the underlying sediments of the Marburg Formation appear on their crests.

On the basalt terrain, scarps and very steep slopes, with steep, narrow-crested side ridges, predominate towards the top of the range and major ridges. Lower down, discontinuous flat benches, or shelves, are developed in places, presumably on softer or more fractured lavas within the basalt sequence. Towards the base of the basalt, less steep hilly country consisting of gently sloping ridge crests interspersed with steeper gullies, is common.

The slopes developed on the sediments of the Marburg Formation are markedly benched, or stepped, on account of softer beds in the sequence, such as shale, siltstone or soft sandstone, while resistant sandstones form intervening scarps or clifflines. Some major sandstone beds form sizeable clifflines that can be traced around hillsides for three or more kilometres. The crests of the main ridges underlain by the sediments are relatively broad, rounded, and gently sloping. At lower elevations in the valleys, broad undulating ridges are separated by gullies with steep sides formed on resistant sandstone beds.

In the stream valleys, alluvium has accumulated in several stages. The oldest deposits now form unusually high terraces (up to 15 m in the Flagstone Creek Valley), which have subsequently been eroded to allow deposition of intermediate and low terraces, presumably following a change in base level of the streams.

In the middle reaches of Flagstone Creek, gently sloping fans or aprons of colluvial/alluvial debris flank the toes of slopes on the Marburg Formation, merging downslope with the highest alluvial terrace.

GEOLOGICAL SETTING

The Toowoomba range and its adjacent east-trending valleys have been carved into a sequence of basalt lavas of Tertiary age, which rest on older sedimentary rocks of the Marburg Formation, deposited in the Clarence-Moreton Basin during Mesozoic times.

BASALT LAVAS AND ASSOCIATED MATERIALS

The basalts in the Toowoomba area form part of an extensive belt of Tertiary basalt and associated lavas that extends from the New South Wales border to north of Kingaroy. This sequence has been termed the Main Range Volcanics by Cranfield & others (1976). Stevens (1969) studied the lavas in the Toowoomba area, which he termed the Toowoomba Volcanics, but this terminology is not followed here as they form only part of a larger sequence.

Stevens (1969) delineated the extent of the lavas in only general terms, and despite subsequent regional mapping reported by Zahawi (1975), Cranfield & others (1976) and Shaw (1979), and some local detailed mapping by Johnston (1965) and Ciesiolka (1974), their extent has never been reliably delineated on an adequate topographic base. Consequently, considerable effort was necessary in the present project to trace the extent of the basalt lavas, as the range of stability problems present on the basalt is different from that present on the underlying Mesozoic sediments.

Attention was also paid to the extent of unconsolidated colluvial (hillslope) debris derived from the basalt (which covers the older rocks in places), as this can be particularly susceptible to failure.

Main Range Volcanics (Tm)

In the Toowoomba area, the Main Range Volcanics are chiefly olivine basalt, although trachyte occurs not far to the west at Cooby Creek, and discontinuous beds of tuff and agglomerate are known in places. No major volcanic centre has been recognised and it is assumed that the lavas originated from a series of small fissures and vents, which gradually built up a sub-horizontal lava plain. Some small centres of eruption have been identified, such as in the Toowoomba Municipal Quarry, but other postulated centres, such as at Ben Lomond in the Murphys Creek valley, are more conjectural. The volcanics were extruded between 25 and 19 million years ago, at a similar time to many other sequences of basalt in southern Queensland.

In the study area, the base of the sequence is usually between 400 and 450 m above sea level, but there is considerable variation due to irregularities in the pre-existing landscape. A basalt-filled valley is evident near Ben Lomond-Spring Bluff in Murphys Creek, and elsewhere higher knobs or ridges of sandstone apparently formed hills which remained above the earliest basalt flows. With the summit of the range at Mount Kynock at 710 m above seal level, the thickness of the sequence in the Toowoomba area is about 300 m. Stevens (1969) identified between 17 and 20 individual flows in the road cuttings of the Toll Bar section of the Warrego Highway, but it is impossible to trace separate flows over any distance.

Pyroclastic rocks, consisting predominantly of bedded lapilli tuff and minor agglomerate, with sporadic basalt bombs, are known at Ballard railway station (where they are about 12 m thick), further east on a ridge south of Murphys Creek (Johnston, 1965), near Harlaxton, in the Municipal Quarry, and on the track from Picnic Point to Mount Table Top (Stevens, 1969). These locations are shown on Map 1.

Colluvium or hillside debris (basalt-derived) (TQcb)

Erosion of the range and associated ridges has resulted in considerable debris accumulating in gullies on the scarps and steep slopes, on the benches, and over the older rocks below the basalt. In the latter situation it may form tongues occupying gullies between ridges, or broader gently to moderately sloping aprons; these have not been recognised separately previously.

The material is a mixture of soil, clay, and cobbles and boulders of basalt, some of these are of considerable size. It generally has a clay matrix of low permeability, and black, reactive montmorillonite soils. Its unconsolidated nature is one of the prime contributing factors to slope instability in the area. The thickness of some deposits suggests that at least some of the material could be as old as late Tertiary.

Colluvium of varying thickness covers much of the basalt terrain, but at the scale of this study it has only been possible to delineate separately the thickest and most obvious deposits, chiefly where they form tongues or aprons over the older rocks. Such deposits of colluvium are far less prevalent than around the base of similar basalt terrain further east (Maleny, Tamborine Mountain, etc.), presumably because of the drier climate prevailing.

Scree

Bare rock scree slopes consisting of steep fans of cobbles and boulders occur in places on the steepest scarps. They generally originate below a cliff line of a resistant basalt flow, in which pronounced columnar jointing allows loosening and toppling of joint blocks.

MESOZOIC SEDIMENTS AND ASSOCIATED MATERIALS

The sedimentary rocks of the study area form part of a large depositional area of Jurassic times known as the Clarence-Moreton Basin. This basin continued westward beneath the present Great Dividing Range to link with the Surat Basin

The unit of interest in the study area is the Marburg Formation, although the slightly younger Walloon Coal Measures may cap some ridges on the southern fringes.

Marburg Formation

The Marburg Formation is a sequence of interbedded sandstone, siltstone, mudstone, shale and conglomerate with minor coal seams. The sandstone is characteristically fine to medium-grained, feldspathic and lithic, and well-bedded, although within the study area, which exposes the upper part of the sequence, some more quartzose sandstones are present. It is considered that the sediments were deposited in a fluviatile (river) environment (Cranfield & others, 1976).

The Marburg Formation in the Lockyer Valley has been examined by McTaggart (1963) who subdivided it into four members, namely the Gatton Sandstone (lowermost), Winwill Conglomerate, Ma Ma Creek Sandstone, and the Heifer Creek Sandstone.

Most of the slopes in the study area are underlain by the Heifer Creek Sandstone Member (Jbmh) (the upper beds of Zahawi, 1975). This unit consists of 180 to 250 m of ferruginous and siliceous coarse sandstone with some siltstone , shale and flaggy sandstone (McTaggart, 1963; Johnston, 1965). Many of the sandstones are massive, with beds up to 20 m thick that are cliff-forming. The older members of the Marburg Formation (the 'lower' beds of Zahawi, 1975) outcrop only on the eastern fringes of the study area, such as in the lower reaches of Murphys Creek and east of Withcott. Because of the very generalised map given by McTaggart (1963) there is some doubt as to where the lower boundary of the Heifer Creek Sandstone Member with these underlying rocks should be placed in detail, and Johnson (1965), Ciesiolka (1974), Zahawi (1975) and Shaw (1979) all give slightly different interpretations. As the unstable slopes are virtually restricted to the steeper, higher country formed on the Heifer Creek Sandstone Member, and as the underlying unit, the Ma Ma Creek Sandstone Member, has similar gross lithologies, the position of the boundary is largely irrelevant for this study, and no attempt was made to re-map it or delineate it on the accompanying map.

The interbedded nature of the sediments of the Heifer Creek Sandstone Member, which leads to benches forming on the softer, readily decomposed sediments, and the accumulation of weathering debris on the slopes, is one of the main factors allowing massive slope failures in the district.

<u>Walloon Coal Measures</u> (Jw)

McTaggart (1963) defined the top of the Heifer Creek Sandstone Member as being a 20 m thick cliff-forming bed of conglomeratic sandstone. This implies that the strata above this bed, which in the study area occur chiefly in the headwaters of Stockyard and Glen Lomond Creeks, belong to the overlying unit, the Walloon Coal Measures.

The Walloon Coal Measures consist of grey shales, siltstones and sandstones that usually weather to a mature topography. They are up to 200 m thick, but in the study area only the lowermost beds remain between the Heifer Creek Sandstone and the overlying basalt.

The interbedded nature of the strata give, in this relatively youthful topography, a similar benched terrain (although less pronounced) and similar stability problems to the underlying units. For this reason, no distinction has been made between the Heifer Creek Sandstone Member and the Walloon Coal Measures for stability purposes.

<u>Colluvium or hillside debris</u> (sediment-derived) (TQcs)

Most of the steeper slopes and benches underlain by the sedimentary units are mantled by colluvial debris of varying thickness. This consists of mixtures of boulders and cobbly to pebbly silts and clays, which grade with depth into weathered softer rocks such as siltstone. The presence of this material is the prime cause of the large-scale movement on the steeper slopes.

As it is extremely difficult to distinguish this material from in-place weathered rock without sub-surface investigation, no attempt has been made to show it systematically on the accompanying maps. However, some locations, chiefly pronounced gullies or aprons beneath cliffs or scarps, where its presence has been confirmed or is suspected, are depicted.

Because of its clayey and unconsolidated nature, and its occurrence in situations where high groundwater pressures can develop, such situations must be considered at risk.

LOW LEVEL COLLUVIAL-ALLUVIAL FANS (TQca)

In the middle reaches of the Flagstone Creek valley, broad, gently-sloping fans or aprons of unconsolidated sediments flank the toes of steeper slopes of the Marburg Formation, leading to the uppermost alluvial flats of the stream course. The exact nature of the origin of these sediments, chiefly pebbly silts and clays, is uncertain, but it is presumed to involve both colluvial and alluvial processes. Some could be as old as late Tertiary.

Because of the gentle slopes there are no stability problems, but the unconsolidated materials are highly prone to gully erosion.

ALLUVIUM (Qa)

Stream alluvium occurs adjacent to all the major streams, and consists of silt, clay, sand and gravel, the latter occurring mainly at depth. Heavy black soils predominate on the alluvial flats, reflecting an origin, in part, from the basalt terrain. At least three terraces can be recognised in places, especially in the upper reaches of Flagstone Creek, where the older, upper terrace is particularly high. Delineation of the various terraces was not relevant for the present study.

The only stability problems are localised bank collapses where the present stream channel is undercutting the edges of terraces. Some of the lower flats would, however, be subject to flooding, and areas of waterlogging may occur.

SOILS

The soils on the eastern flanks of the Toowoomba range have been reported in general terms by Thompson and Beckmann (1959) and Shaw (1979). Ciesiolka (1974) gave details of four soils in the Murphys Creek valley. The following is a summary of these reports, amplified by some observations made during this survey.

The Heifer Creek Sandstone Member supports a heterogenous complex of soils, but mostly shallow to moderately deep texture-contrast soils (red or yellow podzolic) with loamy sands over mottled clay subsoils. Some uniform cracking clay soils are also present, presumably over shale sections of the rock sequence. Zahawi & Trezise (1981) suggested that some of the clays in these soils may be dispersive, which would explain their susceptibility to soil erosion.

The Walloon Coal Measures give rise mainly to moderately deep to shallow dark cracking clay soils. The basalt on the slopes of ridges weathers to shallow dark, non-cracking clay soils (Prairie soils) that grade into decomposed basalt. These are generally stable, except on the steepest gully heads and sides. On the benches, colluvial aprons and in some gullies where accumulations of colluvium are significant, heavy, black cracking clay soils (Black Earths) are present. These are likely to have a high content of montmorillonite, which loses strength on saturation, and accentuates problems of instability in vulnerable locations.

On the crest of the range south of the headwaters of Flagstone Creek, shallow Black Earths and brown skeletal soils have developed on the basalt. To the north on the plateau of Toowoomba City, red krasnozem soils predominate, originating mainly from an old laterite profile that developed on this area of the basalt in Tertiary times. They are deep, friable clayey soils with clay subsoils of relatively uniform appearance. The clays appear to be predominatly kaolinitic. Such soils are reasonably stable except where accumulations of colluvium are present on slopes and in gullies at the edge of the range (Holmes, 1981).

A few limited areas of red soils were observed at much lower elevations on the basalt, such as on the ridge between Glen Lomond Creek and Flagstone Creek. These originated either from patches of laterite that developed at a lower level, or from exhumed lateritic soils that developed between intervals of lava eruption. Ciesiolka (1974) described outcrops of such red soil material ('bole') in the Murphys Creek valley.

GROUNDWATER

The groundwater conditions on the hillsides in the study area have a major influence on the occurrence of instability. The significant factors are the horizontal layering within both the basalt, where vesicular or fractured flows may act as porous zones, and the sediments, where an impermeable shale bed may concentrate water flows immediately above it. In such situations, perched aquifers can develop, feeding water horizontally out onto the flanks of ridges, where it may be 'dammed up' beneath impermeable unconsolidated colluvium or weatered rock, with considerable hydrostatic head. Drilling beneath two landslides in the Monkey Water Holes Creek valley has shown the presence of such perched aquifers (Zahawi & Trezise, 1981; Zahawi, 1983a).

Identification of individual aquifers is not generally possible, although some particularly active layers can be inferred by lines of springs on some benches. However the close stratification of the rocks suggests that many local perched aquifers are present, and it must be assumed that virtually all the flanks of the ridges are influenced to some extent by lateral seepage, and consequent high groundwater pressures, which can reach critical levels in susceptible locations.

TYPES OF LANDSLIDES AND THEIR DISTRIBUTION

Several types of slides can be recognised on the hillsides of the study area, depending on the various topographical and geological situations (see Figures 2, 3). However, gradations between types are common, and the larger slides may exhibit characteristics of more than one type.

Various schemes for the classification of landslides have been developed by research workers, but many are too detailed or unsuitable for Australian conditions. The simplified scheme used in this study is a combination of the schemes of Varnes (1958) and Broms (1975).

Soil creep or 'terracetting' involves small, gradual movements in the upper soil mantle, which commonly give rise to a series of small steps or terraces down a slope. It is more likely to occur on concave sections of slopes where soils are thicker, and can be recognised from a distance by the uneven surface of the slope.

On the basalt terrain, some soil creep and terracetting seems normal under natural forest conditions, mainly in the steep heads of gullies and on the steepest scarps with open eucalypt forest. On cleared slopes, however, the frequency is much increased, and most side slopes beside gullies as well as the scarp lines are susceptible.

On the sedimentary terrain, creep and terracetting is particuarly common on cleared steep slopes, where accumulations of soil, colluvial debris and weathered rock are common.

Zahawi (1983b) reports suggestions that terracetting is the forerunner of larger landslide movements. From observations during this survey, this would seem to be likely on the steep slopes on the sedimentary terrain, but more uncertain on basalt slopes where the soils are thinner.

At the scale of the survey, it has not been possible to identify all areas subject to terracetting, and only the more pronounced disrupted areas are shown on the accompanying maps (as slides or possible slides).

Debris slides and flows have occurred predominantly on the steep to very steep slopes and scarps of the sedimentary terrain. They are shallow, narrow movements of soil, colluvial debris and some weathered rock which move rapidly down slope, often as a viscous fluid, leaving behind an arcuate head scarp. Once initiated, can progress upslope by failure of the head scarp in the colluvium in subsequent periods of activity. Their lower sections have some features of earth flows (Ciesiolka, 1974). They commonly occur on concave slopes where the collvuial debris is thicker or the seepage of groundwater is greater than elsewhere; commonly many adjacent slides disrupt a large proportion of the slope. Although very numerous, such failures are not greatly troublesome for settlement, as they occur on the steepest slopes intrinsically difficult for building. They would be troublesome, however, for any road building on such slopes, as under cutting would add to the instability.

Debris slides also occur on the very steep slopes and scarps of the basalt errain, but there they are generally smaller, narrower and more isolated. Gully sides are especially at risk.

Rotational slides or slumps occur mainly on the steep slopes on the sedimentary terrain. The slides move relatively quickly and exhibit a sizeable semi-circular head scarp, with some indication of a back-tilted upper section, and a disrupted toe section which in some could be classed as an earth flow. They grade into debris slides with increasing steepness of slope (many examples are in fact intermediate between the two types), and into multiple rotational slides on flatter ground of the benches. They occur in a variety of topographical situations on the steep slopes, and are the most difficult to predict. Smaller rotational slides also occur on moderate to steep slopes adjacent to gullies on the basalt terrain.

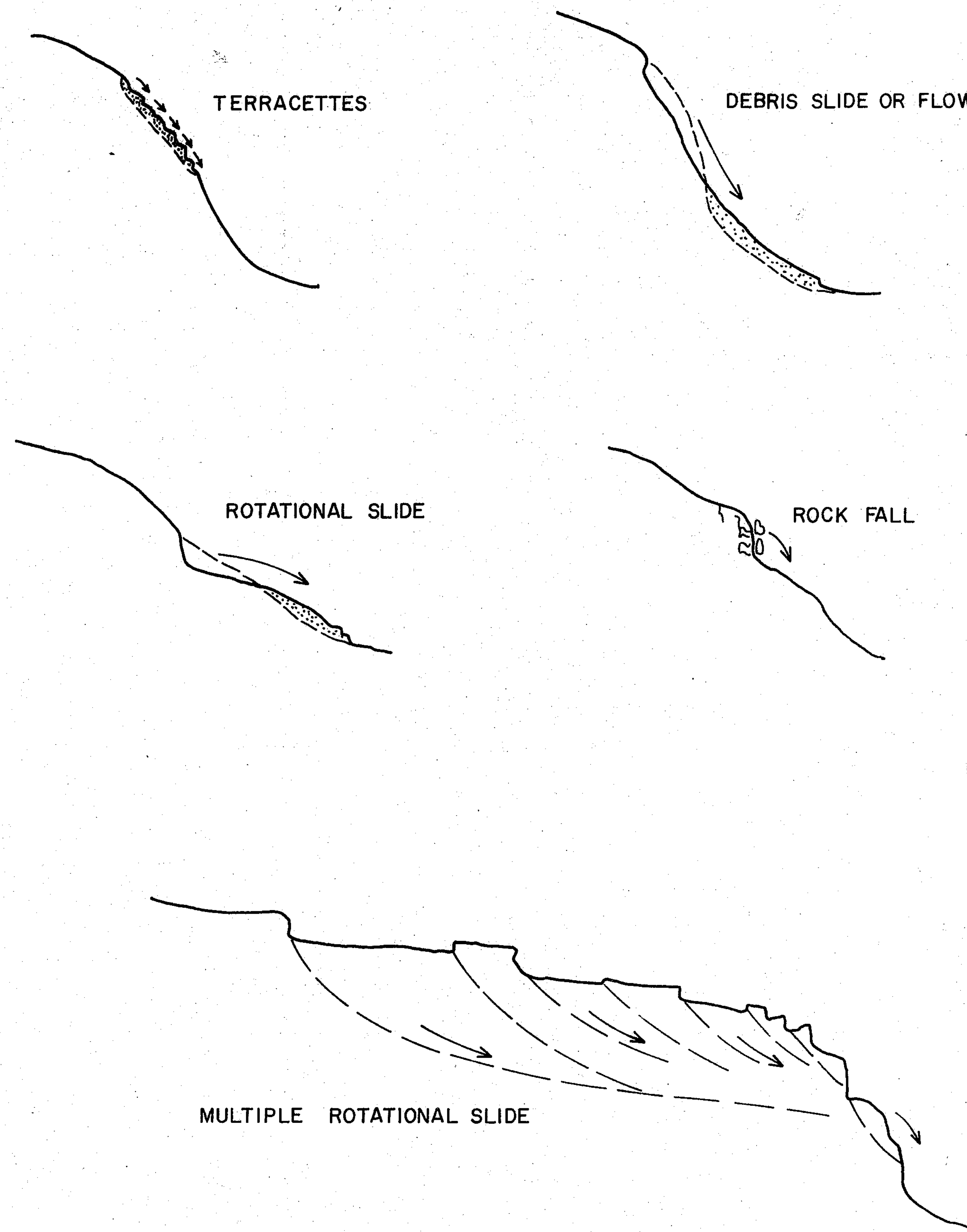

Figure 2 : Types of landslides common in the study area

Complex multiple rotational slides are broad, relatively deep, slow-moving slides which occur on the outer edges of benches on both the sedimentary and basalt terrain. They may also occur above any drop-off on tongues or aprons of colluvium. The slopes of their upper sections are commonly quite gentle, and the semi-circular head scarps may be less than 1 m in height, as movement in the upper parts of the slides usually occurs only in the wettest seasons. Closer to a bench edge, however, movement may be more frequent, and a series of slides and scarps is usually present. These may disintegrate to parasitic debris flows over the bench edge.

Large multiple rotational slides affect many of the smaller, sloping benches on the sedimentary terrain, where they may affect the whole width of the bench (as documented in the Monkey Water Holes Creek area by Zahawi, 1983a). There they may have high head scarps, and deep failure planes which may be within shale bands in the bedrock, rather than merely in the surface colluvium. Where such slides affect the whole width of a bench, colluvium on the next scarp line above may be destabilised by removal of support, resulting in small debris slides or rotational slides there.

On the benches of basalt or basaltic colluvium, the multiple rotational slides tend to be smaller, with smaller head scarps and shallower failure planes in colluvium. They mainly occur around gully mouths and wet concave areas adjacent to the bench edge, and affect the whole width of the bench only where such a wet concave area extends right across the bench.

Such slides on the benches are of great significance for planning of future settlement, as they occur on relatively flat land seemingly suitable for building.

Small rockfalls occur on the cliffs of sandstone that outcrop on many of the scarp lines of the sedimentary terrain. They mainly occur following debris sliding on the slopes immediately below, which removes support and de-stabilises the blocks on the cliff. However, in some situations such as broken clifflines, removal of the vegetation alone seems to have been sufficient to promote movement of the sandstone blocks.

CAUSES OF THE LANDSLIDES

Compared to mountainous areas in other parts of the world, the ranges of southeast Queensland are relatively subdued and mature. In such areas, slopes tend to reach a balance between the progressive weathering of the rocks, and the removal of the weathering debris by water erosion; landslides then occur only rarely and mainly on the

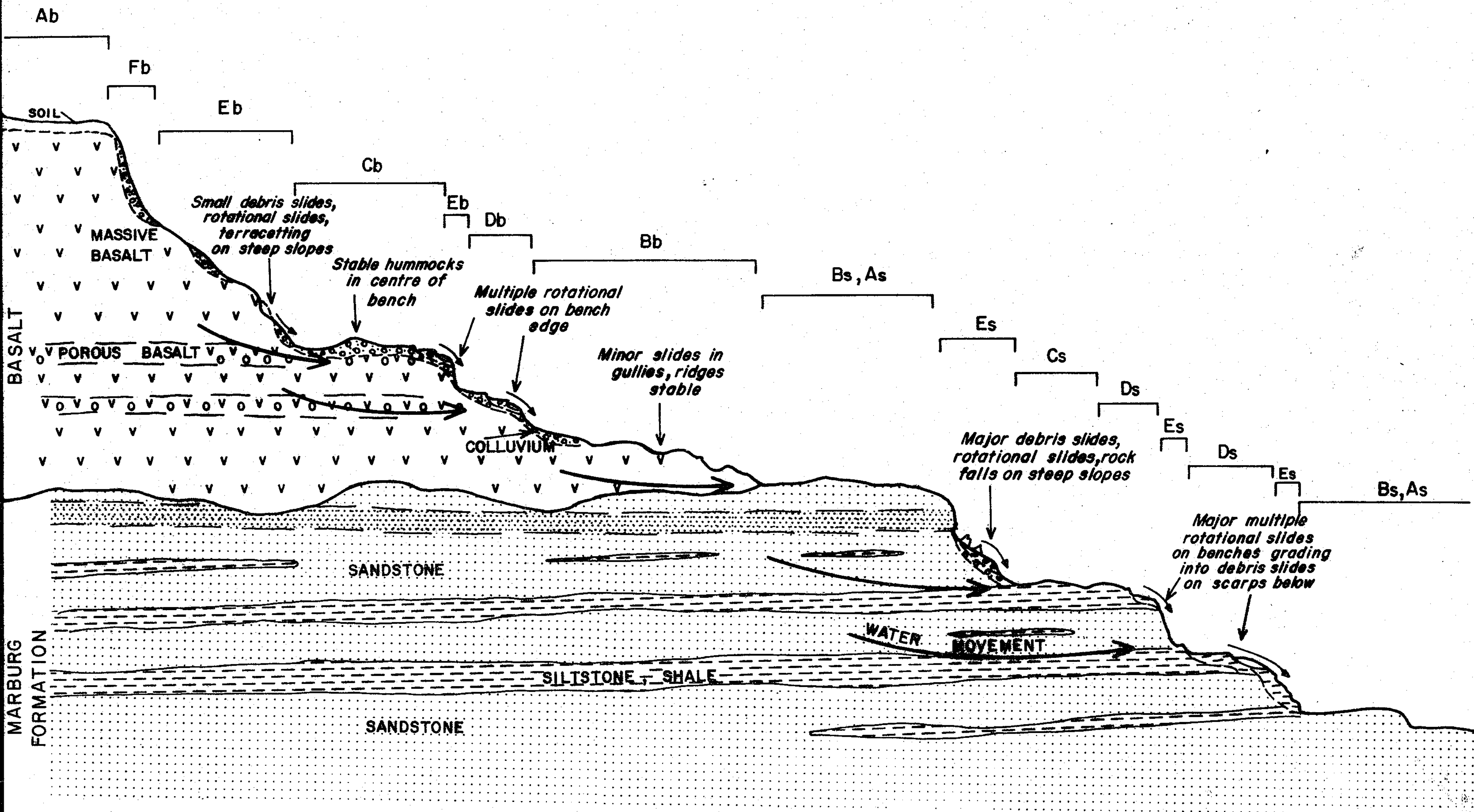

Figure 3: Diagrammatic cross section of typical ridge on eastern side of Toowoomba range, showing locations of slides and stability zones

steepest scarps. Such a balance exists even in geologically sensitive situations, although it may be relatively more delicate.

Where extensive landsliding has occurred in such a mature district over a short period of time, say within the last 100 years, some change must have occurred to alter the balance.

Landslides occur on natural slopes when the strength (shear strength) of the material involved is reduced to below that which is required to support its weight.

The shear strength of a material is governed by the formula:

Shear strength = Cohesion of the material + downward pressure at right angles to any potential failure plane x tangent of the angle of internal friction.

There are only limited ways in which the strength can be reduced. Firstly, the internal properties of the material (cohesion and angle of internal friction) may change by gradual weathering and this can explain the occasional landslides under natural conditions. However, weathering is a slow process, and cannot explain the sudden increase in landslides over a short time period. These properties can also change with the moisture content, but any such changes have been occurring routinely in the past.

Secondly, the downward pressure at right angles to a potential failure plane can be reduced by the development of a reverse, upward pressure. This can occur by a build-up in the pore-water (groundwater) pressure in the material.

Although fluctuating groundwater pressures have occurred periodically in wet seasons for thousands of years, and are part of the natural balance, evidence has become available in recent years that groundwater levels and pressures rise significantly when the natural forest cover is removed. This is mainly due to the loss of transpiration of water by the trees. There are many reports from older residents of rural districts of new springs breaking out after a hillside was cleared or ring-barked. Such general background rises allow higher peak pressures to develop during intense rainfall than was previously the case, and in susceptible locations these may cause a sufficient loss in strength to cause sliding. This effect is particularly important on the benched slopes, where groundwater is fed laterally outwards onto the hillside.

Thirdly, the bulk strength of surface material may be reduced by the loss of tree root support following clearing.

In the study area, cleared slopes on the sedimentary terrain have failed dramatically, while similar slopes still under forest show little movement except for some rock falls from cliff lines on the scarps. On the basalt terrain, cleared slopes also show a greater frequency of slides, although they are generally smaller than on the sediments.

On the benched slopes the most important effect of clearing is the loss of transpiration of the water being fed laterally outwards from perched aquifers, and a consequent rise in groundwater pressure. On the steep slopes, this effect is probably subsidiary to the loss of direct tree root support and the increased rapidity of soil saturation following the loss of the tree canopy.

In summary, the extensive recent landsliding has occurred because clearing of the forest has disrupted a delicate balance in two geologically sensitive situations.

The geological sensitivity results from:

- the horizontal strata on both the basalt and sedimentary terrains directing groundwater flows, through fractured or porous layers above tighter bands, laterally outwards onto the slopes;
- thick accumulations of unconsolidated colluvial debris, and weathered rock on the sedimentary terrain;
- the presence, in places, of beds of soft sediments, particularly beneath the benches, which themselves may fail;
- the presence of swelling clays in the basaltic soil and colluvium, which lose strength on saturation.

The forest clearing has caused:

- a rise in groundwater levels and pressures through reduced transpiration, resulting in a reduction in strength of soil, collvuial debris, and weathered rock, especially on benched slopes;
- increased rate of absorption of rainfall by the soil, reducing the time taken to reach high groundwater pressures;
- decreased release of groundwater pressures on lower slopes because of changes in soil texture and compaction; and

- a direct reduction in strength of surface material through the loss of the binding support of roots, especially on scarps and steep slopes.

The combination of these factors has led to failures in susceptible locations when triggered by heavy rainfall.

Landslides can also be instigated in marginal areas by the activities of man, such as by removal of support at the toes of slopes for road cuttings, loading heads of potential slides by fill or buidlings, and directing surface or groundwater flows to susceptible locations.

PREDICTION OF AREAS AT RISK: STABILITY ZONING

Prediction of the future stability of slopes in landslide-prone areas is fraught with many difficulties, and the present state of science does not allow an absolute guarantee of the stability of any particular area.

To the layman, landslides are visualised as occurring on steep slopes, generally where there is a thick accumulation of soil or debris. However, there are numerous examples of steep, but quite stable hillslides, such as in the older Brisbane suburbs of Paddington, Red Hill and Taringa, and equally numerous examples of major landslides occurring on slopes less than 7° (or 12%). Clearly, any landslide risk assessment cannot be based on slope angle alone.

Similarly, risk assessment cannot be based simply on soil type or thickness (nor on its engineering properties), as similar soils can be stable in one area and unstable in situations close by.

Mathematical analysis of stability is much discussed in text-books, but to obtain the necessary data on the materials present and their properties, and on the groundwater conditions, expensive sub-surface investigations and testing are usually required. Moreover, for un-failed slopes it is difficult to decide where a failure surface may be present so that calculations can be made, and it is uncertain to what level the groundwater pressures could rise in the most intense possible rainfall event, without long-term monitoring. In addition, such calculations are site-specific, and cannot be correlated over even short distances. Such techniques have their uses for specific sites that have already failed or are in danger of doing so, but they are of limited usefulness for overall studies of larger districts.

A more appropriate procedure for ascertaining the likely stability of slopes in regional studies, such as the present one, is to empirically relate known landslide occurrences to particular conditions. If such relationships can be recognsied, zones with similar combinations of conditions can then be outlined. Such an approach has been used to establish the zones of this study (shown on Map 2 and discussed below).

These zones represent areas of similar topography and geology, where the type and extent of instability is similar. Thus one zone shows the essentially stable platueau surface, another shows the steep scarps where debris slides are common and safe building sites are virtually absent, and other intermediate zones, such as on the benches, encompass some stable and some unstable land. They are designed to assist town planners in determining which areas are or are not suitable for particular types of subdivision. It is emphasised that the suitabilities discussed here and shown on the map are based only on stability and topographic considerations; other physical, economic and town planning factors may down grade the suitability of some areas.

It must be thoroughly understood that at the adopted working scale of 1:25 000 it is not possible for each of the zones to represent only one uniform stability. To distinguish stable and unstable land in the intermediate zones, such as on the benches, further more detailed study is needed, in effect to establish a local sub-zoning.

The zones do not distinguish between cleared and uncleared land, as it is possible that further clearing could occur, and landslides can confidently be predicted if the forest is cleared from unstable zones.

DESCRIPTION OF ZONES

The zones below are described in order of increasing severity of constraints. Those with the subscript 'b' are on the basalt terrain, and those with the subscript 's' are on the sediments of the Marburg Formation.

ZONE Af

Allvuial flats along the major streams are shown in this zone. No natural stability problems are known, apart from some bank collapse where the present stream is migrating laterally and is undercutting its banks. The zone includes alluvial terraces of various elevations, some of which may be flood-prone, and in places the heavy black soils could be prone to waterlogging in wet periods.

Such aspects would need consideration before closer settlement, but they are beyond the scope of this investigation.

ZONE Ac

Broad colluvial fans or aprons at the toes of steep slopes, chiefly in the middle reaches of Flagstone Creek, constitute this zone. Slopes are very gentle and no natural stability problems are known, but the unconsolidated colluvial material is very prone to gully erosion, once this is initiated by breaks in the top soil. Use of land in this zone will have to be carefully managed to avoid expansion of eroded areas.

ZONE Ab

This zone incorporates the better land underlain by basalt and basaltic colluvium, which can be divided into three types:

(i) the flat and gently undulating parts of the crest of the Toowoomba range, and other plateau remnants;

(ii) rear sections of a few broad benches on the flanks of ridges;

(iii) some gentle slopes at toes of ridges.

Natural stability problems are not expected within this zone. However, at the edge of the zone on the range crest, some instability could occur by way of up-slope extension of small debris slides on the scarp below. These are most likely to occur in the heads of gullies and other concave areas recessed into the plateau edge, where there may be some accumulation of soil and colluvium.

The type (ii) land included in this zone at the rear of broad benches is considered sufficiently far removed from the potentiallly unstable edges of the benches (zoned Cb or Db) to be classed as stable. However, where a high scarp is present behind the bench, there is some danger of rolling boulders from above. There is also the possibility of some seepage zones or natural lagoons being present. Such aspects would need consideration during design of any closer settlement.

The Ab zone, as it becomes more dissected, hilly, and steeper grades into the Bb zone. On the benches it grades into the Cb zone towards the bench edge.

<u>Suitability</u>: The zone is generally capable of close urban settlement, providing the following precautions are observed.

Precautions: Building on the edge of the range crest should be kept 15 m from the edge of the drop-off (which could be defined as the point where the general slopes becomes greater than 15° or 27%), unless it can be shown that foundations are possible on in-place basalt rather than on deep soil or colluvium. In-place basalt is likely to be at acceptable depths beneath most knobs, ridges, or elevated areas at the range edge, but would be deeper beneath gully heads and concave areas.

Such pronounced gully heads or concave areas would best be avoided for building by including them in large blocks having more suitable house sites, but if they are used, particular attention needs to be paid to foundation design and wastewater disposal, to avoid the possibility of some minor foundation movement. This is especially so if cut-and-fill foundations are being considered.

On the benches (type (ii) land), any seepage zones need to be identified before subdivision layouts are planned. Building should be kept away from the toes of any steep scarps for distances of 20 m to 50 m (depending on the height of the scarp) to avoid the danger of rolling boulders from above.

As most of the zone is on heavy black clay soils, adequate allowance for swelling clays must be made in the design of foundations.

ZONE As

This zone incorporates flat to gently undulating land developed on the sediments of the Marburg Formation. The few areas included are mainly at the base of slopes around the fringes of the study area, but some are on broader ridge crests. The zone is gradational into the more hilly Bs zone.

Natural stability problems are not known, and there are no stability constraints on urban settlement. However, the soils are moderately prone to erosion, and care is necessary in any disturbance to the ground surface and in the disposal of surface waters.

ZONE Bb

The more markedly hilly and dissected areas underalin by basalt constitute this zone. Most are in the foothills below the main escarpment of the range, but some occupy the crests of prominent ridges, and others are near the edge of the range crest. There is considerable variation in the steepness and severity of dissection of these areas, but their essential aspects remain the same. Gentle to moderately sloping ridge crests are separated by moderate to steep slopes adjacent to gullies and intervening valleys. In-place basalt is likely to be close to the surface under most of the more prominent ridges, but accumulations of soil and colluvium are common on gully sides and in concave areas. Some small rotational slides have occurred on such side slopes, and on local steep slopes, soil creep and terracetting affects the soil profile. Seepage zones elsewhere could be the forerunners to such movement. At a more detailed scale of mapping, such gully sides and local steep slopes could be zoned separately from the ridge crests, but that is not possible in the present study. With increasing degrees of steepness and dissection, and decreasing extent and width of ridge crests, the zone grades into the Eb zone.

Suitability: It is considered that the zone is capable of acreage settlement (5-10 ha) with building sites chiefly on ridge crests. However, locally some ridge crests may be sufficiently broad or long to allow several adjacent smaller blocks to be designed, while in steeper and more dissected areas considerably larger block sizes might be necessary.

Precautions: Any subdivisions in this zone should preferably be laid out so that each block has a suitable building site on a ridge crest. Adjacent moderate slopes should only be used for building if it can be shown that no seepage zones are present, that foundations are possible on in-place basalt rather than colluvium, that any colluvium or soil can be retained adequately, and that waste water will be disposed of some distance away in a safe location. Concave sections of the moderate slopes and the local steep slopes in this zone should be avoided for building. Access roads across such slopes to ridge-crest building sites should be laid out to avoid deep side cuts into the soil and colluvium mantle.

As in the Ab zone, building above any major scarp or drop-off should be kept back from the edge (which can be defined as the point where the general slope becomes greater than 15° or 27%) unless it can be shown that foundations are possible on in-place basalt rather than colluvium. This implies that most gully heads and concave embayments should be avoided.

As with the Ab zone, dark black clay soils predominate except on the stoniest ridges, and foundations for any buildings should be designed to take into account swelling clays.

Further clearing of timber on the steep slopes and gully sides within this zone should be avoided.

ZONE Bs

Areas of gentle to moderate slopes, with local steeper slopes, on the sediments of the Marburg Formation constitute this zone. They are commonly broad, rounded slopes, with interspersed local steep slopes formed on resistant sandstone beds adjacent to the drainage lines. They occur both on the lower country fringing the study area and on the summits of the broader ridges between the major creeks, where the ridges are below the level of the basalt.

The only stability problems known are small rotational slides and debris slides in colluvium on the local steep slopes. Such areas would be included in the Es zone with more detailed mapping, but this was impossible here. The soils are moderately prone to erosion.

The zone grades into Zone As on more gentle slopes, but there is usually a sharp junction with the steeper Es zone.

Suitability: Zone Bs is considered capable of small acreage settlement (1-5 ha), with the blocks laid out so that building sites and access tracks are not necessary on the local steep slopes. However, some broader ridge crests may be sufficiently large to allow smaller blocks to be designed locally.

Precautions: The local steep slopes should be avoided for building. Any building above a major scarp or drop off (included in the adjacent Es zone or above local steep slopes) should be kept back 20 m from the edge (which can be defined as the point where the general slope becomes greater than 15° or 27%) to guard against the possibility of rotational slides or debris slides on the scarp below affecting the edge. Further clearing of timber on the local steep slopes and on the adjacent scarps in the Es zone should be avoided, particularly if building is to occur on the suitable slopes above.

As the soils are moderately prone to erosion, care will be necessary in any disturbance to the ground surface and in the disposal of surface waters.

ZONE Cb

This zone consists of two types of land underlain by basaltic material where local instability is known, but where some settlement is still possible. These are

(i) benches on the upper basaltic flanks of the range and major ridges, which are relatively broad and flat.

(ii) gentle to moderately sloping colluvial aprons and tongues at the toes of basaltic slopes.

The benches consist of undulating knobs and depressions which are erratically underlain by both in-place basalt and accumulations of colluvial debris, derived from the slopes and scarps above. Because of the hydrostatic head from above, groundwater pressures in these loose materials can rise to critical values. The crests of the knobs and broad ridges on the benches are considered generally stable (particularly if underlain by in-place basalt), but because of the loose nature of the colluvial debris, any locally steep flanks of these knobs are considered susceptible to small rotational slides. Similarly, the sides of any gullies cutting the bench are considered at risk. On the bench edge, any west, dish-shaped gully mouths and other concave slopes above their edges must be considered prone to multiple rotational slides, although the incidence of these is far less than on higher rainfall plateaux further to the east (Tamborine Mountain, Maleny, etc.). Areas on the bench edge can only be considered stable if underlain by in-place basalt at shallow depth; most such areas would form a gentle knob or ridge extending outwards from other elevated areas in the centre of the bench. In a few cases the lower, sloping outer edge of the bench has been placed in the Db zone, while the Cb zone has been limited to the flatter rear sections. Areas at the rear of benches backed by a steep scarp are subject to rolling boulders and possibly some debris slides from above.

In places, such benches of the Cb zone, with an increase in the degree of dissection and proportion of ridges underalin by in-place basalt, merge with the Bb zone. This may occur laterally or downslope of only a minor scarp or drop-off.

The sloping colluvial aprons included in the zone appear to be stable, but the uncertain thickness and poorly-consolidated nature of the colluvium suggests that local steep slopes, such as beside gullies, are at risk from small rotational slides. Wet seepage areas may also be present, limiting the sites suitable for building.

Suitability: This zone is capable of acreage settlement (for example 5 to 10 ha), with building restricted to the broad knobs in the centre or rear of the benches, or other areas shown to be underlain at shallow depth by in-place basalt. On the colluvial aprons, only areas away from any locally steep slopes should be used. Some benches, although included in the Cb zone on stability grounds, may nevertheless be unsuitable for closer settlement because of their isolated positions midway or high up on inaccessible steep slopes. Such access factors have not been considered in this report.

Precautions: Before any proposed subdivision is allowed in this zone, further more detailed study is required of the area concerned, to map out the unstable, suspect and stable areas as discussed above. Only then should block lay out be designed, so that a safe building site can be included within each block.

On the benches, building should be restricted chiefly to the summits of the knobs in the centre or rear of the benches. Where these knobs are of colluvium, any moderate to steep slopes on their flanks should be avoided for any type of improvements, or for wastewater disposal, to avoid the danger of instigating small rotational slides. The bench edge should be used for building only where it can be shown, such as by back-hoe pitting, that in-place basalt is at sufficiently shallow depths for foundations. At the rear of the benches, building should be kept away from the toe of the scarp above, for distances in the order of 20 to 50 m (depending on the height and steepness of the scarp), to avoid the danger of rolling boulders and debris slides from above.

Drainage of major seepage areas to provide more building sites is not considered feasible. Most of the seepage comes from underground aquifers that would be difficult to tap satisfactorily with conventional drains. Reliance on such artificial systems with inherent problems of blockage is dangerous in residential situations, where proper long-term maintenance of the drains is unlikely.

On the colluvial aprons, any moderate to steep local slopes adjacent to gullies, or on the sides of knobs, should be avoided for construction or wastewater disposal. Seepage zones should be identified and avoided.

Further clearing of timber in the susceptible lcoations of this zone, as discussed above, should be avoided.

ZONE Cs

Two types of land underlain by sediments of the Marburg Formation are included in this zone:

(i) relatively broad, flat benches on the flanks of ridges;

(ii) broad moderate slopes on the lower flanks of ridges.

The benches are mainly underlain by siltstone or shale but some sandstone/siltstone-derived colluvium has accumulated on them in places, particularly in gully or concave areas. Few areas of instability have been recognised on such benches, but as most are still under forest cover, this may not be a valid assessment. The drastic extent to which narrower benches underlain by these sediments (included in the Ds zone, see below) have failed in major multiple rotational slides after clearing, suggests that a conservative approach is essential when dealing with any benches on sediments. Some, such as those with a massive sandstone bed immediately below them, may well be safe, but it is difficult to be sure, even with detailed investigation. Consequently, only broad flat benches with gentle to moderate slopes below their edges, or the rear parts only of similar benches with steep drop-offs below them, have been included in the zone. The outer edges of benches with steep drop offs have been included in the Ds zone.

The type (ii) land included in the zone, that is broad moderate slopes on the lower flanks of ridges, is still largely under forest cover and difficult to assess. However, it is considered that there could be some accumulations of sandstone/siltstone-derived colluvium present in these areas. There is thus the possiblitity of small rotational slides on any local steep slopes, or even of larger multiple rotational slides. Further investigation is needed of the material underlying such slopes and of the availability of building sites before decisions on their use for closer settlement can be made.

Suitability: The zone is considered capable of acreage settlement (5-10 ha) provided the precautions below are observed. On some broader benches, smaller blocks may be possible in places.

Precautions: Before any proposed subdivision is allowed on the benches in this zone, further more detailed examination is required to determine appropriate local set-back distances from the bench edge for building, and to identify any gully or depression areas which should be avoided because of accumulations of loose colluvial debris.

Clearing of timber on the bench edge or on the scarp below should normally be prohibited, if the bench is to be used for building, and subdivisions should be designed to take this factor into account.

As with the Cb benches, buildings should be kept from the toe of the scarp above for distances in the order of 20 to 50 m (depending on the height and steepness of the scarp) to avoid the danger of rolling boulders from above.

On the broad moderate slopes on the lower flanks of ridges, building should be allowed only if further investigation can show that suitable sites are underlain by competent in-place rock, rather than colluvium.

ZONE Db

This zone incorporates some of the more unstable land on the basalt terrain. Two types of land are involved, namely:

(i) benches that are relatively narrow, gently to moderately sloping, poorly drained and have a high proportion of dish-shaped areas and concave slopes, in proportion to elevated knobs. Multiple rotational slides may occur on the bench edge and in concave depressions, and small rotational slides occur adjacent to any gullies cutting the benches. Such benches may be marginal to areas of the Cb zone, from which they are gradational with decreasing areas underlain by basalt, decreasing knob areas, decreasing width and increasing slopes;

(ii) moderate to steep slopes on colluvial tongues of aprons towards the base of the basalt sequence. The loose unconsolidated natured of the colluvium can lead to small rotational slides on local steep slopes, such as beside gullies or pronounced knobs, and there is some danger of larger multiple roational slides. This zone grades from the Cb zone, and with increasing steepness into the Eb zone.

There are relatively few areas included in the Db zone, as it appears that most basalt benches are reasonably stable, and hence classified as Cb. This is in contrast to basalt plateaux further east, such as at Tamborine Mountain and Maleny, where extensive areas are euqivalent to the Db zone. This may be because of the drier climate prevailing on the Toowoomba range.

Suitability: Because of the risk of instability, this zone is considered not capable of most forms of closer subdivision. A few stable building sites may be present, but the difficulty in identifying these, and in providing access and services to them across unstable areas would preclude usual patterns of subdivision.

Precautions: If it is desired to use the few stable building sites present, further investigations to map the unstable, suspect, and stable areas in more detail, as described for zone Cb, are essential. All the precautions outlined for the Cb zone are also required for this zone. Further clearing of forest in this zone should be discouraged.

ZONE Ds

This zone includes many of the major areas of instability on the sediments of the Marburg Formation. It encompasses the hillside benches developed on these sediments (chiefly on siltstones and shales) which are relatively narrow and gently to moderately sloping.Some moderate to steep slopes on tongues and aprons of colluvium, accumulated in gully situations, are also included.

The bench edges, and in some cases the entire widths of benches, are subject to large multiple rotational slides. These have relatively deep failure planes, which may cut the weathered siltstone and shale, as well as surficial colluvial debris. Such slides also disrupt the scarp below, where they degenerate into smaller debris slides. Major multiple roatational slides have also been observed on the tongues of colluvial debris. Major instability is evident in this zone in the valleys of Monkey Water Holes Creek and Puzzling Gully, where benched slopes have been extensively cleared of vegetation. Similar benches elsewhere still under forest cover are apparently stable at present, but they are included in the zone as clearing almost certainly would lead to massive instability.

The zone grades from the Cs zone with a decrease in the width and an increase in the slope of benches, and an increase in the slope of colluvial tongues.

Suitability: The zone is considered unsafe for building and not suitable for subdivision.

Precautions: Further clearing of forest in this zone should be discouraged.

ZONE Eb

Steep to very steep slopes underlain by basalt constitute this zone; these consist of steep, narrow-crested ridges separated by steep-sided gullies. Minor small benches (equivalent to the Db zone), which are too small to show at the scale of mapping, are included. In-place basalt is at shallow depth beneath the crests of most ridges, but gully sides and concave slopes are mantled with accumulations of colluvium.

On gully sides and gully heads, soil creep and terracetting are common in the soil and colluvium; this apparently occurs to some extent under natural forest cover, but is accentuated on cleared country. In cleared areas, many such areas degenerate into small debris slides or rotational slides.

Some isolated stable, but steep, building sites may be present on ridges in the zone, but access to them would be very difficult. The broadest and most accessible fo such ridge crests have already been distinguished separately by being included in the Bb zone.

The Eb zone grades with increasing steepness from the Bb zone, and with even greater steepness into the Fb zone.

PHOTO 1. Major multiple rotational slides on benches underlain by Marburg Formation. Slope zoned Ds (benches) and [illegible] (steep slopes). Upper eastern headwaters of Puzzling Gully.

PHOTO 2. Large multiple rotational slide on moderate slopes on tongue of colluvium derived from sediments of Marburg Formation. Zoned Ds. Murphys Creek valley.

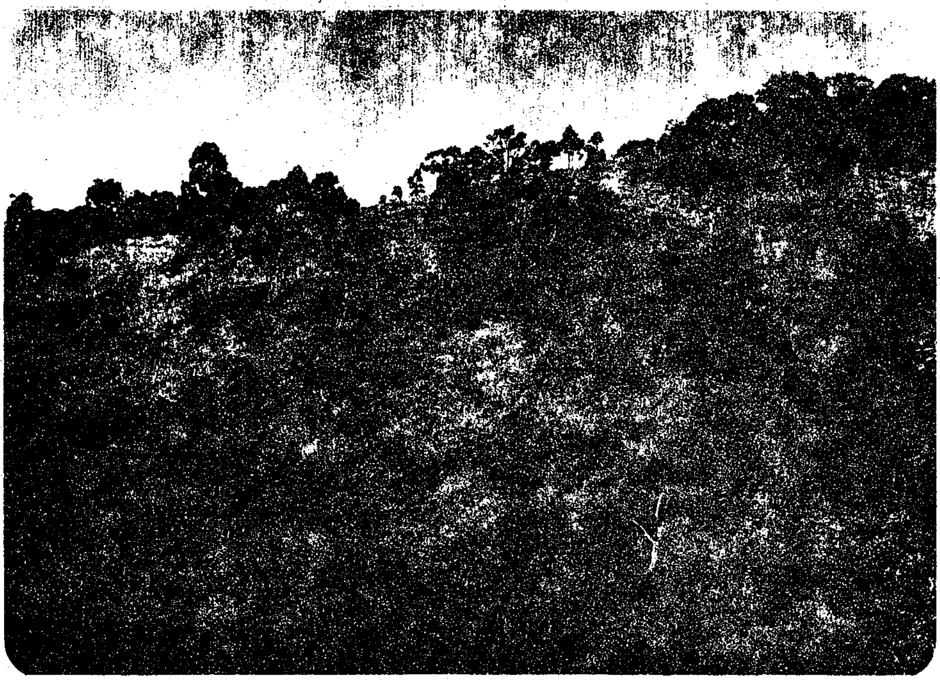

PHOTO 3. Soil creep and terracettes on steep basalt slopes of Zone Eb.

PHOTO 4. Small rotational slides at toe of Es Zone. Valley of Monkey Waterholes Creek.

Suitability: Because of its steepness and frequency of small slides, this zone is considered unsuitable for closer subdivision and building. A few steep individual building sites may be present on the more prominent ridges, but stable access routes to them are likely to be difficult to construct. The gully sides and any concave slopes are unsuitable for building.

Precautions: If it is desired to build on the few steep sites of the ridges, subsurface conditions should be investigated to ensure that footings are on in-place rock rather than colluvium. Cuts into the soil mantle should be minimised, and wastewater should be dispersed some distance away from the site where it cannot promote instability in the soil mantle. Access routes should be planned to minimise cuts and intersections with concave slopes, and appropriate foundations and style of building should be professionally designed.

Further clearing of forest in this zone should be discouraged.

ZONE Es

Steep to very steep slopes developed on the sediments of the Marburg Formation constitute this zone. It includes most of the large-scale slope failures of the district.

Most slopes are mantled by sandstone/siltstone-derived colluvium of varying thickness and weathered rock. Minor benches, too small to be mapped separately as the Ds zone, are included. Some cliff lines developed on resistant sandstone beds are present.

Where the zone has been cleared, large debris slides, rotational slides, and multiple rotational slides (the latter on somewhat lesser slopes) are common. In places, particularly on concave slopes where thick deposits of sandstone/siltstone-derived colluvium have accumulated, almost the entire slope has moved in large overlapping slides. Such large-scale movements may destabilise sandstone cliff-lines above, leading to rock falls. On many slopes, soil-creep and terracetting are evident, and these are considered precursors of more disrupting sliding. Any hillside cuts in the zone, such as for roads, are subject to fretting, slumping, and some rock falls from sandstone bands undercut by slumping of soft weathered siltstone. Much of the zone is still forested and stable, but it can be confidently predicted that clearing of such areas will lead to further large-scale movement.

Suitability: The zone is unsuitable for subdivision or building.

Precautions: Any cuts into the slopes of the zone, such as for roads, should be minimised to avoid high maintenance costs and the possibility of destabilisation of slopes above.

Further clearing of forest in this zone should be discouraged.

ZONE Fb

This zone encompasses those very steep slopes and cliff lines on the major basalt scarps near the crest of the range. Bare rock scree slopes are common. Most slopes are still forested, but small debris slides, rock falls and rolling boulders are common. Such activity could be expected to increase dramatically if the sloeps were cleared

The zone is totally unsuited for building. Further clearing of forest should be discouraged.

RECOGNISED LANDSLIDES

All active landslides that could be recognised on the ground or on air photos, and depicted at the adopted scale, are shown on Maps 1 and 2. Although many of the slides are temporarily stabilised and grassed over, they can be expected to move again after severe wet periods, by upslope migration of their head scarps, and by further movement of the unconsolidated debris in their channels.

POSSIBLE LANDSLIDES

Areas shown in this category are either old landslides, which have apparently stabilised and are grassed over to the extent that no recent movement can be recognised, or particular topographic situations that have a very high probablility of failure in the future.

USE AND LIMITATIONS OF ZONING

Landslide risk zoning at district scale, such as the present study, should be considered only the first step and not the final tool in decision-making for landslide prone areas. It is able to show in a general sense which areas are capable of close settlement, which are capable of some settlement, provided more detailed assessment is undertaken, and which should be avoided. As such, it is suitable for the early stages of Local Authority planning before much pressure for settlement develops in a district. It also provides the essential basic data and guidelines for further closer investigations.

It must be thoroughly understood that the zones established do not include only land of the same stability, as it is impossible at this scale to show all individual unstable or suspect areas specifically. Instead, the zones depict land where a similar range of stability conditions is present. As the boundaries between zones are generally approximate and in places gradational, it should not be implied that they can signify that land on one side is stable and the other unstable. In such boundary situations, general caution and further study on the ground is the appropriate course of action.

For zones that contain some stable and some unstable land, such as the Bb or Cb zones, further study is needed before planning decisions on proposed subdivision or building can be made. Such work should be based on the observations made in this study, and on the precautions recommended for each zone; it would be essentially a sub-zoning of the area in question.

It is essential that this second stage work be undertaken prior to subdivision, so that an appropriate subdivision density and layout can be designed, which will avoid unstable and suspect areas. It is not appropriate to have this work done later at the building approval stage. Once blocks have been created over unstable land, there is little a new owner can do except abandon his investment, sell it to another unsuspecting purchaser, or embark on expensive engineering schemes such as drainage, which may or may not be successful.

It should be realised that no matter how closely an area is investigated, there will remain parts whose stability remains suspect. Some investigators with an engineering background may take the view that sufficient subsurface investigation, testing of materials, mathematical calculation and foundation design will resolve the situation. Most geologists, however, probably feel that the likely groundwater pressures and positions of possible failure planes are too uncertain to allow meaningful calculation, and thus unlikely to resolve the stability of suspect areas.

Dealing with these suspect areas, and deciding at what stage investigations have reached their limits of certainty, are the most difficult decisions for planners, as there is considerable scope for disputation and court action. The geological view is that because of the inherent uncertainty of subsurface geological and groundwater conditions, a conservative approach is essential. Two methods of dealing with such land, namely (1) incorporting it into large acreage blocks with at least one stable building site per allotment, or (2) allowing several small blocks on the stable sites and designating the suspect areas as public land, may both be appropriate depending on the circumstances, such as ease of access, provision of services, and ease of administration by the Local Authority.

In some cases, further third stage work may be required, such as the design of foundations and wastewater disposal for individual building sites.

In order to implement the findings of this study, it is seen as appropriate to add notations to Shire Town Planning Schemes and Strategic Plans to the effect that closer settlement around these foothills will be subject to the recommendations and precautions set out in this report.

For the second stage work prior to subdivision approval, it is seen as appropriate for Local Authorities to require developers to retain geotechnical consultants experienced in slope stability to report on the land in question and design subdivision layout, or alternatively to retain such consultants themselves with costs paid by the developers.

The third stage work on individual blocks is visualised as being carried out by consultants for owners, builders, or developers, possibly as a condition of building approval by the Local Authortiy.

STABILISATION AND REHABILITATION OF LANDSLIDES

This study has adopted a philosophy of avoidance of landslides or suspect areas when considering suitability for closer settlement. In contrast, some engineers may feel that suspect or even obviously unstable areas could be stabilised by sufficient subsurface drainage or other means. However, to base the long-term safety of residential housing on drainage systems which could unknowingly clog or be interfered with by residents in the future must be considered risky. In addition, the costs are likely to be more than could be considered for normal residential situations. Drainage and other sophisticated remedial measures could be appropriate for larger commercial or industrial projects which can bear the costs and provide long-term maintenance of drains, but an element of uncertainty as to the effectiveness of the measures would always remain. Such development is, however, unlikely in the low-density settlement occurring in the district at present.

Apart from considerations of stability of building sites, there appears to be considerable community concern, from aesthetic and economic viewpoints, that landslides should be minimised, stabilised, and in the long-term brought back into some form of productive use.

In a rural situation, reduction of groundwater pressures, and hence increasing stability, by extensive drainage schemes is not economic. The only way this is likely to be achieved is by a long-term programme of replacing the natural forest cover over the unstable ground and immediately adjacent areas, so as to increase water transpiration. There is little information available at present as to what density of vegetation cover is required to do this satisfactorily. It is suspected that full forest cover may be needed, as it must be remembered that the residual strength of failed materials is commonly less than it was in the unfailed state, and consequently there is probably a need to reduce groundwater pressures to less than original levels.

Further long-term experiments are needed on such aspects, as is more immediate investigation of the tree species and planting techniques suitable for the various types of unstable land in the district.

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