



**Figure 2.9** Translational debris slide with movement initiated along steeply dipping planar discontinuities in highly weathered bedrock. (Location: Nambukavesi-Namosi road in Waindina River catchment)



**Figure 2.10** Unstable road cutting near Galoa on the Suva-Nadi Highway. Failure is translational, involving residual soil sliding along an irregular, steeply-dipping interface with underlying weathered bedrock, and compounded by shallow rotational movements in the displaced debris mass.

weathered rock regolith. For example, Irfan (1993) described a creep-induced landslide in volcanic saprolite in Hong Kong where creep movements appear to have developed as a result of mineralogical changes. The creep occurred in part of the weathered regolith characterised by the presence of hydrated halloysite and smectite - clay minerals with relatively high values of cation exchange capacity and swelling potential, possibly produced by seasonal wetting/drying - immediately underlying the near-surface residual soils which were dominated by *non*-swelling dehydrated halloysite and kaolinite. A discrete shear plane eventually developed due to a localised rise in pore pressure, probably during an intense rainstorm. The creeping layer continued to deform until a landslide was triggered by undercutting during engineering works. Irfan also suggested that deeper creep may be initiated in the saprolite by mineralogical changes along relict joints or fissures as a result of downward-percolating groundwater. It is of interest to note that mineralogical analysis of a sample collected during the present study from a relict joint surface in saprolite exposed in the backscarp of a large landslide at Wainigasau, showed the clay mineralogy to be dominated by hydrated halloysite with subordinate smectite.

*Post-failure creep* involves small renewals of movement on pre-existing slip surfaces, for example, at times of seasonally high groundwater levels. Recognition of post-failure creep is extremely useful in back-analysing landslide movements as the factor of safety can be taken as unity with some confidence, enabling mass strength of the slipped material and/or pore water conditions at time of failure to be accurately calculated.

#### 2.5.1.2 Falls

*Falls* involve the detachment of a mass of rock, soil or debris from a steep slope along a surface on which little or no shear displacement takes place. Failures are generally initiated by tension cracks or fissures followed by abrupt release of the rock/soil mass. The size of the falling masses is generally governed by bounding discontinuities such as bedding, joints and sheared zones, relict features of which may be present even in highly to completely weathered regolith. Falls may also occur in 'intact' residual soils particularly along river banks and coastal cliffs which are being actively eroded by stream or wave action and from over-steepened slopes formed by landslide backscarps and man-made cuts. Falls may occur from almost any steep natural and man-made slope in almost all rock and soil types, but on a regional basis are probably not as significant a hazard as other types of slope failures in south east Viti Levu. Locally, however, rockfalls comprising blocks up to 3 m in diameter have occurred in steep slopes of Suva Marl in the vicinity of Suva cemetery. Some of the falls resulted in destruction of buildings and fatalities (Keefe, 1980).

#### 2.5.1.3 Flows

A *flow* comprises a spatially continuous movement in which surfaces of shear are short-lived, closely spaced and not usually preserved. The distribution of velocities in the displacing mass resembles that in a viscous fluid whereby inter-granular movements predominate over shear surface movements. There is a complete gradation between *debris flows* and *earth flows*, based on the predominance of coarse or fine material. There is also a gradation between debris/earth slides and flows depending on lithology, shear strength, water content and mobility of the materials involved. They tend to exhibit a wide range of movement rates from very slow (< 1.5 m/yr) to extremely rapid (> c. 3 m/sec).

A variety of terms have been used to describe flow movements which are essentially the same process but involving different materials and rates of movement. They include earthflows, mudflows, debris flows, debris torrents, debris avalanches and flowslides. In south east Viti Levu, flows involving residual soils and weathered regolith are extremely widespread. Howorth *et al.* (1980) used the term debris flow to describe flows involving regolith in the Wainitubatolu catchment near Korovou village which, in some instances on steep slopes, also show characteristics of debris avalanches. The terms earthflow and mudflow are also used by Howorth *et al.* (1993) to describe flows in residual red soil fills triggered by heavy rainfall associated with Cyclone Kina. Lawson (1993) states that most flows in the region are debris flows consisting of a wet, variable mixture of material ranging in grain-size from clay to boulders. Following this earlier work, the terms earthflow and debris flow are described in detail below.

**Earthflows** are slow to moderately rapid flow movements involving dominantly argillaceous debris on moderately steep natural slopes or in relatively uniform residual soil fills forming engineered earthwork slopes. They usually involve lobate or elongate masses of accumulated debris in a softened clayey matrix. They develop from an initial sliding movement in fine-grained material where water contents are sufficiently high for the sliding mass to become remoulded and flow as a viscous fluid. Movement continues until the flow material reaches a lower gradient and/or drains sufficiently for the shear strength to increase to a point where further movement is inhibited. Earthflows frequently develop at the foot of rotational slumps in both natural and earthwork slopes. Where the slide and flow components are roughly equal in proportion, they are more correctly termed slump-earthflows and represent a particularly common type of complex landslide movement. Earthflows, and slump-earthflows, are usually characterised by a steep back scarp and a more gently inclined front slope, or accumulation zone. Once initial stability has been attained, forward movement of the flow toe may recur periodically due to undrained loading of the main slide debris from falls and shallow slides at the rear scarp. Movement may also be maintained or re-activated by removal of the supporting toe material by stream erosion or excavation.

**Debris flow** is here restricted to rapid to extremely rapid flows involving residual soil and weathered rock debris on steep mountain slopes. They are by far the most common type of landslide in south east Viti Levu (Lawson, 1993). They may occur almost solely in the surficial residual soils (weathering Zone VI material) to form relatively shallow fine-grained debris flows (mudflows in some classifications), or involve more granular regolith down to and including weathering Zone IV. For example, in their study of typical landslides in part of the Wainitubatolu River catchment immediately south of Korovou village, Howorth and Prasad (1981) identified 28 landslides triggered by extreme rainfalls associated with cyclone Wally. Virtually all of these slides were rapid debris flows involving 'red' regolith comprising weathering Zones IV, V and VI. In the majority of these failures, shear surfaces of initiating slide movements were developed either within Zone IV material or close to the boundary with weathered rock (Zone III/IV).

The development of debris flows is favoured by abundant water, unconsolidated source material, slopes steep enough to induce flowage in the material and, in most cases, insufficient protection of the ground by vegetation cover. All these requirements are met in south east Viti Levu. Debris flows are generally initiated by a sliding failure followed by the rapid transformation of the displaced mass into a flow of wet saturated debris which can be

potentially very destructive. Below the headslide source area, they are usually characterised by a narrow elongated mid-portion ('flow track' or 'torrent track') and a bulbous toe or 'debris fan' developed where the slope gradient becomes low enough to arrest movement (Figures 2.11 and 2.12). The initial slide area is usually completely vacated of debris which can move with considerable erosive power. If the supply of saturated debris is sufficient and the slope steep enough, they may travel large distances, sustained and enlarged by further slides and bank collapses generated by their own erosion. Following cyclone Wally, Howarth *et al.* (1980) and Lawson (1993) describe the widespread development of debris flows initiated on both steep planar hillslopes and within drainage lines or slope depressions. In the majority of cases, the flows developed from initial slides on upper slopes close to the ridge line. The torrent tracks of these flows often form elongate, bare stretches of soil or exposed rock of variable dimensions depending on local topography, the nature of the underlying slope materials and the erosive power of the flowing debris. Torrent tracks range from steep-sided channels eroded into underlying regolith to debris-covered stretches along which only vegetation has been stripped.

Debris flows similar to those experienced in Viti Levu have been reported from many tropical and sub-tropical regions, particularly following high rainfall events associated with cyclones or severe storms. For example, following hurricane Hugo which struck eastern Puerto Rico in 1989, Larsen and Torres Sanches (1992) describe the widespread occurrence of shallow 'soil slips' and debris flows in residual soils overlying saprolite. Rouse (1990) also describes numerous small extremely rapid 'flowslides' which occurred in Dominican residual soils as a result of two hurricanes, David and Frederick, in 1979. The term 'flowslide' (equivalent to debris flow here) is used to describe a disintegrating subaerial slide where part of the normal stress is temporarily transferred onto the fluids of the void space (liquefaction), with a consequent sudden decrease in strength. The stress transfer results directly from the initial sliding failure, after which the moving debris becomes a rapidly flowing fluid mass. It is this sudden liquefaction of the slide debris which is critical to the development of these rapid flows. However, even during extreme cyclonic rainfalls not all slides translate into debris flows.

Lawson (1993) has reviewed a large amount of available data pertaining to rain-induced landsliding and the development of debris flows in south east Viti Levu. The following general conclusions may be drawn from the data presented in his report:

- provided sufficient water is available, most of the residual soils/weathered regolith have the potential to flow, despite widely varying clay contents and plasticities
- the potential for liquefaction is not sensitive to clay content and is highest in soils/regolith characterised by an open-textured, 'bonded' fabric with high void ratios and porosities
- rapid debris flows occur most frequently on steep slopes from initial slide movements in soils/regolith prone to liquefaction
- slow earthflows develop from slides (mainly slumps) in dominantly fine-grained clay regolith characterised by relatively low void ratios and porosities due to the absence of an open-textured 'bonded' fabric



**Figure 2.11**  
Landslide headscarp and upper incised torrent track of the Wainigasau debris flow.



**Figure 2.12** View looking upslope from distal end of the Wainigasau debris flow towards torrent track and headslide. The debris fan, comprising residual soil, cobbles and boulders, is gradually becoming revegetated.

The development of particular landslide types is clearly dependent upon a complex inter-relationship between such factors as moisture availability, topography and the physical and geotechnical properties of the slope-forming materials. The effect of these factors on general hillslope stability in south east Viti Levu is discussed briefly below.

### **2.5.2 The Serua Hills landslides of 1980**

Various mention has been made in the foregoing sections to the devastating landslides events in the Serua Hills in 1980. A summary of those events and conclusions drawn is provided below.

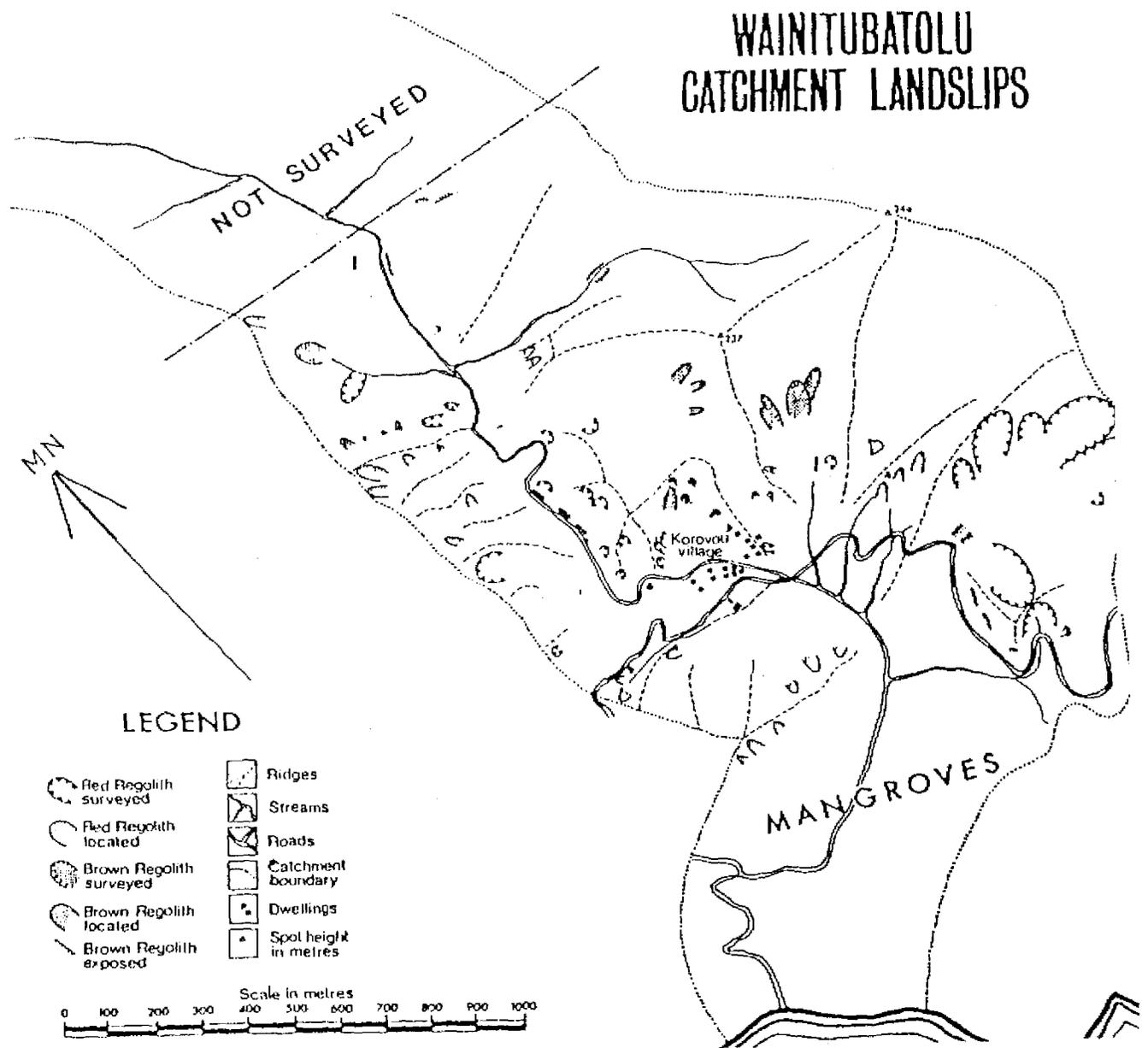
Extensive landsliding occurred in the southern coastal area of the Serua Hills in the period 1-5 April 1980 during the passage of, and following, cyclone Wally. This part of the Serua Hills appears to be particularly vulnerable to landsliding and was the area worst affected by this cyclone. This storm track passed from north to south centrally through Viti Levu (Figure 2.3). Up to 45 fresh landslides were reported from an aerial survey flown along the mountainous section of the highway (Lawson, 1993). The following is largely drawn from information recorded at the time and shortly afterwards by Howorth and co-workers.

A study of the landsliding in the Serua Hills by Howorth *et al.* (1980) looked at the coastal strip between Navua and Korovou. Their report gave a detailed account of the exceptionally high rainfall levels during the passage of cyclone Wally as well as descriptions of the resulting devastation to the local population, property and road system. Peak water discharge rates measured near the mouths of the Navua and Rewa rivers apparently correlated with the triggering of landslides. The great majority of the slides involved only regolith material; in only one instance was the removal of bedrock observed.

The Howarth *et al.* (1980) report also included a detailed examination of the Wainitubatolu catchment, a sub-site within the above area. This was one of the areas most severely affected by landslide activity. Their map of landslips is reproduced here as Figure 2.13. The study addressed the question of the location of slope failure and presented a model to explain landslide occurrence within the catchment. Up to 74 landslides, mainly debris flows, were recorded. In many cases, landslide depth corresponded to regolith thickness. As is characteristic of rainfall-induced surficial landslides, the mass movement occurred where the landform or configuration of the bedrock surface facilitated the concentration of slope water. More than half of the landslides originated in slope depressions or drainage lines, with initial failure taking place on an upper slope, ridge or summit.

Clues to the triggering mechanism were provided by the evidence of water seepages at the bedrock/regolith interface, along which failure tended to start. It was suggested by the authors that the intensity of rainfall was such that a perched water table was formed above relatively permeable bedrock causing pore water pressures in the regolith mantle to increase sufficiently to cause failure.

Another potentially critical condition identified from this study is the stabilizing effect of vegetation. Variations in the stability of the soil mantle appeared to be related to the density and type of vegetation cover. A forested slope with deep, penetrating root systems stabilises the surface much better than grass or crop vegetation. Evidence of this kind of control was



**Figure 2.13**

Distribution of landslides in the Wainitubatolu catchment (reproduced after Howorth, Crozier and Grant, 1981).

observed with the May 1979 rainstorm during which landslides were apparently confined to cultivation plots. However, this hypothesis is contradicted by the observation of Howorth *et al.* that landslides were equally developed on forested and grassland slopes in the Wainitubatolo catchment during cyclone Wally. The vegetation factor in controlling landslides was tested against slope angle. It was assumed that landslides in forest cover require steeper slopes than those on grassland or garden areas. However, results from two test sites showed that the mean slope angle on forest and grassland landslides were not significantly different. It was concluded that the sheer intensity of rainfall and the shallow rooting of trees (< 1 m) resulted in landslides occurring on slopes of similar gradient irrespective of vegetation cover.

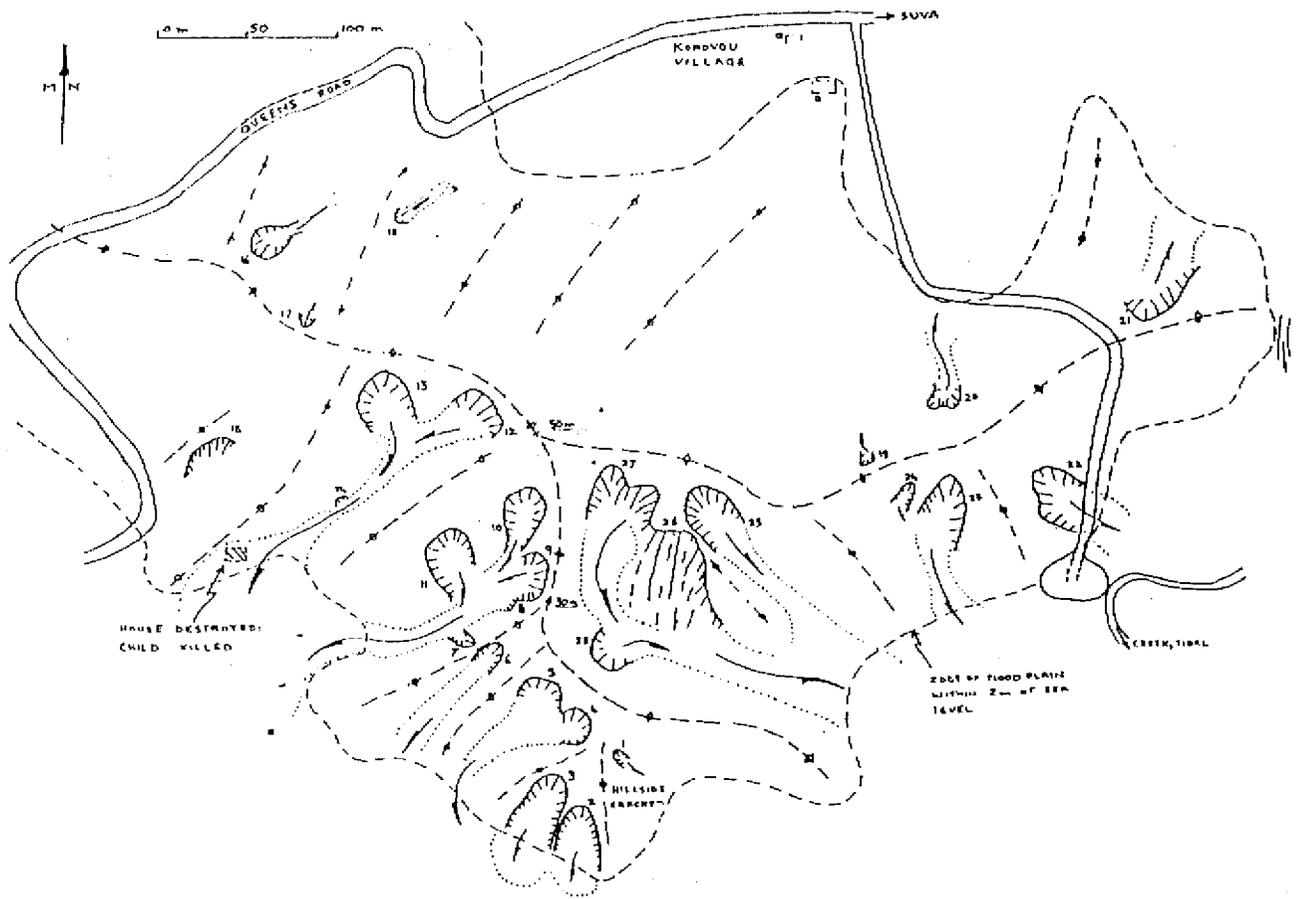
The importance of soil/regolith type as a control of slope stability was addressed by Howorth *et al.* (1980). Two soil types were distinguished in their study: red clay and brown gravelly clay. A comparison of landslide distribution in the catchment showed a much higher incidence of landslides, and hence instability, within the red clay zone. The gravelly clay soils are, allegedly, more stable due to the gravel fraction with its strong internal friction and greater permeability. The brown gravelly soils are thinner than the red clay type and allow tree roots to anchor onto bedrock. However, the distribution of red and brown soils is rather localised in this study area and it is difficult to extrapolate this local classification to the scheme outlined in section 2.3.

It was concluded that the landsliding activity in the Wainitumbatolo catchment was the result of an exceptional high-intensity rainfall event. The steep to moderate nature of the slopes and the disposition of weakly-vegetated and unconsolidated landslide material indicated that the area would be highly prone to further mass movement under even a lower intensity rainfall event. An important statement in this report is that slope stability is related to the maturity or age of the regolith developed on the land surface. Thus, it was postulated that red clay soils are more mature than gravelly soils, and are more prone to rainfall-induced landsliding.

Details of the morphology and distribution of 28 landslides in the Korovou village area associated with the same cyclone event were documented by Howorth and Prasad (1981). Their map of landslides is reproduced here as Figure 2.14. The area is formed of a single ridge of volcanic bedrock mantled by thick red soils. This study is similar to the earlier one of Howorth *et al.* (1980) in that it concentrates on the detail of landslide morphology and mass movement i.e. position of failure, dispersal of debris and details of the soil (regolith) profiles.

A number of significant results emerged from this detailed study and are summarised as follows:

- Most of the slides were located at the headwaters of drainage or in interfluvies close to south-facing ridge crests. Minor failures developed along drainage lines.
- Slides were mainly debris avalanches or debris flows with upper slide areas generally totally evacuated of debris, which in some cases was displaced onto the coastal floodplain.



**Figure 2.14** Map of landslides in the Korovou area (reproduced after Howorth and Prasad, 1980).

- The majority of slides involved regolith ranging from surficial residual soil down to 'strongly weathered' rock, with failure surfaces commonly developed at or close to moderately weathered rockhead.
- The majority of slopes appear to have been initiated on maximum slopes of between 26° and 44°.

### 2.5.3 Factors controlling hillslope stability in south east Viti Levu

Based on the above, and on work done in similar tropical settings elsewhere, this section attempts to summarise the main factors thought to influence or control hillslope stability and landsliding in south east Viti Levu.

The majority of landslides occur, or are at least initiated in the case of debris flows, by shear failure within the regolith. This takes place when the available shear strength of the slope materials is exceeded by the *in situ* stresses. This may occur by a reduction in shear strength due to an increase in pore water pressures, or by an increase in shear stress due to static and dynamic loads. Static stresses may be increased by over-steepening of slopes due to removal of support by erosion and excavations, or by surcharge loads resulting from engineering structures or even landslide debris. Increased dynamic loads may be caused by earthquake shocks or by the movement of tall trees during high winds where stresses are transferred to the slope material by agitation of the root system. Once failure is initiated, the shape of the resulting shear surface is largely governed by the composition and thickness of the slope-forming materials and the presence of pre-existing weaknesses or discontinuities in the slope.

That landsliding is closely related to high magnitude rainfall events is clearly indicated by the extensive slope failures which have occurred during major storms and cyclones. In the case of widespread debris flow development, exceedingly high rainfalls appear to be required before pore pressures are elevated sufficiently to induce failure and subsequent flow. During these high rainfalls, landslides occur on slopes of widely varying slope angle, but the location of these slides may in some cases be related to the nature of the surface regolith. For example, Howorth *et al.* (1980) note that in the Wainitubatolu catchment near Korovou village following cyclone Wally, five times as many slips occurred in highly weathered 'red' regolith as in less weathered 'brown' regolith, despite the latter having steeper mean slope angles (32° as opposed to 27°). It was also noted that landslides occurred in both forested and non-forested areas on slopes of similar gradient. Other records of landsliding elsewhere in south east Viti Levu note that landsliding events have involved the complete regolith cover down to weathered rockhead, or occur mainly in non-forested areas under cultivation or pasture. It is also interesting that in reports of earlier work on landslides in Viti Levu, the majority of failures are reported to have occurred or started on upper slopes at or near the slope crest. This tends to indicate that the sliding is caused by downward percolation of water rather than by a rising groundwater table, as the latter would have been likely to influence the lowest slopes first and to the greatest extent (Vaughan, 1985).

Residual red and brown soil/regolith deposits (pedologically classified as latosols) are ubiquitous in the steep terrain most prone to landsliding in the study area, and are generally characterised by high void ratios and porosities, and low saturated unit weights. Factors affecting the stability of similar latosol soils in Dominica, with respect to widespread shallow

landsliding following severe rainfalls, have been described in several publications (Rouse *et al.*, 1986; 1990; Reading, 1991). In addition to instability due to severe rainfalls, these studies attempt to explain the stability of these soils on slopes of about 30° under the 'normal' very wet conditions of a humid tropical environment very similar to that found in Viti Levu. Since most of the shallow slope movements in these residual soils are essentially planar in character, and because the relatively high effective strengths of the soils were little different from residual values, the Infinite Slope Method of analysis (Skempton and De Lory, 1957) was used to determine characteristic limiting slope angles for stability. Limiting stability angles were calculated for 'wet' conditions where the water table was at the ground surface, and for 'dry' conditions where the water table was below the shear plane. The results showed that the maximum stable slope angles for the two moisture conditions were approximately 12° and 30°, respectively. When compared with a natural slope angle of 30°, this means that pore pressures would have to remain close to zero for stability. Almost identical results are obtained when this analysis is applied to slopes in south east Viti Levu. Based on soil and strength properties presented by Lawson (1993), limiting stability angles for 'wet' and 'dry' residual soils on these slopes range from 12°-16° and 30°-35°, respectively. Again, when compared to typical natural slope angles of 30°-38° in the area, pore pressures approaching zero (equivalent to unsaturated conditions) must apparently be operating for stability to be maintained.

It is known that, at least during the wet season, moisture levels in wet tropical soil and weathered rock often lie close to saturation (Brand, 1982) so that the explanation of this apparently anomalous stability must depend on additional factors related to the soil structure. Most notable of these are the high porosities, permeabilities and infiltration capacities associated with the open-textured 'bonded' structure of the residual soils and the effect of soil suction in increasing *in situ* shear strength. There is increasing evidence that even in the wet season soil suction forces play an important role in the stability of tropical residual soils. Wesley (1977), for example, notes that similar soils in Indonesia frequently have deep water tables and retain negative pore pressures (soil suction) despite being saturated almost to the ground surface. The combination of high *in situ* strengths and relatively high permeabilities in such soils means that only prolonged high intensity rainfall can elevate pore water pressures to levels capable of inducing widespread landsliding; these are critical factors controlling landslide occurrence in south east Viti Levu. Moreover, once sliding is initiated, a vast amount of soil water is available for the rapid translation of debris slides into debris flows.

In the latosol soils of Dominica, two potential saturation levels related to decreases in permeability with depth were identified (Rouse *et al.*, 1986). Firstly, a perched saturation zone may occur near the base of the highly permeable topsoil; here, perched saturation conditions occur only during heavy rainfall with sustained intensities which exceed the subsoil (weathering Zone IV-V) permeability. The cohesive strength of this layer may preclude slides if it is very shallow, and particularly if added cohesion is provided by a forest root mat. However, if this horizon is relatively thick and forest cover is absent, shallow slides are likely to occur. The second, semi-permanent, saturation zone lies at the regolith/weathered rock boundary (junction of weathering Zones IV/III) and is a critical depth for landsliding in these slopes. This saturation zone needs to expand considerably before instability occurs, and is likely to be associated with landslides triggered by prolonged high intensity rainfalls related to cyclones.

The presence of these potential saturation zones in the Viti Levu regolith, goes some way towards explaining the occurrence of landslides on mainly unforested slopes following heavy rains associated with severe storms, and on virtually any slope regardless of vegetation cover during cyclonic rainfall conditions. Clearly, a threshold rainfall effect must be associated with the onset of landsliding in the tropically weathered regolith-covered slopes in Viti Levu. Attempts to calculate this threshold value were made by Lawson (1993) using information on rainfall intensity and storm duration both resulting in landsliding and where no landsliding occurred. The results, plotted on an X - Y diagram, show that an asymptotic curve separates rainfall-related landslides from rainfall patterns not related to landslides. This curve is regarded as an empirical lower-intensity threshold above which rainfall-inducing landslide events could be expected to occur.

It is clear from this and earlier studies that landslides can be triggered by sufficiently high rainfall on virtually all slopes in the study area irrespective of slope angle and vegetation cover. The extent of this widespread landsliding has been established from aerial photograph analysis. Site specific occurrence of individual landslides appears to be controlled to a large extent by the variation in the material, geotechnical and hydrogeological properties of the regolith mantles. These factors pose particular problems in the preparation of meaningful landslide hazard maps based on rapid reconnaissance techniques.