A STUDY ON SLOPE INSTABILITY ABOVE CHAPMAN'S PEAK DRIVE, CAPE PENINSULA, SOUTH AFRICA.

By

DUNCAN GEORGE JAMES SCOTT

Submitted in Fulfillment of the Requirements for the Degree of
MASTER OF SCIENCE

Department of Environmental and Geographical Science
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"In all mountain roads, falls of rocks and slips of earth are likely to occur, especially during winter rains and stormy weather (*sic*) and this remark must especially apply in this case where the precipitous mountain krantzes face largely towards the 'weather' side. It is, of course, a practical impossibility to remove all loose stones and ensure the stability of all banks above the road (all reasonable steps appear to have been undertaken up to this stage). Careful and constant patrolling will probably prove a necessity for some years to come, and must be accepted as a normal duty and expense attached to a road of this description. For the ongoing reasons it may ultimately prove advisable to close the road entirely, or after dark, as traffic will not only be menaced by debris actually falling while passing, but (also by) that which becomes scattered over the road surface". **T.W.W. Perry (1922)**

Abstract

Chapman's Peak Drive was constructed along a natural unconformity below Chapman's Peak, a suite of slopes that rise directly from the ocean to their summit. A seemingly increased frequency of rockfalls and the death of a young woman in December 1999 led to the closing of the Drive as a public thoroughfare. At the beginning of the year 2000 Chapman's Peak Drive featured in both local and international media because of the wildfires that swept through this area and large portions of the rest of the Cape Peninsula. This led to a heightened public awareness of the obvious physical danger to traffic on Chapman's Peak Drive. This problem of rockfall activity onto Chapman's Peak Drive is not a new, or unexpected, one as all roads constructed within mountainous terrain will inevitably experience some sort of mass movement of slope material onto their surface at some stage.

The study focuses on the movement of slope material onto Chapman's Peak Drive and the relevant contributions of those factors that tend to influence these types of activities. This research set out to investigate the various geomorphic controls causing the hazardous conditions experienced along Chapman's Peak Drive. The intention was to generate data as concerned the genesis of regolith material and its subsequent downslope movement, as well as identifying patterns within sediment movements and the falling of rock material onto the Drive in the form of mass movement events. Human activity impacts in the form of the rock barring/clearing of certain areas of Chapman's Peak and wildfires that swept through the area were also to be assessed.

These objectives were achieved using a combination of the monitoring of slope processes on Chapman's Peak, the granular composition analysis of slope material samples, the analysis of oblique photographs and orthophoto maps, and an archival investigation. Slope surface sediments were captured during rainfall events using Gerlach troughs while designated plots were monitored for clast movement. Rocks falling onto Chapman's Peak Drive during rainfall events were also collected and recorded. These sediments were subsequently analysed and all gathered data examined statistically. A principal component analysis was performed on the fallen rock data in an attempt to identify the controlling factors of this process along Chapman's Peak Drive.

With the use of these investigative tools it was discovered that the presence of steep slopes and/or the absence of a protective vegetation cover above a particular point on Chapman's Peak Drive, as well as the intensity of rainfall events, all play a role in the initialisation of mass movement events in that area. Statistical analyses undertaken showed that during lower intensity rainfall events the absence of vegetation proved the controlling factor while the presence of steep slopes became most important when rainfall intensities increased. Where rock barring/clearing had been undertaken it seems to have had a positive influence in reducing the impacts of mass movement events within those areas.

The first step in the development of mitigating measures aimed at minimising mass movement hazard along Chapman's Peak Drive is the investigation of the mechanisms that control mass movement and the identification of those areas most active geomorphologically, as well as the assessment of the effectiveness of certain mitgatory tools. This research provides this initial foundation upon which the design and implementation of such measures can be based.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Most of the Earth's surface comprises slopes with the exception of plains and terraces resulting from river deposits. Even seemingly flat areas, such as Africa's plateau, in fact comprise of hillslopes of low angle between valley floors and the higher crests of interfluves (Selby, 1982). It follows therefore that, if slopes comprise the bulk of the surface morphology of the Earth, they need to be monitored and managed correctly. Various processes occur on slopes that eventually lead to the downslope movement of material. These movements take place either with or without the direct assistance of flowing water (Carson and Kirkby, 1972). The movement, in bulk, of slope forming materials from higher to lower ground without the direct assistance of a fluid transport agent (air, water or ice), but being acted upon by gravity, is termed mass movement (Goudie, 1995). There is a great range in rates of movement between and within the different process types (Figure 1.1). Slope materials can topple, fall, flow, slide or creep as they make their way downslope (Zaruba and Mencl, 1982; Varnes, 1978).

Once slope failures impact directly upon people and/or property they are classified as disasters (Cooke and Doornkamp, 1990). Apart from being an important factor in the modification of slopes, slope failures can become of considerable economic significance both directly and indirectly (Tobin and Montz, 1997). The largest known landslide, the Saidmarreh landslide, occurred 10 000 years ago in the Zagros Mountains of Iran. It had a length of 15km and shifted a total of 20km from source to destination (Murck et al., 1997). A landslide the magnitude of that of the Saidmarreh slide would cause enormous loss of life and property were it to take place in an inhabited area. Indeed, landslides can, and do, cause loss of life on a large scale to take place in an inhabited area. An estimated 22 000 people were killed by debris flows in the town of Armero, Columbia during November 1995 (Cooke and Doornkamp, 1990). Other examples of major landslide disasters are given in Table 1.1. A further example of relatively large-scale damage caused by a landslide took place in Dunedin, New Zealand, in 1979 when 62 houses were either shifted from their original position or destroyed during landslide activity that lasted for 30 minutes (Coombs and Norris, 1981). On another occasion, a landslide in Te Aroha,

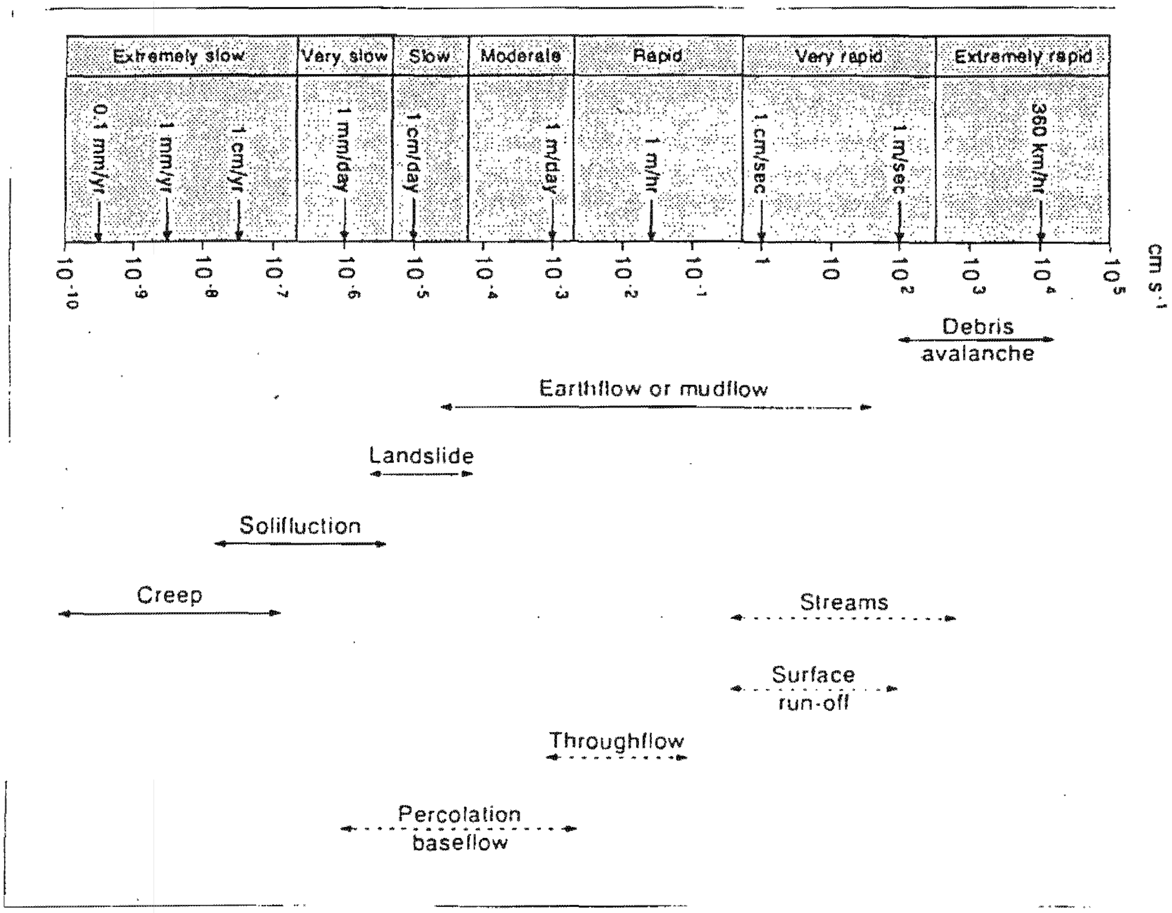


Figure 1.1: General ranges of transport velocities that operate on slopes (Clark and Small, 1982).

Place	Date	Type of landslide	Est. max speed	Impact
Goldau, Switzerland	2 Sept. 1806			457 people killed
Elm, Switzerland	1881		44 m/s	115 people killed
Java	1919	Debris flow		5100 killed, 140 villages destroyed
Kansu, China	16 Dec. 1920	Loess flows		10 000+ killed
California, USA	31 Dec. 1934	Debris flow		40 killed, 400 houses destroyed
Kure, Japan	1945			1154 killed
SW of Tokyo, Japan	1958			1100 killed
Ranrachirca, Peru	10 June 1962	Ice and rock avalanche		3500+ people killed
Vaiont, Italy	1963	Rockslide into reservoir	50 m/s	about 2600 killed
Aberfan, UK	21 oct. 1966	Flowslide?	8.8 m/s	144 people killed
Rio de Janeiro, Brazil	1966			1000 killed
Rio de Janeiro, Brazil	1967			1700 killed
Virginia, USA	1969	Debris flow		150 killed
Japan	1969–72	Various		519 died, 7328 houses destroyed
Yungay, Peru	31 May 1970	Earthquake-triggered debris avalanche–debris flow	133 m/s	up to 25 000 killed
Chungar	1971			259 people killed
Hong Kong	June 1972	Various		138 killed
Kamijima, Japan	1972			112 killed
S. Italy	1972–3	Various		about 100 villages abandoned affecting about 200 000 people
Mayunmarca, Peru	25 Apr. 1974	Debris flow	39 m/s	town destroyed, 451 killed
Mantaro Valley, Peru	1974			450 killed
Mt. Semeru	1981			500 killed
Yacitan, Peru	1983			233+ killed
W. Nepal	1983			186 killed
Dongxiang, China	1983			227 killed
Armero, Colombia	Nov. 1985	Lahar		about 22 000 killed

Table 1.1: Some major disasters caused by landslides (Cooke and Doornkamp, 1990).

New Zealand caused several million dollars worth of damage and the loss of the lives of three people (Montz, 1992). Most individual slope failure events however do not cause significant losses but their cumulative effects can amount to millions of dollars in damage each year (Tobin and Montz, 1997).

In areas of high relief, such as the Cape Peninsula of the Western Cape, for example, mass movements are especially common, as illustrated by Boelhouwers *et al.* (1998). Recently, the population of the Cape Peninsula area has witnessed the destructive capabilities of landslides in the form of debris flows in the suburbs of Glencairn and Fish Hoek. These debris flows either badly damaged or destroyed large amounts of private property during the evening of April 21 1999, (False Bay Echo, April 22, 1999).

This research project investigates a spatially limited, but nonetheless significant geomorphic problem involving a suite of slopes on Chapman's Peak in the Cape Peninsula, Western Cape, South Africa.

1.2 Events Leading to the Closure of Chapman's Peak Drive

When a cliff face develops, slope retreat and replacement occurs as the upper reaches of the cliff face begin to weather and erode. This process deposits talus material at the foot of the cliff as the oversteepened slope attempts to adjust (Moon and Dardis, 1988). With the high cliffs and road cuttings along and above Chapman's Peak Drive, a scenic drive around part of the western coast of the Cape Peninsula, Western Cape, South Africa (Figure 1.2), largely facing in the direction from which the Peninsula's most harsh weather systems approach, it seemed inevitable that rock material would fall onto the Drive (Perry, 1922). Undercutting of a more resistant overlying formation, as the weaker formation below eroded more rapidly, led to the development of large rock overhangs also presenting a clear and present threat of rockfall. Bearing the full brunt of these weather systems would maximize the effects of the weathering forces and agents of erosion on Chapman's Peak, accelerating these processes of slope retreat, replacement and undercutting. Therefore, it seems it was inevitable that loss of life or injury would occur along the Drive, and indeed it did, finally culminating in the closure of the Drive.

Figure 1.2: The study locality. Arrow A indicates the position of control slopes investigated during this study. Arrows B and C point to the beginning and end, respectively, of the other section of Chapman's Peak Drive monitored. Inset: Star indicates the position of Chapman's Peak on the Cape Peninsula.

A seemingly increased frequency of rockfalls and the death of a young woman in December 1999 led to the closing of the Drive as a public thoroughfare. At the beginning of the year 2000 Chapman's Peak Drive featured in both local and international media because of the wildfires that had swept through this area and large portions of the rest of the Cape Peninsula between January 18 and 21 of that year. This media coverage led to a heightened public awareness of the problems that were at that time being experienced on Chapman's Peak Drive. The rockfall phenomenon represented an obvious physical danger to motorists and therefore required some form of scientific investigation, on a local scale, in order to aid the better understanding of the problem. An improved understanding may enable the development of an effective management plan, utilising accurate local data, thereby maximizing its effectiveness.

This problem of rockfall activity onto Chapman's Peak Drive is not a new, or unexpected, one. Perry (1922), the Inspecting Roads Engineer, first inspected the Drive immediately upon its completion. Upon ending this first inspection, of Chapman's Peak Drive, Perry (1922) stated that all roads built on mountain slopes are likely to experience rockfalls and earth slips along their length. He thought that this would be particularly true in the case of the road built along the slopes of Chapman's Peak as these "face(d) largely towards the 'weather' side" (Perry, 1922, p. 1).

Bearing the following examples of rockfall and earth slips in mind, as well as the eventual closure of the Drive, it seems that this prediction proved true for Chapman's Peak Drive. Various incidents of rockfall had occurred during the 1980's and 1990's that had led to temporary closures of Chapman's Peak Drive on those occasions. During the month of July 1987, a Regional Services Council workman was struck on the shoulder by a falling clast. This, accompanied by a rockfall of between 10 and 13 metres wide and 1 metre high, resulted in the closure of Chapman's Peak Drive until the road could be cleared (Saturday Argus, 1987).

Two visitors to Cape Town, a Mr. Erasmus and his wife, were both injured by falling material when they stopped their vehicle at one of the rest points to take a few photographs of the cliffs above. The Saturday Argus of 18 March 1989 reported this incident. Mrs. Erasmus luckily was not seriously injured but her husband suffered a multiple fracture of his right arm. During October of the same year, Mr. Ronnie Brouwer of Hout Bay died when a boulder fell and rolled into his car crushing the driver's side. This accident took place on the "Noordhoek side" (Cape Times, 1989) of Chapman's Peak Drive. Mrs. Brouwer was in the car at the time of the accident but luckily escaped unharmed.

On the 26 June 1991, a stone hit the bonnet of Mr. Steve Sandomierski's car as he was driving along Chapman's Peak Drive and he stopped to inspect the damage. When climbing out of his vehicle, a large boulder landed on it. Some smaller clast then struck Mr. Sandomierski's head, leaving him with superficial head and thigh wounds (Stop Press, 1991).

Chapman's Peak Drive also required closing during the year of 1993 in order to allow the authorities to repair the road's surface because rocks had fallen and caused damage during a storm in July of that year. Repairs to the road surface had been completed by August of that year but the reopening of the road was delayed due to a subsequent slip-fall above Flora Bay (Cape Argus, 28 September, 1997).

Mr. Klaus Mannhardt and his wife, of Gauteng, were travelling along Chapman's Peak Drive, during 1997, when a large boulder smashed into the side of their Jeep and killed him instantly. The boulder was so large that it was necessary to fragment it, using dynamite, before removal from the accident scene. Two subsequent rockfall events resulted in the closure of the drive (Cape Times, 17 November, 1997).

There were various incidents of rock material falling onto Chapman's Peak Drive during December 1999 and a young woman driver from Noordhoek, Lara Callige, was killed and her sister, Olga, seriously injured on their way home when a 500kg boulder fell and crushed their car (Cape Argus, 26 January 2000). After the wildfires had burnt and removed the vegetation cover from the slopes of Chapman's Peak, 12 major rockfalls took place along the drive within the next two days (Cape Argus, 22/23 January, 2000).

With all this rockfall activity in the area, it seems inevitable that remediation work along the slopes and road cuttings above the Drive would have had to been performed to ensure the safety of travelers along its length. According to the 1999 Preliminary Geotechnical Investigation (M. J. Mountain and Partners, 1999), undertaken to determine the stability and safety of the road cuttings along Chapman's Peak Drive, it seems the area has undergone virtually no safety work within the 77 years between the original opening of Chapman's Peak Drive and its closure in 1999. The clearing of fallen material and the repair of damaged or scarred road sections and cuttings (evidence of rockbolting) seem to have been the only activities undertaken. Ross (2000) indicates that on two occasions, once in 1977 and again in 1980, sections of the road were washed away and therefore needed replacing. After the incident of 1980, the replacement of this washed away portion of road, with a bridge, became necessary. Only one event of road upgrading, not necessitated by storm damage, seems to have been reported. This took the form of road widening along 3000ft of the drive during 1962 (Ross, 2000).

1.3 The Significance of Chapman's Peak Drive

Chapman's Peak Drive is an important link between the city bowl of Cape Town and its Southern suburbs, especially those along the Atlantic coastline, for both personal and commercial travel activities. Cape Town's major transport routes are already heavily burdened with rush hour traffic as can be evidenced on any working day. Chapman's Peak Drive is part of an important alternative route for southern suburbs inhabitants.

With its breathtaking views of both the Atlantic Ocean and the high sea cliffs, on the landward side, Chapman's Peak Drive has itself become an important tourist attraction over the years. Tourist volumes in Cape Town have grown enormously since South Africa became a democracy in 1994. Before its closure early in the year 2000, an estimated 3500 vehicles travelled along Chapman's Peak Drive daily. Included in these figures were an average of 35 luxury 50-seater coaches and dozens of minibuses carrying international visitors (Cape Argus, 26 January 2000). With the Drive closed it is feared by those involved in the tourist trade in the Noordhoek valley (Figure 1.2) that their business concerns will die a slow death (Cape Argus, January 26, 2000). One such entrepreneur, Mary Nel, remarked that, after the closure of Chapman's Peak Drive, business had dropped by 95% during the month of January 2000 (Cape Argus, January 26, 2000). The alternative routes between Hout Bay and the rest of Cape Town do not pass through the Noordhoek valley and so these businesses no longer enjoy exposure to this continual throughflow of tourists.

The closure of Chapman's Peak Drive forced the organisers of the internationally renowned *Cape Argus*/Pick 'n Pay Cycle Tour, the Rotary Club of Claremont and the Pedal Power Association, to design an alternative route for the race excluding the Drive. Chapman's Peak Drive, with its scenic splendour, has been one of the key marketing features throughout the history of this race and as such, the exclusion of the Drive from the race was thought highly problematic. An independent study commissioned by the Cape Town Cycle Tour Trust showed that approximately R100 million in revenue was generated in the Western Cape as a direct result of the cycle race during the year 2000 (Cape Argus, October 26, 2000). According to Ken Sturgeon, joint tour chairman during the year 2000 and a Rotary Club member, about 80 000 people entered Cape Town for the year 2000 event. Of these people, 39 856 people from 37 different countries actually took part in the race itself. In the year 2002, 35 000 people took part in the race, more than half of whom were tourists (www.cycletour.co.za, 6 April, 2002). These figures have increased rapidly from the original number of 525 starters in the first race in 1978. The race is in fact now the world's biggest timed cycling event of its kind (Old Mutual, 2000).

Another important sporting event whose route has been disrupted is the Old Mutual sponsored Two Oceans Marathon. Chapman's Peak Drive has been an important leg of the Two Oceans Marathon throughout the history of the race and for the same reason associated with the *Cape Argus*/Pick 'n Pay Cycle Tour, it is believed the exclusion of the drive from the race will negatively impact upon its popularity. Once again, it has been necessary that the organisers identify an alternative route for the event. Approximately 13 000 runners participated in the 1999 marathons, 70% of whom lived outside of Cape Town. Also competing were 500 international athletes (Old Mutual, 2000). In the year 2002, 7266 people took part in the ultra-marathon part of the event. Of the entrants 68% were tourists in Cape Town (www.twooceansmarathon.org.za, 6 April, 2002). As in the case of the cycle tour this marathon draws many visitors, not only the runners but their friends and families as well, to the Western Cape generating millions of rands in revenue and allowing the city of Cape Town the opportunity for advertising its attractions on both a national and international stage.

It is therefore imperative that this area be made safe for travel as the permanent closure of the route would not only worsen the aforementioned traffic pressure on Cape Town's remaining road system but would also result in the probable loss of large amounts of tourist capital for both Cape Town and South Africa as a whole.

1.4 Hypothesis

In light of the emerging pattern of rockfalls onto Chapman's Peak Drive, coupled with the desirability for safely re-opening this route to vehicular and pedestrian access, an investigation into the causes of these problems, whether natural or because of human intervention, is required. Firstly, some form of working hypothesis is essential. This hypothesis is as follows:

Risk, as reflected in rockfalls onto Chapman's Peak Drive, is directly related to prevailing slope and weather conditions at any given point and time. The impacts of wildfire on the vegetation of the slopes of Chapman's Peak are the most important contributing factor to slope failure and rockfalls occuring.

1.5 Aims

With the above hypothesis in mind, it is then necessary to obtain data pertaining to the genesis of the regoltih and falling rock material ultimately causing the hazardous conditions experienced along Chapman's Peak Drive. Using this information, this study endeavours to evaluate the impact of human activities on the natural rates of movement of slope materials as well as rockfalls. It is the intention of this investigation to supply accurate and current information for the more effective management of the slope areas along and above Chapman's Peak Drive.

1.6 Objectives

1) To identify patterns among sediment movements and rockfalls by correlating recorded weather conditions with slope events.

2) To draw comparisons between a slope cleared of loose rocks and debris (barred)(as described by Bennett and Doyle, 1997) and an adjacent control slope which has not been cleared (unbarred) with respect to differences in their sediment yields and number of clasts released during equal rainfall events.

3) To attempt to gauge how effective rock barring measures have been in combating rockfall along that section of Chapman's Peak Drive beyond "The Lookout" (when travelling towards Noordhoek).

4) To identify the most highly active rockfall areas so that, in future, these may be more closely monitored and increase safety along Chapman's Peak Drive.

1.7 Structural Outline

This dissertation comprises seven chapters. The broad structure of this study comprises three parts, according to the following divisions:

1.7.1 Background and context

Chapter One discusses recent rockfalls along Chapman's Peak Drive and the significance of the drive. Included are the working hypothesis, aims and objectives of the investigation. Chapter Two provides information on the regional setting, site and history of the study area, while in Chapter Three a literature review of slope movements is given. Chapter Four presents information on the methodologies and research procedures implemented.

1.7.2 Observation, analysis and classification

Chapter Five offers insight into the findings resulting from the laboratory analysis of the soil data, statistical analysis of the fallen clast data and the interpretations of the aerial imagery.

1.7.3 Interpretation, discussion and conclusions

Chapter Six discusses the implications of these findings, presented in Chapter Five, with respect to the hypothesis, aims and objectives described in Chapter One. Chapter Seven, the final of this dissertation, presents the conclusions of this study, linking the findings and various arguments raised during its course.

CHAPTER TWO

PHYSICAL AND HISTORICAL BACKGROUND OF THE STUDY AREA

2.1 Introduction

This chapter introduces the relevant physical and historical background pertinent to this study. Topics discussed include the physical setting of the study site, geomorphology, geology, climate and vegetation, as well as the historical background, of Chapman's Peak Drive.

2.2 Geographical Setting and Geomorphology

Chapman's Peak Drive, the setting for this investigation, overlooks the Atlantic coast between Hout Bay and Noordhoek (Figure 1.2). The study area comprises the slopes and cliffs above the section of Chapman's Peak Drive from just before "the Lookout", when travelling from Hout Bay (Figure 2.1), and ends at the point at which the drive leaves the peak at its southern end. Chapman's Peak is part of a series of high cliffs that rise directly from the ocean surface to their summits at an altitude of 700m. The two sites under investigation for sediment and clast movements were situated on the slopes just before "the Lookout" when traveling from Hout Bay. One is unbarred and the other a barred slope cleared of potentially unstable rocks. This barring/clearing was done in the attempt to remove all rock material thought to pose a risk of movement from the slope down onto Chapman's Peak Drive. The two sections are located directly adjacent to each other and have equal gradients of 32^0. Both slopes face in a Northerly direction and are 50 metres in length. The regolith is a mixture of soil matrix and pebble to boulder sized sandstone rocks and is between one and two metres deep. There is no distinct gullying but a few rills are evident. At the head of each slope are cliffs of approximately five metres in height (Figure 2.2). The explanation for the choice of these two slopes for investigation is given in detail in a later section.

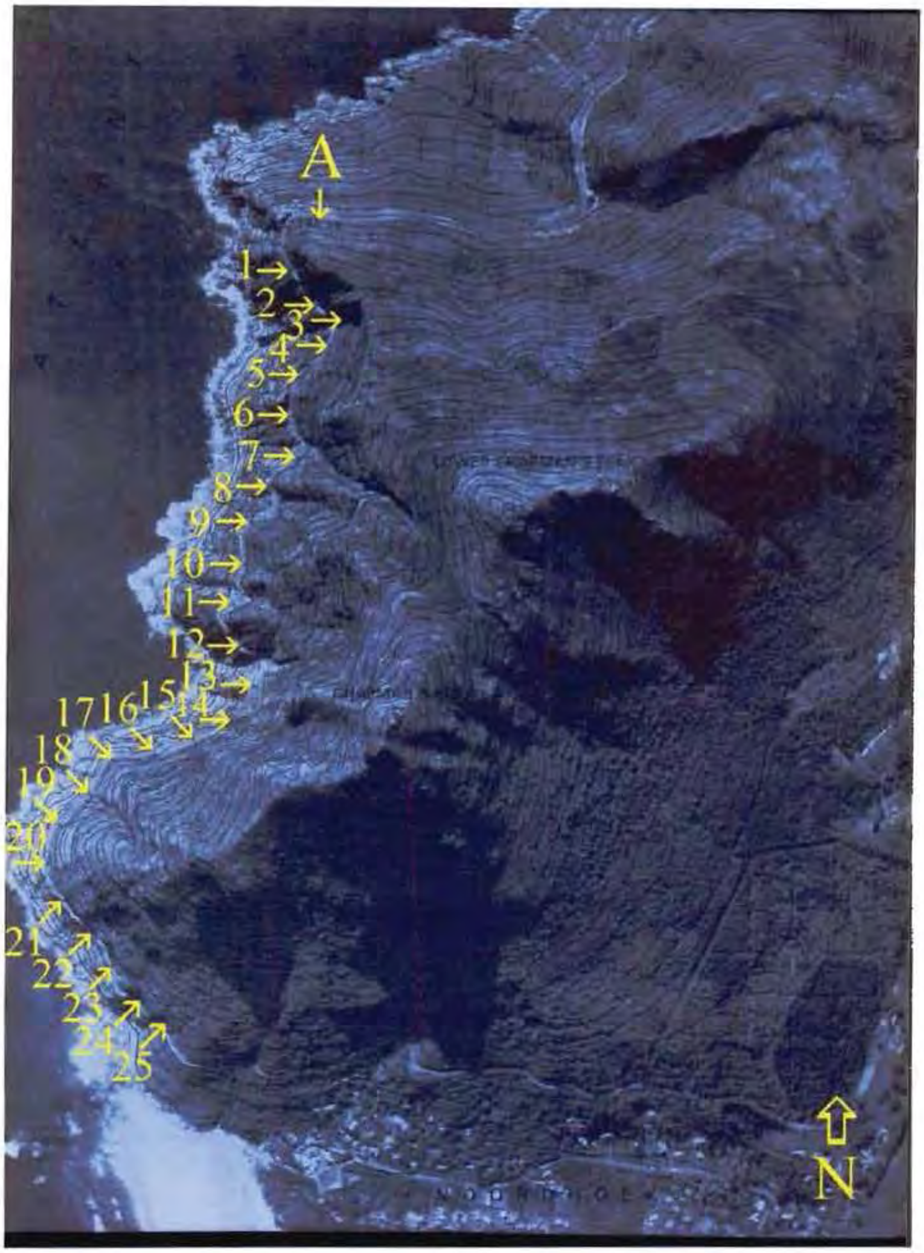


Figure 2.1: **Positions of barred and unbarred slopes, indicated by arrow A, and positions of sample points/road cuttings along Chapman's Peak Drive, indicated by numbered arrows.**

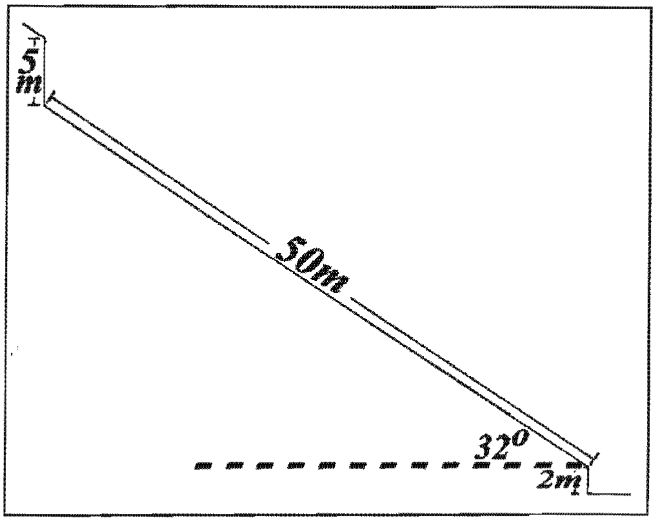


Figure 2.2: Representative cross-section of barred and unbarred slopes.

2.3 Geological Formations

As the lithology of Chapman's Peak has, as will be shown, a direct influence on sediment yields and slope failure in the study area, a detailed explanation of the existing geology of the study area, as well as its history, is necessary. The stratigraphic column of Chapman's Peak is typical of the Cape Peninsula of the Western Cape (Figure 2.3). Haughton (1933) produced the first comprehensive account of the geology of Cape Town and its surrounds. Theron (1984) updated this work.

Most of the Drive was cut into rock that forms part of the Table Mountain Group (Figure 2.4). The Table Mountain Group consists of the Graafwater, Peninsula and Pakhuis formations (Table 2.1) and is the base of the Cape Supergroup. Chapman's Peak Drive itself was constructed along the unconformity between granites belonging to the Cape Peninsula Pluton (a part of the Cape Granite Suite which intruded into the late Neoproterozoic Malmesbury Group) and the Table Mountain Group. The intrusion of previously deposited sedimentary rocks produced this granite surface approximately 600 million years ago (M.J. Mountain and Partners, 1999). The maroon sandstones, siltstones and shales of the Graafwater Formation overlie this "gently undulating and weathered granite surface (produced) about 450 million years ago" (M.J. Mountain and Partners,

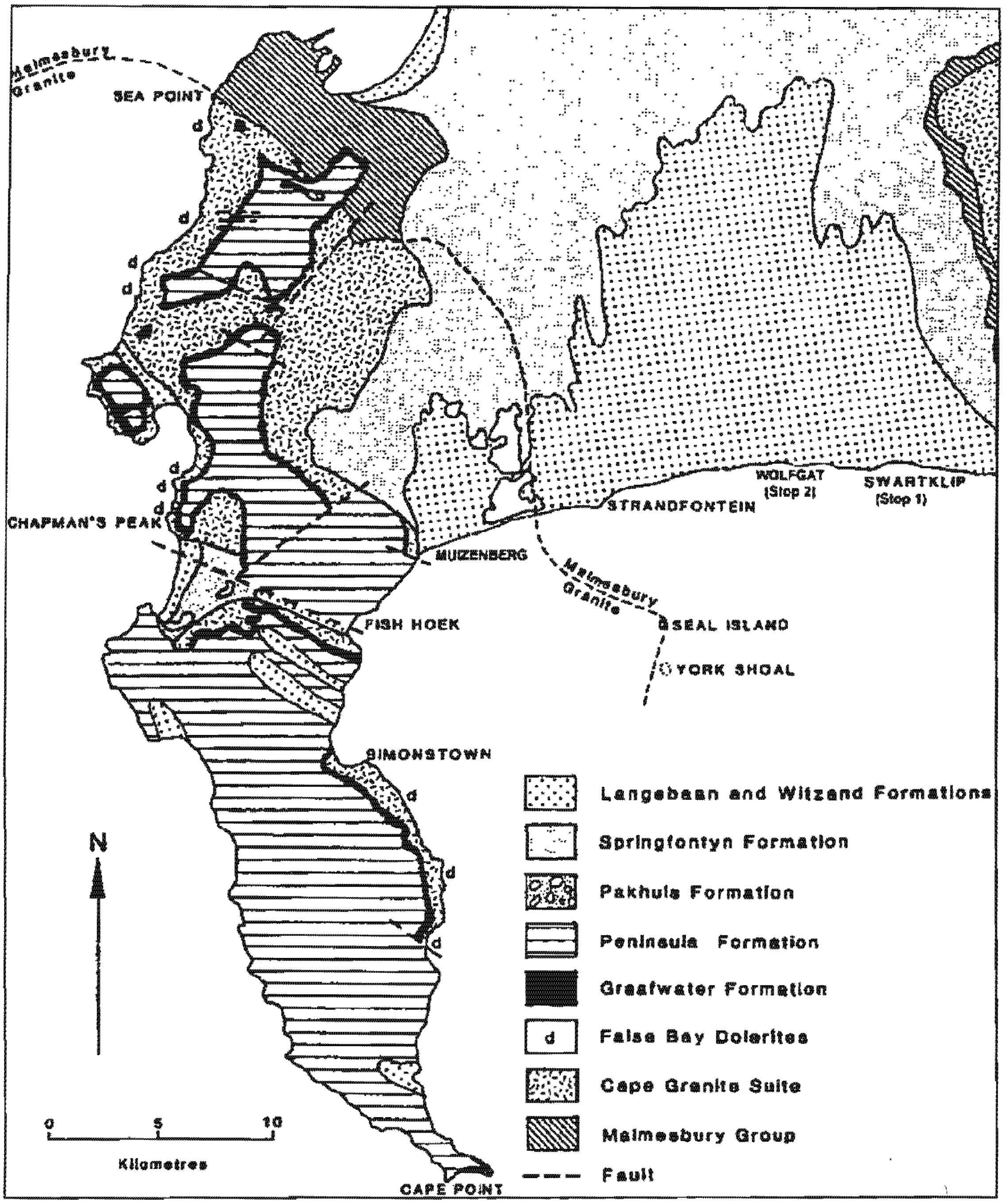


Figure 2.3: Geological map of the Cape Peninsula and the Cape Flats (Reid *et al.*, 1998).

1999, p. 3). The thicker-bedded, paler-coloured sandstones of the Peninsula Formation in turn overlie the Graafwater Formation. Together, the Graafwater and Peninsula Formations form the distinctive ramparts of the local landscape (M.J. Mountain and Partners, 1999).

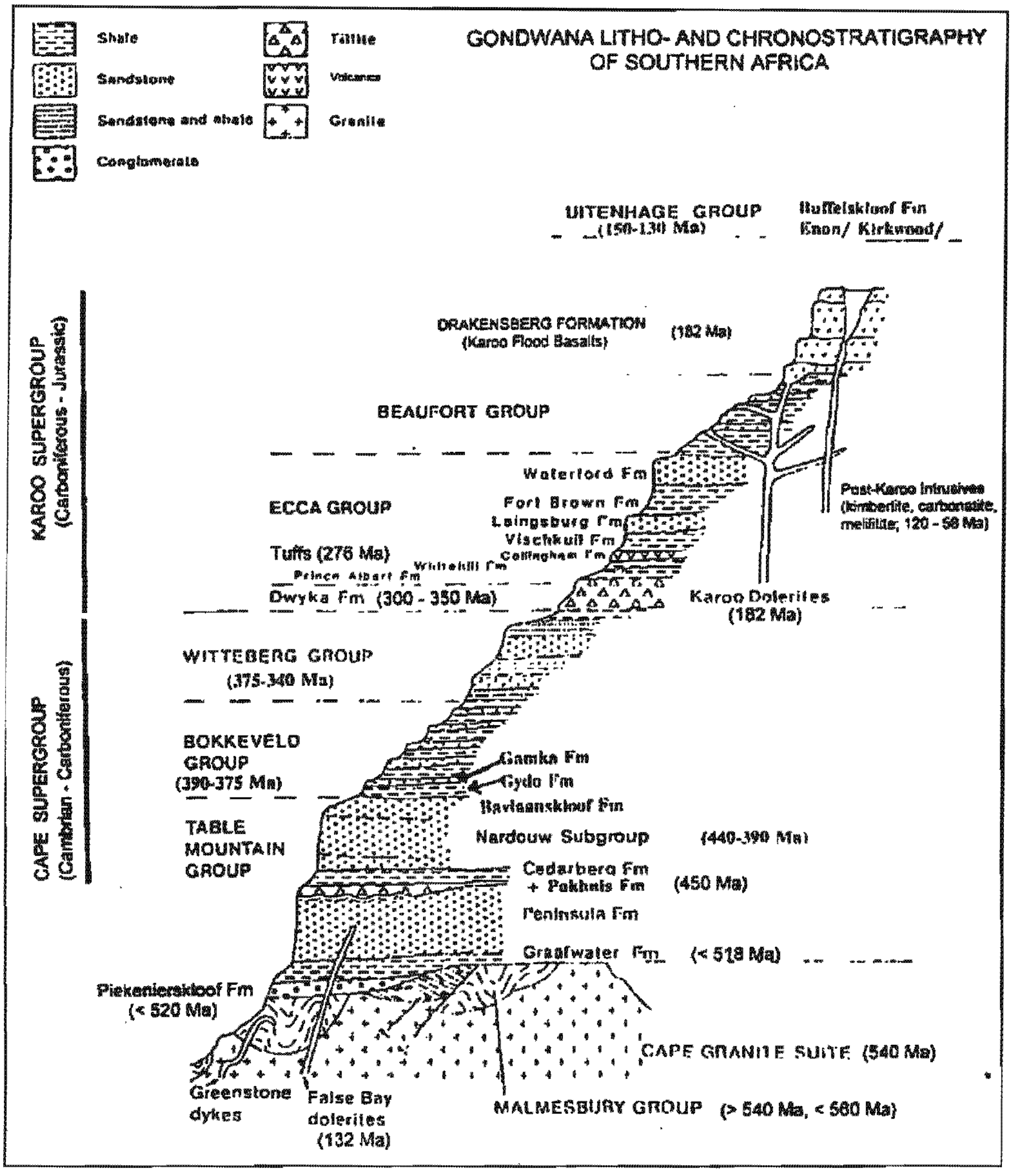
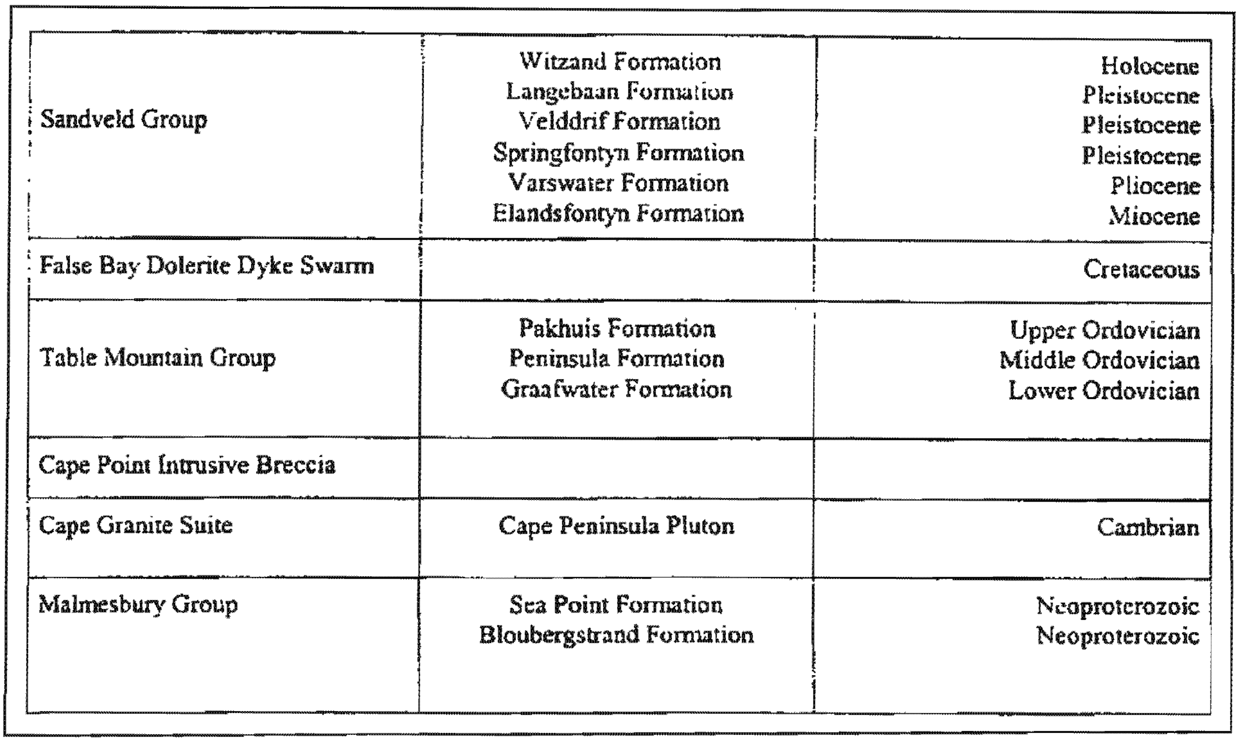


Figure 2.4: Stratigraphic column of the Gondwana sequences (Reid *et al.*, 1998).

The Lower Ordovician Graafwater Formation has a thickness of about 70 metres and consists of quartz-arenite (sandstone) facies, an interbedded arenite-siltstone facies and a mudstone facies (Figure 2.5). Turner (1986, 1987, 1990) investigated a 55m thick Graafwater Formation and separated it into three parts, namely an upper, middle and lower section. He found the upper and



Sandveld Group	Witzand Formation Langebaan Formation Velddrif Formation Springfontyn Formation Varswater Formation Elandsfontyn Formation	Holocene Pleistocene Pleistocene Pleistocene Pliocene Miocene
False Bay Dolerite Dyke Swarm		Cretaceous
Table Mountain Group	Pakhuis Formation Peninsula Formation Graafwater Formation	Upper Ordovician Middle Ordovician Lower Ordovician
Cape Point Intrusive Breccia		
Cape Granite Suite	Cape Peninsula Pluton	Cambrian
Malmesbury Group	Sea Point Formation Bloubergstrand Formation	Neoproterozoic Neoproterozoic

Table 2.1: Lithostratigraphy of the Cape Peninsula (Reid *et al.*, 1998).

lower sections similar lithologically, finding erosively based, fining-upward arenite – silty mudstone – mudstone sequences. These arenites are medium-to-coarse sandstones and are trough-crossbedded. The azimuths of these troughs point toward an origin to the North-east and a South-westward transport direction from that origin. The silty mudstones and mudstones are characterized by desiccation cracks (Flemming, 1988). The middle section investigated differed from this and consisted of 30m of fine- to medium-grained red sandstones with abundant rippled and mudcracked bedding planes. Desiccation cracks (subaerial) within this section, along with syneresis cracks (subaqueous) are markedly smaller than the desiccation cracks within the upper and lower section's mudstones. The existence of burrows, within this middle section, point to minor shallow-marine incursions having taken place at some time as well.

The Graafwater Formation was deposited under environmental conditions that fluctuated between hot and cold temperatures and intermittent flooding. This resulted in the creation of these sandstone, siltstone and mudstone/shale beds within the formation (M.J. Mountain and

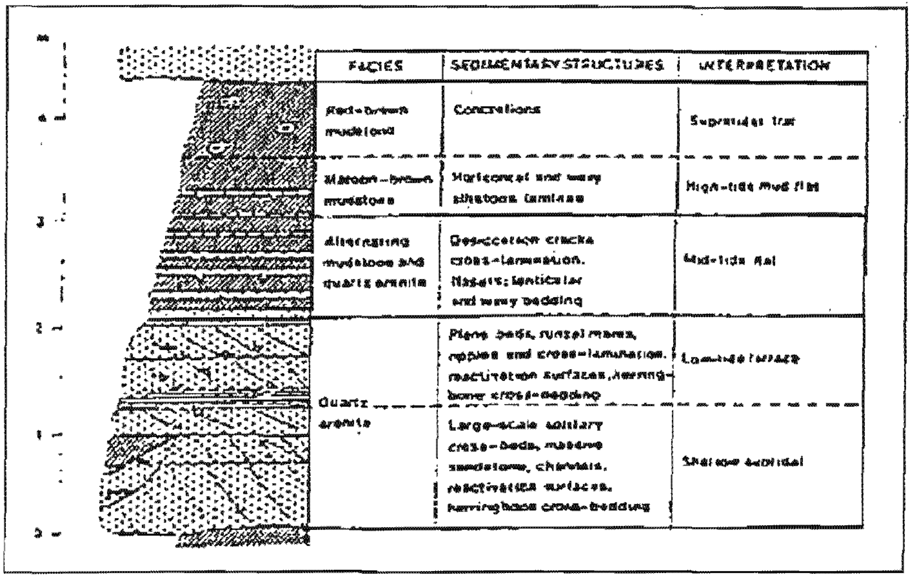


Figure 2.5: Facies of the Graafwater Formation (Tankard and Hobday, 1977).

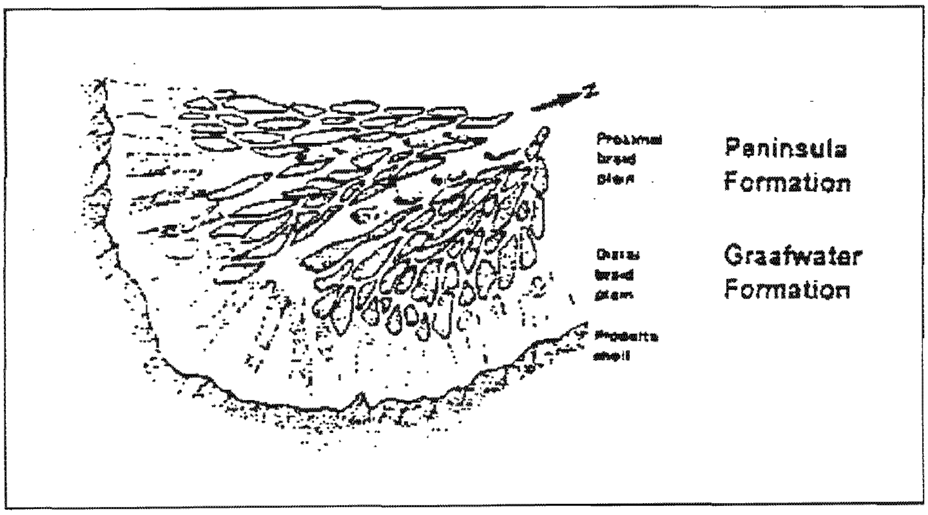


Figure 2.6: Schematic depositional model for the Graafwater and Peninsula Formations, Table Mountain Group (Turner, 1990).

As with the Graafwater Formation, Turner (1987) separated the Peninsula Formation into upper, middle and lower sections (Figure. 2.7). Turner's (1987) upper and middle sections were in fact the same part of the formation described by Fuller and Broquet (1990) as the Platteklip member and his lower the equivalent of their Leeukop member. Turner (1987) identified an erosional base for the Peninsula Formation. The lower section of his sub-division of the formation has a thickness of up to tens of metres. There are well-developed fining-upward sequences as well as crossbedded units up to two metres thick. Also present are megachannels greater than 10m in thicknesses and ranging from 200m to 300m in width. The ichnofacies, discovered by Broquet (1990), are to be found at the top of upward-fining sequences within sandstones and siltstones, mudstones being rare. The middle section is composed of arenites coarser and pebblier than those of the lower section. Cross-bedded megasets can be up to eight metres thick. Pebble, cobbles and boulders of quartzite and vein quartz often overlie basal scour surfaces. Within the upper section, only smaller clasts (40mm maximum diameter ie. very coarse pebbles) exist and there are fewer of these. Megachannels are present and they can be 40m deep and range from 200 – 300m wide. These megachannels indicate a transport direction from north to south.

The sediments of the Peninsula Formation were deposited under conditions different to those experienced during the time of deposition of the Graafwater Formation, and these sediments were differently sourced as well. Clayey, thinly-bedded deposits created this formation as they settled on an "inland, slowly–subsiding alluvial plain" which was inundated by "shallow seas for short periods" (M.J. Mountain and Partners, 1999, p. 4). Hobday and Tankard (1978) interpreted the depositional environment of the Peninsula Formation as being characterised by the existence of coastal barriers with an adjacent inner shelf, strongly affected by tidal currents. Fuller (1984) and Turner (1990) however suggested rather the existence of a proximal braidplain environment. This area would have experienced cycles of progradation followed by minor transgressions allowing marine trace fossils like *Cruziana* to form before the subsequent phase of progradation could begin.

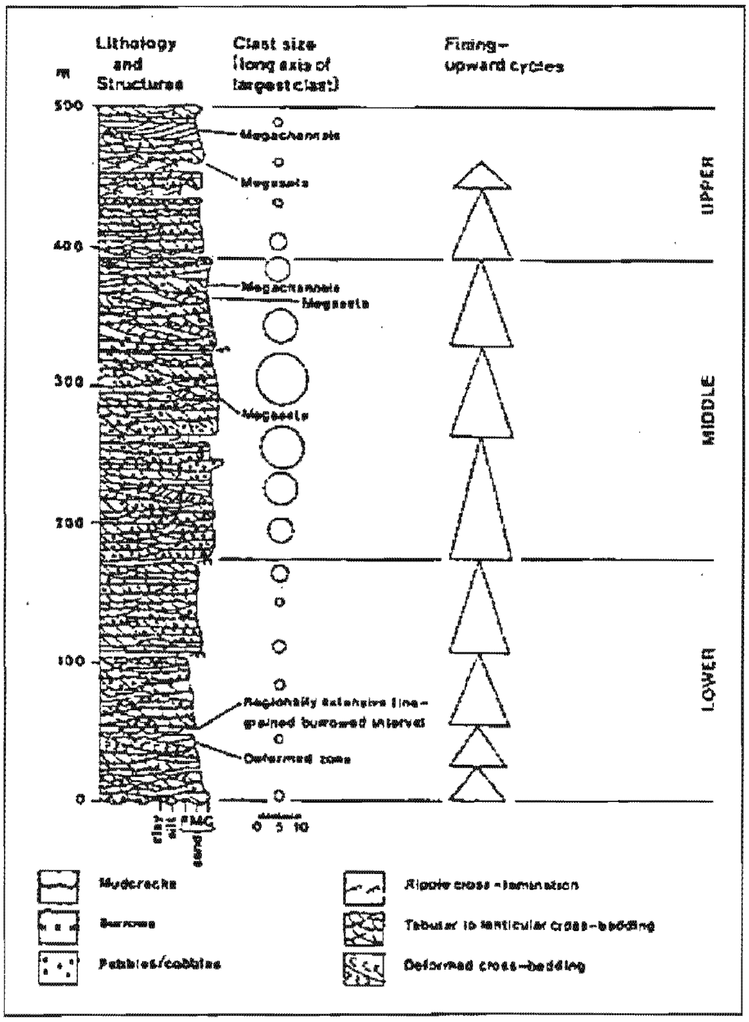


Figure. 2.7: Generalised section of the Peninsula Formation (Turner, 1990).

2.4 Engineering Geological Assessment

MJ Mountain and Partners (1999) produced an engineering geological assessment of the Chapman's Peak area and provides on the condition of the various lithologies present on Chapman's Peak. Knowledge of these conditions is often vital in explaining why a body of rock acts and reacts, to various pressures, in the way it does. The engineering properties of the rock masses of Chapman's Peak, primarily in terms of the three geological formations, are discussed.

MJ Mountain and Partners (1999) describes "rock masses" as being "composed of blocks of 'rock material' whose engineering properties (basically strength) are modified by the discontinuities that traverse them, and their state of weathering" (MJ Mountain and Partners, 1999, p. 4).

2.4.1 Cape Granite

As discussed previously, the Cape Granite lies at the base of the three lithologies exposed on Chapman's Peak. The Cape Granite is massive, homogenous and a high-strength rock with an unconfined compressive strength (UCS) greater than 180 Megapascals (Mpa). This body of rock is generally unweathered except for its upper surface. This upper surface is about 1m to 1.5m thick with an average UCS of approximately 55Mpa. When building the road, wherever possible, this upper surface was removed allowing the road to be built on the more stable bedrock.

Two predominant sets of vertical joints were found in the Cape Granite rock mass. The most important set trends in a direction that is slightly west of north. Therefore, many of the continuous joints are parallel or sub-parallel with sections of the road. The second set, more widely spaced, and less continuous than the first, trends at an angle 10" south of east. This second set plays less of a role in affecting the stability of Chapman's Peak Drive.

Stress-relief joints are however the most significant when considering possible damage to the drive. These develop along discontinuities close to the surface when natural erosive processes have removed rock material or when blasting has taken place for construction purposes. When these discontinuities run parallel to the cliff face, this process forms extensive joints that dip steeply towards the ocean.

Preliminary studies performed showed the stability of the granite rock mass as being "satisfactory" (MJ Mountain and Partners, 1999, p. 6). Suggestion, however, was that a more detailed engineering geological investigation of this rock mass be undertaken at a later stage.

2.4.2 Graafwater Formation

The Graafwater Formation lies in the middle, between the Granite and Peninsula Formation, on Chapman's Peak. From an engineering viewpoint it is the most problematic, as well as unpredictable, of the three rock types of Chapman's Peak. This is due to the heterogenous nature of this rock mass where lithologies vary from sandstone through siltstone to very fine-grained shales. Rock strata are also thinly-bedded in most cases. With lithologies so variable, the rock strengths of layers is also highly variable with minima of 1Mpa to 17Mpa and maxima of greater than 150Mpa recorded. Weathered faces of shale and sandstone have even lower UCS values. Weaker layers, which weather and erode more rapidly, become increasingly undercut creating caves and overhangs that eventually become unstable and fall.

Another important characteristic of the Graafwater Formation is the density of its internal joints. Combined with the thinly bedded nature of this formation a rock mass of "small angular blocks" (MJ Mountain and Partners, 1999, p. 6) is produced. These joints are oriented in very similar fashion to those within the Cape Granite, with the lesser set parallel or sub-parallel to Chapman's Peak Drive. This forms detached stacks/columns of rock along most of the vertical cliff faces as well as within some of the road cuttings. The regional angle of dip of strata being approximately 3° to 6° in an easterly direction has some impact in stabilising these stacks by causing them to lean towards the mountain's side. However, as these stacks are undercut or their lateral support removed, they must eventually topple.

2.4.3 Peninsula Formation

The Peninsula Formation is lithologically more homogeneous than the Graafwater Formation and has thicker beds. It forms a significantly harder rock mass than the Graafwater Formation because it composes mainly quartzitic sandstones and sandstones. As a result, the Peninsula Formation has formed a more resistant cap over the Graafwater Formation. Even though the Peninsula Formation possesses these resistant properties in general, there are weaker layers of rock at some points which weather and erode and rapidly undercut the overlying beds. This creates very large overhangs, the largest of which occur directly below Chapman's Peak.

Thick bedding and wide joint spacing are characteristic of this formation. There are however also some occurrences of "fairly thin lenses of weaker shaly material" (MJ Mountain and Partners, 1999, p. 6). This does not pose as significant a problem within this formation as within the Graafwater but where thin bedding does occur problems similar to those experienced within the Graafwater Formation can arise.

In instances where the highly-jointed Graafwater Formation's foundation type support has been removed the Peninsula Formation is able to "bridge the void" (MJ Mountain and Partners, 1999, p. 6) due to its arching abilities resulting in large rock overhangs developing. This is because it is composed of stronger, more homogenous, rock material than the Graafwater. The removal of weak rock occurs more rapidly than upward arching and when the arch eventually fails, a large amount of rock material (the overhang) falls towards Chapman's Peak Drive.

2.5 Present Climate

2.5.1 Introduction

When studying geomorphological processes (mass movement, erosion, etc.) it is important to consider the role of climatic influences. Dominant climatic conditions obviously play important roles as the controlling factors of these geomorphic processes. With Chapman's Peak facing in the direction from which the area's rainfall approaches during its rainy season, and with a seemingly positive relationship between the occurrence of rainfall and rockfall, discussion of the climatic conditions of the area is important.

2.5.2 Circulation

The Cape Peninsula, at approximately 34° South, is situated within an area influenced by the descending limbs of the Hadley and Ferrel Cells (Thomas and Shaw, 1991b). Therefore its weather patterns are dominated by the sub-tropical anti-cyclones of the general circulation (Figure 2.8), those being the South Indian anti-cyclone off Durban's coast and the South African anti-cyclone off the Namib coast (Van Heerden and Hurry, 1988). These cells shift about 6° northwards during winter (Figure 2.9)(Preston-Whyte and Tyson, 1988).

Schulze (1965), along with Jackson and Tyson (1971), suggest that South Africa is almost entirely affected by the westerly circulation, to a greater extent in winter than in summer. They state further that weather in South Africa, and the Cape Peninsula in particular, are influenced greatly by perturbations in the southern hemisphere's westerly circulation. These take the form of a succession of cyclones and anti-cyclones shifting from west to east along the coast of South Africa. Schulze (1965, p. 313) made the following statement about the study area:

> "The region enjoys a climate similar to Mediterranean countries, receiving the bulk of its rainfall in winter from about May to September, and having a warm to hot dry summer. The rainfall is profoundly influenced by the very pronounced orographical features, resulting in annual amounts of the order of 3000mm in some mountain kloofs, as against 400 - 500mm on the Cape Flats."

During dry seasons, there are usually four to five days of rain per month, while during the rainy season figures as high as fourteen to fifteen rainy days are common in Cape Town.

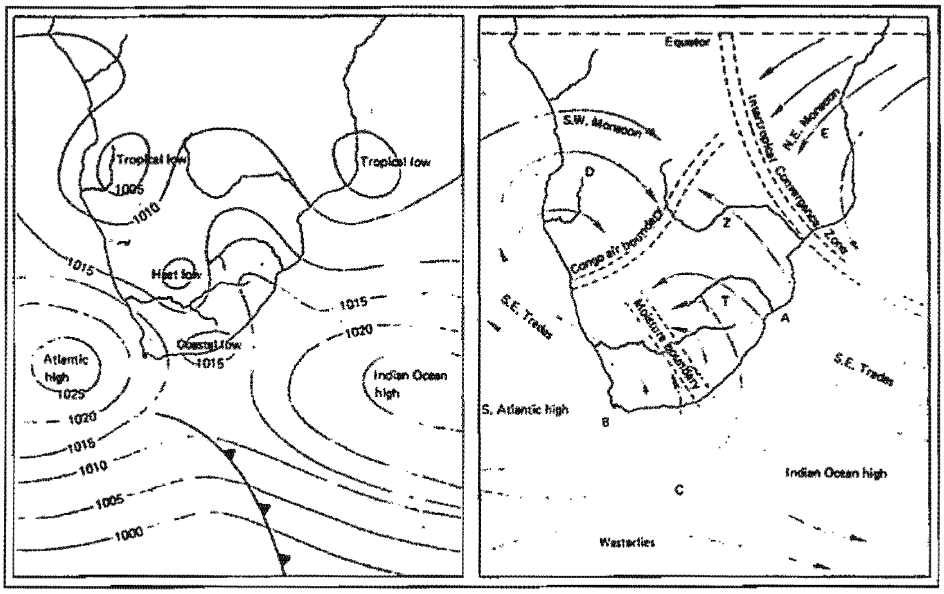


Figure 2.8: Simplified movements in the pattern of pressure distribution for mid-summer (above left) and Basic movements of air masses over Southern Africa in summer (above right) (Van Heerden and Hurry, 1988).

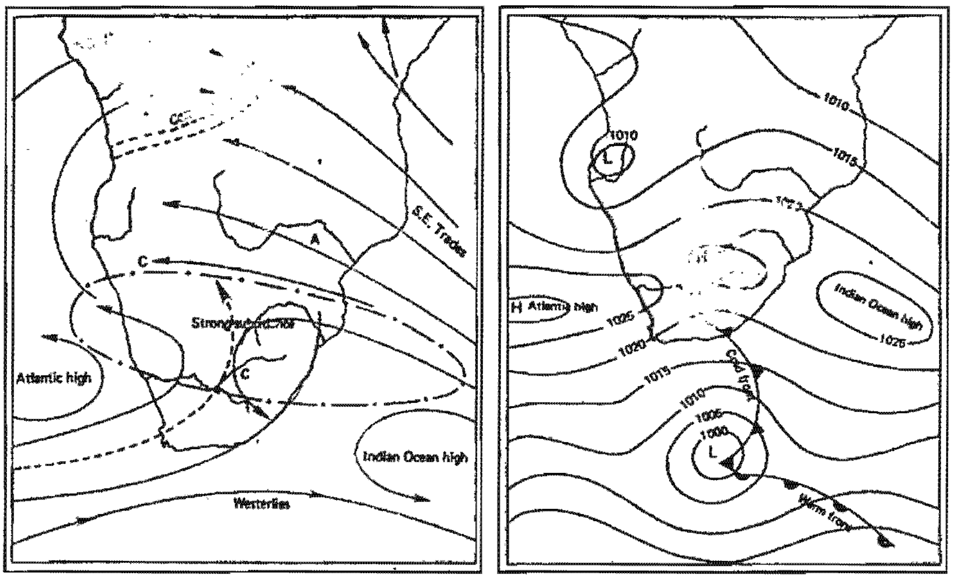


Figure 2.9: Simplified movements in the pattern of pressure distribution for mid-winter (above left) and Basic movements of air masses over Southern Africa in winter (above right) (Van Heerden and Hurry, 1988).

2.5.3 Rainfall

The rainfall is mainly cyclonic and orographic in nature but on about four to five occasions per year, thunderstorms do occur. Hail only accompanies these thunderstorms on very rare occasions. Rainfall figures are presented in Tables 2.2, 2.3 and 2.4. Schulze (1965, p. 313) made the following statement about the study area:

> "The region enjoys a climate similar to Mediterranean countries, receiving the bulk of its rainfall in winter from about May to September, and having a warm to hot dry summer. The rainfall is profoundly influenced by the very pronounced orographical features, resulting in annual amounts of the order of 3000mm in some mountain kloofs, as against 400 - 500mm on the Cape Flats."

STATION	LATITUDE	LONGITUDE	HEIGHT	PERIOD	RAINFALL
	South	East	Metres	Years	Millimetres
Sea Point	33° 55'	18° 23'	23	29	586.5
Camps Bay	33° 56'	18° 23'	15	17	618.0
Royal Observatory (C.T.)	33° 56'	18° 29'	12	109	627.4
Table Mountain (McL's B.)	33° 58'	18° 26'	1092	43	1972.0
Newlands (Monte B.)	33° 58'	18° 28'	23	16	1662.4
Kirstenbosch	33° 59'	18° 26'	89	36	1364.5
Claremont (Bis. Crt.)	33° 59'	18° 28'	30	34	1424.2
Kenilworth	34° 00'	18° 29'	27	25	1207.0
Wynberg (B. Vista)	34° 00'	18° 28'	61	7	1303.0
Muizenberg (Pav.)	34° 06'	18° 28'	15	8	481.8
Simonstown (wood)	34° 12'	18° 26'	30	23	809.8
Klawer Camp	34° 12'	18° 25'	293	7	739.9
Smitswinkel Bay	34° 16'	18° 28'	15	31	698.2
Cape Point	34° 21'	18° 30'	217	47	333.0

Table 2.2: Stations in the Cape Peninsula reflecting average rainfall (Schumann, 1950).

STATION	LATITUDE	LONGITUDE	HEIGHT	RAINFALL
	South	East	Metres	Millimetres
Cape Town (Fire Station)	33° 56'	18° 26'	53	545.6
Cape Town (Royal Observatory)	33° 56'	18° 29'	12	576.9
Table Mountain	33° 59'	18° 23'	686	1242.3
Kirstenbosch	33° 59'	18° 26'	89	1342.5
Tokai	34° 03'	18° 25'	56	914.6

Table 2.3: Stations in the Cape Peninsula reflecting rainfall normals (1921 – 1950) (Schumann, 1950).

Year	J	F	M	A	M	J	J	A	S	O	N	D
2000	16.1	0.0	12.9	13.8	62.3	92.5	46.3	46.2	66.6	6.6	6.8	5.9
2001	8.3	4.7	2.5	39.4	80.5	62.3	207.8	97.5	47.0	26.3	12.7	6.4

Table 2.4: Average monthly rainfall figures for Cape Town (sampled at Cape Town International Weather Office) over the study period (SAWB).

During dry seasons, there are usually four to five days of rain per month, while during the rainy season figures as high as fourteen to fifteen rainy days are common in Cape Town. Snow does fall on the mountains to the east of Cape Town (Hottentots Holland) but this snow soon melts and is only present for a few days. Snow has fallen on Table Mountain as well. This is however a very rare occurrence.

2.5.4 Wind and Cloud

During summer a subtropical high-pressure system, situated at approximately 30^0S, controls weather patterns with winds blowing anticyclonically around this high-pressure system. This causes winds to blow predominantly from the south-east during summer and results in the "tablecloth" which develops over the mountains of the Cape Peninsula (Schulze, 1965, p.314). This "tablecloth" is in fact orographic cloud, *stratocumulus lenticularis,* developed by moisture-laden winds blowing off the Indian Ocean (Preston-Whyte and Tyson, 1988).

The summer circulation over the peninsula is distinctive. This season is dry and windy with southerly to south-easterly winds blowing for 60% of the time (Schulze, 1965). The alignment of the local mountains affects the direction and force of these winds. The anticyclonic Cape

South-Easters are infamous for being strong and gusty and may blow at gale force for two to three consecutive days in the peninsula area.

2.5.5 Temperature and insolation

Table 2.5 indicates the average monthly temperatures experienced in Cape Town during the study period.

Year		J	F	M	A	M	J	J	A	S	O	N	D
2000	Maximum	28.4	27.5	26.0	24.1	21.2	20.3	17.9	19.0	18.7	22.5	24.7	24.4
2000	Minimum	15.8	16.9	15.7	11.8	10.3	9.4	8.1	9.8	9.0	10.4	13.9	15.3
2001	Maximum	26.3	28.0	25.6	22.6	20.6	18.1	17.9	17.0	18.9	21.8	24.6	25.9
2001	Minimum	15.5	16.0	13.8	12.4	10.5	8.5	8.3	9.3	10.2	12.9	14.8	15.8

Table 2.5: Recorded average monthly temperatures during the study period (sampled at Cape Town International Weather Office) (SAWB).

The summer and winter seasons are easily distinguishable with the average maximum temperatures decreasing gradually between January and August/September and then once again rising as the year ends. There were no great differences between the average monthly temperatures when comparing each individual month of 2000's figures with its corresponding month of the following year.

According to Schulze the sunshine duration for the area varies from a figure in excess of 70% of the possible maximum during summer down to about 60% during winter (Table 2.6).

STATION - CAPE TOWN (23YEARS)	DECEMBER	MARCH	JUNE	SEPTEMBER
Possible duration (hours/day)	14.4	12.3	9.9	11.9
Maximum	82	82	75	73
Minimum	70	65	46	53
Range	12	17	29	20

Table 2.6: Maximum and Minimum mean monthly sunshine duration (Schulze, 1965).

2.6 Vegetation

The role of vegetation, as a protective barrier against the agents of erosion is always important. With this barrier removed from Chapman's Peak by the wildfires that moved through the study area in January 2000, it is important to provide insight into what types of vegetation had been present before these fires and how they influenced slope stability there.

When the first Dutch settlers arrived in the south-western Cape they named the dominant vegetation type they found there "fijnbosch" (Cowling, 1992). It is the major contributor of species to the Cape Floristic Region (Bond and Goldblatt, 1984 and Cowling and Holmes, 1992). Taylor (1978) suggested that this vegetation type was given this name because of its small- or fine-leaved nature. Boucher (1987) on the other hand thought it might have been in reference to its potential as a forestry resource with it being too slender for harvesting. Attempts were made by some to assign the vegetation type a less colloquial name. An example of such a name was the term Macchia proposed by Acocks (1953). However, the term Fynbos endured and became firmly entrenched in biological literature (Cowling, 1992).

There is a great amount of biotic diversity amongst the fynbos plant types on the slopes of Chapman's Peak. On the peak and slopes *Protea lepidocarpodendron* (blackbeard protea) and *Leucospermum conocarpodendron* (Kreupelhout) are to be found. Also present are other fynbos species including aromatic herbs and bulbs (e.g. Guernsey lily – *Nerine sarniensis*) and an assortment of different reeds. Moisture is supplied by the prevailing south-easterly wind that regularly generates cloud cover above Chapman's Peak (Hout Bay Museum, 1992).

On the cliff faces, the plants present are those having adapted to survival in such precarious and difficult environments. These species have evolved their root systems (roots have elongated) to improve their anchoring ability. Examples of these are wild aster (*Limonium scabrum*), red crassula (*Rochia coccinea*), climber's friend (*Cliffortia ruscifolia*) and many vygies (Hout Bay Museum, 1992).

In the ravines with their relatively sheltered conditions and abundant moisture, it is possible for certain forest trees to grow. Trees such as the wild peach (*Kiggeleria africana*), the wild olive (*Olea africana*) and the buttonwood (*Grewia occidentalis*) grow in the higher altitudes with milkwood (*Sideroxylon inerme*) found in the lower ravines (Hout Bay Museum, 1992).

The predominant alien species that exist on the slopes of Chapman's Peak are *Acacia cyclops* (Rooikraans), *Acacia mearnsii* (Black Wattle), *Acacia longifolia* (Long-leaf Wattle), *Acacia saligna* (Port Jackson), *Albizia lophantha* (Stinkbean) and Pine (*pers. comm.* C. Chaney). No record was made of the degree of infestation of these species, before the fires of January 2000, and due to the extent of damage done by the fires, it was not possible to determine this information.

2.6.1 Fire management history in Western Cape Fynbos

The presence of alien invasive plants, within a fynbos biome, seems to have quite considerable influences upon that biome when impacted upon by wildfire (expanded later). With Chapman's Peak, having had these alien plant species present before the fires of January 2000, it seems important to discuss the issue of fire management practices utilized in the Western Cape of South Africa.

Originally, fires were considered a menace within the Western Cape. Dutch settlers in fact tried their utmost to limit their frequency (rather unsuccessfully) and imposed heavy penalties for veld-burning. The real effort to curb these fires moving through the fynbos came at the beginning of the 20th century. A report by the Drought Investigation Commission (1923) {cited in Cowling, 1992} stated that veld-burning was in fact detrimental and suggested that management procedures be put in place to conserve certain catchments from burning and grazing. Various botanists of standing at the time (Margaret Levyns, Rudolph Marloth, Neville Pillans) joined in this argument fires could in fact have threatened the continued existence of many fynbos species (Richardson and Van Wilgen, 1992). These beliefs and practices were continued until the 1960's when it eventually became apparent from fynbos management research that to prevent species extinction fire was in fact a crucial tool and it was not practical to exclude fire from management efforts such as the removal of alien trees and shrubs and creating fire breaks to prevent large runaway wildfires developing. In 1967 it was recommended by authorities that controlled burning of "foothills and parts of the mountain veld between kloofs, and where no specific or recognised marshes and perennial springs occur" should be implemented. The first major burn for management purposes occurred near Grabouw in the Kogelberg State Forest. This event took place in 1968 under the control of the Department of Forestry. Regular prescribed burning was implemented in the mid 1970's and nowadays forms the cornerstone of fynbos management techniques (Richardson and Van Wilgen, 1992).

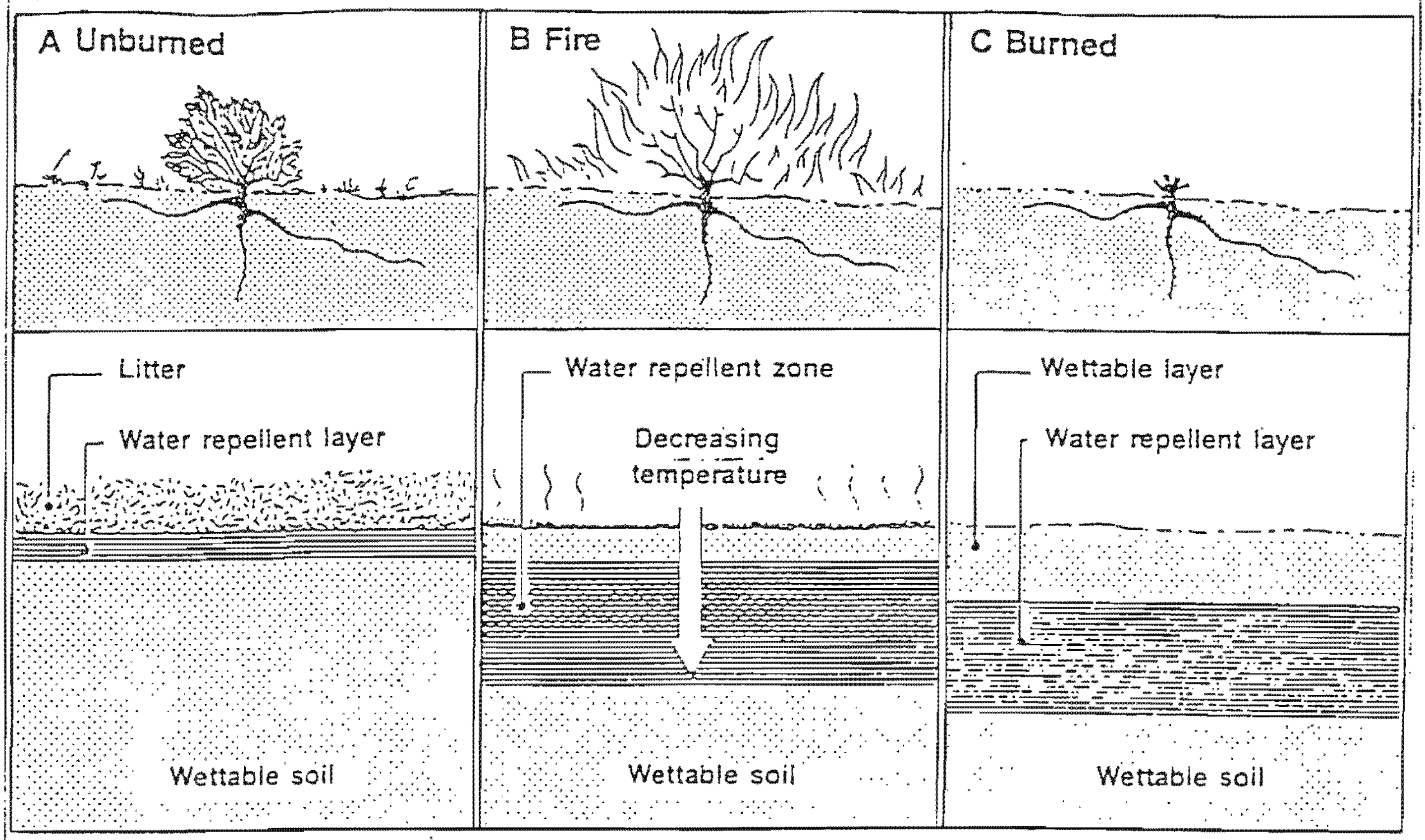
2.6.2 The impact of alien invasives and fire

When an area has been burnt, as is the case in this investigation of Chapman's Peak, it is important to draw attention to the impacts that are caused, especially when the these impacts have now changed because the historically dominant vegetation type in the area has become invaded, altering the fire characteristics that exist during a period of burning. Total biomass is a good predictor of fire intensity (Foden, 1997). Moisture content within fuel is an important factor in controlling fire intensity (Bond and Van Wilgen, 1996; Richardson and Van Wilgen, 1986). Wind speed (and therefore fire rate of spread) during burning also influences fire intensity (Hobbs and Gimingham, 1984). The exact effects of wind on fire intensity are however not known. Hobbs and Gimingham (1984), Sparling and Smith (1966) and Smith and James (1978) (cited in Hobbs and Gimingham {1984}) all found that increased wind velocities have a reducing effect on fire intensities, while Daubenmire (1968) and Whittaker (1961) (both cited in Hobbs and Gimingham, 1984) found the opposite true.

Burning an area of land removes the protective layer above the ground previously provided by the vegetation (Morgan and Rickson, 1995). It has been suggested that increased fire intensity, due to the alien vegetation being present at the time of burning, results in increased soil erosion (Scott and Van Wyk 1992; Bond and Van Wilgen, 1996; Lindley et al., 1988, Swanson, 1981 all cited in Whelan, 1995) in mountainous, rocky areas. Higher intensity fires result in considerably greater soil losses resulting from erosion as reported by Soto and Diaz-Fierros (1998) when they compared runoff and soil erosion from two plots, one exposed to a low-intensity burn and the other a higher intensity wildfire. According to Tinley (1985), fires that burn at very high temperatures, such as those that occur in stands of alien vegetation can cause organic material present in the surface layers of the soil to alter chemically and create an impervious crust within the soil. This physical change results in the increased water repellency of the soil. This increased repellency, brought about by the coating of the soil particles with particular organic substances, decreases the absorptive ability of the soil (Figure 2.10) (DeBano et al. 1967 in Scott and Van Wyk 1990; Whelan 1995). This acquired characteristic of repellency retards water infiltration and/or percolation resulting in greater runoff volumes (DeBano, 1971 [cited in Scott and Van Wyk, 1995]). This therefore induces greater soil erosion down slope (Swanson, 1981 [cited in Whelan, 1995]).

McCormick (2000) investigated slopes on Chapman's Peak. He concluded that although there was a likely increase in fire intensities, caused by the presence of alien vegetation, it is rather the "quantity and more importantly the intensity of a rainfall event that is the most important factor", (McCormick, 2000, p. 53) which determines whether a slope will fail or not. However, it was discovered that after a forest fire in Israel, runoff was 500 times and sediment yield 100 000 times greater in burnt areas when compared to those spared from the fire (Inbar et al., 1998).

Pieterse and Cairns (1986) suggest that the short juvenile period (<5 years) and large annual production of hard-coated seeds of alien invasive plants allow them to outgrow their fynbos competitors, which have slow post-fire germination rates after fires. This means that once wildfire has swept through an already invaded area the new post-fire vegetation type will be almost all, if not all, alien in nature (Tinley 1985). Alien trees and shrubs are also extremely resilient to fire when compared to the indigenous fynbos (Richardson and Van Wilgen, 1992). Richardson and Van Wilgen (1986) found that there were large decreases in species numbers and vegetation cover once a wildfire had moved through an area of felled *Hakea* stands in the Wemmershoek area. The findings of Van Wilgen and Holmes (1986) (in Richardson and Van Wilgen {1986}), after the burning of piles of *Acacia cyclops*, supported this evidence. Breytenbach (1986) undertook a similar experiment but within the confines of a nursery. He reported similar findings and stated that in *Hakea*-invaded sites seedling numbers dropped drastically after experiencing burning.



SOIL WATER REPELLENCY IS ALTERED BY FIRE.

A) BEFORE FIRE, HYDROPHOBIC SUBSTANCES ACCUMULATE IN LITTER LAYER AND MINERAL SOIL IMMEDIATELY BENEATH IT.

B) FIRE BURNS VEGETATION AND LITTERLAYER, CAUSING HYDROPHIBIC SUBSTANCES TO MOVE DOWNWARD ALONG TEMPERATURE GRADIENTS.

C) AFTER A FIRE, WATER-REPELLENT LAYER IS PRESENT BELOW AND PARALLEL TO SOIL SURFACE ON BURNED AREA

Figure 2.10: Fire-induced water repellency in soil (Taylor, 1999).

2.7 History of Chapman's Peak Drive

2.7.1 Initial history

It is important to discuss the history of Chapman's Peak Drive in order to understand why this road is so important from a historical perspective as well as to generate an appreciation of what a difficult engineering feat had been accomplished upon completion of the drive. It is also important to identify that the need for constant maintenance was identified at the time of construction by the then Inspecting Roads Engineer Mr T. W. Perry (see quote later in this section) and that this warning seems not to have been heeded by the responsible authorities according to the 1999 geotechnical report of M.J. Mountain and Partners. The reasons for selecting a road route along these cliffs, and not other alternative locations, are also explained.

According to Borchers (1971), Hout Bay was originally named Chapman's Chaunce (meaning Chance) by John Davis, the Pilot of the English ship "Consent" (Captain: David Middleton), on 29th July 1607 at 6.30pm. John Chapman, a Master's mate, was sent into the bay at dusk on a chancy venture to determine whether a harbour existed there or not. The name was recorded in John Davis' voluminous "Rutter, or Sailing Directions" and subsequently sold to the East India Company. This document was then issued to all of the Company's Captains and as a result, the name stuck. Chapman's Peak only received its title in about 1856. As the title suggests the cliffs were named after the bay they overlook. Chapman's is the oldest English name on the South African coast (Borchers, 1971).

2.7.2 Construction

The construction of a road linking Hout Bay and Noordhoek was originally proposed in 1910 during an exchange of ideas between the Commissioner of Public Works and the Cape Peninsula Publicity Association in March 1910 (Ross, 2000). The Commissioner of Public Works deemed this task impossible at that time (as stated in a letter to the Cape Peninsula Publicity Association in March 1910). The then Administrator of the Cape Sir Frederick de Waal was strongly in favour of this project and was the main force behind its construction (Ross, 2000). He employed the well-known mountaineer William C. West to determine and flag the route for construction (Green, 1960). The road was to be named "The Hout Bay-Noordhoek Road". This title was deemed inadequate for a motorway that was to be, once completed, such a great feat of engineering (Provincial Secretary, 1922). They therefore decided that the drive should carry the name of the cliffs along which it was to be constructed. When Administrator de Waal developed the idea of a road between Hout Bay and Noordhoek two possible routes were suggested. The first called for construction in the valley between Chapman's Peak and Noordhoek Peak. The other suggested a route along the cliffs above the sea. At the time, the task seemed too difficult and expensive to be undertaken (Lundy, 1984). This did not hold Administrator de Waal back and he employed surveyors to inspect the possible alternative routes. The area in the valley between the Chapman's and Noordhoek Peaks was identified as being inappropriate for road construction as the area was characterised by steep unstable slopes that often had surveyors scrambling around on their hands and knees (Lundy, 1984). This confirmed the cliff route as the only viable alternative. The survey work for this route, undertaken by Charl Marais, a man who was himself born in the Cape in 1862, began in 1915 (Ross, 2000).

Construction by the Cape's Divisional Council began in 1916 and by 1917 the section of the drive between Hout Bay and the "Lookout" had been completed. The rest of the drive was eventually opened on 6 May 1922 by the then Governor-General of the Union of South Africa, His Royal Highness Prince Arthur of Connaught (Ross, 2000). The construction actually follows "a natural ledge developed by differential erosion along the unconformity between the Cape Granite and overlying Table Mountain Group" (Reid *et al.*, 1998).

The construction involved great skill in both mountaineering and engineering due to the inaccessibility of the site. The newly formed Union government of that time provided the approximately 700 convict labourers used to build the drive (Lundy, 1984). The total project cost eventually amounted to a total of R40 000 (Ross, 2000).

The Inspecting Roads Engineer Mr T. W. W. Perry examined the road on 15 February 1922. In his report, he made the following statement:

> "In all mountain roads, falls of rocks and slips of earth are likely to occur, especially during winter rains and stormy weather (*sic*) and this remark must especially apply in this case where the precipitous mountain krantzes face largely towards the 'weather' side. It is, of course, a practical impossibility to remove all loose stones and ensure the stability of all banks above the road (all reasonable steps appear to have been undertaken up to this stage). Careful and constant patrolling will probably prove a necessity for some years to come, and must be accepted as a normal duty and expense attached to a road of this description. For the ongoing reasons it may ultimately prove advisable to close the road entirely, or after dark, as traffic will not only be menaced by debris actually falling while passing, but (also by) that which becomes scattered over the road surface".

From this statement, it is obvious that the potential for rockfalls, along Chapman's Peak Dive, was recognized at an early stage in the Drive's existence.

2.7.3 Current ownership of the study area

The study area falls within the Cape Peninsula National Park and as such is under the jurisdiction of the Cape Peninsula National Parks Board.

2.8 Summary

In this chapter, the physical environment of the study area, Chapman's Peak, has been described. Three different lithologies are exposed in the on Chapman's Peak, namely Cape Granite forming the base, overlain by the weaker shales and mudstones of the Graafwater Formation which is in turn overlain by the sandstones of the Peninsula Formation. The Engineering Geological Assessment of the area highlights that the undercutting of the Peninsula Formation, as the Graafwater erodes more rapidly beneath, causes conditions that can promote the falling of slope material onto Chapman's Peak Drive. With the study area exposed to wildfires during January 2000, the impacts of such fires, especially with the historically dominant vegetation type invaded, thereby altering the amount and type of fuel available for combustion, was also discussed and the adverse effects thereof highlighted. Importantly, it was shown in the discussion on the history of construction of Chapman's Peak Drive, that the Inspecting Roads

Engineer present at the time of completion of the Drive, Mr T.W.W. Perry, stated that that a road such as this, built along the coast, on the side of a mountain, especially one facing in the direction of the dominant rain-bringing weather systems, is always going to experience problems with slope material falling onto the road. In spite of this warning, there seems that very little work, in terms of prevention of slope failure onto the Drive, has been undertaken on the slopes above Chapman's Peak Drive since then. The following chapter, Chapter Three, presents the research design and methodology used in achieving the objectives of this study.

CHAPTER THREE

THEORETICAL BACKGROUND

3.1 Introduction

The movement, in bulk, of slope forming materials from higher to lower ground without the direct assistance of a fluid transport agent (air, water or ice), but being acted upon by gravity, is termed mass movement (Goudie, 1995). Water and ice are however, often involved in the initialisation of mass movement events. Their roles are the reduction of strength in slope materials and the promotion of plastic and fluid type behaviour in soils. These effects can be brought about by the exposure of a body of slope material to the agents of erosion over an extended period. An example of this is the repeated application of stress to a body of rock through the process of ice wedging. This may occur repeatedly without damage to the rock but eventually a fragment of the rock may break loose and move off downslope. The inclusion of the impacts of erosive forces in the discussion of controlling factors of mass movement is therefore necessary. Rockfalls are one particular form of mass movement. With rockfalls onto Chapman's Peak Drive being a focus of this investigation, a discussion of significant factors causing rockfalls is necessary. When water flowing over a slope is able to suspend and remove soil grains from the soil surface then overland flow/slope wash is taking place (Allen, 1997). Immediately a distinct difference is noticed between the mediums involved during the mobilisation of slope materials during mass movement and overland flow events. As the identification of sediment movements on the barred and unbarred slopes above Chapman's Peak Drive is another of the focuses of this study it is important that the relevant theory on the overland transport of sediments be discussed. In so doing, a theoretical understanding of the problem at hand is achieved before the gathering of physical field data takes place.

An initial grasp of the theoretical background of slopes in general, and within the study area in particular, is important. This is because the real-world physical characteristics of slopes often make the application of mechanical and mathematical principles to slope stability problems difficult. These include factors such as geological conditions, topographical setting and material types. Having this background knowledge can assist the researcher in modifying sampling techniques in such a way as to achieve the best possible results when used in that particular study area. Slope analysis results can produce information useful in determining the frequency, nature and magnitude of potential future slope failures (Goudie, 1995).

3.2 Geomorphology and Slopes

Geomorphologists focus their studies on the nature and origin of landforms, the study of processes that alter and create landforms, and with material composition. The magnitude, frequency and rate of operation of such processes are also emphasised. For example, if weathering rates are slower than transportation rates, then only a thin soil cover will remain with the opposite effect if the transportation rate becomes slower than the weathering rate. Geomorphology has recently become much more of an applied science, concentrating on present day processes and how they affect and shape our physical environments. This obviously includes the impacts of human activities on these environments as well. With the slopes of Chapman's Peak having been impacted upon by man the geomorphic investigation of slope processes in the study area of this dissertation is an important step in explaining the problems presently experienced there.

As geomorphologists are concerned with slope stability and form, and their obvious inter-relationships, they will therefore also be interested in the aspect, length, inclination and curvature of slopes. Determining factors, regarding slope stability may include general aspect of the slope and obviously therefore its duration of exposure to direct sunlight. This factor can alter the amount of water retained within different slopes that may be similar in material constitution, angle of slope and geology. The presence of excess water can influence factors such as water table levels, pore water pressures and seepage (Goudie, 1990). Surface drainage patterns often indicate the nature of underlying soil or rock formations and can therefore give some indication of the ability of a slope to resist the forces which cause fluctuations in the amount of water within a slope (Selby, 1993).

The suggestion has been made that a morphometric approach may be used in determining what causes slope failure (Crozier, 1973). Unique indices are defined with regards to the form that a landslide takes. An example given is the depth to length ratio sometimes called the Skempton ratio (Allen, 1997). This index is recognized as being of vital importance when attempting to determine the cause of a slope movement. Geomorphologists can contribute to understanding and preventing slope failures by identifying landslide-prone slopes through geomorphological mapping (this practice attempts to "identify and classify slopes, recognize past and present processes and the relationship between form and processes occurring within the slope materials" {Chowdhury, 1978, p. 9}), aerial photography and land-systems mapping (Brunsden *et al*, 1975).

3.3 Mass Movement

Mass movement is an important component in the transfer of sediments, especially within mountainous terrain as exist on Chapman's Peak. There is a great range in rates of flow between and within the different process types (Figure 1.1) of mass movement. The primary mechanisms for mass movement are creep, flow, slide, heave, fall and subsidence and, by definition, all take place on slopes (Murck *et al.*, 1997). These types of movements of material downslope all represent forms of slope failure. This is because all forms of mass movement, in fact, involve the failure of stabilising forces usually prohibiting material movement on any particular slope. The most important, however, in the case of Chapman's Peak, and that which will be the focus of this chapter, are rockfalls and landslides. An important question to consider, when reviewing literature on mass movement, is what factors can initialise the mass movement of material on slopes by influencing the stability of those slopes? The most important of these factors include the influences of gravity, and therefore the gradient (steepness) of the slope, water (the hydrologic characteristics of the slope), vegetation cover, the nature of the slope material and the occurrence of a trigger event. The causes, processes and mechanisms of mass movement comprise a complex topic, with a vast body of literature, which can only be touched on here. Readers are referred to Embleton and Thorne (1979), Selby (1993) and Allen (1997).

3.3.1 Types of mass movement processes

In essence, all types of mass movement are in fact forms of slope failure. The constant force exerted by gravity, on mountain cliffs and hillslopes, makes them vulnerable to failure. When slope failure does occur, unstable material is moving downslope to a new location where it no longer threatens slope stability. As discussed previously, there is a wide range of materials and processes that can be involved in mass movement events. To be able to distinguish between them involves the consideration of the following criteria: velocity and mechanism of movement; mode of deformation; water content; material; mode of deformation; and the geometry of the moving mass (Selby, 1993). Allen (1997) suggests that the most widely used classification scheme for mass movement (Table 3.1) is that of Varnes (1978) who recognized the processes of creep, flow, slide, heave, fall and subsidence as being the primary mechanisms for mass movement as illustrated in Figure 3.2. Even though there is this large variability of mass movements in nature according to Varnes (1978), these gravity driven movements affecting slopes are simplified into three main categories by Allen (1997), namely:

- Turbulent hyperconcentrated flows;
- Plastic flows which move as laminar flows;
- Rock avalanches and falls, slides and slumps generated by gravitational instability only.

With the main concern along Chapman's Peak Drive involving the falling of clast material onto the road surface, the latter, more rapid mass movement processes on rock hillslopes, are the focus of this discussion. For more in-depth discussions of mass movement processes in soils see Embleton and Thorne (1979), Selby (1993) and Murck *et al.* (1997).

3.3.1.1 Slumps

This particular type of failure involves the rotational movement of rock or regolith along a curved, concave-up surface. The directions of motion are a combination of both downslope and outward, away from the slope face. They are relatively long when compared to their thickness and have a Skempton ratio greater than 0.33 (Allen, 1997). The Skempton ratio is the ratio of the deposit thickness to its length (Skempton and Hutchinson, 1969). According to Table 3.1 this type of mass movement ranges in speed from what Varnes (1978) refers to as extremely slow to moderate. Varnes (1978) includes slumps as a category of slide type failures while Murck *et al.* (1997) have identified them as their own particular type of mass movement.

3.3.1.2 Slides

In this type of mass movement, the displacement of slope material is translational in nature. In other words, there is no rotational vector involved, only a uniform, single direction movement

Primary mechanism			Mass movement type	Materials in motion	Moisture content	Type of strain and nature of movement	Rate of movement
Lateral component predominant		Creep	Rock creep and continuous creep	Especially readily deformable rocks, such as shales and clays and soil	Low	Slow plastic deformation of rock, or soil producing a variety of forms including cambering, valley bulging and outcrop bedding curvature	Very slow to extremely slow
		Flow	Solifluction	Soil	High	Widespread flow of saturated soil over low- to moderate-angle slopes	Very slow to extremely slow
			Gelifluction	Soil	High	Widespread flow of seasonally saturated soil over permanently frozen subsoil	Very slow to extremely slow
			Mudflow	>80% clay sized	Extremely high	Confined elongated flow	Slow
			Slow earthflow	>80% sand-sized	Low	Confined elongated flow	Slow
			Debris flow	Mixture of fine and coarse debris (20–80% of particles coarser than sand-sized)	High	Flow usually focused into pre-existing drainage lines	Very rapid
			Debris (rock) avalanche (sturzstrom)	Rock debris, in some cases with ice and snow	Low	Catastrophic low-friction movement of up to several kilometres, usually precipitated by a major rockfall and capable of overriding significant topographic features	Extremely rapid
			Snow avalanche	Snow and ice, in some cases with rock debris	Low	Catastrophic low friction movement precipitated by fall or slide	Extremely rapid
	Slide	*Translational*	Rock slide	Unfractured rock mass	Low	Shallow slide approximately parallel to ground surface of coherent rock mass along single fracture	Very slow to extremely rapid
			Rock block slide	Fractured rock	Low	Slide approximately parallel to ground surface of fractured rock	Moderate
			Debris/earth slide	Rock debris or soil	Low to moderate	Shallow slide of deformed masses of soil	Very slow to rapid
			Debris/earth block slide	Rock debris or soil	Low to moderate	Shallow slide of deformed masses of soil	Slow
		Rotational	Rock slump	Rock	Low	Rotational movement along concave failure plane	Extremely slow to moderate
			Debris/earth slump	Rock debris or soil	Moderate	Rotational movement along concave failure plane	Slow
		Heave	Soil creep	Soil	Low	Widespread incremental downslope movement of soil or rock particles	Extremely slow
			Talus creep	Rock debris	Low		
Vertical component predominant		Fall	Rockfall	Detached rock joint blocks	Low	Fall of individual blocks from vertical faces	Extremely rapid
			Debris/earth fall (topple)	Detached cohesive units of soil	Low	Toppling of cohesive units of soil from near-vertical faces such as riverbanks	Very rapid
		Subsidence	Cavity collapse	Rock or soil	Low	Collapse of rock or soil into underground cavities such as limestone caves or lava tubes	Very rapid
			Settlement	Soil	Low	Lowering of surface due to ground compaction usually resulting from withdrawal of ground water	Slow

Table 3.1: Classification and characteristic of the major types of mass movement (Varnes, 1978).

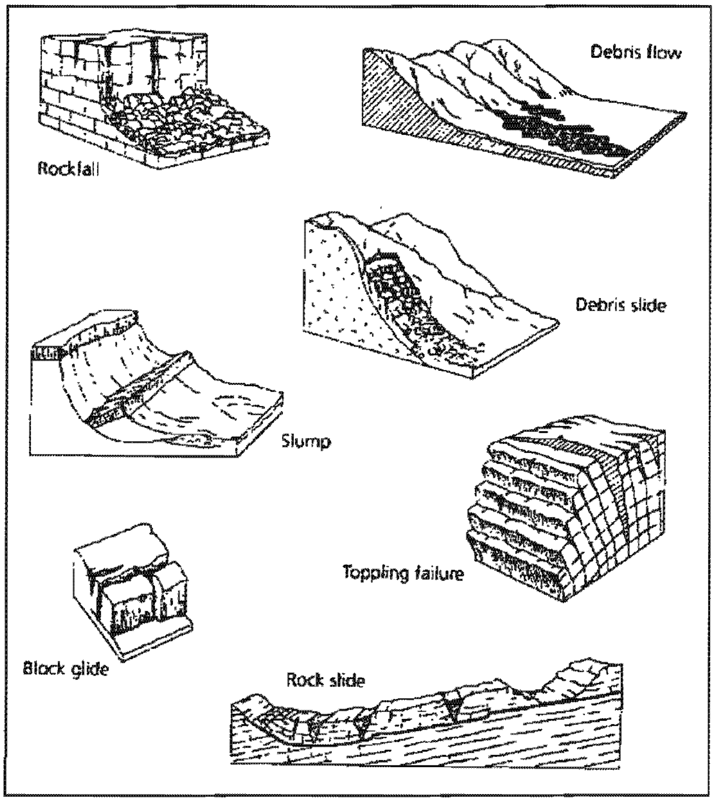


Figure 3.1: The primary mechanisms for mass movements (Varnes, 1978).

Murck *et al.* (1997). For this reason, it seems, Murck *et al.* (1997) have distinguished between slides and slumps. Allen (1997) however, uses the Varnes (1978) classification, suggesting that there is a lateral component to the downslope movement of slides. Slides are relatively short compared to their thickness and have Skempton ratios less of than 0.15 (Allen, 1997). According to Varnes (1978), slope material can move downslope at velocities ranging from very slow to rapid during translational slide events.

Okura *et al.* (2000) performed outdoor experiments, analysing runout distances and the individual movements of landslide blocks, as well as using numerical simulations, in an attempt to learn more about the mechanism of rockfall fluidisation. In the various experiments, the number and size of the blocks was varied on each occasion. In the numerical simulations performed, the positions of individual rocks were traced in three-dimensional space from landslide initiation until final deposition. A positive correlation between landslide volume and runout distance became evident. However, the runout distance of the gravity centre of deposited rockfall mass had a negative correlation with the volume of rock involved.

3.3.1.3 Falls

These types of failure involve the sudden, vertical movement of slope material. They are particularly common in steep, mountainous terrain and take place in the surface zones of soil or rock. Failure is often three-dimensional in character and involves the detachment of small or large rock fragments. It may also be two-dimensional in nature with slab-type sections of rock falling. This is all dependent on the number of discontinuities involved and the relative orientation of slopes. An example of this kind of event is the eventual detachment and falling of rock overhangs from a cliff face, after undercutting has occurred over time. They take the form of either rockfalls or debris falls. The release of only fragments of bedrock is termed a rockfall. Rockfalls can involve the detachment of a single fragment or huge masses of rock. The release of these large masses of rock is sometimes also referred to as a rock avalanche. When regolith and plant material accompanies this bedrock material, then the event is called a debris fall. When the vertical line through the centre of gravity of individual blocks (which have lost lateral support) falls outside of the blocks' respective bases, then a toppling type failure usually occurs (Figure 3.1) on rock slopes. Varnes (1978) describes the velocity of this type of slope failure as ranging from very to extremely rapid.

When rock or debris is free falling through air, its velocity (v) can be calculated using the following equation:

$$v = \sqrt{2gh}$$

where h is the distance fallen vertically before impact. From this equation, it can be seen that, when free falling, a rock will accelerate as it moves towards the Earth's surface and therefore the higher the point from which the rock falls, the greater will be its terminal velocity before its eventual impact downslope.

3.3.1.4 Flows

Once a landslide has occurred, the slipped debris usually quickly attains a stable position and the process ceases. Sometimes, however, it is possible for this debris to become mobilised into a flowslide, a movement that may continue for some distance. There are many different types of flowslide, differing widely in mechanics of operation (Goudie, 1990). Debris from high-magnitude rockslides can trap compressed air as it falls and move on an air cushion for several kilometres at very high velocities. Flowslides in coarse regolith material can be triggered by very high pore-water pressures and maintained by constant addition of water to the mass (Allen, 1997). The mechanics of flowslides are poorly understood because, with the exception of mudslides, they tend to take place very rapidly (Goudie, 1990). For western Cape examples of this type of slope process consult Boelhouwers *et al* (1998, 2001).

3.4 Overland Flow/Surface Wash

As water flows over the surface of a slope it possesses the potential to erode soil when the shear stress applied to the soil layer exceeds the forces of resistance holding the grains in place. These forces of resistance to erosion are proportional to the weight of individual grains acting vertically and to the cohesion between grains. Those forces tending to promote movement are several. Firstly, flowing water exerts a shear stress at its base that tends to roll or push grains along the bed. Secondly, a fluid flowing past a particle on its bed tends to set up a pressure gradient from base to top of the grain, causing a vertical lift force to act. Thirdly, the downslope component of the grain's own weight acts to move the particle along the bed (Allen, 1997).

Water flowing down a slope may be laminar or turbulent in nature. Laminar flow exists when the flowlines in water are parallel are to each other with no lateral or vertical mixing throughout the fluid. With this type of flow velocity increases steadily from the bed. When turbulent flow occurs vertical mixing does take place resulting in faster water from the top of the flow mixing with the slower water near the bed and vice versa (Finlayson and Statham, 1980). Therefore velocity increases more rapidly close to the bed within a turbulent flow and a greater degree of erosion is caused than that resulting from laminar flow. Unconcentrated sheetflow can be laminar or turbulent depending on the depth and slope of flow and upon the amount of turbulence created by impacting raindrops. However, once flow becomes concentrated into well-defined flow paths, then it is usually turbulent. This means that concentrated flow will be more erosive than slower unconcentrated flow (Selby, 1993).

It is important to note that a critical depth of overland flow is necessary before any sediment transport will take place. At the crest of a slope only a small depth of overland flow is possible during a rainfall event as the catchment area is limited. Therefore little or no overland flow erosion is likely in this area. Further downslope, as the catchment area increases, the depth of flow increases accordingly eventually reaching a critical depth at which erosion begins (Selby, 1993).

Once overland flow has begun it usually tends to become concentrated into somewhat well defined flow paths. This can be due to the existence of minor irregularities within the microtopography of slopes that cause flowing water to converge towards certain points. This results in concentrated flows with raised velocities and erosive capabilities. When these flow paths deepen sufficiently and become recogniseable channels they are called rills. If rills persist from storm to storm they can become a part of the permanent drainage system (Goudie, 1990). However, if these rills are destroyed by weathering processes during rainless periods and then reform at different locations on the slope with renewed rainfall activity, they can contribute to uniform slope lowering over time.

3.5 Factors influencing slope stability

All slopes, when exposed to weathering processes, will attempt to achieve what is termed a steady-state condition. A slope reaches this condition by having a slope angle permitting the movement of regolith along its surface such that the amount of regolith material reaching any point on the slope's surface is equal to the amount of material moving downslope from that point. The most important factors upsetting this steady-state condition on a slope's surface are now discussed.

3.5.1 Gravity and slope gradient

The downslope movement of slope material without the direct assistance of a fluid transport is termed mass movement. Therefore, by definition, gravity plays the most important role in controlling this downslope movement. At any time there are two opposing forces acting on a body of rock or debris that will either keep it in place or cause it to shift downslope. These forces are termed the shear strength/shear force and shear stress (Murck *et al.*, 1997) acting on slope material.

Gupta (2001), in a study of landslide activity in the Du Toits Kloof in the Western Cape Mountains of South Africa, found that the number of landslides, occuring within his study area, related to the angle of slope upon which the material was present. Gupta (2001) found that a particular range of slope angles exhibited landslide frequencies that clearly distinguished them as an important controlling factor in this regard. As stated previously (in 3.3.2.1), steeper slope angles result in increased shear forces being exerted on a body of slope material and greater shear strength is then required to prevent movement. Gupta (2001) therefore, through his investigations of these case examples, has supported the theory that gravity and slope angle are important controlling factors of mass movement.

3.5.2 Water

Water is usually present within rocks and regolith near the Earth's surface and it can often be a critical contributing factor resulting in mass movement (Plummer and McGeary, 1996). According to Selby (1993), water is the most important factor contributing to the failure of bodies of soil on slopes. When a slope is too steep and/or has lost its vegetation cover, and if the slope material is subsequently saturated, the individual particles become lubricated and the friction between them decreases. When large amounts of water are absorbed, for example, when the water table rises because of a heavy downpour, the pore pressure created within a body of slope material is sometimes great enough to separate the grains (Finlayson and Statham, 1980). This decreases the material's shear strength and allows the particles to flow past each other in a fluid like manner. The threshold crossed when this occurs is termed the liquid limit (Murck, *et al.* 1997). This process can also allow material to flow on lower angled slopes on which it normally would not (Finlayson and Statham, 1980). This process is termed solifluction (Murck *et al.*, 1997).

The movement of some large rock masses can also been attributed to the water pressure in voids within those rock masses. When two rock masses trap water between them, pressure is placed on that water. If this pressure is great enough, a buoying effect is produced which can be strong enough to support the mass of the overlying body of rock (Plummer and McGeary, 1996). This therefore reduces friction along the points of contact between the two bodies of rock. The presence of a small amount of water however, within slope materials, actually tends to bind the particles together through surface tension created by the thin film of water around the particles (Plummer and McGeary, 1996; Römkens *et al.*, 1997). The formation and enlargement of cracks within bodies of rock and the removal of basal support can be brought about by increased quantities of water within these bodies and usually precede fall type mass movement events.

Moon *et al.* (2001), when investigating the impacts of different rainfall regimes, found that as rainstorm intensities were increased so did the amount of soil yielded by a slope. The relationship was non-linear with increases in sediment yields growing out of proportion to the increases in storm intensities. This relationship was most evident when rainstorm events with initially high intensities occurred. When rainstorms of lesser intensity occur their erosive power reduces as a large amount of their initial precipitation infiltrates the soil. Also, rainstorms with lower initial rainfall intensities, allow greater opportunity for surface sealing to develop, thereby further reducing the possible erosive impact of subsequent rainstorms. When examining the effects of soil water pressure in prepared beds of Grenada Loess soil, Moon *et al.* (2001) discovered that decreasing soil water pressure resulted in a marginal change in run-off rates but appreciable increases in the sediment concentration within this run-off. These findings will be of great assistance in the explanation of variation within the amounts of sediment on the barred and unbarred slopes as well as facilitating the understanding of how soil moisture regimes within, and on the surface of, slopes become affected by different types of rainfall events.

3.5.3 Vegetation

The nature of the vegetation cover (height, structure and spacing) on a slope is an important controlling factor of stability as, once properly established, it can act as a filter or barrier between rain and soil, thereby protecting soil form eroding. Apart from the simple interception of rainfall, the intensity, momentum, drop size distribution and areal distribution of rainfall can all be altered by the nature of the vegetation cover present. Plants also increase the friction of the soil surface, decreasing the velocity of runoff (Rowland, 1993). The cohesiveness of a body of soil also improves when a system of roots, that supply mechanical reinforcement to that soil, is present (Selby, 1993; Morgan and Rickson, 1995). This is especially apparent in shallow soils where adjacent plants will have shallow, intertwined roots (Selby, 1993). The plants also act as windbreaks, decreasing wind velocity by increasing surface roughness (Tinley, 1985). The leaf litter and the living plants act as shields against rain splash and surface runoff, helping preserve soil structure, and the litter acts as a sponge as it is able to absorb more water than its dry weight and therefore the absence of these will promote erosion. Water accumulates on the leaves themselves and evaporates directly from them without ever reaching the soil (Tinley, 1985; Young, 1972; Selby, 1993). Plants also control soil moisture content and the height of the water table through the processes of transpiration and interception and are therefore able to offset erosion and/or a mass movement event by avoiding saturation of the soil (Selby, 1993).

The removal of roots from the earth leaves channels within the soil. This allows water to move more freely within the soil (increases permeability). As a result, this allows the more rapid shifting of the water table during rainstorm events, thereby decreasing the amount of time and water needed for substantial erosional action to start occuring, possibly as a debris flow or slumping type failure (Selby, 1993).

Plants also insulate the soil and rocks against high and low temperatures thereby reducing the chances of cracking, frost heaving or needle ice formation in cold climates. The latter aid the compaction of soil as well. The penetration of plant roots into fractures and fissures can also bring about mass movement. As these roots gradually grow and expand in these spaces within a body of rock, they can force the detachment of parts of the rock and lead to a rockfall event. On the other hand, however, roots can also bind or stabilise rock material by fixing loose particles in place against other more stable rocks (Panizza, 1996).

The vegetation cover is a slope stability factor where the human influence is of particular importance (Goudie, 1995). In the case of Chapman's Peak, this influence expressed itself in the form of wildfires during January 2000. Evans (1980) suggests that there is a relationship between runoff and erosion and the amount of bare ground within an area. The relationship is a positive one with both increasing as the proportion of bare ground increases. In fact, in one particular study (Martinez-Mena *et al.*, 2000), the energy available for erosion by runoff decreased by 75 percent and that available for rainfall by 50 percent, for a plot still possessing its natural vegetative cover when compared to a neighbouring plot whose vegetation had been manually removed. Runoff is also related to the amount of plant cover by way of the fact that slopes with large amounts of plant cover will have increased organic fractions thus raising infiltration capacities (Rowland, 1993 [in Holland, 2000]). In the Western Cape high infiltration rates are associated with high vegetation density. This results in saturation and pore-water pressure build-up during the winter season leading to slope failure occuring mostly towards the end of the winter season and under high, rather than low levels of vegetation cover (Boelhouwers *pers. comm.*). These high infiltration capacities decrease the amount of overland flow possible and will therefore decrease erosion resulting from this agent. With the relationship that exists between mass movement and erosion, with erosive forces acting over a period of time often being a trigger mechanism for mass movement, knowing what factors influence the amount of erosion possible is important in understanding where and when mass movement can happen. The relationship between vegetation and slope stability is discussed in more detail by Gray and Leiser (1982), Greenway (1987) and Yim *et al.* (1988), who provide a specific case study.

3.5.4 Geology and nature of the slope material

Knowledge of the local geology of the area is very important when attempting to analyse slopes and their problems as in most cases it has great influence on the manner in which a slope will behave. According to Selby (1993), the stability of a rock hillslope is subject to the angle at which partings within the underlying geology dip, with respect to the angle of that hillslope, rather than the intact strength of the body of rock being the dominant factor controlling failure. With the presence of these partings within the slopes of Chapman's Peak indicated during the engineering geological assessment, the geology and nature of slope material could prove a very important controlling factor of rockfall there.

Simply measuring intact rock strength will not provide an adequate representation of a rock's ability to withstand erosion and a subsequent mass movement event. A number of other factors require investigation as well. The following example elaborates on this idea. A solid mass of rock possessing a high level of intact strength may be very resistant to the agents of erosion. On the other hand, a body of rock having high intact strength, but which is highly shattered, can easily erode because in this case each smaller piece of rock erodes individually. This happens even though the smaller pieces have the same high intact strength as the original mass. Therefore, it is important to include all factors tending to influence rock strength both positively as well as negatively (Selby, 1993).

Many rock mass strength classifications have been devised for engineers. Examples of these are given in Muller (1958), Pacher (1958), Deere and Miller (1966), Piteau (1971, 1973), Wickham *et al.* (1972) and Bieniawski (1973, 1989).

The following are the parameters most commonly used for classification purposes (Selby, 1993):

a) Intact rock strength;
b) State of weathering;
c) The spacing of faults, joints, bedding planes, foliations or other partings;
d) Orientation of these with respect to a cut slope;
e) Width of bedding planes, joints as well as any other partings;
f) Lateral or vertical continuity of these partings;
g) The existence of infill or gouge material within the partings;
h) Water movement both internally as well as escaping from the rock.

These eight parameters have been assimilated into a single classification by Selby (1980) with the intention that they be utilized, by geomorphologists, for field studies of intact rock mass strength. For further explanation and discussion on the above parameters, consult Selby (1993).

Moon (1984) investigated the role played by rock mass strength characteristics in influencing the form of the Cape Fold Mountains. Within these mountains, structural controls seemed to dominate the development of rock slope forms. Moon (1984) attempted to determine whether this was in fact the case or whether the strength of the rock masses on which they were formed or the dominance of denudational processes had the greatest influence on slope form. This was achieved through the investigation of the rock mass strength characteristics of the region. Moon (1984) made use of the Selby (1980) technique of rock mass strength classification as explained above. It was found that, in general, landscapes of the Cape Mountains reflect the controls exerted on their development by structure, surface processes and the characteristics of the surface material. The existence of strength equilibrium forms in an area where the dominance of structural control could be expected lent further support to previously published assertions on the widespread occurrence of forms developed in relation to rock strength control. On strength equilibrium slopes it was found that variability of form was determined by variations in intact rock strength and joint spacing. Roughness of spacings was also found to be an important control of the stability and forms of slopes on dipping strata, not only where joints were oriented favourably but also on dip slope forms. Denudational slope forms were also found that point to past periods during which surface processes dominated over structural and strength controls.

Moon *et al.* (2001) applied three published rock mass classification systems (RMR, SMR, RMS) to weak Waikato Coal Measure mudrocks. They found that, under certain conditions, the contribution of intact rock mass strength was greatly overestimated, thereby indirectly supporting the view of Selby (1993) that this is only one of a number of factors important in initiating landslide activity.

In a study of landslide activity in the Du Toits Kloof in the Western Cape Mountains, South Africa, Gupta (2001) found that the number of landslides, occuring within his study area, related directly to the different lithologies underlying their initial point of failure. The presence of major shear zones also influenced the distribution of landslide events. The investigation established a positive relationship between the number of landslides within an area and the distance of that area from a major shear zone.

3.5.5 Trigger events

A combination of factors is usually responsible for triggering mass movement or slope failure events. For example, a moderate-size earthquake may not bring about the failure of a slope under normal conditions, but when a similar intensity earthquake takes place in an area underlain by sensitive soils (those that lose their shear strength when their internal structures are disturbed) a mass movement event might take place. Another example could be a slope, destabilised to some extent by construction, but that would not fail under normal conditions. A particularly intense rainfall event in that area could trigger a mass movement/slope failure event. The most common trigger mechanisms, according to Murck *et al.* (1997), are changes in the hydrologic characteristics of an area, volcanic eruptions, slope modifications and earthquakes. The most pertinent of these to this study are the changes in hydrologic characteristics and slope modifications as neither any volcanic eruptions or earthquakes have occurred, during the study period, within a proximity that could have any influence on the study area. The last recorded volcanic activity to take place within the western Cape area originated within the proximity of Tulbagh during 1969 (Boelhouwers, 1993). The impacts of volcanic eruptions and earthquakes although not important within the time scale of this study are important when considering impacts on a geological time scale and could prove important as long-term considerations and for the purposes of this study, they will not be discussed further. However, the vibrations caused by traffic as vehicles move along the Drive could possibly influence the stability of slope material on Chapman's Peak.

a) Changes in hydrologic characteristics

Particularly intense or prolonged rainfall can alter the drainage patterns and amount of subsurface water within a body of slope material and cause the saturation of this slope material. As discussed earlier, increasing quantities of moisture within slope material can lead to instability and possible mass movement/slope failure events. This holds true for both soils and rock material on slopes with the risk of mass movement changing as the drainage and subsurface water characteristics change. Polemio and Sdao (1999) investigated the role of rainfall in landslides in the Southern Apennines, Italy. They made use of a hydrological and statistical model based on a long-term series of daily rainfall data. Their aim was to discover what rainfall duration is most critical in triggering landslide activity. A precipitation threshold was generalised through the definition of some probability classes of cumulative rainfall. These classes pointed towards thresholds beyond which the reactivation of landslides was likely to occur. They identified cumulative rainfall events lasting between 10 and 90 days as the types most likely to affect slope stability in that area.

Dai and Lee (2001), investigating both frequency-volume relationships and the prediction of rainfall-induced landslides in Hong Kong, found that landslides, having failure volumes greater than $4m^3$, have cumulative frequency-size distributions with a power-law dependence on the volume of failure. They also found that when correlating the amount of rain that fell with the number of landslides that occurred, it became clear that 12-hour continuous rainfall was the most important category in predicting the number of landslides that took place. However, when the failure volume of landslides increased, the most important rainfall event variable began to vary between the shorter duration (12-h rolling rainfall) type event and that of relatively long duration (24-h rolling rainfall).

Römkens *et al.* (2002) investigated the changes in soil erosion under different rainfall intensities, surface roughness conditions and soil water regimes. They found that a sequence of rainstorms of decreasing intensity, on an initially air-dry smooth soil surface, caused more soil loss than a sequence of similar storms of increasing intensity. They also found that initially smooth, uniform soil surfaces yield less soil than initially rough surfaces and that subsurface soil water pressure affected sediment concentrations in runoff but had only a marginal influence on runoff amounts. As the agents of erosion can often play a role in the initialisation of mass movement events, how they react to changes in soil moisture conditions is also important to consider.

With the changes in drainage and subsurface water characteristics, because of the wildfires on Chapman's Peak alluded to in Chapter One, this factor should be afforded due consideration in this study.

b) Slope modifications

The modification of slopes, either naturally or because of human intervention, can lead to rockfalls/landslides in that area. When roads are cut into regolith or unstable rock material, the risk of occurrence of rotational landslides increases. This risk increases significantly in cases when the new slope created exceeds the angle of repose possible for that particular type of slope material or where natural planes of weakness become exposed (Panizza, 1996). This type of mass movement event is especially common along roads cut into mountainous and coastal cliffs composed of deformed sedimentary and/or metamorphic rocks (Murck *et al.*, 1997).

Gupta (2001) discovered that 35% of landslides occuring within his study area took place beside road cuts, implying that the presence of road cuts was a dominant factor causing landslide activity in that area. With all the criteria necessary for the triggering of landslides seemingly (Murck *et al.*, 1997) present on Chapman's Peak, it seems that this type of trigger mechanism is likely to be highly influential in determining the frequency and location of such landslide activity within the study area of this dissertation.

c) Vibration effects

Vibration effects generated by vehicular traffic along the Chapman's Peak Drive could possibly influence the stability of slope material on Chapman's Peak. Generally vibrations occur in urban areas and can be caused by pile driving, traffic, heavy machinery or the passing of trains. Soil and rocks are subjected not only to static loads, for example gravity, but to dynamic loads in the appearance of vibrations as well. If these vibrations are sufficiently strong they can cause damage. Vibration effects may not cause the immediate release of slope material but their cumulative impact over time could be aggravating the problems of slope stability on Chapman's Peak. A review of researches on ground-borne vibrations induced by traffic loads is presented by Hung and Yang (2001). Historically, many different approaches have been adopted in analysing traffic-induced vibrations. These included analytical approaches, field measurements, empirical prediction formulas, and numerical simulations. In their discussion, Hung and Yang (2001) separate the relevant literature into these four major categories and review them accordingly. In particular, remarks are made regarding the development of techniques for wave isolation.

3.6 Summary

This Chapter has introduced the reader to some of the processes and consequences of mass movement and overland flow events on hillslopes, (with greater focus placed on rock hillslopes and their processes) and the various trigger mechanisms of these slope processes. The discussion in Chapter Six and Seven should be considered against the theoretical background presented in this Chapter.

CHAPTER FOUR

RESEARCH METHODOLOGY

4.1 Introduction and Research Design

In the previous chapter, mass movement theory related to this investigation was reviewed and discussed. In this chapter the various research methods utilised are discussed. The research methodology employed was chosen for its ability to deliver information that could be used in the realisation of the previously described research objectives.

In terms of this study's objectives (Chapter One), a brief research design is provided. Firstly, it was decided that a deductive investigation method be used whereby a tentative hypothesis, concerning the attribute or problem, is formulated. Inferences arising from that hypothesis can then be tested with actual findings in the field. Following a morphometric approach to the investigation, observations are used to establish fundamental empirical associations between divergent features of the landscape. With these associations identified, this study sought to establish association and correlation between certain variables, implementing an empirical approach, as suggested by Reynhardt (1980). By doing this, any subsequent data processing is made far easier.

To facilitate a comprehensive investigation of conditions of slope and slope failure on Chapman's Peak it was necessary to monitor slope activity over at least two rainfall seasons. This was because, with the wildfires of January having removed the protective layer of vegetation from the slopes of Chapman's Peak, simply monitoring the area over a short time period would not have given any indication of conditions usually occuring there when vegetation is present (Plate 4.1). By monitoring during the second rainfall season, once much of the vegetation had regrown, later comparison between these two slope conditions would be possible. Due to the extensive destruction of vegetation on Chapman's Peak by the wildfires of 2000, it was not possible to compare burnt and unburnt slope areas. However, by monitoring the slopes both without and with some vegetation cover it would be possible to identify both short and long term problems as concerns rockfall and sediment movement on Chapman's Peak. The actual rock barring activities themselves took a lot longer than initially predicted, thereby reducing the available fieldwork time for investigation during the first rainfall season since access to the

Plate 4.1: Indicates the degree to which slopes on Chapman's Peak had been burnt during the wildfires of 2000 (5/3/2000).

appropriate slope was prohibited at this time (Plate 4.2). This meant that no monitoring was possible during the first half of the winter of 2000 and made it necessary for further observations during the first half of winter 2001. Slope process monitoring was also interrupted during 2000 because of these access restrictions, resulting in a gap of just over a month between the first and second recorded dates of collection of rockfall, rainfall and sediment data. This however did not have a particularly strong negative impact on the effectiveness of the study as it facilitated the comparison between a slope denuded of its vegetation cover (Plate 4.3) and the same slope with some degree of revegetation later (Plate 4.4). Eight sediment traps were employed in the capture of slopewash erosion on the barred and unbarred slopes. These were left in place until one of the eight had filled to maximum capacity, until the winter rainfall season had ended or, as on the last occasion, the traps needed to be removed due to time constraints. The time between the traps' placement on the slope and their removal, for whichever reason, was termed a period and these periods are used as mechanisms for the grouping of trapped sediment data in this study.

Plate 4.2: Access restrictions that led to the delay and interruption of monitoring on site (5/3/2000).

The collection of fallen clasts along the part of the study called Chapman's Peak Drive (as opposed to the barred and unbarred slopes) was only possible during the second rainfall season. Although it would have been preferable for this to have been done over both seasons, during the first, Chapman's Peak drive had been left buried beneath slope material, released during slope failure and rock-barring activities (Plate 4.5). This made it impossible to distinguish between what had already fallen and freshly released slope material. Fortunately, this material was removed from the drive at the beginning of the rainfall season of 2001. With the collection of fallen slope material required on a regular basis, this activity frequently coincided with rainfall events. Conditions at the base of the barred and unbarred slopes were fairly safe but there existed a real physical danger along Chapman's Peak Drive during rainy and windy conditions and it was decided, therefore, to halt investigations along this section following the second round of clast collections (Plates 4.6 A and B). Only clasts longer than 10cm along their longest axis were collected and recorded because, with the focus of this investigation being the danger to

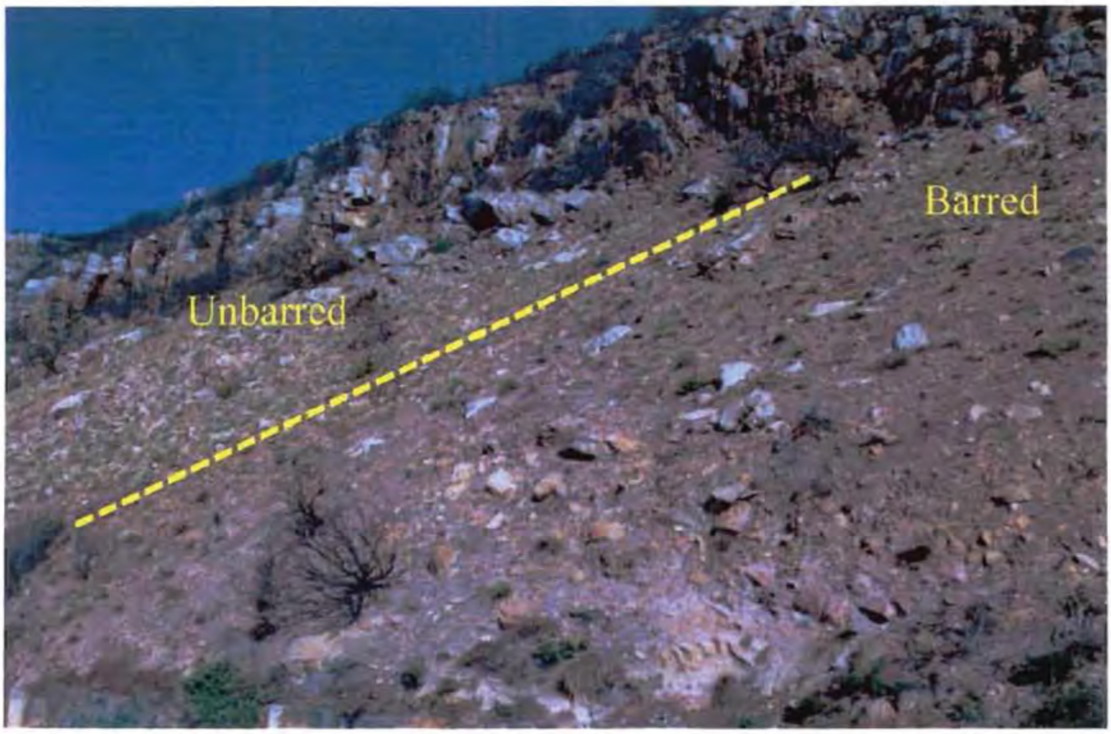


Plate 4.3: Barred and unbarred slopes at the beginning of the study period. The striped line indicates the boundary between the two (20/7/2000).

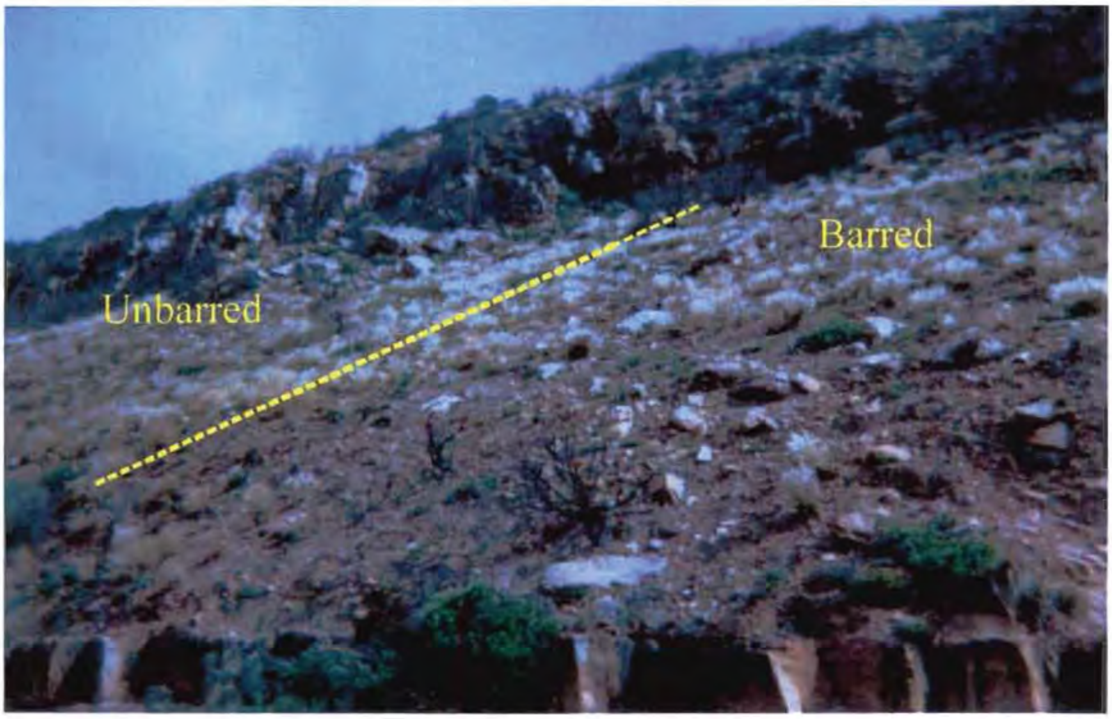


Plate 4.4: Barred and unbarred slopes at the end of winter 2000. The striped line indicates the boundary between the two (25/10/2000).

Human traffic along Chapman's Peak Drive, as represented by the movement of slope material onto the Drive, clasts smaller than these were insignificant as they were unlikely to be problematic in terms of vehicular or personal access. A limitation of measuring fallen clasts, at the base of a particular slope, lies in their fragmentation as they collide with the road's surface. As this happens, the clasts are often broken into smaller pieces and therefore give an inaccurate reflection of the size of clasts that had originally fallen from the slope above. This was more of a limitation when collecting clasts that had fallen from the cliffs and road cuttings along the Chapman's Peak Drive section of this study. When clasts fell from the barred and unbarred slopes, the distance that they fell was usually insufficient to cause their fragmentation and therefore this factor is not considered as having a negative influence on the accuracy of the study that took place within that area.

Plate 4.5: Barring activities released large amounts of slope material onto Chapman's Peak Drive making the identification of material falling after these activities had ceased very difficult. The arrow, indicating the road-side barrier, gives some indication to the depth of material left on the surface of the Drive (5/3/2000).

A range of methodologies for monitoring slope processes has been outlined by Young (1972), Young *et* al. (1974), Gardiner and Dackombe (1983), Cooke and Doornkamp (1990), Goudie

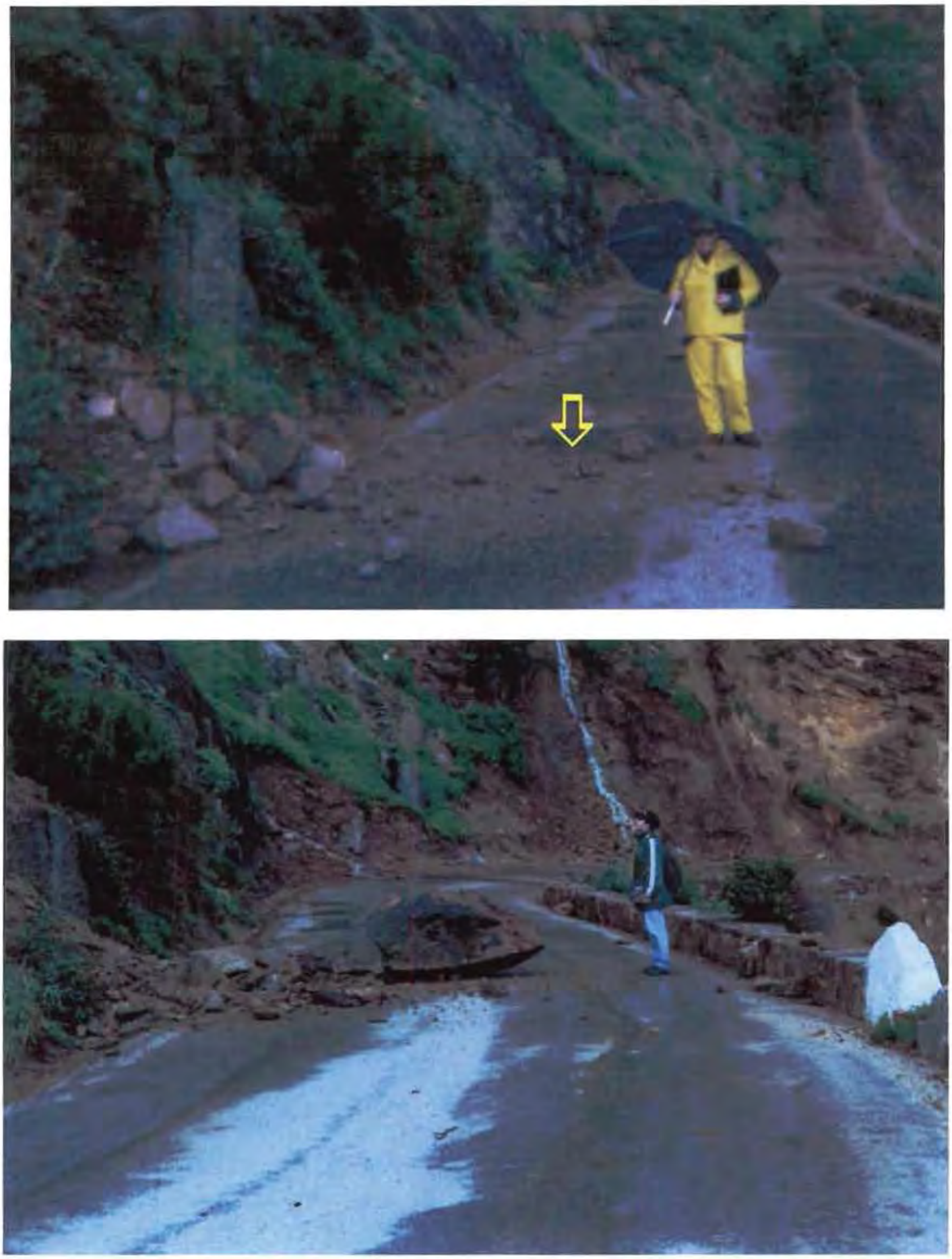


Plate 4.6: A (Top): Day 2 of monitoring and only a few smaller clasts along the Drive (30/6/2001).
B (Bottom): Day 3 of monitoring and a very large boulder now lies in the position shown by the yellow arrow in 6 A (4/7/2001).

(1990, 1995). The methods selected for this study, described below, were chosen as part of this research strategy because they effectively targeted those parameters thought of as important indicators of the problems being experienced along Chapman's Peak Drive. Sediment traps were used as indicators of erosion on slopes, rather than erosion pins, as traps give an easily quantifiable amount of actual slope material being eroded, from a larger area, whereas pins will only give an indication of changes on a much smaller scale. The movement of clasts along the barred and unbarred slopes were thought important as this would help in establishing the origin of clasts falling to the Drive at the base of either slope. Zero or negligible clast movement within a demarcated area may indicate that clasts were not moving downslope and, accordingly, not falling. Due to the inaccessibility of large areas of Chapman's Peak, making gound-truthing very difficult, it was necessary to make use of remote sensing techniques for the gathering of much of the information regarding slope characteristics. Orthophotos and oblique photographs of the area were used in this regard. Finally, the various statistical analyses were chosen for their collective ability to identify trends and relationships within the data collected, making it possible to recognise variables important in bringing about the hazardous conditions currently experienced along Chapman's Peak Drive.

Four main divisions exist within this chapter:

1) The discussion of methods utilised to gather clast and sediment data.
2) The description of laboratory procedures performed in determining the granular composition and basic chemical analysis of sediment samples collected. Included is the determination of the mass of the trapped sediments.
3) Oblique photography and orthophoto analysis of the study area.
4) The statistical analysis of data, gathered during steps (1), (2) and (3), in order to identify possible inter-variable relationships.

4.2 Field Methods

Field methods are largely based on the principles outlined by Gardiner and Dackombe (1983). Slope profiles as well surface soil and rock movements on both the barred and unbarred slope were investigated. Clasts yielded by the slopes above the various road cuttings along the stretch of road below Chapman's Peak were collected as well. Fallen clast data from along Chapman's Peak Drive was also obtained from the company responsible for the rock barring activities.

4.2.1 Slope profile measurements

Two adjacent slope sections, a barred and unbarred, were investigated (Plate 4.3). Their slope angles were calculated with the use of an Abney level, a tape measure and a ranging rod as described by Goudie (1990). As the slopes were comparatively uniform along their width, only one representative profile measurement was calculated for each slope.

4.2.2 Surface-water flow erosion

Employing sediment traps as a means of measuring erosion by flowing water on slopes is widely practised. This type of experiment involves the digging of a box into the slope, with its top flush with the ground's surface, catching any overland flow and most of its entrained sediment. The Gerlach trough (Gerlach, 1967) was designed specifically for this purpose (Figure 4.1). To ensure that only surface-water flow erosion is caught in the traps, and that no splashed material is collected, a lid for the box is necessary. Also necessary, are drainage holes, to allow the escape of excess water. This prohibits the trap from overflowing which would result in the loss of the finer entrained materials.

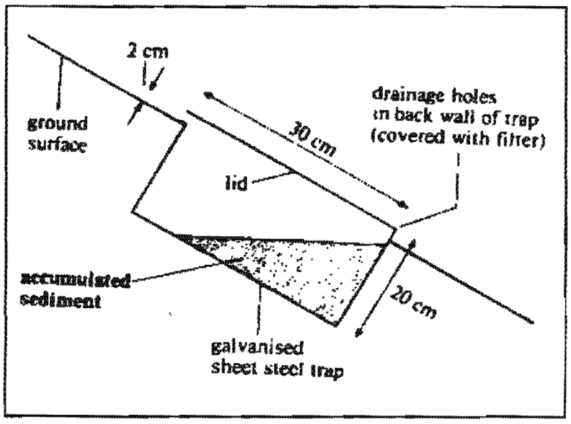


Figure 4.1: A sediment trap to measure surface-water flow erosion (Gerlach, 1967).

For the purposes of this part of the investigation, modified Gerlach troughs were created from oil tins measuring 30cm, 20cm and 15cm along their respective axes. Eight of these modified troughs were constructed in total. The tins were cut open along one of their sides (Plate 4.7), as per the method described by Reynhardt (1979), creating an entrance point for sediment to enter the trap. This left the upper part of the tin intact as a lid prohibiting the collection of splashed material. The traps were dug into the ground with the uplslope lip of the openings aligned flush with the ground surface and care was taken not to disturb the area of slope above each trap. In so doing any overland flow moving down the slope toward the sediment trap is captured, in the process also capturing any entrained sediment. By leaving the spouts of each oil tin open, water is allowed to escape thereby preventing the trap from overflowing also preventing the loss of finer grain sized particles.

Plate 4.7: Modified Gerlach trap used in this study.

Four traps (1 – 4) were dug into the barred slope and another four (5 – 8) in the unbarred slope. Since the barred and unbarred slopes were adjacent, they share a common boundary which was in fact perpendicular to the section of Chapman's Peak Drive below them, creating a reference point from which measuring could be done accurately. From a point 10m above the foot of the slope, along this common boundary, the slope positions for each of the sediment traps was calculated moving horizontally, first in one direction and then the other, from the original point along the common boundary. A 10m horizontal interval was left between each trap position.

The traps were inspected regularly during rainfall periods. Once one of the eight traps filled to maximum capacity all were removed and their contents cleared. The time, which passed between the placement and removal of the traps, was recorded as a rainfall period. Each was subsequently replaced into its original position, once again ensuring that the minimum amount of disturbance of the slope area above each trap took place. This was done during the latter stages of the winter season of the year 2000 (August until October) and the earlier stages of the winter of 2001 (May until July).

4.2.3 Collection of rainfall data

A standard manual rain gauge (Plate 4.8), positioned on the slope into which the sediment traps were dug, captured this data. Rainfall readings were taken as close to 08h00 as possible in the morning if rainfall had occurred during the previous 24 hours. This is why the rainfall event dates in the tables in Chapter Five (Tables 5.1 and 5.2) record two dates for a single event as it was impossible to identify whether the rain had in fact fallen during the first date shown, the early hours of the following morning or both.

Plate 4.8: The standard manual rain gauge used in this study (2/8/2000).

4.2.4 Collection of fallen clasts

Clasts moving off the slope and onto the road surface were collected and their longest-axis measurements recorded in an attempt to monitor surface clast movement on the barred and unbarred slopes. The clasts were collected along two sections of Chapman's Peak Drive, each measuring 40m in length, one along the base of the barred and the other along the base of the unbarred slope. It was decided to only record rocks greater than or equal to 10cm along their longest axis. This size rock possesses the potential to do significant damage to either a person or vehicle once it had fallen the distance between the edge of the slope, at the top of the road cutting, and the road. Smaller clasts were therefore excluded from this study.

During the winter of 2001, once the road had been cleared of fallen debris, it was possible to measure the long-axes of fallen clasts along Chapman's Peak Drive from the Lookout all the way South to the Noordhoek side (Figure 2.1). This is the section of road, along which the previously mentioned deaths occurred. It also has the drive's highest slopes, reaching a maximum height of 440m above the Drive, above it.

4.2.5 Clast data from MJ Mountain and Partners

MJ Mountain and Partners recorded the size and number of clasts that had fallen onto Chapman's Peak Drive on 8 February 2000. That data was graciously made available for use in this study and is subsequently presented in Chapter 5.

4.2.6 Marking of clasts and monitoring of their movement

In order to achieve this objective it was decided to implement the following experiment. A plot of three metres squared was pegged on both the barred and unbarred slopes. These plots were positioned centrally, in both vertical and horizontal dimensions, on both slopes and as such were further upslope than the sediment traps. A wire barricade was placed along the downslope edge of each plot to trap any shifting clasts. Clasts within the plots having long-axes measuring 10cm

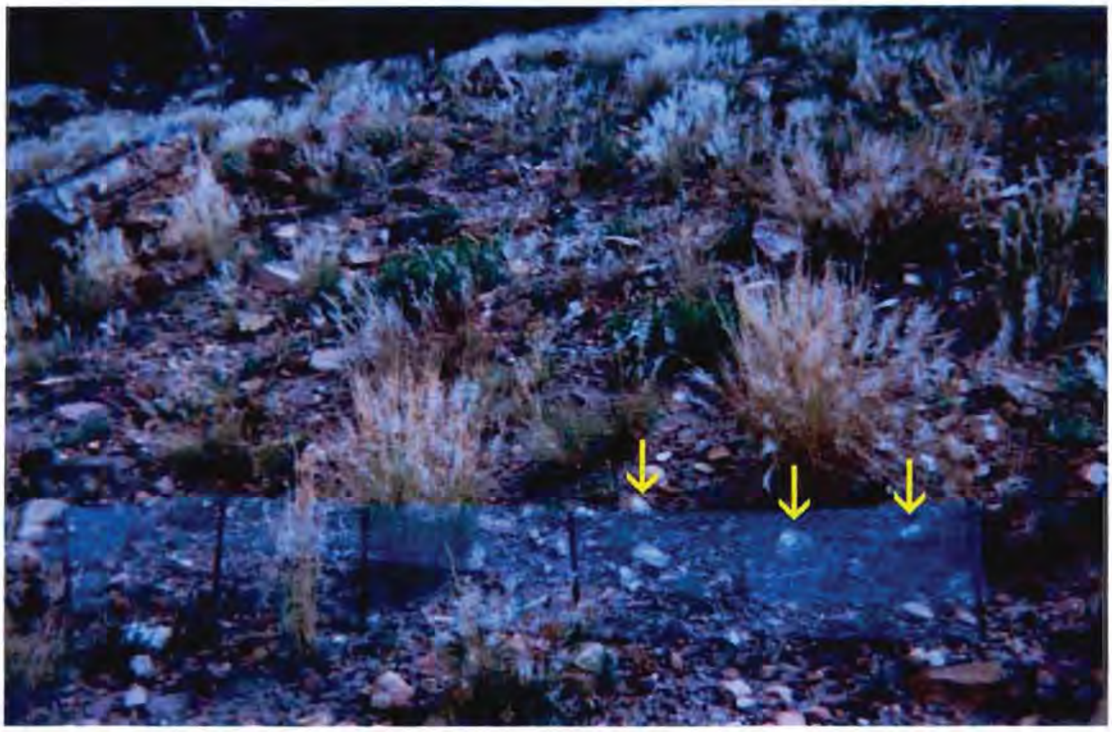


Plate 4.9: Plot on the barred slope used to measure the movement of clasts. Arrows show examples of marked clasts (25/10/2000).

or more were marked and their positions recorded (Plate 4.9). These plots were then inspected after each rainfall event in order to ascertain a rate of downslope movement.

4.3 Laboratory Methods

4.3.1 Granular composition analysis

A granular composition analysis, performed on two sets of four grab samples, one set taken from each of the two slopes under investigation, was undertook in an attempt to gain insight as to the physical characteristics of the sediments present on the slopes. These grab samples were collected from positions half a metre below each sediment trap.

A further granular composition analysis of materials was performed on sediments captured in one of the traps (Trap 3). This would enable a comparison of the physical characteristics of sediments, for example organic content and grain size distribution, between materials captured during the different rainfall periods. The decision was made to only investigate the sediments from one of the traps because it was felt that changes experienced by all the traps would be similar as local conditions were the same for all. Therefore, the shifts in these characteristics in one case would be indicative of the group as a whole. It was also decided that the biggest changes might be experienced between sediments captured during the first, second and fourth rainfall periods and therefore only these were investigated.

The eight grab samples taken, all of mass 100g, were passed through a 2mm sieve in order to separate the fine fraction ($\leq -1\phi/2000\mu m$) from the coarser fraction ($> -1\phi/2000\mu m$) (McManus, 1988). This was also done for the three samples captured in sediment trap 3 during rainfall periods one, two and four.

The finer fraction of each sample was oven dried for 24 hours at a temperature of 45^0C. In order to obtain the sand fraction ($\geq 4\phi/63\mu m$) for analysis in a settling column decantation, sieving and washing through a 0.0625mm sieve was undertaken. These new sub-samples were then placed once more into the oven and dried for 24 hours at a temperature of 45^0C as the sand fraction requires drying before use in the settling column for that apparatus to perform effectively (Tucker, 1988).

Once the sub-samples had dried they were processed through a splitter to ensure a random sample with 3g of material taken from each and individually analysed using a computerized settling column apparatus (Figure 4.2) (Tucker, 1988). This is done in order to ascertain the percentages of fine, medium and coarse sand present using the principle that sediment settling out of suspension at different velocities correlates directly to the grain size of the particles. This is based on Stokes Law of settling:

$$\text{Stokes Law:} \quad V = 1/18 * \{(\rho_s - \rho_f)gd^2\} / \mu$$

Where:

V = Settling velocity of particle

ρ_s = Density of particle

ρ_f = Density of fluid

μ = Dynamic viscosity of fluid

g = Gravitational constraint

d = Particle diameter

By means of the settling column analysis (Leeder, 1989), it was possible to generate the following Folk and Ward (1957) statistical parameters:

- Mean – the average grain size of the sediment sample.
- Median – the grain size for which half of the particles (by weight) are coarser and half are finer.
- Sorting – a measure of the sorting or uniformity of the sample.
- Skewness – a measure of the asymmetry of the distribution of the sample.
- Kurtosis – a measure of the peakedness or flatness of the distribution curve.

Folk and Ward (1957) first described these moment statistics. They developed equations on log-normal distributions representative of these parameters for grain size distribution within a sample. Using these parameters (mean, median, sorting, skewness and kurtosis) above a good idea of distribution in grain sizes amongst sand fraction samples can be calculated.

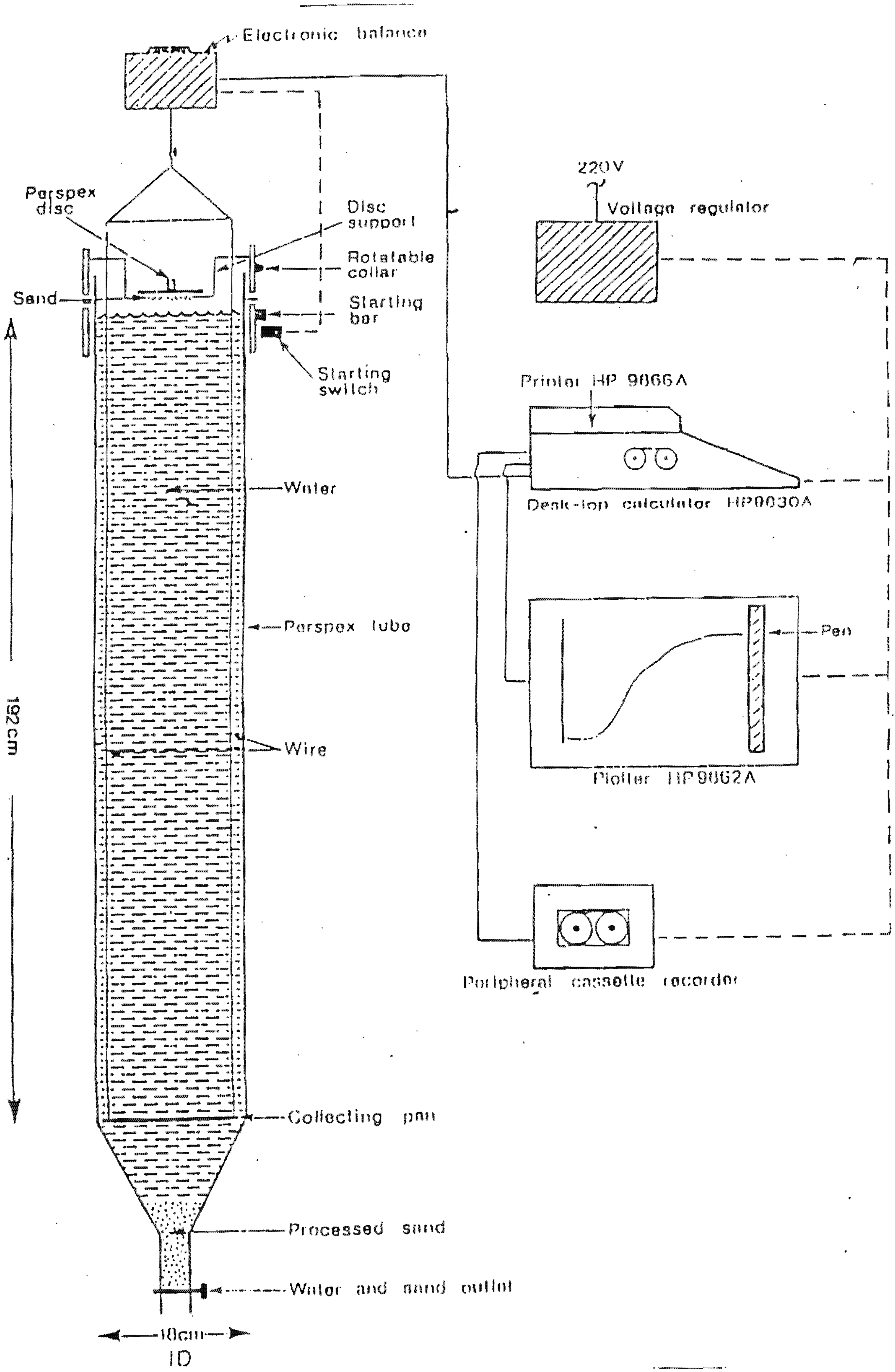


Figure 4.2: Configuration of the settling column.

provided an oblique view of Chapman's Peak. The orthophoto map of the study area, obtained from the Chief Director of Surveys and Mapping, was also used for further analysis. The orthophoto map used was 3418 AB 8 Chapman's Peak and had a scale of 1:10 000.

4.4.1 Oblique view photographic analysis

Two sets of oblique view photographs of Chapman's Peak were used as a base for the first part of this analysis. One of these sets was taken during November 1999, before the fires, and another in March 2000, after the fires of January 2000. From them MJ Mountain and Partners produced an A3 size digitised oblique view of the peak. Using this digitised view of the mountainside above Chapman's Peak Drive the area covered by vegetation for both the pre- and post-fire sets of photographs were identified. Their respective positions and extents were traced onto an overlay in each case. This was undertaken in an attempt to identify to what extent the fires destroyed the protective vegetation cover of the section of Chapman's Peak above the drive.

The overlays produced were then placed over a standard sheet of graph paper. All those blocks above the road and below the water divide of Chapman's Peak, and that were half or more filled by a part of Chapman's Peak, from the image on top, were counted to produce a figure for the total area of Chapman's Peak above the drive. To then calculate the percentage of vegetation cover on Chapman's Peak destroyed by the fires of 2000, the overlays constructed from the oblique photographs, taken before and after the fires, were placed over a standard sheet of graph paper. All blocks on the sheet of graph paper, at least half filled by vegetation cover on the overlay, were then counted to obtain a total for both before (Appendix A) and after the fires (Appendix B). The difference between these two figures would then give an indication of the extent of destruction imposed by the fires on the vegetation cover of Chapman's Peak.

A bare rock index was also produced using these same overlays. At each sample point/road cutting on the post-fire overlay a line was drawn perpendicular to Chapman's Peak Drive up the face of the slope of Chapman's Peak. If no vegetation was present along this perpendicular line, drawn up the slope, then an index value of one was assigned to that sample point. The presence of vegetation above any sample point decreased the index value for that point resulting in a figure of less than one. The results produced were used in the multivariate statistical analysis.

MJ Mountain and Partners also supplied a digitised oblique view of Chapman's Peak, showing where clearing/barring activities had been undertaken. The degree of clearing/barring performed was also included on this digitised image.

4.4.2 Orthophoto map

The 1:10 000 orthophoto map 3418 AB 8 Chapman's Peak was used to generate data such as distances from the road to the crest of the slope above or the respective extents of the different lithologies of which Chapman's Peak is composed.

An index, to be used in the statistical analysis, was developed from this data. The thickness of the Graafwater Formation (Gfm) at each sample point was taken as having the value one. The Peninsula Formation (Pfm) was then assigned a corresponding value dependant on its extent in relation to that of the Gfm. This index was titled a shale band index to be used for the multivariate statistical analysis.

4.5 Statistical Methods

In order to identify significant relationships between the different variables investigated, a statistical analysis of the data gathered from both the barred an unbarred study slopes as well as that from the rest of the Drive, was undertaken. Calculation of the correlation coefficient, r, was recognized as an effective manner of achieving this goal and this statistical technique is discussed here. Further multivariate statistical techniques were also employed namely Principal Component Analysis (PCA) and cluster analysis. The correlation matrices, PCA and cluster analysis were undertaken using the statistical package *Statistica* (2002 edition). These particular forms of analyses were selected for their ability to provide information that will be important in identifying components responsible for rockfalls along Chapman's Peak Drive.

4.5.1 Correlation matrices

A correlation matrix analysis is an effective tool for determining relationships between the different variables. For that reason this type of analysis was in the investigation of field data collected from the barred and unbarred slopes. The Pearson product-moment correlation coefficient (r), or simply the correlation coefficient, is a dimensionless value referring specifically to linear correlation, making comparisons between sets of observations or different pairs of variables possible (Webster and Oliver, 2001). For procedure see practical examples in Till (1974) and Marsal (1987). A correlation coefficient measures relationships between variables and can range in value from 1 to –1. If the units of both variables being compared are large then $r > 0$ and the variables are positively correlated. However, when the units of the variables vary in opposite directions (one increases while the other decreases) then a negative correlation exists with $r < 0$. No linear correlation exists when $r = 0$ (Webster and Oliver, 2001).

4.5.2 Standardisation

This process converts the attributes of the original data set to new unitless attributes thereby enabling the comparison of variables with different units (Davis, 1986). Before performing the PCA and cluster analysis the fallen clast and slope indices data from the larger section of this study's area, termed Chapman's Peak Drive, first had to be standardised. This was accomplished using the standard *Statistica* procedure for standardisation. This produces a new data set with a mean of 0 and a standard deviation of 1 for each variable (Holmes, 1998). This removes the scale attributes of the original data set and therefore no single variable is weighted at the expense of another and allows data sets with very different scales to be compared effectively (B. Hewitson, *pers. comm.*).

4.5.3 Principal component analysis

This form of multivariate analysis is the most widely used by earth scientists (Davis, 1986). It is purely exploratory or inductive in nature aiming to "describe the variation of the *n* individuals in *p*-dimensional space in terms of a set of uncorrelated variables which are linear combinations of the original variables" (Everitt and Dunn, 1983, p. 39). PCA can be used to clarify relationships within a complex set of observed measurements (Till, 1974). The new variables deduced by the PCA are identified in decreasing order of importance with the first accounting for as much of the variation in the original data set as possible. This is a fine instrument for pinpointing order or patterns within a data set and for this reason it was chosen as an analysis tool of the combined fallen clast and slope characteristic data from the longer Chapman's Peak Drive section of this study. If most of the variation in the original data set can be accounted for using only the first few components produced by the PCA then it can be argued that little information will be lost if only these few are used in summarizing the data thereby decreasing the number of variables to be studied (Johnston, 1978). Everitt and Dunn (1983) believe that the ability of a PCA to accomplish this reduction in dimensionality enables a simplification of any further analysis.

The components or eigenvectors produced are the new factors and the component loadings are the inter-correlated variables and components (Davis, 1986). The total variance accounted for in a component is termed the eigenvalue (Davis, 1986). Through the examination of component loadings and eigenvalues linear relationships or patterns within a data set can be identified. Component loadings can also be rotated further highlighting important variables and reducing noise within the data set more.

4.5.4 Cluster analysis

Single-linkage clustering and Ward's Minimum Variance clustering methods were utilized for the analysis of the combined fallen clast and slope characteristic data from the longer Chapman's Peak Drive section of this study. Single-linkage clustering was chosen for its capacity to recognize outliers and Ward's method for its ability to recognize groups (B. Hewitson, *pers. comm.*) both of which are important in identifying active rockfall areas along Chapman's Peak Drive. Because of the ability of a PCA to reduce noise within a data set it was decided to perform both these clustering methods on the PCA results obtained as well as on the standardized raw data.

Cluster analysis attempts to find groupings of phenomena in parameter space by computing "distances" between observations (B. Hewitson, *pers. comm.*). There is no one correct classification of the data. Different numerical strategies will often produce different results (Williams and Lance, 1977). Although this type of analysis originated in biological taxonomy, it is generally applicable to all types of data (Hartigan, 1975). A cluster analysis attempts to separate a set of objects into constituent groups (classes, clumps, clusters) in such a way that members of any particular group differ as little as possible from each other, according to a chosen criterion (Spath, 1980). This allows relationships within groups to be identified (Davis, 1986). Romesburg (1984) describes the necessary procedures to be implemented when undertaking a hierarchical cluster analysis.

4.6 Summary

This chapter has reviewed the design, methods and procedures utilised in this dissertation. The field-work and laboratory analysis that took place, as well the use of oblique photographs and orthophotographs was discussed. Also presented was a comprehensive description of the statistical methods used. The following chapter offers a discussion of the findings established through the use of the various methodologies of this chapter.

CHAPTER FIVE

ANALYTICAL RESULTS

5.1 Introduction

This chapter presents the results obtained during the investigations described in the previous chapter. The slope profiles of the study area are presented first. Following this the fallen clast data from the unbarred slope, barred slope and then for Chapman's Peak Drive (from the Lookout to its most Southerly point) along with the associated rainfall data is provided. The results of slope clast movement investigations on the barred and unbarred slopes are then presented. Sediment yields are presented, followed by the results of the granular composition analysis. The final part of this chapter introduces the results of the various statistical analyses undertaken.

5.2 Slope Profiles

A mean slope angle of 32° was measured for both the barred and unbarred slopes investigated, therefore allowing this variable to be considered a constant for subsequent comparisons.

5.3 Fallen Clast Data

The following data are presented by way of a table. Table 5.1 presents fallen clast data from the barred and unbarred slopes investigated and Table 5.2 those for Chapman's Peak Drive (as described in Chapter Four). Relevant points emerging from the data are subsequently elaborated upon.

The measure of the longest axis of each clast is really a measure of clast size due to the fact that most clasts collected had shapes which were relatively spherical with a = b = c approximately (where a, b and c represent the various axes of each clast). Taking this fact into consideration it was decided that clasts could therefore be referred to in terms of size relative to each other (bigger, smaller and so on) based on a measurement of their longest-axis.

5.3.1 Unbarred and barred slopes

Dates	Rainfall (mm)	Unbarred Slope			Barred Slope		
		Number of Clasts	Mean clast length (cm)	Range in clast lengths (cm)	Number of Clasts	Mean clast length (cm)	Range in clast lengths (cm)
Year 2000 1-2/08/2000	9	15	11.46	14.5 - 10 = 4.5	34	12.35	21.5 - 10 =11.5
2-3/09/2000	6	1	11.50	0	12	13.82	21 - 10 = 11
12-13/09/2000	2.5	0	0	0	1	10.50	0
13-14/09/2000	5	0	0	0	1	10.00	0
16-17/09/2000	10	1	11.00	0	4	11.13	12.5 - 10 = 2.5
23-24/09/2000	10	2	24.50	31.5 - 14.5 = 14	2	12.75	15.5 - 10 = 5.5
24-25/09/2000	2	0	0	0	2	13.25	14.5 - 12 = 2.5
25-26/09/2000	5	5	12.30	17 - 10 = 7	7	12.07	15.5 - 10 = 5.5
30/09/2000 -							
01/10/00	8	0	0	0	4	15.63	19 - 11.5 = 7.5
09-10/10/2000	2	1	13.00	0	5	12.60	18 - 10 = 8
23-24/10/2000	2	1	10.00	0	11	13.00	17.5 - 10 = 7.5
Year 2001 24-25/05/2001	24	27	19.22	65 - 10 = 55	9	15.00	22 - 10 = 12
25-26/05/2001	15	5	12.80	15 - 11 = 4	8	12.13	21 - 10 = 11
31/05/2001 -							
01/06/2001	8	1	13.00	0	4	12.75	14 - 11 = 3
27-28/06/2001	23	2	23.00	25 - 21 = 4	6	15.16	18 - 13 = 5
2-3/07/2001	>50	17	21.18	56 - 14 = 42	3	17.00	24 - 10 = 14
4-5/07/2001	24	4	15.00	16 - 14 = 2	1	13.00	0
5-6/07/2001	7	2	30.00	35 - 25 = 10	3	14.00	17 - 10 = 7

Table 5.1: Rainfall and clast data for the barred and unbarred slopes.

Two separate relationships are discussed in the ensuing three paragraphs. Firstly the relationship between the number of clasts yielded and rainfall is shown and this is followed by comments on the relationship between clast length (size) and rainfall in the second and third paragraphs.

Referring to Table 5.1 a difference in the number of fallen clasts from each slope can be seen for the first recorded rainfall event of 9mm. On this occasion, the barred slope yielded more than twice as many as the unbarred. The trend of greater or equal numbers of clasts, falling from the barred slope, continued for the rest of the winter of 2000. At the beginning of the winter of 2001 this trend seemed to reverse with three times as many clasts yielded by the unbarred slope during the first recorded rainfall event. For the majority of the remaining rainfall events the barred slope once again yielded a greater number of clasts thereby reverting back to the original trend. However, it must be noted that the number of clasts measuring longer than 50mm, collected after the highest recorded rainfall event (2-3/07/2001), was in fact much greater for the unbarred slope with the figure being almost six times greater than that for the barred slope. During the winter of 2000 it can be seen that on four occasions no clasts fell from the unbarred slope whereas clasts were found at the base of the barred slope on every occasion. During the winter of the following year there was not a single occasion on which no clasts were found at the base of either slope.

In Table 5.1 it is apparent that whenever clasts were yielded by both slopes (as a result of the same rainfall event) during the winter of 2000 their respective mean longest-axes measured seemed to be relatively similar. There is, however, one exception. This occurred as a result of the rainfall event of 23-24/09/2000 with the mean value of the clasts' long-axes measured being almost twice as large for the unbarred slope. On eight of the eleven occasions on which clasts were collected during 2000 the mean lengths were longer for the barred slope.

During the winter of 2001, however, the mean clast longest-axes measured after each rainfall event were greater for those clasts collected at the base of the unbarred slope. The difference was more noticeable on two occasions. The first of these was subsequent to the rainfall event of 27-28/06/2001 when the mean length of those clasts yielded by the unbarred slope was slightly greater than one and a half times that of those from the barred. On the second occasion the mean length was more than twice as great for those clasts collected at the base of the unbarred slope. Therefore it can be seen that on all three occasions when noticeable disparities occurred between the mean longest-axes lengths of the clasts collected after individual rainfall events the mean was always greater for those originating from the unbarred slope.

With the limited number of clasts collected after each rainfall event, it was decided that instead of using standard deviation as an analytical tool, the calculation of the range in sizes encountered would prove more effective. Included in this column was the size of the largest and smallest clasts collected for each event. These figures were included so as to allow the reader to identify where the largest clasts were in fact falling. As can be seen in the columns listing ranges of clast longest-axes lengths in Table 5.1, during the winter of 2000 the longest clast retrieved from the base of the unbarred slope measured 31.5cm in length meaning it was 10cm longer than the longest from the base of the barred slope. During the winter of 2001 however there proved to be a greater difference of 41cm between the longest clasts found with a clast of 65cm gathered from the base of the unbarred slope being the longest. Also, the four longest clasts shown in the above table are all from the unbarred slope. These have a mean longest-axis length of 45.25cm while the longest four from the barred slope have a mean of 21.25cm showing a difference of 24cm.

5.3.2 Chapman's Peak Drive

From Table 5.2 it can be seen that the first rainfall event precipitated less than half that of the second. After this first event clasts were found at the base of six of the 25 road cuttings monitored while subsequent to event two clasts were found beneath nine of the road cuttings. A noticeable feature is that clasts did not fall from all the same cuttings during event two as they did during the first. Cuttings number 12 and 13 yielded clasts only during event one while cuttings 1, 5, 23, 24 and 25 only as a result of the second. Of the cuttings from which clasts fell during both events, more clasts were collected after the second event in all instances. In fact, a total of 62 clasts were collected after the first event and 195 after the second. This shows a mean number of fallen rocks of approximately 10 per road cutting for the first rainfall event and approximately 21 for the second indicating that approximately double the number fell.

However, the mean size (mean clast longest axis measurement) of yielded clasts, for those four cuttings that yielded clasts during both rainfall events, were in fact larger as a result of

Date	Rainfall (mm)	Cutting Number	Number of Fallen Clasts	Mean Long-axis Measurement (cm)	Range of Long-axis Measurements (cm)
29-30/06/2001	23	1	0	0	0
		2	0	0	0
		3	0	0	0
		4	16	29.44	45 - 21 = 24
		5	0	0	0
		6	0	0	0
		7	0	0	0
		8	0	0	0
		9	0	0	0
		10	0	0	0
		11	0	0	0
		12	12	23.92	32 - 16 = 16
		13	9	23.22	41 - 16 = 25
		14	1	41.00	0
		15	8	29.75	49 - 16 = 33
		16	16	29.44	45 - 20 = 25
		17	0	0	0
		18	0	0	0
		19	0	0	0
		20	0	0	0
		21	0	0	0
		22	0	0	0
		23	0	0	0
		24	0	0	0
		25	0	0	0
3-4/07/2001	>50	1	39	26.64	66 - 15 = 51
		2	0	0	0
		3	0	0	0
		4	22	21.82	58 - 13 = 45
		5	24	22.54	48 - 14 = 34
		6	0	0	0
		7	0	0	0
		8	0	0	0
		9	0	0	0
		10	0	0	0
		11	0	0	0
		12	0	0	0
		13	0	0	0
		14	13	40.38	73 - 26 = 47
		15	30	37.90	205 - 15 = 190
		16	38	37.39	80 - 19 = 61
		17	0	0	0
		18	0	0	0
		19	0	0	0
		20	0	0	0
		21	0	0	0
		22	0	0	0
		23	5	41.80	75 - 15 = 60
		24	9	31.66	43 - 20 = 23
		25	15	31.93	57 - 20 = 37

Table 5.2: Rainfall and clast data for Chapman's Peak Drive

the first rainfall event for two of the four cases. At these locations though it is important to note that the larger clasts gauged fell after the second event in all four cases as can be seen when studying the column which portrays the range of long-axis measurements in Table 5.2.

The largest clast collected after the first rainfall event measured 49cm and that collected after the second event 205cm along their respective longest axes. In fact, each individual road cutting except two (namely cuttings 5 and 24) actually had a greater longest axis measured after event 2 than the longest measured axis for all the cuttings (49cm) after the first event. The range in sizes is also greater with increased rainfall having taken place. A mean range size (excluding cuttings not yielding clasts) of 60.89cm was calculated for the second event and only 24.60cm for the first with the maximum range gauged at 190cm from clasts yielded by cutting 15 after the second rainfall event.

5.3.3 MJ Mountain and Partners fallen clast data

The company responsible for the rock barring activities on Chapman's Peak monitored the number of clasts that fell onto Chapman's Peak Drive's surface on the 8 February 2000. The results of this undertaking can be seen in Table 5.3. It should be noted that road cuttings 23 to 25 were not monitored on this occasion.

Table 5.3 indicates that clasts were collected at the bases of cuttings 1 through 9 on this occasion. These clasts seem to have been mostly smaller than 20cm along their longest axes. Cuttings 1 and 9 however produced larger clasts measuring between 30 and 40 cm in length. Cuttings 12, 13, 15 and 16 all yielded clasts showing some similarity to the data collected after the recorded rainfall events of this study. The data from these four road cuttings produced similar findings with three of the four yielding clasts with a longest axis measurement of 25cm and the other a maximum length of 15cm.

Date	Cutting Number	Clast lengths (cm)
08/02/2000	1	<5<40
	2	5 - 10
	3	soil - <15
	4	soil - >10<15
	5	soil - 20
	6	<10
	7	soil - <10
	8	<10
	9	>10 - 30
	10	
	11	
	12	20 - 25
	13	soil - 15
	14	
	15	soil - 25
	16	soil - 25
	17	
	18	
	19	
	20	
	21	
	22	
	23	not monitored
	24	not monitored
	25	not monitored

Table 5.3: Clasts yielded by Chapman's Peak (MJ Mountain and Partners, 2000).

5.4 Slope Clast Movement

Slope clast movement experiments were undertaken on two separate three metre square areas. One of these was situated on the barred slope and the other on the unbarred slope (as described in Chapter three). No clast movement was recorded within these areas on either the barred or unbarred slopes after any of the rainfall events during the study period.

5.5 Sediment Yields From Study Slopes

As discussed in the previous chapter, the time that passed between the placement of the traps into the slope surface, and their subsequent removal, was recorded as a rainfall period. The reasons for the their particular time of removal from the slope was discussed in the research design of this dissertation.

Period	Total Rainfall	Trap Number	Trapped sediment mass (g)
1 (1/2 August 2000)	9mm	1	Approx. 3300 (Full)
		2	Approx. 3300 (Full)
		3	Approx. 3300 (Full)
		4	Approx. 3300 (Full)
		5	Approx. 3300 (Full)
		6	Approx. 3300 (Full)
		7	Approx. 3300 (Full)
		8	Approx. 3300 (Full)
2 (3 September - 24 October 2000)	60.5mm	1	203.12
		2	727.60
		3	667.67
		4	186.59
		5	502.24
		6	433.38
		7	226.30
		8	583.76
3 (19 - 26 May 2001)	50mm	1	214.79
		2	2043.21
		3	144.21
		4	Approx. 3300 (Full)
		5	174.92
		6	50.25
		7	421.74
		8	317.37
4 (1 June - 6 July)	138mm	1	219.98
		2	469.20
		3	102.65
		4	905.07
		5	93.41
		6	116.70
		7	616.30
		8	289.41

Table 5.4: Trapped sediment masses on the barred (traps 1 to 4) and unbarred (traps 5 to 8) slopes.

During the first recorded period, which lasted from 1-2nd August 2000, 9mm of rainfall were precipitated. This resulted in the overfilling of all eight sediment traps on both the barred and unbarred slopes as can be seen in Figure 5.1. Consequently they were all recorded in Table 5.4 as full.

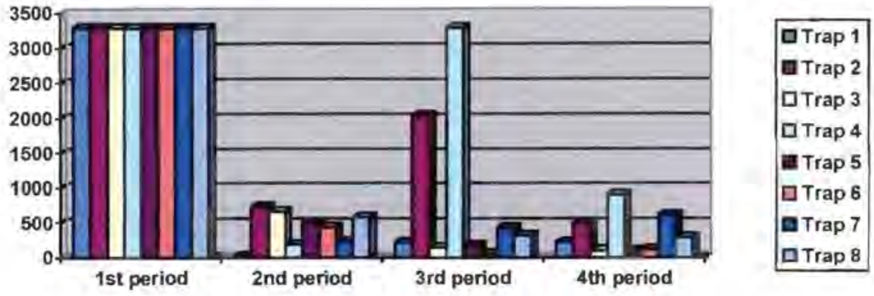


Figure 5.1: Comparative sediment masses caught in traps 1 to 8.

The next period over which rainfall was recorded was substantially longer. This lasted from 3 September 2000 until 24 October 2000. A total of 60.5mm of rainfall was recorded for this time. This was a considerably higher rainfall figure than for period one. The highest recorded rainfall event during this time was measured at 10mm. This in fact occurred on two occasions. There was also a third event measured at 8mm. Even with these events taking place no traps were filled during the second time period. In fact the greatest mass gauged for any of the traps was 727.60g indicating that the trap had effectively only captured 22.12% of its maximum capacity. This sediment was captured in trap two on the barred slope. Total sediment yields for the individual slopes indicated that only slightly more had been captured on the barred slope during this period.

Period 3 exposed the slopes to 50mm of rainfall between 19 May and 26 May 2001. This fell during three rainfall events, the greatest measuring 24mm, almost half of the total. Trap 4 was filled completely while trap 2 was filled to 62.12% of its maximum capacity. On the other hand, the trap most filled on the unbarred slope was only filled to 12.82% of its maximum capacity. This meant that there was considerably less sediment captured from the unbarred slope.

During period 4 more than 50mm was precipitated during a single rainfall event with a total of 138mm falling between 1 June and 6 July 2001. The trap with the greatest amount of sediment caught was situated on the barred slope. This was trap 4 and it was filled to 27.52% of its total capacity. Total sediment captured for the individual slopes was found to be 52.08% greater from the barred slope.

From the data in Table 5.4 it is also evident that, while a great deal less rain fell during the first monitored periods for each winter when compared to the second, sediment traps only filled to maximum capacity during the first rainfall periods. Also, considerably less rainfall was required to completely fill the traps during period 1 than any of the other periods. Period 1 was the only to have all traps completely filled. Period 3 showed great disparity when comparing yields from the two slopes, with the barred slope producing considerably more, while during periods 2 and 4 the traps in place captured similar amounts of sediment from the barred and unbarred slopes.

5.6 Granular Composition Analysis

5.6.1 Textural classes

As can be seen in Table 5.5 the sand sized fraction dominates the samples in all cases. For this reason it was decided to undertake a settling column analysis of the sand fraction as opposed to using other methods (Figure 5.2). These sand percentages range from a maximum of 82.96% to the lowest figure of 63.11%. This minimum figure from sample 2 is the only one which gives the sand fraction as being less than two thirds of the total sample mass. On all occasions, fines comprised the smallest fraction of the sample analysed with a maximum of 9.99% measured while coarse particles reached a maximum 31.49% (Sample 2).

Sample	% Coarse	% Sand	% Fines
1	20.91	69.53	9.56
2	31.49	63.11	5.40
3	20.18	69.83	9.99
4	14.37	82.85	2.78
5	11.21	81.29	7.50
6	9.03	82.96	8.01
7	25.80	67.57	6.63
8	13.63	79.15	7.23

Table 5.5: Textural classes of grab samples.

When analysed, the samples of trapped sediments from rainfall periods 1, 2 and 4 (Table 5.6) exhibited similarity with the grab samples from Table 5.1 in that they comprised primarily sand particles. The percentages of sand in the trapped samples were however much larger with the minimum measured at 92.38% of the total mass. Percentages calculated from the sediment captured during period 1 displayed a similar relationship to those from the grab samples in that the percentage coarse particles determined was greater than that of the fines.

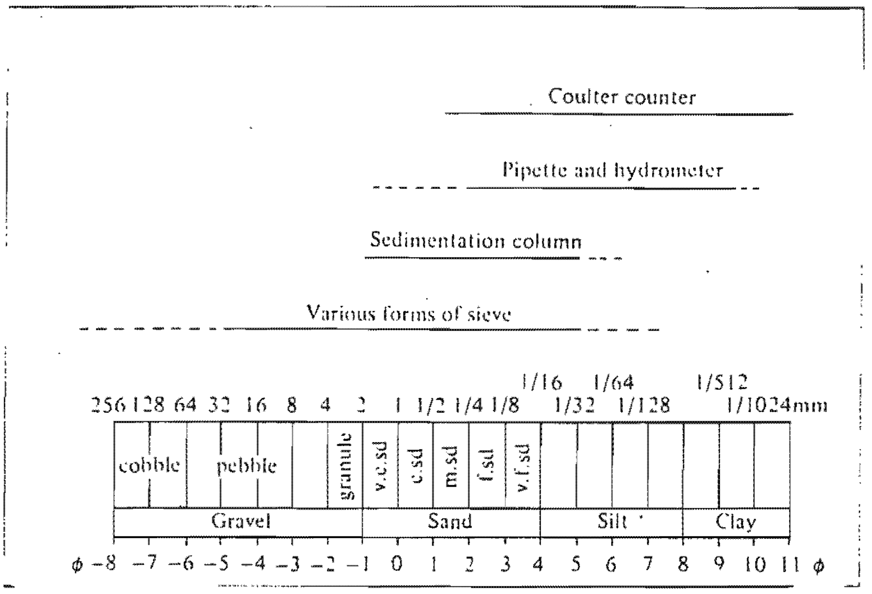


Figure 5.2: Wentworth grain-size classification, together with the range of various analysis techniques (Buller and McManus, 1979).

This relationship was however reversed during periods 2 and 4. Period 1 shows the highest percentage coarse particles and sand particles trapped for all three events.

Period	% Coarse	% Sand	% Fines	% Organics
1	4.55	93.31	2.14	3.33
2	1.54	92.47	5.99	4.67
4	2.25	92.38	5.37	4.00

Table 5.6: Textural classes of trapped samples

The highest percentage of organics was measured for the sample captured during rainfall period 2. This analysis was performed on three, three gram sub-samples independent of the those analysed to produce the other data for Table 5.6.

5.6.2 Settling column results

The results of the settling column analysis described in Chapter Three are presented in Table 5.7 and Table 5.8. Table 5.7 shows the results derived from the analysis of the eight grab samples (as described in Chapter Four) and Table 5.8 those from the three samples of trapped sediments.

Sample	Mean ϕ	Median ϕ	Sorting	Skewness	Kurtosis
1	2.41	2.43	0.83	-0.08	1.22
2	2.27	2.29	0.78	-0.06	1.18
3	2.39	2.39	0.71	-0.03	1.19
4	2.14	2.16	0.78	-0.06	1.22
5	2.33	2.33	0.75	-0.03	1.16
6	2.27	2.27	0.70	-0.01	1.21
7	2.27	2.26	0.71	0.02	1.18
8	2.28	2.25	0.71	0.06	1.25

Table 5.7: Descriptive statistics for the sand fraction of grab samples.

The mean size value measured for all eight grab samples ranged from 2.14 ϕ to 2.41 ϕ. This indicated that the mean grain particle size classified, according to the Wentworth size class scale, is fine sand. The median particle sizes also fell within the Wentworth size class boundaries of 2.0 ϕ to 3.0 ϕ for fine sand suggesting that these samples be classified as such.

The column in Table 5.7 presenting figures for sorting, a measure of the range of grain sizes present and the magnitude of the spread or scatter of these sizes around the mean size (Boggs, 1995), shows values ranging from a minimum of 0.70 to a maximum of 0.83. Four of the samples are moderately sorted (Folk and Ward, 1957). Three of the remaining four have a sorting value which places them on the boundary between samples classified as being moderately sorted or moderately well sorted. Sample 6 is classed as being moderately well sorted but is only 0.1 ϕ above this boundary.

Figures from Table 5.7 show skewness characteristics, a measure of the asymmetry of the distribution of the sample, indicating all samples have distributions that are near symmetrical (classified according to Boggs, 1995). Various degrees of peakedness or sharpness are shown by grain-size frequency curves. This degree of sharpness is known as kurtosis and it is usually calculated along with the other grain-size parameters. According to Boggs (1995) however the geological significance of this parameter is not known. He states further that it seems to lend little assistance in the interpretation of grain-size data. Therefore the figures for this parameter, produced during the settling column analysis, are not discussed further.

Period	Mean ϕ	Median ϕ	Sorting	Skewness	Kurtosis
1	2.09	2.09	0.67	-0.04	1.28
2	2.15	2.16	0.69	-0.01	1.20
4	2.15	2.14	0.71	0.03	1.21

Table 5.8: Descriptive statistics for the sand fraction of trapped samples.

Table 5.8 indicates the trapped samples from all three periods as falling within the boundaries denoted for fine sand (Wentworth size class) when considering the data for both the mean and median. The data indicates a slight decrease in mean particle size when comparing period 1 to both period 2 and 4.

The sample analysed from period 4 falls on the boundary between moderately and moderately well sorted while the other two samples are classifiable as the latter. The sediment captured during period 1 is shown as the best sorted of the three.

The frequency curves for the samples from all three periods fall within the category near symmetrical. There is a trend though of slight differences in skewness between the periods. Period 1 is the coarsest skewed, period 2 slightly less and period 4 is actually slightly fine skewed. The implications of these findings will be discussed in Chapter Six.

5.7 Oblique View Photographic and Orthophotographic Analysis

5.7.1 Identification of Burnt Slopes

This analysis was performed as per the description in Chapter Four and produced the following results:

1. Percentage Exposed Cliffs (pre-fire) = 39.86%
2. Percentage Vegetated Area (pre-fire) = 60.14%
3. Percentage Vegetated Area (post-fire) = 10.31%
4. Percentage Chapman's Peak as a whole burnt (post-fire) = 49.83%
5. Percentage of Previously Vegetated Areas now Burnt = 82.86%

This indicates that almost 50% of the total surface area of Chapman's Peak was left as burnt slopes as a result of the fires of January 2000. Also important to note is the figure portraying the percentage of previously vegetated areas now burnt which shows that 82.86% of the protective layer of vegetation which existed before the fires swept through had been removed.

5.7.2 Degree of clearing/barring performed

Appendix C shows these worked areas and the various coloured shadings denote the degree of clearing achieved in that particular area. This information is summarised in Table 5.9.

When an area is described in Table 5.9 as being partially cleared it means that between 30-70% of suspected unstable material in that area was removed by rock fragments falling during clearing of another area further upslope. An area described as slightly cleared means that less than 30% of suspected unstable material in that area was removed by falling rock fragments. The areas described as possibly more dangerous have been expressed as such because fallen rock material, having collided with that section of slope, might possibly have reduced slope stability in those areas, thereby increasing the risk of future rock falls.

Cutting Number	Degree of Rock Barring Undertaken
1	Totally cleared (TC)
2	Slightly cleared (SC) - TC top third
3	Partly cleared (PC) - TC top third
4	PC - TC top fifth (at crest)
5	None
6	None
7	None
8	Possibly more dangerous (PMD)
9	PMD
10	PMD
11	SC
12	SC
13	Bottom sixth = N; Cliffs = PC; Top third = TC
14	Bottom sixth = SC; Cliffs = PC; Top third = TC
15	Bottom sixth = SC; Cliffs = PC; Top third = TC
16	PMD
17	PMD
18	None
19	Bottom (most) = N; Small top section = TC
20	Bottom (most) = N; Small top section = TC
21	SC; Top fifth = TC
22	SC; Top fifth = TC
23	SC; Top fifth = TC
24	SC; Top fifth = TC
25	SC; Top fifth = TC

Table 5.9: Clearing (rock barring) status of the slopes above the road cuttings along Chapman's Peak Drive.

As can be seen only the slopes above road cutting 1 were classified as having been totally cleared/barred. On the other extreme of the scale no barring work was done on cuttings 5, 6, 7 and 18. Cuttings 8, 9, 10, 16 and 17 were in fact categorised as being possibly more dangerous once the barring work had ceased. All the slopes above the remaining cutting were cleared/barred to some degree. In total 13 of the 25 road cuttings had at least some part of the slopes above them classified as having been totally cleared.

5.7.3 Geology/Lithology extents

The vertical extents of the geologies/lithologies above Chapman's Peak Drive were measured from an annotated orthophoto (Appendix D) produced by MJ Mountain and Partners. The values in Table 5.10 indicate the maximum extent in metres of the respective geologies/lithologies above Chapman's Peak Drive at the same points at which fallen clasts had been collected.

Cutting Number	Graafwater Fm	Peninsula Fm
1	30	50
2	30	80
3	30	100
4	40	130
5	60	200
6	80	270
7	60	370
8	50	370
9	70	340
10	70	350
11	80	370
12	60	380
13	40	400
14	40	360
15	50	300
16	70	290
17	70	270
18	70	220
19	60	190
20	60	170

Table 5.10: Geology/Lithology Extents

The maximum extent of the Graafwater Formation (Gfm) ranged between 30m and 80m. The Peninsula Formation (Pfm) however had a much larger range with a minimum of 50m and a maximum of 400m being measured. This table also indicates that at all sample points, except number one, the Pfm is thicker. In some instances, where Chapman's Peak reaches its maximum extent, the Pfm is in fact nine to ten times thicker than the Gfm. Therefore the thickness of the Pfm at a sample point is the most important factor in determining whether a large maximum height above the drive is reached or not.

5.7.4 Slope angle and slope length

These parameters were calculated from the orthophoto using trigonometry. The results can be seen in Table 5.11.

Cutting number one had the highest calculated slope angle and the slope remains steep until cutting three with the two steepest slopes of all within this group. However, these slopes are relatively short in length when compared with those further along Chapman's Peak Drive. Therefore, they do not possess the dimensions that would enable the development of large bare cliff face areas to the extent that is possible further along the Drive. These first three

Cutting No.	Slope Angle	Slope Length
1	57.99	94.334
2	48.01	134.54
3	52.43	164.01
4	38.66	320.16
5	41.99	403.61
6	42.77	544.89
7	36.50	622.01
8	29.54	689.64
9	32.47	651.92
10	33.93	662.87
11	37.23	628.01
12	40.91	595.48
13	48.81	531.51
14	45.81	502.09
15	50.19	390.51
16	44.03	417.25
17	37.65	442.04
18	32.15	413.4
19	32.21	355.11
20	29.54	344.82

Table 5.11: Slope angles (in degrees) and lengths (metres) above Chapman's Peak Drive.

slopes comprise mostly Graafwater Formation. Observations made from the oblique photographs taken of the study area have shown that the largest cliff faces seem to only be present within the Peninsula Formation with the thicker bedding and higher resistance to erosion of its comprising rocks. The next group of steep adjacent slopes began at cutting 13 and continued until number 16.

5.8 Statistical Analysis

5.8.1 Coefficients of correlation

It is important to determine whether linear correlation for a set of data is justified. This is done by calculating the sample size (N) and then using that information in conjunction with a table showing confidence limits for correlation coefficients (r) (Table 5.12) (Marsal, 1987).

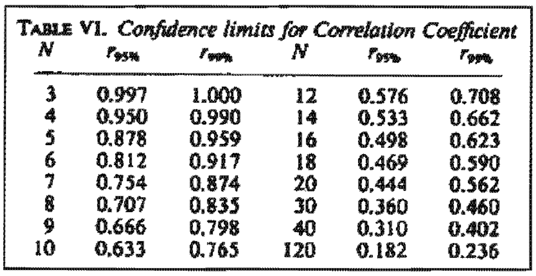


TABLE VI. *Confidence limits for Correlation Coefficient*

N	$r_{95\%}$	$r_{99\%}$	N	$r_{95\%}$	$r_{99\%}$
3	0.997	1.000	12	0.576	0.708
4	0.950	0.990	14	0.533	0.662
5	0.878	0.959	16	0.498	0.623
6	0.812	0.917	18	0.469	0.590
7	0.754	0.874	20	0.444	0.562
8	0.707	0.835	30	0.360	0.460
9	0.666	0.798	40	0.310	0.402
10	0.633	0.765	120	0.182	0.236

Table 5.12: Confidence limits for correlation coefficient (Marsal, 1987).

5.8.2 Correlation matrices

Correlation matrices were drawn up to illustrate linear relationships between the different variables identified while investigations were underway on site. The first of these is presented in Appendix E. This matrix was constructed from data collected on the two study slopes (barred and unbarred). The sample size for this matrix is N = 18 and therefore linear correlation is justified with a probability of 95% if $-0.469 > r > 0.469$ (Table 5.12). All justified coefficients within this matrix are printed bold.

Separate correlation matrices were constructed to highlight the relationships between certain variables considered more significant. These are presented in Table 5.13 to Table 5.15. Table 5.13 shows the relationship between the amount of rainfall experienced and the number of clasts that fell from the unbarred and barred slopes. The correlation coefficient (r) for the unbarred slope is justified, with a probability of 95%, and shows a positive correlation, while r for the barred slope is not justified for a probability of that percentage. It does however allude to a slight negative correlation. Therefore, there is a definite trend that when the amount of rain falling within the study area increases then the number of clasts released from the unbarred slope will increase. However, it is suggested that fewer clasts might fall from the barred slope.

	Unbarred Slope Number of clasts	**Barred Slope Number of clasts**
Rainfall	0.5488	-0.1049

Table 5.13: Correlation between rainfall and number of clasts yielded by the barred and unbarred slopes. Correlations are significant at $p < .05000$ with N=18 (Casewise deletion of missing data).

The correlation coefficients for rainfall and mean long-axis measurements of fallen clasts for the two slopes are shown in Table 5.14. Strong (justified) positive correlations are revealed in both cases indicating increased mean long-axis measurements with increased rainfall. In other words, larger clasts will fall when higher rainfall figures are experienced.

	Unbarred Slope Mean	Barred Slope Mean
Rainfall	0.72	0.70

Table 5.14: Correlation between rainfall and the mean lengths of clasts yielded by the barred and unbarred slopes. Correlations are significant at $p < .05000$ with N=18 (Casewise deletion of missing data).

When examining r in Table 5.15 it clearly shows that neither are justified with a chance of 95%. There does, however, seem to be a stronger correlation between rainfall and the range in long-axis measurements of fallen clasts from the unbarred slope than those from the barred.

	Unbarred Slope Range	Barred Slope Range
Rainfall	0.44	0.12

Table 5.15: Correlation between rainfall and range in the mean lengths of clasts yielded by the barred and unbarred slopes. Correlations are significant at $p < .05000$ with N=18 (Casewise deletion of missing data).

5.8.3 Multivariate statistical analysis

The data generated from the collection of fallen clasts from cuttings 1 to 20 along Chapman's Peak Drive (Table 5.2) was incorporated into a table along with the other values calculated for the slopes above the drive (slope angle and length, bare rock and shale band indexes) (Appendix F). The data were then standardised and a Principal Components Analysis (PCA) conducted. Ten matrices of random numbers (Appendix G), generated using *Microsoft Excel 2000*, were subjected to PCA analyses as well. These data sets were equal in dimensions to the data sets of fallen clasts from Chapman's Peak Drive. The Eigenvalues produced by the PCA analyses of these random number sets (Appendix H) were used to determine the level of confidence with which the results of the PCA analyses of the fallen clast data matrices of this study could be viewed. Single-linkage and Ward's type cluster analyses were also performed on the standardised fallen clast data.

5.8.3.1 Principal components analysis

A PCA was employed in an attempt to identify some pattern within the data set. The various cuttings at which fallen clasts were collected were set as the cases for the analysis. These were configured as rows within the data matrix. The different variables were configured as columns. Each row represents the physical characteristics of the slope above that point as well as its fallen clast data. Three matrices were constructed. The first reflects fallen clast data after the initial 23mm rainfall event. The second shows the fallen clast data after the 50mm rainfall event and the third combines the fallen clast data from both of these events. This raw data is given in Appendix I.

The PCA of the 10 random number sets produced various eigenvalues for component's 1 to 4. These were arranged in descending order (Table 5.16) in order to provide a table that would supply the various confidence limits with which the results of the PCA of fallen clast and slope characteristic data could be viewed. An eigenvalue falling between the largest and second largest Eigenvalues from the PCA of the random numbers represents a confidence level of 90%. An eigenvalue falling between the second and third highest could be viewed with a confidence level of 80% and so on (B. Hewitson *pers. comm.*).

Percentiles	Component 1	Component 2	Component 3	Component 4
100th	2.243598	1.729802	1.097767	0.975666
90th	2.234062	1.654503	1.040286	0.954092
80th	2.064461	1.548652	1.037814	0.931386
70th	2.020343	1.489537	1.033977	0.866704
60th	1.84764	1.481946	1.020365	0.788982
50th	1.84242	1.456872	0.963518	0.75046
40th	1.72149	1.439857	0.94624	0.739273
30th	1.717867	1.377965	0.928135	0.669434
20th	1.690144	1.321877	0.855434	0.652589
10th	1.648782	1.25853	0.675078	0.528498

Table 5.16: Eigenvalues of random number sets (in descending order) showing percentiles which can be used as confidence limits.

Tables 5.17 and 5.18, and Figure 5.3, represent the results of a PCA run on the first data matrix (after 23mm of rain had fallen). Component 1 has an eigenvalue that exceeds that of the largest of the eigenvalues calculated from the random number sets. This is the case for component 2 as well and therefore both results are accepted with 100% confidence. Both components 3 and 4 have eigenvalues that fall below the 20% confidence limit, indicating they are not particularly important, and will therefore be disregarded.

Value	Eigenvalue	% TotalVariance	Cumulative Eigenvalue	Cumulative %
1	2.746422	45.77370	2.746422	45.77370
2	1.820466	30.34110	4.566888	76.11480
3	0.912097	15.20162	5.478985	91.31642
4	0.263044	4.38406	5.742029	95.70048

Table 5.17: Retained principal components from PCA (unrotated) of fallen clast data after the 23mm rainfall event.

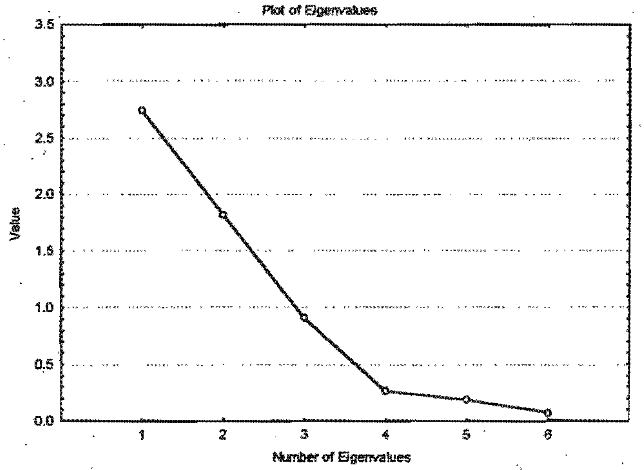


Figure 5.3: Scree plot of Eigenvalues from PCA (unrotated) of fallen clast data after the23mm rainfall event.

Variables	Component 1	Component 2	Component 3	Component 4
Bare Rock Index	**-0.844589**	-0.181135	0.307978	0.392088
Shale Band Index	-0.551678	0.674096	0.445869	-0.126169
Slope Length	0.146970	**0.959140**	0.111447	-0.003354
Slope Angle	-0.666031	-0.580260	0.327680	-0.300588
No_Fallen_Rocks	**-0.709299**	0.145644	-0.645167	-0.034039
Mean Axis Length	**-0.872033**	0.235348	-0.287077	-0.043229
Expl.Var	2.746422	1.820466	0.912097	0.263044
Prp.Totl	0.457737	0.303411	0.152016	0.043841

Table 5.18: Component loadings and explained variance from PCA (unrotated) of fallen clast data after the 23mm rainfall event.

The data highlighted in bold (in all the PCA's) indicates where loadings are greater than 0.7. In this case (Table 5.18) a strong relationship is shown between the bare rock index and both the number of fallen clasts and mean long-axis lengths of the clasts respectively. This relationship represents the first principal component (component 1) and is responsible for just under 46% of the total variance within the data set. Component 1 was interpreted as representing the degree to which the slope above a sample point was vegetated. Principal component two, accounting for just over 30% of the variance, was interpreted as reflecting the extent (thickness) of the Peninsula Formation (Pfm) exposure above Chapman's Peak Drive.

The two principal components were subjected to a non-orthogonal rotation (varimax rotation) in an attempt to further clarify component loadings (Table 5.19). The explained variance for both components, once rotated, were very similar to those from the unrotated data.

Variables	Component 1	Component 2	Component 3	Component 4
Bare Rock Index	0.264781	0.134542	0.374130	**0.875523**
Shale Band Index	0.179974	**0.931237**	0.102104	0.251899
Slope Length	-0.001062	**0.771661**	-0.572240	-0.176239
Slope Angle	0.127693	-0.039229	**0.928230**	0.313957
No_Fallen_Rocks	**0.964062**	0.002773	0.032842	0.105899
Mean Axis Length	**0.831123**	0.294272	0.189720	0.294544
Expl.Var	1.738986	1.568908	1.376542	1.057593
Prp.Totl	0.289831	0.261485	0.229424	0.176266

Table 5.19: Component loadings and explained variance from PCA (varimax rotated) of fallen clast data after 23mm rainfall event.

Noticeably, the slope angle variable is now also marked as important in the second component column, but slope length still has a greater loading. A negative correlation is indicated between slope length and slope angle.

The tables produced by the PCA of the fallen clast data after the 50mm rainfall event can be seen below. In Table 5.20 component 1 has an eigenvalue which allows this result to be viewed with a confidence level of 100%. The eigenvalue for the component 2 falls within the 90th percentile allowing a 90% confidence level with this result. The eigenvalue for component 3 places it in the 50th percentile and that of component 4 in the 10th percentile, and therefore neither is considered important for this set of data. Component 1 accounts for almost 49% of the total variance within the data set and component 2 for 27.6%.

Value	Eigenvalue	% Total Variance	Cumulative Eigenvalue	Cumulative %
1	2.934163	48.90271	2.934163	48.90271
2	1.656269	27.60449	4.590432	76.50720
3	0.978025	16.30041	5.568457	92.80761
4	0.268531	4.47551	5.836987	97.28312

Table 5.20: Retained principal components from PCA (unrotated) of fallen clast data after the 50mm rainfall event.

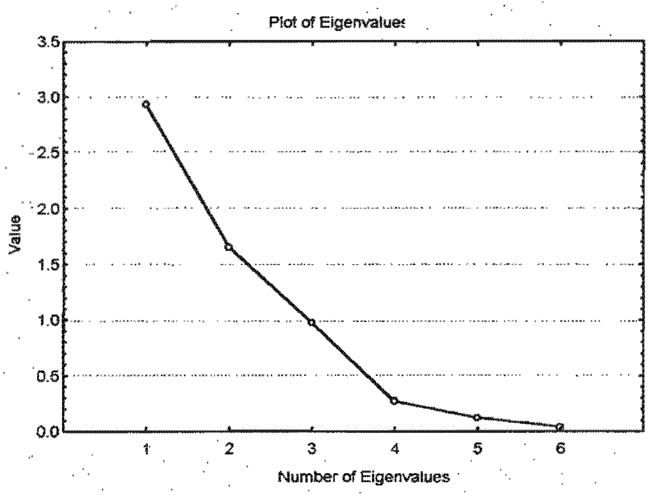


Figure 5.4: Scree plot of Eigenvalues from PCA (unrotated) of fallen clast data after the 50mm rainfall event.

The bare rock index is now no longer recognised as being statistically important with the slope angle variable taking its place (Table 5.21). Therefore, component 1 is interpreted as indicating that the existence of steep slopes above a sample point is the most important factor in determining the number and size of the clasts falling from Chapman's Peak onto the drive below. Component 2 highlights the shale band index as being important. As the thickness of the Graafwater Formation (Gfm) is a lot more constant than that of the Pfm (Table 5.10) it will mostly be because of changes in the extent/thickness of the Pfm that variation within this index will arise. Therefore, component 2 can be interpreted as the vertical extent/thickness of the Pfm.

Variables	Component 1	Component 2	Component 3	Component 4
Bare Rock Index	-0.635508	0.570974	-0.364317	0.365945
Shale Band Index	0.066442	**0.972121**	0.059925	-0.155771
Slope Length	0.654027	0.560565	0.466231	0.006800
Slope Angle	**-0.849990**	0.192080	-0.342245	-0.329033
No_Fallen_Rocks	**-0.846155**	-0.173345	0.463371	0.005681
Mean Axis Length	**-0.812197**	0.063736	0.540826	0.044823
Expl.Var	2.934163	1.656269	0.978025	0.268531
Prp.Totl	0.489027	0.276045	0.163004	0.044755

Table 5.21: Component loadings and explained variance from PCA (unrotated) of fallen clast data after the 50mm rainfall event.

Variables	Component 1	Component 2	Component 3	Component 4
Bare Rock Index	0.174898	0.143204	**0.925304**	0.298729
Shale Band Index	-0.059237	**0.933275**	0.296170	0.122724
Slope Length	-0.152340	**0.784477**	-0.206513	-0.527391
Slope Angle	0.324593	-0.038609	0.374230	**0.858996**
No_Fallen_Rocks	**0.929971**	-0.206915	0.080516	0.215939
Mean Axis Length	**0.951681**	0.022405	0.169210	0.152959
Expl.Var	1.933209	1.551721	1.161715	1.190342
Prp.Totl	0.322202	0.258620	0.193619	0.198390

Table 5.22: Component loadings and explained variance from PCA (varimax rotated) of fallen clast data after 50mm rainfall event.

When the data from the 50mm rainfall event was rotated (varimax raw) little difference could be noticed between the explained variance now shown (Table 5.22) and that from before it was rotated. This was true for both components 1 and 2.

A PCA run on the sum of the data, collected during both rainfall events, produced the following results. Once again, the eigenvalues for components 1 and 2 places them in the 100th and 90th percentiles respectively. Component 3 falls within the 20th percentile and component 4 in the 10th, illustrating their continued irrelevance. Component 1 now accounts for 49.3% and component 2 for 27.9% of the total variance within this data set (Table 5.23).

Value	Eigenvalue	% Total Variance	Cumulative Eigenvalue	Cumulative %
1	2.959141	49.31901	2.959141	49.31901
2	1.675099	27.91832	4.634240	77.23733
3	0.927683	15.46139	5.561923	92.69872
4	0.270244	4.50407	5.832167	97.20279

Table 5.23: Retained principal components from PCA (unrotated) of fallen clast data after summing the results from both rainfall events.

For component 1 (unrotated) bare rock index, slope angle, number of fallen clasts and the mean long-axis lengths are shown as having component loadings which mark them as important (Table 5.24). The larger component loading, assigned to the slope angle index, highlights its importance over the bare rock index. Component 2 specifies that the shale band index and slope length are important variables. In this case the shale band index is however, shown as being substantially more important.

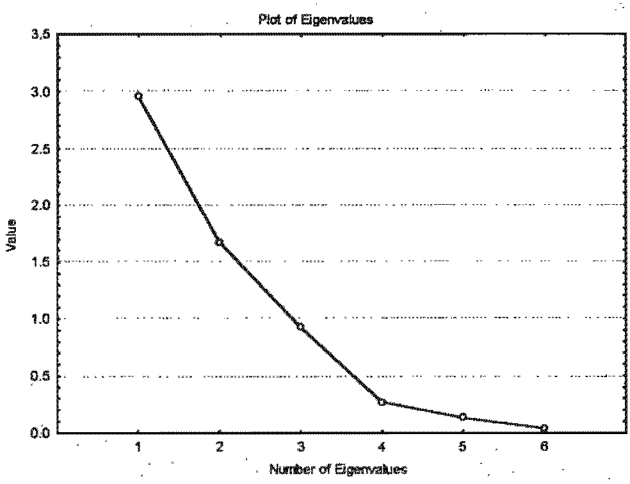


Figure 5.5: Scree plot of Eigenvalues from PCA (unrotated) of fallen clast data after summing the results from both rainfall events.

Variables	Component 1	Component 2	Component 3	Component 4
Bare Rock Index	**-0.715539**	0.416333	-0.416505	0.372435
Shale Band Index	-0.085242	**0.972298**	-0.057372	-0.154333
Slope Length	0.575938	**0.704931**	0.358484	0.017277
Slope Angle	**-0.863990**	0.018603	-0.354298	-0.322929
No_Fallen_Rocks	**-0.798084**	-0.171950	0.545204	0.055129
Mean Axis Length	**-0.851326**	0.171934	0.446800	-0.009840
Expl.Var	2.959141	1.675099	0.927683	0.270244
Prp.Totl	0.493190	0.279183	0.154614	0.045041

Table 5.24: Component loadings and explained variance from PCA (unrotated) of fallen clast data after summing the results from both rainfall events.

Variables	Component 1	Component 2	Component 3	Component 4
Bare Rock Index	0.208989	0.148408	**0.917805**	0.299075
Shale Band Index	0.006099	**0.942618**	0.281588	0.109006
Slope Length	-0.142730	**0.774105**	-0.199718	-0.545844
Slope Angle	0.328110	-0.038207	0.363836	**0.857404**
No_Fallen_Rocks	**0.948313**	-0.196532	0.087547	0.145623
Mean Axis Length	**0.909689**	0.126643	0.228758	0.241127
Expl.Var	1.898572	1.565915	1.153917	1.213764
Prp.Totl	0.316429	0.260986	0.192320	0.202294

Table 5.25: Component loadings and explained variance from PCA (varimax rotated) of fallen clast data after summing the results from both rainfall events.

The rotated loadings (varimax raw) show little difference in the total variance accounted for by the respective components (Table 5.25). The loadings highlighted in bold are also similar in size. Considering that in virtually all cases the unrotated and rotated PCA results were so similar, the decision to perform the rest of the analyses on only the unrotated PCA results was made.

5.8.3.2 Cluster analysis

Two methods of cluster analysis were performed using the standardised fallen clast data. These were single-linkage clustering, for its ability to identify outliers, and Ward's method due to its capacity to identify groups within a data set. These were chosen because of the importance of this information within the context of this study.

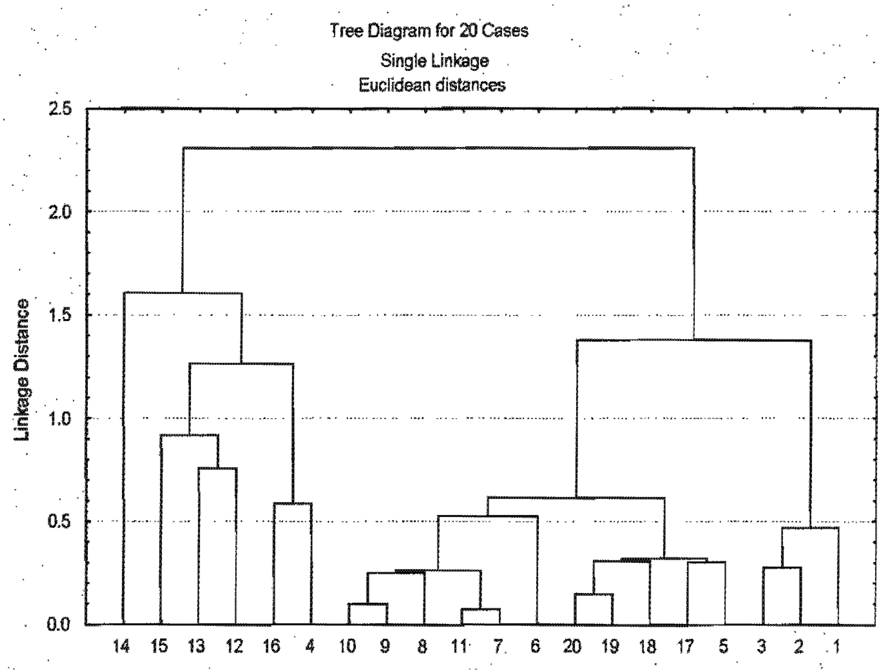


Figure 5.6: Single-linkage clustering of standardised data from 23mm rainfall event.

Single-linkage clustering identified sample point (cutting) 11 as an outlier within the data collected as a result of the 23mm rainfall event when the tree was cut at a linkage distance of 1.5 (Figure 5.6). The Ward's clustering method identifies two main groupings within this data set when cut at a linkage distance of 9 (Figure 5.7). Sample points (cuttings) 1, 11, 12, 13, 15 and 16 are grouped separately from the rest.

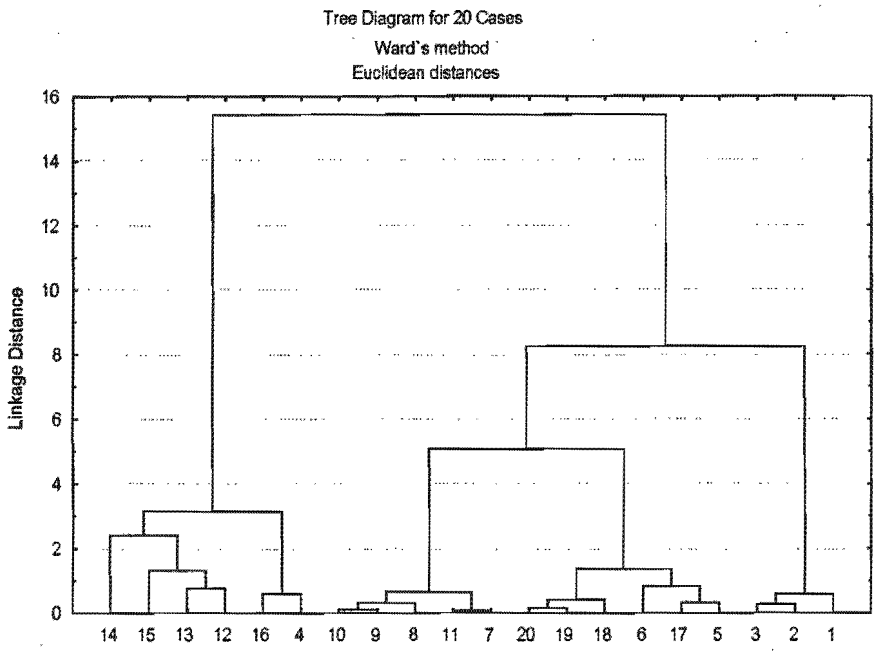


Figure 5.7: Cluster analysis of standardised data (from 23mm rainfall event) by Ward's method.

When analysing the data from the 50mm rainfall event the single-linkage type clustering analysis identified sample point (cutting) 1 as an outlier on this occasion when the tree is cut at a linkage distance of 1.5 (Figure 5.8). The Ward's method analysis once again identified two major groupings of sample points (cuttings). On this occasion the tree was cut at a linkage distance of 8. Cutttings 1, 4, 5, 14, 15 and 16 were grouped separately from the rest forming a sub-set within the greater data set (Figure 5.9).

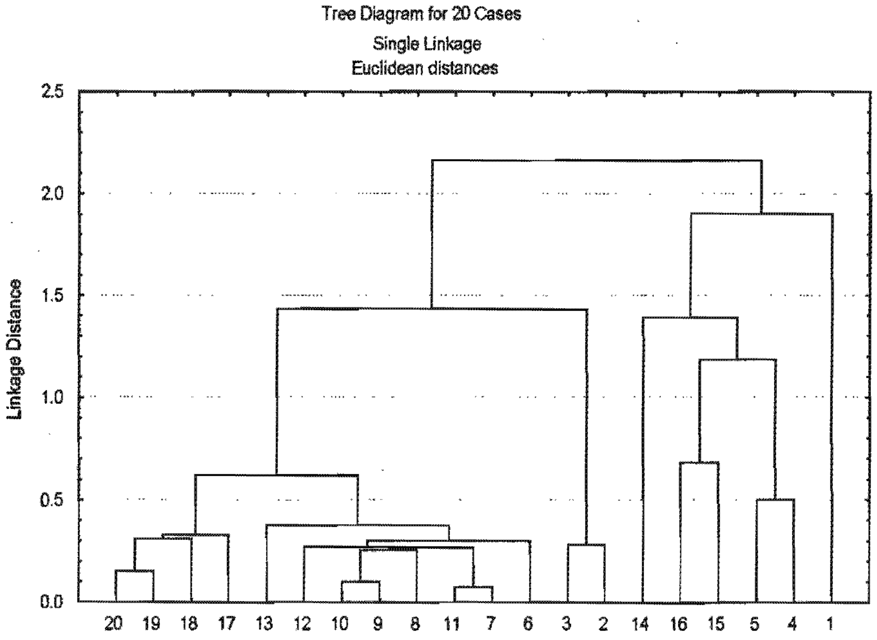


Figure 5.8: Single-linkage clustering of standardised data from 50mm rainfall event.

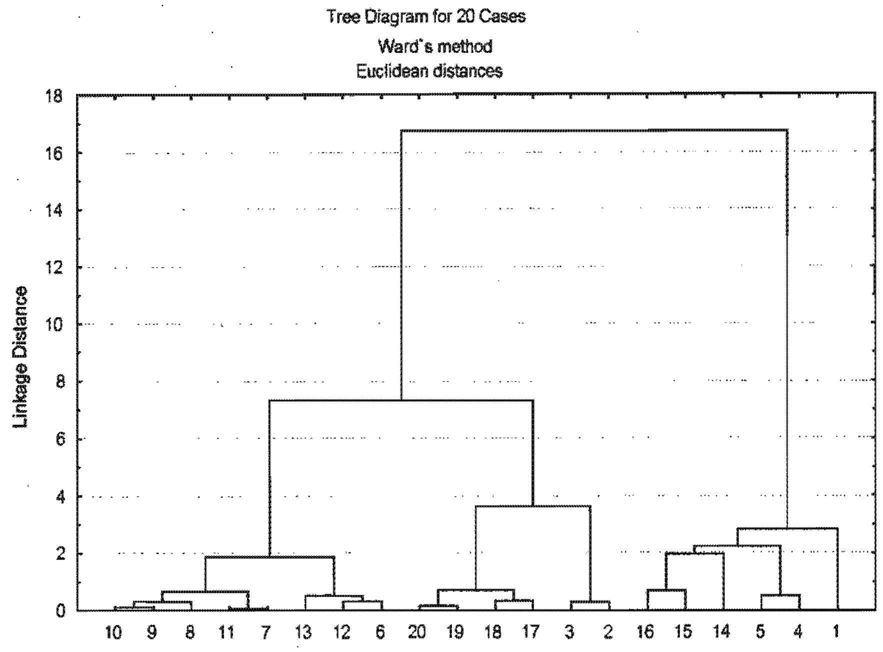


Figure 5.9: Cluster analysis of standardised data (from 50mm rainfall) event by Ward's method.

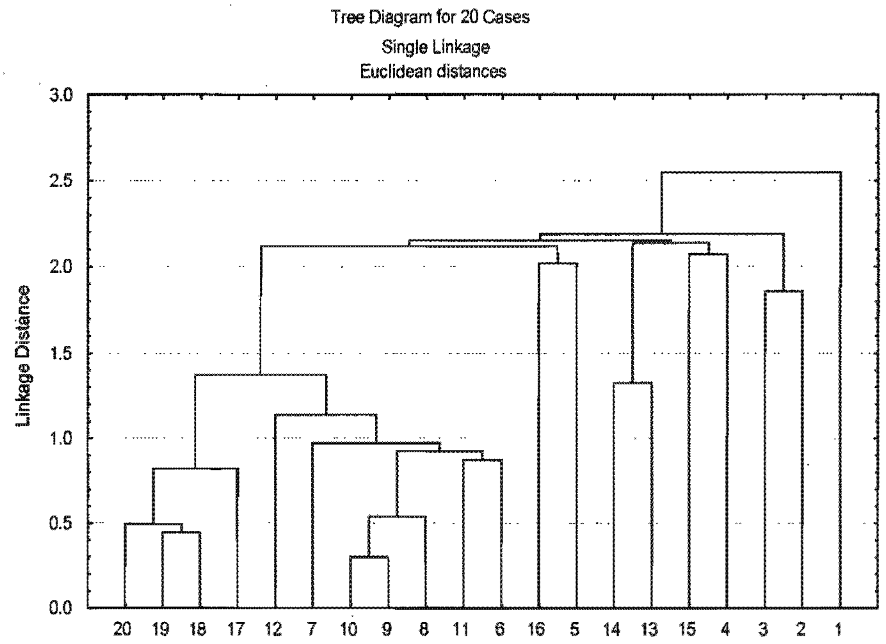


Figure 5.10: Cluster analysis of standardised data (sum of the results from both rainfall events) using the single-linkage method.

When the combined data from both rainfall events (Figure 5.10) was analysed utilising the single-linkage clustering method sample point (cutting) 1 was classed as the single outlier which is in agreement with the results from the 50mm event's results (Figure 5.9). The Ward's method analysis once again identified two main groupings with sample points (cuttings) 1, 4, 5, 13, 14, 15 and 16 grouped separately (Figure 5.11).

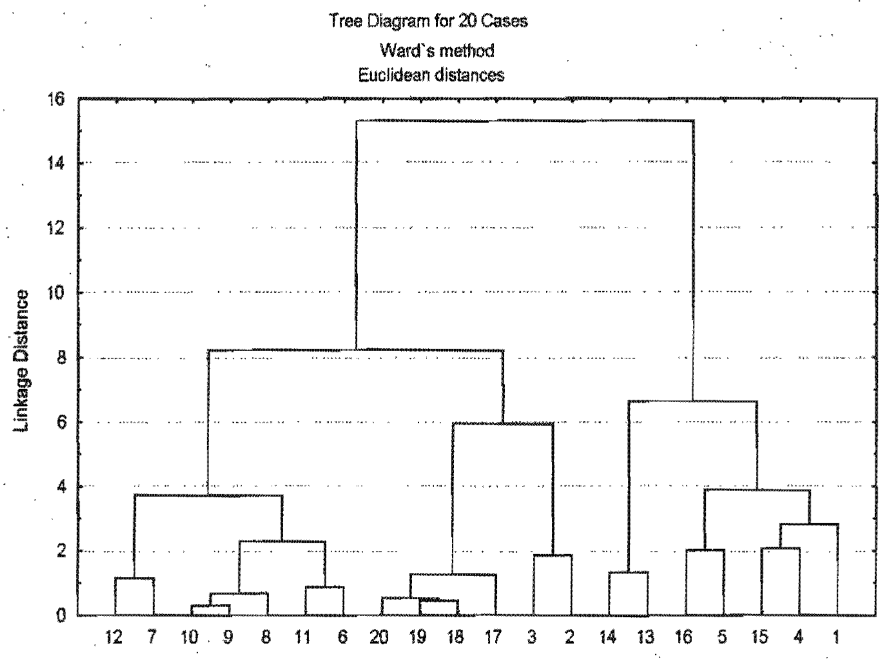


Figure 5.11: Cluster analysis of standardised data (sum of the results from both rainfall events) by Ward's method.

5.9 Summary

This chapter has presented the findings of the various investigative and analytical tools used during this study. A discussion of the significance of these findings and analyses, and their implications for mass movement hazards on Chapman's Peak, will follow in Chapter Six.

Sediment movement (slopewash erosion) investigations on the barred and unbarred slopes, when related to rainfall events that took place during the study period, discovered that, initially, with little vegetation regrowth having taken place, large amounts of sediment was moving downslope. The fact that all sediment traps filled up overnight on both slopes with little rain having fallen was evidence for this statement. This situation changed as vegetation cover began to establish itself on the slope once again. The amount of sediment yielded did not always seem to enjoy a positive relationship with the amount of rain that fell and the influences of other controlling factors required consideration. In general, the barred slope yielded greater amounts of sediment during the various rainfall periods.

Correlation between the number of clasts falling and the amount of rain that fell showed a strong positive relationship between these two variables for the unbarred slope but a weak negative relationship for the barred slope. Strong positive relationships were discovered for both slopes when correlating the size of clasts and amounts of rain that fell while, when correlating the range in clast sizes with rainfall, the relationships for both slopes were positive. However, the correlation was much stronger for the unbarred slope.

The investigation of clast movement on the barred and unbarred slopes revealed that no movement took place within the study plots as far as clasts with longest-axes measurements longer than 10cm were concerned.

The Principal Components Analysis (PCA) performed on the data generated from clasts collected along Chapman's Peak Drive showed different variables identified as principal components for explaining the variance within the data sets. Fallen clasts were collected after two rainfall events measuring 23mm and 50mm respectively. The PCA of the data collected after the first, smaller rainfall event identified the absence of vegetation cover above a sample point as the most important variable controlling where clasts fell. When, during the second rainfall event the amount of rainfall increased, the most important controlling variable changed to the presence of steep slopes above a particular sample point. When the data sets from the two individual rainfall events were added together both these variables were identified as important in controlling clast release but the presence of steep slopes above a sample point was given a higher factor score highlighting it as the most important.

Cluster analyses of the fallen clast data from Chapman's Peak Drive identified the most active areas as far as falling clasts was concerned. When the two fallen clast data sets for the Drive were added together the single-linkage cluster analysis of this new data set recognized sample points 1, 4, 5, 14, 15 and 16 as forming a distinct group within the data. These were identified as the most active sample points as far as rockfall was concerned when these cluster analysis results were compared with the fallen clast data sets.

CHAPTER SIX

DISCUSSION

6.1 Introduction

The previous chapter presented the results of the field, laboratory, imagery (side view and orthographic) and statistical analyses. This chapter interprets the results of Chapter Five and discusses their possible implications. The reader is reminded that this discussion is considered in light of information offered in the physical description of the study area (Chapter Two) and literature review (Chapter Three).

6.2 Comparison and Analysis of Barred and Unbarred Slopes

6.2.1 Sediment movement

The comparison of two slopes, one unbarred and the other barred, with regard to their sediment and clast yields resulting from comparable rainfall events, was one of the main aims of this investigation. Initial results from the first recorded rainfall event in 2000 showed that sediment yields for both slopes were identical with all eight sediment traps filled to maximum. A relatively small rainfall event of 11mm brought about these yields. Rainfall recorded over virtually the next two months, totalling 60.5mm, was not able to repeat this achievement. In fact, only a single trap, on the barred slope, filled to maximum at any other stage during the study period. This was during period three (the first of 2001) in which three rainfall events took place. The highest amount of rainfall recorded from these three events measured 24mm, indicating that during that particular event, more than twice the amount of rain fell when compared to the first recorded rainfall event in 2000. The following period recorded 138mm with more than 50mm precipitated during a single event but it was still not sufficient to fill any of the sediment traps.

With the exception of period one, during which all traps filled totally, the traps on the barred slope captured more sediment than those on the unbarred slope. Total yields from both slopes during period two were also very close to being equal. During the periods of recorded rainfall in 2001 this was however not the case. Period three showed total yields from the barred slope being almost six times as much as those from its unbarred counterpart. This trend continued during period four but the difference was not as large. On this occasion, yields from the barred slope were only one and a half times as great as the unbarred. This data therefore distinctly highlights that, during 2001, sediment yields from the unbarred slope reduced by a larger percentage than those from the barred slope.

One possible cause for so much more sediment moving off the slope during the first rainfall event, with only a small amount of precipitation (11mm) occurring, could have been that this was one of the early rainfall events during the first winter after the wildfires of January 2001. Wildfires during January 2000 had destroyed virtually all vegetation on the surface of the barred and unbarred slopes leaving these slopes directly exposed to the erosive impacts of precipitation as it fell during the first post-fire rainfall season. This could explain why during the first rainfall event of only 11mm resulted in such large quantities of sediment becoming trapped. These slopes had been left unprotected against the agents of erosion for the duration of a great portion of the summer season before any rain fell to provide the moisture necessary for vegetation growth (Plate 4.1). In addition, the study slopes lie on the lee side of the mountain when the predominant summer wind blows, thereby minimizing the effects of sediment removal by wind transport. These are possible explanations for the large difference in the amount of sediment trapped during the first and second rainfall periods.

Another contributing factor could have been the possible existence of an impervious crust within the upper layer of soil on these slopes. Raised intensities during the wildfires described in Chapter One, caused by the presence of alien plant species on the slopes, could have created this crust (Tinley, 1985; Scott *pers. comm.*). This increases the water repellency of the surface sediments, thereby increasing surface runoff and consequently increases erosion downslope and also therefore, increases the possibility of a mass movement event in this area of increased overland flow. The laboratory analysis of sediments captured during rainfall periods one, two and four indicated that overland flow transported the greatest volumes of larger diameter particles during the first period. In fact, this figure was more than twice as great as that for period four which had the second highest figure. The settling column analysis also indicated that, within the sand fractions of the samples trapped, the sample captured during period 1 is most coarse skewed, that captured during period 2 slightly less so and that of period 4 is actually slightly fine skewed. This entrainment and transport of these larger sediment particles was possible because of the increased overland flow resulting from the existence of such an impervious crust. Add to that the fact that the workers who had been clearing the barred slope had walked extensively over its surface further loosening the surface sediment.

Sediment losses were not as severe during period two as vegetation had once again begun to establish itself and protect the slope's surface (Plate 4.2). The newly rooted vegetation would also have had the impact of fragmenting any existing impervious crust within the sediment surface thus allowing rainwater to percolate down through the sediment instead of forcing it to flow along the slope surface and in so doing cause greater erosive damage. This argument seems to be supported by the fact that the percentage fines trapped increases for period two, while the percentage coarse particles decreases, indicating a type of overland flow having a velocity with insufficient capacity to transport any substantial amount of larger diameter sediment particles. The few small individual rainfall events which occurred during period two (Table 5.1; sediments were captured during the same rainfall events after which clasts were collected) would also have contributed to a raised percentage fine particles trapped as these small events would only have had the capacity to shift small grain sized particles.

If an impervious crust was not formed by the wildfires of 2000 then another explanation for the reduction in volumes of sediments trapped during period two would need to be sought. One such possibility could have been that much of the remaining loose regolith, left behind after rainfall period one, could have been shifted offslope during rainfall events that occurred between the recorded periods one and two, leaving behind a slope requiring a greater erosive energy to remove sediment which was more firmly secured. This could possibly have been brought about by the removal of loose surface sediment leaving exposed deeper sediments, which had been more firmly compacted at depth, and which was as a result more resistant to erosion.

The subsequent recorded period, number three, occurred at the beginning of the next winter rainfall season. With the sediments once again exposed to weathering processes and erosive forces during summer, without any significant rainfall events to remove eroded material from the slope surface in the interim, it would be expected that more sediment would be readily available for entrapment during period three than during four. This in fact seems to be the case as even though almost three times the amount of rain fell during the fourth period as the third (both spanned the same amount of time), almost two and a half times more sediment was trapped during period three in comparison to period four. Further growth of vegetation between the third and fourth periods could also have retarded the movement of slope sediments.

The possible causes for the disparity in yields between the barred and unbarred slopes during periods three and four of 2001, and not during the previous year's records, could have been the following. With the larger clasts, which normally stabilize sediments on a slope (Selby, 1993), having been removed during rock-barring activities the barred slope would have been left with more of a long term stability problem, at least as far as surface sediments are concerned. The initial problems causing increased sediment yields, as discussed earlier, would have influenced quite similarly on both slopes with the removal of vegetation by wildfire and the existence of an impervious crust viewed as the most significant of these problems. Therefore, sediment losses would have been equal. Once the impacts of those two major factors decreased then the lesser factors could come into effect making their presences felt in determining the amount of sediment yielded. With the angle of slope and degree of vegetation regrowth for the barred and unbarred slopes being equal these factors could not cause any disparity. The destruction of the impervious crust would also have taken place on both slopes with the amount of vegetation regrowth having been equal. Therefore, the absence of the larger clasts from the barred slope, as a controlling factor in sediment loss, received the opportunity to become the significant factor in determining sediment yields.

The differences in sediment yields between the barred and unbarred slopes was considerably greater during period three when compared to period four. Possibly the further regrowth of the vegetation could have been reducing the impacts caused by the removal of the larger clasts from the barred slope.

6.2.2 Rockfalls

When considering the data pertaining to clasts collected at the base of each of the study slopes it is interesting to note that over both winters a general trend starts to develop whereby more clasts were to be found at the base of the barred slope on most occasions. There are exceptions however. These seem to occur when a high magnitude single rainfall event arrives at the beginning of a rainfall period. Under these conditions, the unbarred slope yields a greater number of clasts. Even though more clasts may have fallen from the barred slope on most occasions it is important to note that the four largest clasts to fall from either slope all originated from the unbarred slope with the largest measuring 65cm along its longest axis. This compared to the longest yielded by the barred slope measuring only 24cm. When studying the mean axes lengths of clasts collected during 2000, the values for both slopes seem quite similar for both slopes but those from the barred slope are in fact longer for eight of the eleven rainfall events. This trend reverses the following winter (2001) with the average being longer for the unbarred slope on every occasion. From these findings there is evidence that the barring activities performed have been effective in achieving their aim of reducing the mean size of clasts falling to the road surface.

The correlation matrix produced during the statistical analysis of the fallen clast data from both the barred and unbarred slopes shows a strong positive correlation between the amount of rain that falls and the number of clasts that fell from the unbarred slope. On the other hand, no strong relationship between these two variables exists for the barred slope. The evidence points towards a possible slightly negative relationship. When correlating the mean clast long-axis of fallen clasts and rainfall variables for the two study slopes, there existed strong, positive relationships in both cases. When correlating the range in mean clast lengths with the amount of fallen rain for both slopes, neither correlation was justifiable with a probability of 95%. A possible positive relationship between these two variables existed for both slopes. This relationship was statistically more important in the case of the unbarred slope.

Taking this information into account, the statistical analysis seems to indicate that as the amount of rain that falls increases then the number of clasts falling from the unbarred slope increases, as does the mean size of those clasts whereas, for the barred slope, only the size of the clasts increase. What is also important is that the range in the sizes of fallen clasts seems to increase more significantly for the unbarred slope, when compared to the barred. Therefore, the rock-barring activities seem to have achieved some level of success in that they have reduced not only the number of clasts that fall, but also the range in the sizes of clasts that fall.

6.2.3 Clast movements on slope

With no movement at all of clasts with longest axes ≥10cm recorded within the designated study plots on either the barred or unbarred slopes investigated, it could be assumed that the clasts found at the base of each slope have fallen from the cut face of the regolith above the road. This is contrary to the originally anticipated behaviour of the clasts, which proposed that they moved downslope along the surface of each slope, and then fell from its edge onto the road below (MJ Mountain and Partners, 1999). This was the thinking behind the removal of clasts from the surface of the barred slope. If the former is in fact the cause, then a different approach is required to curb the problem of clasts falling from regolith-covered slopes onto the road surface.

6.3 Chapman's Peak Drive

As discussed in Chapter Two, for the purposes of this investigation, Chapman's Peak Drive as a whole was separated into two sections. The first of these was the smaller section of Chapman's Peak Drive below the barred and unbarred slopes (about 80m in length) and the second composed the rest of the drive below Chapman's Peak. It is this second section that is now discussed.

6.3.1 Oblique view and orthophoto analyses

The extent of vegetation destruction by the wildfires of January 2001 exceeded 82%. From the oblique view photographs taken, before the wildfires, it was calculated that around 60% of the surface area of Chapman's Peak was covered by vegetation. With just over 80% of this protective cover removed from a steeply sloped surface it was thought that this destruction of vegetation would have a significant impact on the stability of material on Chapman's Peak (MJ Mountain and Partners, 1999). The debate on the possible impacts of fire on slope stability in the area, especially with the presence of larger alien species, is discussed earlier.

6.3.2 Rockfalls

When considering Table 5.2 only four of the 25 cuttings monitored yielded clasts after both rainfall events. These were cuttings 4, 14, 15 and 16. During event one road cuttings 12 through 16 all yielded clasts. This identified a concentrated area of activity as no other set of adjacent cuttings yielded clasts during this rainfall event. Following the second rainfall event, clast collection took place at the foot of only three from this group, cuttings 14 through 16. The biggest clasts yielded during this event were however considerably larger than the biggest from the first event when comparing those three cuttings at the base of which clasts were collected after both incidents of rainfall. As a result of the second rainfall event clasts were yielded by two further groups of adjacent cuttings with 4 and 5 forming the first set and cuttings 23, 24 and 25 the second. Therefore, activity was not quite as concentrated as during the first rainfall event. In fact, clasts fell from nine road cuttings during event two as opposed to only six during the first.

The Ward's method cluster analysis (which took into account only cuttings 1 to 20) performed on the clast data from the first rainfall event identified two main groupings. Cuttings 1, 11, 12, 13, 15 and 16 formed one of these groupings and all the rest of the cuttings the other group. The clast data from the second event identified cuttings 1, 4, 5, 14, 15 and 16 as being a distinct group and the rest of the cuttings as another group when analysed in this fashion.

MJ Mountain and Partners collected fallen clasts along Chapman's Peak Drive only a short while after the wildfires had destroyed most of the vegetation on Chapman's Peak. This task was performed during February 2000, a summer month for the study area. Little or no rainfall was associated with the yielding of this slope material onto Chapman's Peak Drive. In the short-term (after the wildfires), the first few cuttings (numbers 1 to 9) seemed to have been more active when compared to the data collected after the recorded rainfall events of this study (which took place during the winter of the following year). Importantly, the most active areas identified by the post-rainfall event data collected during this investigation, are once more highlighted. This indicates that these areas could pose a more significant danger in terms of falling clasts, as they seem to represent a greater long-term concern to slope stability. The implications of these findings will be discussed later when the effectiveness of the rock barring activities employed are debated.

6.3.3 Multivariate statistical analysis

The results produced by the Principal Component Analysis (PCA) performed on the fallen clast data from Chapman's Peak highlighted the various components responsible for rockfalls onto Chapman's Peak Drive. When the smaller rainfall (recorded as a figure of 23mm) event transpired the most important variable highlighted by the PCA to be the bare rock index. This component can be interpreted as the degree to which the portion of slope directly above a particular road cutting along Chapman's Peak Drive is vegetated. The component explained just more than 45.5% of the total variance within the data set, when unrotated, and this figure decreased to just below 45% when the data was varimax rotated. Therefore, the amount of vegetation present was the most important controlling factor in determining whether clasts fell or not. The secondary component highlighted during the unrotated PCA was the slope length variable. This component was responsible for approximately 30% of the explained variance within the data set. When the data was varimax rotated the slope angle variable now also became statistically important with the explained variance of this secondary factor increasing to approximately 31%. These two variables, slope length and slope angle, are negatively related. The slope length variable was interpreted as representing the vertical extent of the Peninsula formation above each road cutting.

This was however not the case when a greater figure of 50mm of rainfall was recorded. On this occasion, the variable scoring the highest component loading was in fact the angle of the slope above a particular road cutting. This variable represented 48.9% of the total variance when the data was unrotated. When a varimax rotation was performed this figure decreased to 48.6%. The most important contributing factor influencing slope angle on Chapman's Peak is the presence of cliff faces. Large slope angles usually indicate the existence of a large percentage of bare cliff faces above a road cutting. For the most part these cliffs are comprised of strata belonging to the Peninsula Formation (Pfm) cliffs. Therefore the slope angle variable can be interpreted as an indicator of the amount of bare cliff face above a road cutting (sample point). The secondary component was identified as the shale band index variable for the PCA analyses of the rotated and unrotated data. The explained variance for both of these sets of data was just below 28%. This factor was interpreted as representing the thickness of the Peninsula Formation.

When the data sets from the two rainfall events were added together, and a PCA run on the unrotated data, both the slope angle and bare rock index variables were marked as significant. Therefore, component 1 was a combination of these two variables. Component 1 explained 49.3% of the total variance within the data set. When examining the component loadings more closely it can be seen that slope angle, with a loading of 0.86, is regarded as a more influential variable than the bare rock index which has a loading of only 0.72. This was altered slightly when the data was varimax rotated with the slope angle loading remaining 0.86 and the bare rock index loading increasing to 0.76. Therefore it could be said that the most important controlling factor, according to this principal component analysis, in determining whether clasts will fall onto Chapman's Peak Drive at any given point is the presence of a high percentage of bare cliff faces above that point. The presence of vegetation on the slopes and the thickness of the Peninsula formation above a particular road cutting (sample point) also play an important role in this regard.

McCormick's (2000) comments made after he investigated slopes on Chapman's Peak that it is the "quantity and more importantly the intensity of a rainfall event that is the most important factor", (McCormick, 2000, p. 53) which determines whether a slope will fail or not are also significant when considering the fallen clast data sets. When the data sets from both rainfall events were summed the PCA recognised slope angle as being more important than the bare rock index. Originally, the slope angle variable had been identified as the most statistically important variable during the PCA analysis of the larger recorded rainfall event of 50mm while the most influential variable in the PCA of the 23mm rainfall event data had been the bare rock index. Therefore, the question must be asked whether the intensity of the rainfall event is not in fact the most important contributing factor as McCormick (2000) proposes.

The role of vegetation cover seems most important with a smaller rainfall event of around 25mm. When a larger rainfall event of around 50mm is experienced the presence of a high percentage of bare cliff faces above a particular point on Chapman's Peak Drive will play a greater role in the release of clasts onto that area below Chapman's Peak. This therefore implies that rainfall intensity is indeed a very influential factor in controlling the movement of slope material onto Chapman's Peak Drive.

6.4 How Effective Have Rock Barring Measures Been?

6.4.1 Barred and unbarred slopes

As discussed earlier, rock-barring activities seem to have achieved some level of success in that they reduced not only the number of clasts that fell, but also the range in the sizes of those fallen clasts. Barring activities performed also seemed to have been effective in reducing the mean size of clasts falling to the road surface as during the winter of 2001 the mean clast longest-axis measurements were longer for the clasts yielded by the unbarred slope after every rainfall event.

6.4.2 Chapman's Peak Drive

In order to be able to accurately answer this question it is necessary to link the fallen clast data gathered during this study with the fallen clast data obtained from MJ Mountain and Partners. Which slope areas were barred, and the degree to which those slopes were cleared/barred, also then requires incorporation into the argument.

The fallen clast data recorded during this study shows the following: During the first recorded rainfall event of 23mm road cuttings 4, 12, 13, 14, 15 and 16 (Figure 2.1) all yielded clasts. The second event left clasts at the bases of cuttings 1, 4, 5, 14, 15, 16, 23, 24 and 25. The data collected on 8 February 2000 (Table 5.3) by MJ Mountain and Partners identified cuttings 1 to 9, 12, 13, 15 and 16 as those which had released clasts. Only road cuttings 1 to 22 were monitored on this occasion. Therefore, in order to achieve an equitable comparison, the data gathered from the final three cuttings sampled during the fieldwork stage of this study, are disregarded. Some degree of clearing/barring was performed on the slopes above all the road cuttings that had yielded clasts. Cutting 16 was the only one of these road cuttings that became classified as possibly being more dangerous (as described in Chapter Five), after the clearing/barring had been performed. The slopes above four other road cuttings were identified as possibly being more dangerous after the rock clearing/barring activities but none of these yielded clasts after the two recorded rainfall events.

As can be seen the work done on the slopes above the first nine road cuttings seems to have been relatively effective with only a single one of these cuttings having released clasts during the first recorded rainfall event and only three during the second. This is a significant reduction when compared to the data collected on 8 February 2000. The clearing/barring activities were not as effective where large cliff areas were present above the road cuttings. The slope areas above cuttings 12 to 16 were active on all three recorded occasions even though a fair amount of barring work is claimed to have been completed there. The slopes of Chapman's Peak above these five road cuttings have slope angles between 40° and 50° combined with slope lengths between 417m and 595m. This combination, as discussed earlier, signifies the existence of large Peninsula Formation cliffs above those cuttings (Appendix A). The slopes above the first three road cuttings monitored only reached a maximum length of 164m. Therefore, when for example the top third of a slope was classified as totally cleared, there was not a great extent of slope area above that cutting that could still supply material for falling. However, when the top third of the slope above one of the road cuttings numbered 12 to 16 was designated as having been totally cleared, there remained a large portion of that slope above the drive that could supply material to fall onto Chapman's Peak Drive.

The fact that clasts fell at those cuttings on and above which clearing/barring work was undertaken indicates that those responsible for implementing these activities had been effective in targeting the high-risk areas, as far as rock fall was concerned, along Chapman's Peak Drive. Unfortunately, this clearing/barring operation never reached completion due to financial reasons. Had the funding been available, the results achieved in the areas on and above road cuttings 1 to 9, could possibly have been emulated along the very active (high percentage cliff) areas further along the Drive as well.

6.5 Recent Increases In Rockfall Frequency?

This is an important question, and a difficult one to answer. As discussed earlier various factors seem to play a role in what material moves off the slopes above Chapman's Peak Drive. The impacts of alien plant species burning within an area historically dominated by fynbos species has an adverse effect on slope stability by raising fire intensities. This in turn can produce a soil surface crust that will increase surface runoff and the rate of erosion downslope (Tinley, 1985; Whelan, 1995). This higher erosion rate can remove the material that stabilises clast material on slopes thereby increasing the risk of this clast material moving off downslope. Countering this argument, however, are the findings produced by McCormick (2000) who suggested that, after higher intensity wildfires burnt an area on Chapman's Peak, it was the intensity of the rainfall event rather than the existence of an impervious crust that determined whether a slope would fail or not. The presence of alien vegetation also results in the lowering of the water table. Slope instability became more pronounced (landslides) in the Cape Granite slope above the Hout Bay side of Chapman's Peak Drive after the clearing of alien plants (Boelhouwers, *pers. comm.*).

Another argument is that eventually, over time, the internal shear strengths of natural slopes can reduce. In this fashion, a slope can remain stable for a considerable length of time and then suddenly fail. Chowdhury (1978) suggested a number of possible causes for such failure. One of these, which seems particularly pertinent to the conditions on Chapman's Peak, is the impact of sustained gravitational forces on a slope. This may cause gradual decreases in shear strength over time and may not cause immediate failure but eventually lead to the event occuring. This type of event could possibly occur along an ancient tectonic shear zone, slip surface or along significant natural discontinuities. In the case of Chapman's Peak, the Graafwater Formation (Gfm) was deposited unconformably upon the granites belonging to the Cape Peninsula Pluton. More accurately, according to Boggs's (1995) classification, the stratigraphic column of Chapman's Peak represents a nonconformable contact. Chapman's Peak Drive itself was constructed along this natural unconformity.

The engineering geological assessment performed by MJ Mountain and Partners (1999) identified various factors that could contribute to instabilty within the formations from which

Chapman's Peak composes. Their findings support this idea of gradual decreases in shear strength over time culminating in the eventual falling of material to the drive below. They pointed out that near-surface discontinuities, when eroded over time, eventually form stacks/columns that while stable at first will eventually topple releasing rock material to fall down slope. This is because the stabilising material below or adjacent to these stacks erodes and subsequently removed over time. These types of discontinuities are present on many of the cliff faces and road cuttings of Chapman's Peak and as such are a very real concern. They are most likely a significant contributor to the increases in falling clast activity along Chapman's Peak Drive. In fact, in the engineering geological assessment performed (MJ Mountain and Partners, 1999), mention was made that within the Peninsula Formation the largest overhangs and arches occur in the area directly below Chapman's Peak itself. In Figure 2.1 it can be seen that the road cuttings that were recorded as being most active during this study in fact occur at the base of this area thereby further supporting the statement that this is an important factor in determining the amount and location of fallen clast material along Chapman's Peak Drive.

Another factor leading to increased rockfall activity along Chapman's Peak Drive could be the following: erosive agents have only acted upon the rock material exposed during road cutting activities since the road's construction between the years 1916 and 1922. Before this time, naturally exposed slope and cliff faces, on the rest of Chapman's Peak, were already being exposed to erosive agents and a natural equilibrium reached. This would therefore produce a more or less fixed natural rate of rock falls. With the more recently exposed road cuttings now having been exposed for approximately 80 years, erosive forces may have had sufficient opportunity to remove the stabilising rock material surrounding the previously referred to stacks/columns. Vibration effects induced by traffic flow along Chapman's Peak Drive could also be having some long-term influence on the slope stability of Chapman's Peak especially along the road cuttings which are obviously very close to the Drive's surface (Hung and Yang, 2001). This could be a possible explanation as to why the large rock that fell and killed the young lady was yielded during December 1999, a summer month, without associated rainfall. Large amounts of traffic along the Drive during the peak of the summer tourism season could possibly have led to this mass movement event. With these previously inactive road cuttings now also yielding rock material it could be expected that an increase in the total amount of this material falling onto Chapman's Peak Drive would occur.

When slope failures occur, within an area uninhabited by humans, they don't become described as disasters. This title is only assigned once there is an associated loss in human life or loss and/or destruction of property. In the case of a road such as Chapman's Peak Drive, where there are no buildings along the side of the road, human lives and vehicles are at risk. With the increases in population size over time, coupled with the increased attractiveness of Cape Town as a tourist attraction, the associated increases in traffic along Chapman's Peak Drive would proportionally increase the risk that someone might suffer injury or damage to their property. This might possibly have lead to the *perception* of an apparent increase in rock fall activity along the drive.

Improvements in the ability of the various media to inform a far greater portion of the public of such losses of life and damage to property might also play a role in promoting this perception of increased rockfall activity if it is indeed only a perception. If there is a real increase in activity then this ability of the media might make the increase seem larger than it actually is. Earlier rockfall activity might only have come to the attention of those employed to remove that fallen material and possibly a few personal contacts of those workers. These types of events attract far greater attention nowadays and a far greater number of people are aware of them due to these improved media capabilities.

6.6 Summary

This chapter has dealt with the comparison of a barred and unbarred slope on Chapman's Peak concerning the clasts and sediment yielded by both and clast movements along their respective surfaces. A comparison of clasts collected along Chapman's Peak Drive following rainfall events of different intensities, and the possible causes for disparity within this data, were also discussed. Also evaluated were the effectiveness of the rock-barring activities undertaken on Chapman's Peak as concerns the movement of clast and sediment material onto the Drive. The final part of this chapter discussed the seemingly increased frequency of mass movement events on Chapman's Peak and the various factors possibly responsible. These issues will be further discussed and synthesised in Chapter Seven, where overall conclusions will be drawn.

CHAPTER SEVEN

CONCLUSIONS

7.1 Introduction

This chapter first presents a summary of the findings realised during this investigation. The reader's attention is then drawn to the assumptions and limitations of this study followed by the salient issues and points that have emerged during this research. A brief discussion on the mitigation and management of mass movement hazards, as experienced on Chapman's Peak Drive, is then provided and the dissertation ends with a concluding statement.

7.2 Summary of Findings

This research set out to investigate the various geomorphic controls causing the hazardous conditions experienced along Chapman's Peak Drive. The intention was to generate data as concerned the genesis of regolith material and its subsequent downslope movement. It was also intended to identify patterns within both these sediment movements and the falling of rock material onto the Drive in the form of mass movement events. Human activity impacts in the form of the rock barring/clearing of certain areas of Chapman's Peak and wildfires that swept through the area were also to be assessed.

Slopewash erosion was measured during winter rainfall events using sediment traps placed on adjacent slopes cleared of their vegetation by wildfires during January 2000. The surface of one of these slopes had been cleared of loose rock material and is referred to as a barred slope. The other slope, left uncleared of its loose surface rock, is referred to as unbarred. The size and number of clasts falling from these two slope was also recorded. Yielded clasts were also collected along the rest of the Drive below Chapman's Peak during the winter rainfall season of 2001 once the Drive had been cleared of fallen slope material. Data generated by MJ Mountain and Partners, from the collection of clasts that had fallen along Chapman's Peak Drive, was also included in the investigation. An attempt was made to record the movement of clasts on the barred and unbarred slopes. This was done by marking certain clasts with paint and then monitoring their movement downslope. MJ Mountain and Partners also provided two sets of oblique photographs that could be used in conjunction with geological and orthophoto maps, to produce a description of the physical characteristics of Chapman's Peak important to this study.

These characteristics were then used to develop a set of indices to be used in the Principal Components Analysis of the fallen clast data. Once this data had been generated, various statistical analytical tools were used to establish patterns within the data sets.

When considering sediment movements (slopewash erosion) on the barred and unbarred slopes with rainfall events it was found that initially, with little vegetation regrowth having taken place, large amounts of sediment was moving downslope as the sediment traps filled up overnight on both slopes with little rain having fallen. This situation changed as vegetation began to establish itself on the slope once again. The amount of sediment yielded did not always seem to enjoy a positive relationship with the amount of rain that fell and the influences of other controlling factors required consideration. In general, the barred slope yielded greater amounts of sediment during the various rainfall periods.

Correlation between the number of clasts falling and the amount of rain that fell showed a strong positive relationship between these two variables for the unbarred slope but a weak negative relationship for the barred slope. Strong positive relationships were discovered for both slopes when correlating the size of clasts and amounts of rain that fell while, when correlating the range in clast sizes with rainfall, the relationships for both slopes were positive. However, the correlation was much stronger for the unbarred slope.

The investigation of clast movement on the barred and unbarred slopes revealed that no movement took place within the study plots as far as clasts with longest-axes measurements longer than 10cm were concerned.

The Principal Components Analysis (PCA) performed on the data generated from clasts collected along Chapman's Peak Drive showed different variables identified as principal components for explaining the variance within the data sets. Fallen clasts were collected after two rainfall events measuring 23mm and 50mm respectively. The PCA of the data collected after the first, smaller rainfall event identified the absence of vegetation cover above a sample point as the most important variable controlling where clasts fell. When, during the second rainfall event the amount of rainfall increased, the most important controlling variable changed to the presence of steep slopes above a particular sample point. When the data sets from the two individual rainfall events were added together both these variables were identified as important in controlling clast release but the presence of steep slopes above a sample point was given a higher factor score highlighting it as the most important.

Cluster analyses of the fallen clast data from Chapman's Peak Drive identified the most active areas as far as falling clasts was concerned. When the two fallen clast data sets for the Drive were added together the single-linkage cluster analysis of this new data set recognized sample points 1, 4, 5, 14, 15 and 16 as forming a distinct group within the data. These were identified as the most active sample points as far as rockfall was concerned when these cluster analysis results were compared with the fallen clast data sets.

7.3 Assumptions and Limitations

The following should be kept in mind when considering the conclusions reached during this research:

- The adjacent barred and unbarred slopes in which the Gerlach traps were placed were carefully selected to be as similar as possible. The assumptions were then made that the source material, stone abundance, vegetation density and degree of vegetation cover destruction and drainage conditions would be taken as equal.

- When all Gerlach traps were filled to maximum capacity it was assumed that the same amount of sediment was moving off the slopes above those traps.

- When analysing captured sediments, assumptions were made which sometimes hampered the deductive approach of this investigation.

- Due to the manner in which sediments were captured it was not possible to determine exactly from where on the slope this material originated.

- No testing was done for the loss of suspended sediment from the Gerlach troughs. The assumption was made that due to the coarseness of the slope material this loss would have been insignificant.

- Due to the hazardous nature of data collection activities, as well as the limited funds available, rockfall data was only gathered along the Chapman's Peak Drive section of the study area on two occasions thereby limiting the predictive capability of this research.

- With the equipment available for this research it was impossible to determine the intensity of individual rainfall events over the 24 hour monitoring periods and the assumption was made that larger rainfall totals indicated higher rainfall intensities.

- As discussed in the research design, monitoring of the study area was not possible during the first half of the winter rainfall period of 2000, as the local authorities had prohibited access.

- No attempt was made to determine whether the material falling onto Chapman's Peak Drive was sourced from cliff faces or debris slopes. As a result of this it could not be determined whether the rockfalls were related to the primary weathering of cliffs or the mobilisation of already loose material.

7.4 Conclusions

The reader's attention is first drawn to the following important points discovered during the literature review.

- The existing characteristics of the geology making up the stratigraphic column of Chapman's Peak, with the thicker-bedded, more resistant sandstones of the Peninsula Formation overlying the more easily eroded Graafwater Formation sandstones, siltstones and shales has, because of differential weathering, led to the development of Peninsula Formation overhangs. These create the distinctive ramparts of the local landscape. The existence of discontinuities within the Cape Granite and Graafwater Formation, as well as the thinly-bedded and highly-jointed nature of the Graafwater Formation creates stacks/columns of rock material as erosion occurs. These stacks/columns eventually topple, removing the basal support of the Peninsula Formation.

- According to the 1999 Preliminary Geotechnical Investigation (M. J. Mountain and Partners, 1999), undertaken to determine the stability and safety of the road cuttings along Chapman's Peak Drive, it seems the area has undergone virtually no safety work within the 77 years between the original opening of Chapman's Peak Drive and its closure in 1999. The clearing of fallen material and the repair of damaged or scarred road sections and cuttings (evidence of rockbolting) seem to have been the only activities undertaken.

- The potential for the existence of hazardous conditions, along Chapman's Peak Dive, was recognized at an early stage in the Drive's existence. Evidence for this was present in the form of a report, delivered upon completion of the Drive, by Mr T. W. W. Perry the Inspecting Roads Engineer of that time. In this report Mr. Perry stated that all roads constructed within mountainous areas will experience the adverse effects of mass movement events. He subsequently pointed out that, with Chapman's Peak facing largely in the direction from which the rain bringing winter weather systems approach, the threat of occurrence of mass movement events is increased.

The reader's attention is now drawn to the following important points that have arisen as a result of this investigation. These conclusions should be considered in light of the stated aims and objectives of this dissertation presented in Chapter One.

- From the oblique view photographic analysis it was calculated that almost 50% of the total surface area of Chapman's Peak was left as burnt slopes as a result of the wildfires of January 2000. Also important to note is that 82.86% of areas vegetated before the wildfires were left without their protective layer of vegetation after the fires had swept through the area.

- The cluster analyses of the numbers and sizes of clasts yielded along Chapman's Peak Drive highlighted the slopes above six sample points, road cuttings number 1, 4, 5, 14, 15 and 16, as being the most active.

- The Principal Components Analysis (PCA) performed on the data generated from clasts collected along Chapman's Peak Drive highlighted different variables as being the most important, in controlling the release of slope material, after each individual rainfall event. After the first, smaller rainfall event the absence of vegetation cover above a sample point was identified as the most important variable controlling where clasts were released on Chapman's Peak. When the amount of rainfall increased, as was the case during the second rainfall event, the most important controlling variable changed to the presence of steep slopes above a particular sample point. When the data sets from the two individual rainfall events were added together both these variables were identified as important in controlling clast release. However, the presence of steep slopes above a sample point was given a higher factor score highlighting it as the most important controlling variable.

- McCormick's (2000) commented after he investigated slopes on Chapman's Peak that it is the "quantity and more importantly the intensity of a rainfall event that is the most important factor", (McCormick, 2000, p. 53) which determines whether a slope will fail or not are also significant when considering the fallen clast data sets. As mentioned in the previous point, when the rainfall intensity changed the component identified by the Principal Components Analysis changed thereby indicating that the intensity of a rainfall event could also play a role in controlling the release of clasts onto Chapman's Peak Drive.

- When analysing the effectiveness of rock-barring mitigation measures distinction between the different slope types upon which these activities were implemented is necessary. One of these categories is represented by the barred control slope of this study, a regolith-covered slope and the other category by the steeper, mostly bare-rock cliff faces above the Chapman's Peak Drive area of this investigation. Findings indicated that barring activities had had a negative influence on the stability of sediment on the barred control slope. Evidence of this was discovered during the capture of slopewash erosion when a greater total amount of sediment was caught in the sediment traps on the barred slope, when compared with the unbarred. However, when examining findings from the fallen clast analysis at the base of the two control slopes it was found that barring activities had been effective in reducing the number of clasts, with longest-axes greater than or equal to 10cm in length, falling from the barred slope. These barring activities were also effective in reducing the range in sizes of clasts that fell from the barred slope, when compared to the unbarred. When examining the findings from the analysis of the other slope category on Chapman's Peak it was discovered that where rock barring mitigation measures were completed, they were effective in reducing the number of clasts that were released onto Chapman's Peak Drive.

- Unfortunately, the clearing/barring operation on Chapman's Peak was not completed due to financial reasons. Had the funding been available, the positive results achieved from the barring which had been performed could possibly have been reproduced at other points along the Drive.

- With no movement at all of clasts with longest axes ≥10cm recorded within the designated study plots on either the barred or unbarred slopes investigated, it could be assumed that the clasts found at the base of each slope have fallen from the cut face of the regolith above the road. This is contrary to the originally anticipated behaviour of the clasts, which proposed that they moved downslope along the surface of each slope, and then fell from its edge onto the road below. This was the thinking behind the removal of clasts from the surface of the barred slope. If the former is in fact the cause, then a different approach is required to curb the problem of clasts falling from regolith-covered slopes onto the road surface.

- A number of different variables could be responsible for the apparent increase in the occurrence of mass movement activity along Chapman's Peak Drive. The first of these is the introduction of larger alien plant species into the study area altering the amount of fuel available to wildfires and the impacts of these fires. Secondly, the sustained effects of gravity could have lead to gradual decreases in shear strength on the slopes of Chapman's Peak which are now culminating in the increased frequency of mass movement events there. A third possibility could be the existence of near surface discontinuities within the different lithologies comprising Chapman's Peak. Over time, with erosion, these develop into stacks/columns that eventually topple and release slope material onto Chapman's Peak Drive. Fourthly, road cuttings along the Drive have in recent years been exposed to vehicular traffic induced vibration effects that may be adversely affecting the stability of those slope areas near to the Drive's surface. With the increase in traffic along Chapman's Peak in recent years the chance of someone being injured or their vehicle damaged increases and as a result the general public becomes more aware of these events. This problem of vibration effects is illustrated in the following example.

7.5 Mitigation and Management of Mass Movement Hazards

A number of choices are available as management options of mass movement hazards. These are: (1) Do nothing and accept the loss; (2) Remove the problem; (3) Avoid the site; and (4) Mitigation works. The first solution of doing nothing is only realistic when the problem cannot be avoided and the costs involved in stabilisation work are prohibitive, or when this stabilisation work is of a trivial nature. Where the hazard poses a significant threat, forecasting of the hazards and a civil defense programme are essential for the minimisation of losses. In some instances the problem can be mitigated, as was thought on Chapman's Peak, using a technique called scaling/barring where loose slope material is removed.

The best solution, however, is the avoidance of problem sites. Mass movement inventory maps and hazard maps are of particular use in this regard and enable the incorporation of the potential future impacts arising from these problems into the design of any development in those areas. Avoidance of a problem area is not always possible though, particularly when dealing with areas with only slight stability problems. When development is necessary within these types of areas it is important that constructions have a positive impact on the slope stability of that area. This could involve the installation of efficient drainage systems, the reduction of slope angles or the

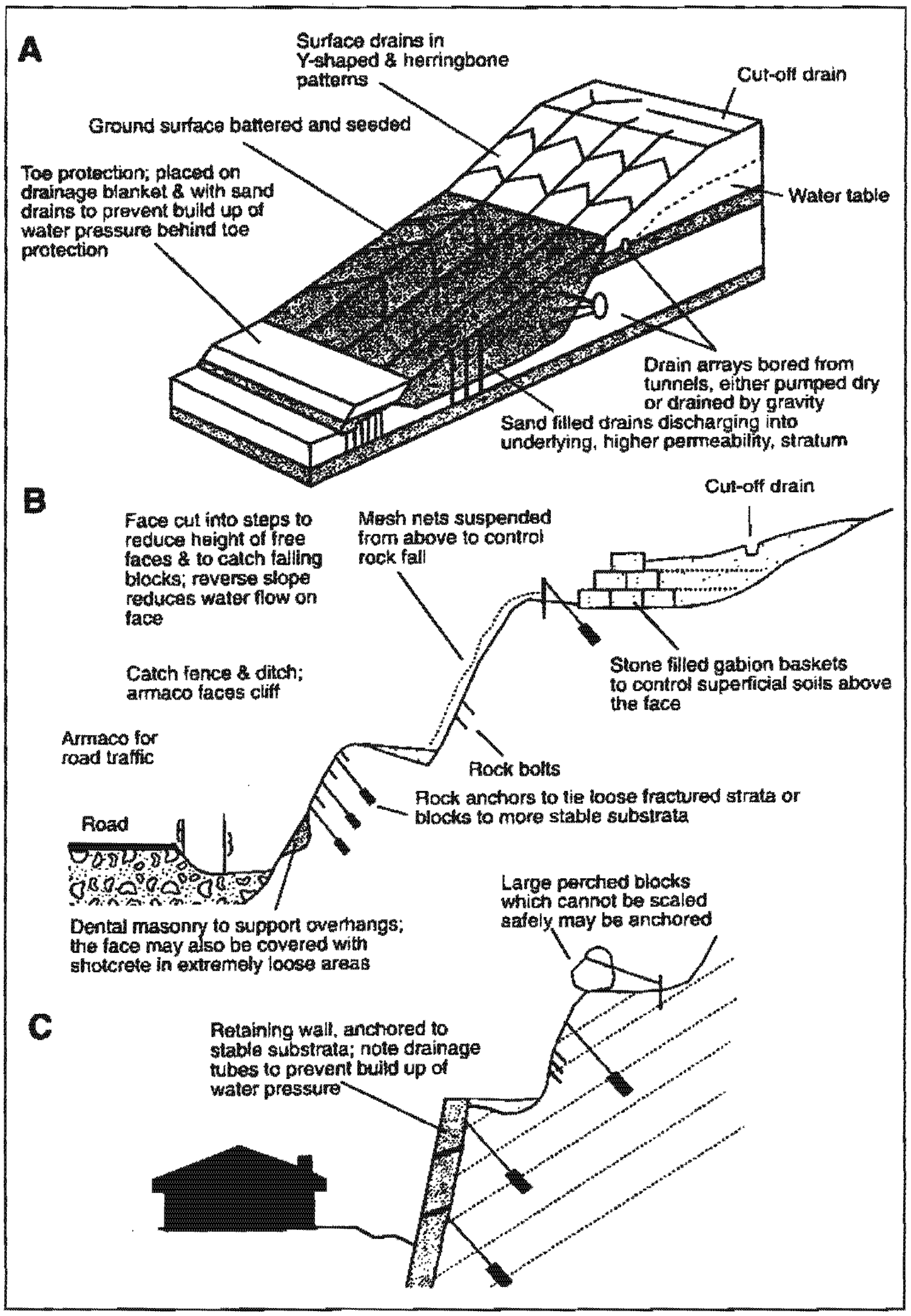


Figure 7.1: Methods of slope stabilisatioin. A. 'Soft rock' or sediment cliffs. B and C. 'Hard rock' slopes (Bennett and Doyle, 1997).

careful design of fill areas ensuring the minimisation of any increases in weight acting on the slope. When development has already taken place within an unstable location or where no alternative locations for development exist, mitigation work and site management are essential. Figure 7.1 illustrates some of the possible mechanisms utilised in the stabilisation of slopes.

Spiker and Gori (2000) have presented a report outlining the key elements of a comprehensive and effective national strategy for reducing losses from landslides on a nationwide scale in the United States. It includes activities at the national, State, and local levels, in both the public and private sectors. The report provides an assessment of the status, needs, and associated costs of this national landslide hazards mitigation strategy. The essential elements of a National Landslide Hazards Mitigation Strategy include the development of new partnerships between government at all levels, academia, and the private sector, and expanding landslide research, mapping, assessment, real-time monitoring, forecasting, information management and dissemination, the development of mitigation tools, and emergency preparedness and response. The strategy makes use of new technological advances, enlists the expertise associated with other related hazards such as floods, earthquakes and volcanic activity, and utilizes incentives for the adoption of loss reduction measures on a nationwide scale.

7.6 Concluding Statement

This dissertation has focussed on slope hazards, in the form of rockfall and slopewash currently experienced along Chapman's Peak Drive, a road constructed along a natural discontinuity between granites belonging to the Cape Peninsula Pluton and the Table Mountain Group in the Cape Peninsula, South Africa. It has shown that the presence of steep slopes and/or the absence of a protective vegetation cover above a particular point on Chapman's Peak Drive, as well as the intensity of rainfall events, all play a role in the initialisation of mass movement events in that area. Further research into the specific slope areas yielding clast material, that falls to the Drive below is required, as well as a more in-depth investigation of the possible specific mitigation measures, used elsewhere under similar conditions, that could be implemented most effectively above Chapman's Peak Drive. These in turn will hopefully lead to the eventual reopening of Chapman's Peak Drive to public thoroughfare.

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APPENDIX A

Vegetation cover on Chapman's Peak before the wildfires of January 2000 (oblique view).

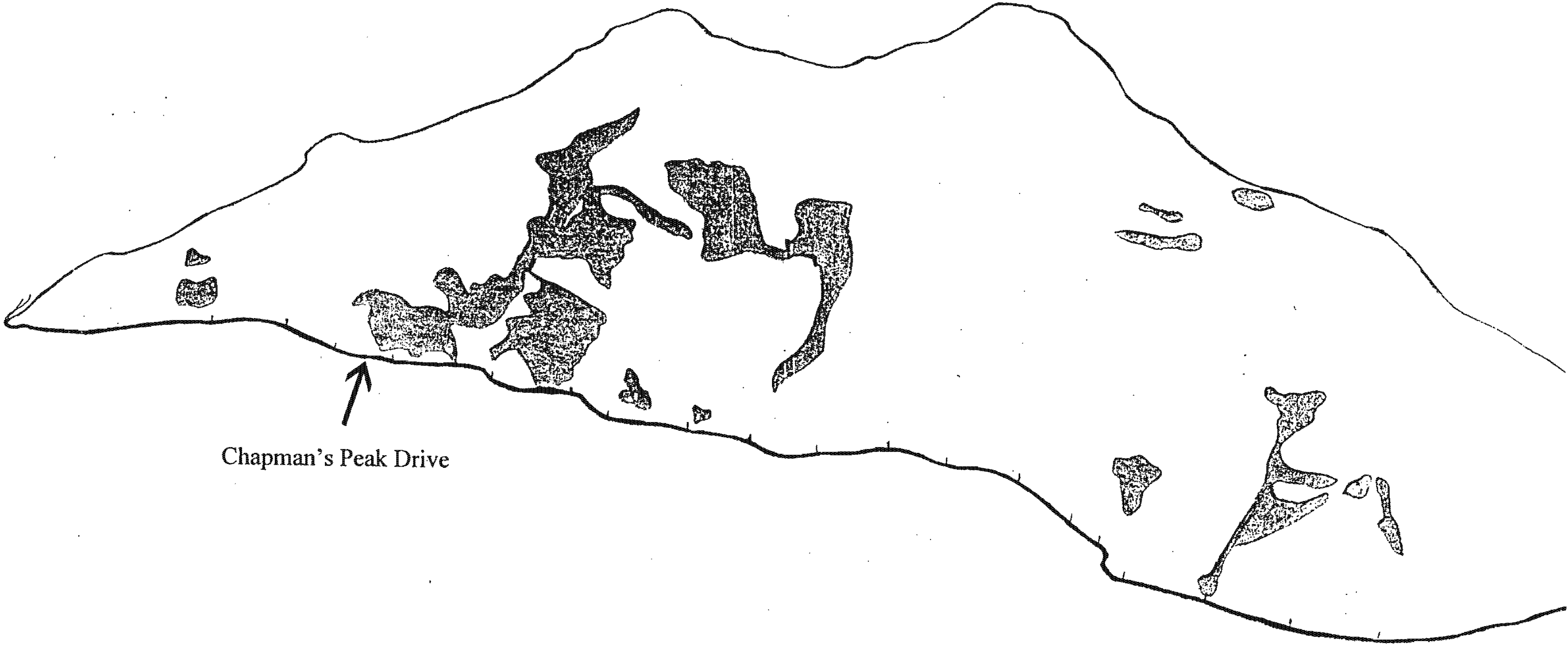
Shaded areas represent vegetation cover.


Chapman's Peak Drive

APPENDIX B

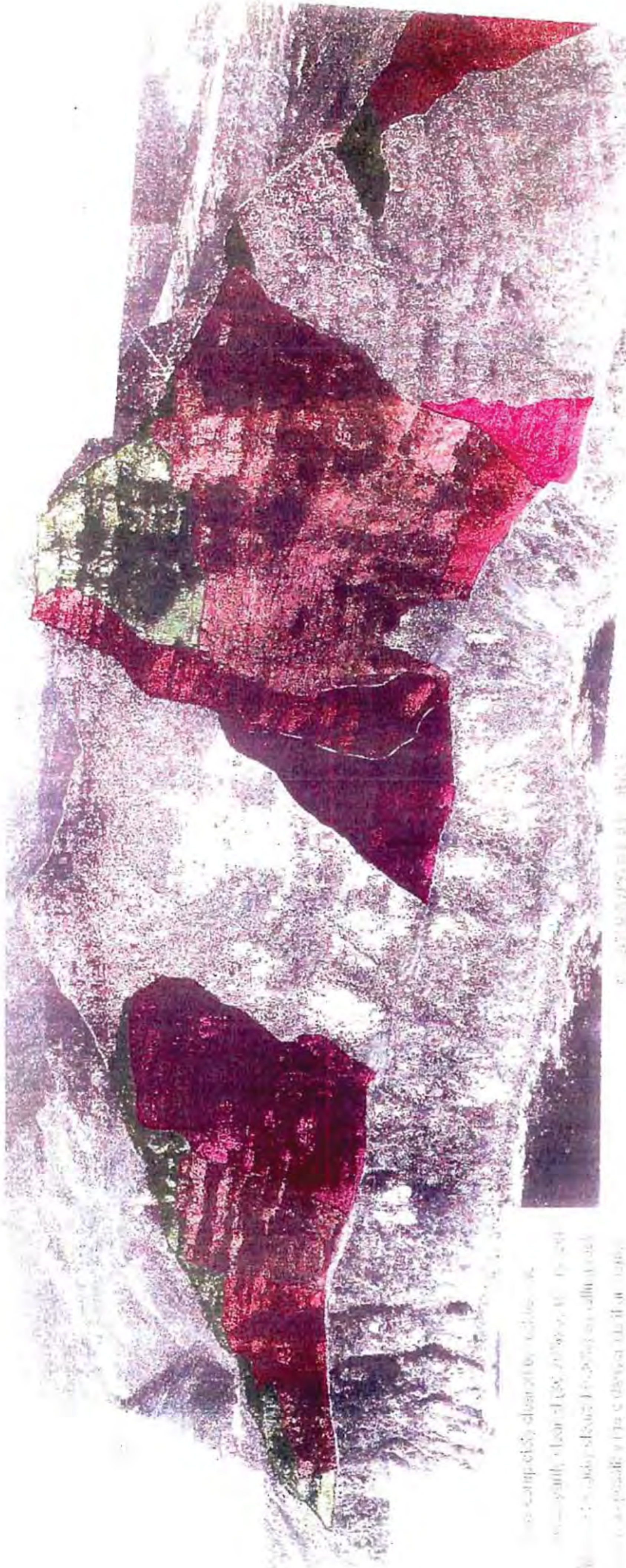
Vegetation cover left on Chapman's Peak after the wildfires of January 2000 (oblique view).

Shaded areas represent vegetation cover.


Chapman's Peak Drive

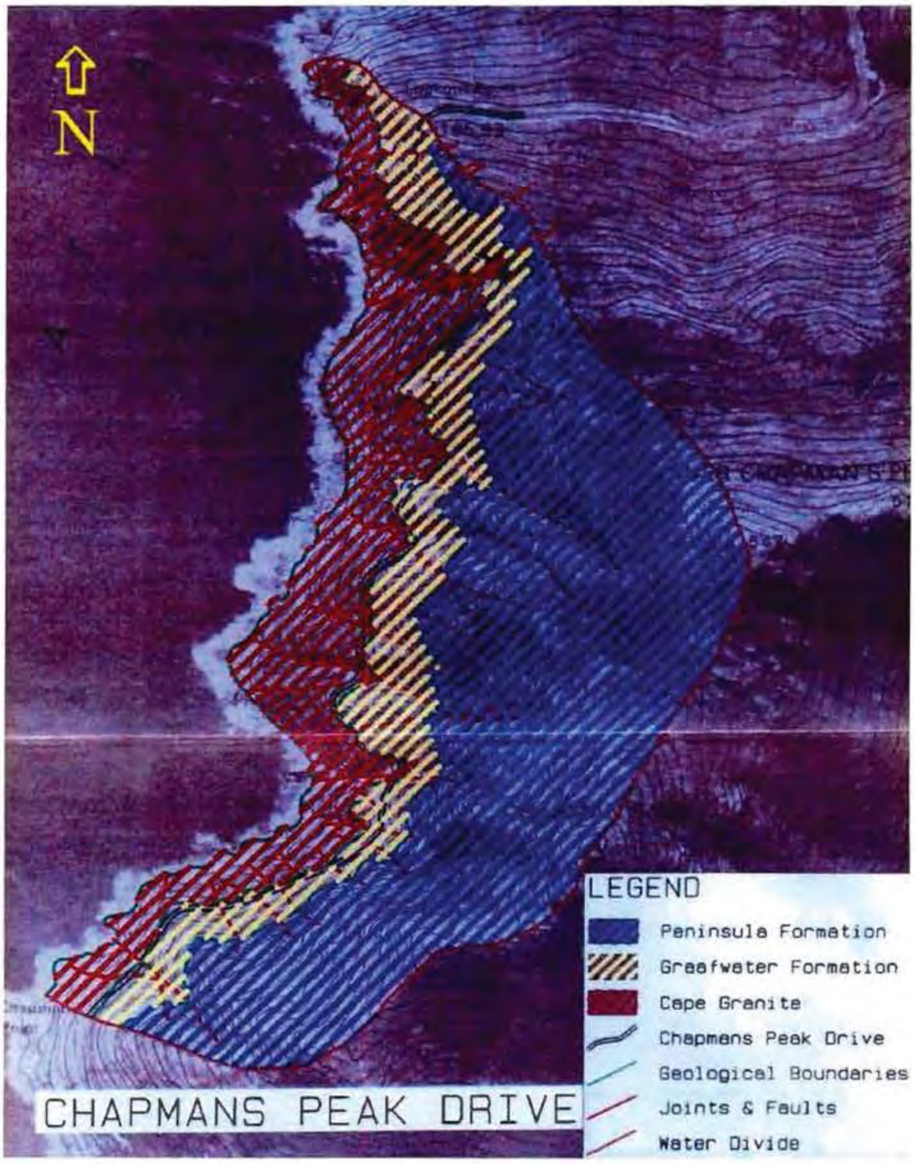
Appendix C

Oblique view of extent of work areas and extent of completed rock barring at 12 May 2000 (MJ Mountain and Partners, 2000).



Appendix D

Annotated orthophotograph showing the extents of the underlying geology/lithology of Chapman's Peak (MJ Mountain and Partners, 1999).


N
LEGEND
Peninsula Formation
Graafwater Formation
Cape Granite
Chapmans Peak Drive
Geological Boundaries
Joints & Faults
Water Divide
CHAPMANS PEAK DRIVE

Appendix E

Correlation table relating results of clast collections and rainfall monitoring on the barred and unbarred slopes.

Correlations marked in bold are significant at $p < .05000$ with N=18 (Casewise deletion of missing data).

			Unbarred Slope			**Barred Slope**		
		Rainfall	**Number of Clasts**	**Mean clast size**	**Range in clast sizes**	**Number of Clasts**	**Mean clast size**	**Range in clast sizes**
Rainfall		1	**0.55**	0.38	**0.66**	-0.1	**0.63**	0.45
Unbarred Slope	**Number of Clasts**	**0.55**	1	0.35	**0.88**	0.41	0.43	**0.64**
	Mean clast size	0.38	0.35	1	**0.47**	0.03	0.45	0.4
	Range in clast sizes	**0.66**	**0.88**	**0.47**	1	0.01	**0.56**	**0.56**
Barred Slope	**Number of Clasts**	-0.1	0.41	0.03	0.01	1	0	**0.53**
	Mean clast size	**0.63**	0.43	0.45	**0.56**	0	1	**0.61**
	Range in clast sizes	0.45	**0.64**	0.4	**0.56**	**0.53**	**0.61**	1

Appendix F

Index and fallen clast data tables for the Chapman's Peak Drive section of this study.

1. For the 23mm rainfall event.
2. For the 50mm rainfall event.
3. For the total sum when adding the 23mm and 50mm rainfall event.

Cutting No.	Bare Rock Index	Shale Band Index	Slope Length	Slope Angle	No_Fallen_Rocks	Mean Axis Length
1	1.00	1.67	94.334	57.99	0	0
2	0.29	2.30	134.54	48.01	0	0
3	1.00	2.25	164.01	52.43	0	0
4	1.00	2.30	320.16	38.66	16	29.44
5	0.24	2.38	403.61	41.99	0	0
6	0.18	5.17	544.89	42.77	0	0
7	0.61	6.40	622.01	36.50	0	0
8	0.26	3.86	689.64	29.54	0	0
9	0.13	4.00	651.92	32.47	0	0
10	0.19	3.63	662.87	33.93	0	0
11	0.28	5.30	628.01	37.23	0	0
12	1.00	6.80	595.48	40.91	12	23.93
13	1.00	9.00	531.51	48.81	9	23.22
14	1.00	8.00	502.09	45.81	1	41.00
15	1.00	5.00	390.51	50.19	8	29.75
16	0.03	3.14	417.25	44.03	16	29.44
17	0.19	2.86	442.04	37.65	0	0
18	0.08	2.14	413.4	32.15	0	0
19	0.20	2.17	355.11	32.21	0	0
20	0.07	1.83	344.82	29.54	0	0

Cutting No.	Bare Rock Index	Shale Band Index	Slope Length	Slope Angle	No_Fallen_Rocks	Mean Axis Length
1	1.00	1.67	94.334	57.99	39	26.64
2	0.29	2.30	134.54	48.01	0	0
3	1.00	2.25	164.01	52.43	0	0
4	1.00	2.30	320.16	38.66	22	21.82
5	0.24	2.38	403.61	41.99	24	22.54
6	0.18	5.17	544.89	42.77	0	0
7	0.61	6.40	622.01	36.50	0	0
8	0.26	3.86	689.64	29.54	0	0
9	0.13	4.00	651.92	32.47	0	0
10	0.19	3.63	662.87	33.93	0	0
11	0.28	5.30	628.01	37.23	0	0
12	1.00	6.80	595.48	40.91	0	0
13	1.00	9.00	531.51	48.81	0	0
14	1.00	8.00	502.09	45.81	13	40.38
15	1.00	5.00	390.51	50.19	30	37.9
16	0.03	3.14	417.25	44.03	38	37.39
17	0.19	2.86	442.04	37.65	0	0
18	0.08	2.14	413.4	32.15	0	0
19	0.20	2.17	355.11	32.21	0	0
20	0.07	1.83	344.82	29.54	0	0

Cutting No.	Bare Rock Index	Shale Band Index	Slope Length	Slope Angle	No_Fallen_Rocks	Mean Axis Length
1	1.00	1.67	94.334	57.99	39	26.64
2	0.29	2.30	134.54	48.01	0	0
3	1.00	2.25	164.01	52.43	0	0
4	1.00	2.30	320.16	38.66	38	25.13
5	0.24	2.38	403.61	41.99	24	22.54
6	0.18	5.17	544.89	42.77	0	0
7	0.61	6.40	622.01	36.50	0	0
8	0.26	3.86	689.64	29.54	0	0
9	0.13	4.00	651.92	32.47	0	0
10	0.19	3.63	662.87	33.93	0	0
11	0.28	5.30	628.01	37.23	0	0
12	1.00	6.80	595.48	40.91	0	0
13	1.00	9.00	531.51	48.81	9	23.22
14	1.00	8.00	502.09	45.81	14	40.43
15	1.00	5.00	390.51	50.19	38	36.18
16	0.03	3.14	417.25	44.03	54	35.04
17	0.19	2.86	442.04	37.65	0	0
18	0.08	2.14	413.4	32.15	0	0
19	0.20	2.17	355.11	32.21	0	0
20	0.07	1.83	344.82	29.54	0	0

Appendix G

Random number matrices generated using the *Excel 2000* package to be used in determining the level of confidence with which the results of the PCA analyses of the fallen clast data matrices of this study could be viewed.

15.79578	8.708546	91.54675	63.52588	90.58851	57.68148
40.38171	13.77177	20.48811	47.63005	1.683417	1.760608
95.70932	66.84936	60.53263	96.91528	20.87968	32.22071
57.16549	37.5406	12.15378	69.15759	58.57805	7.977426
94.20533	39.22217	92.85879	79.06276	20.27294	13.46222
37.43243	49.4094	52.61543	57.09283	73.65117	36.01621
38.82334	89.1122	12.85069	82.55176	31.75034	70.99884
36.92434	24.52871	31.36366	35.41013	76.78726	46.62807
97.90905	61.23978	12.7571	54.40243	84.20117	93.65946
78.72209	22.51831	87.28991	35.11147	14.64985	31.06113
40.58554	34.26138	80.93627	6.004615	68.24115	67.29894
18.47675	20.79457	87.36686	97.89855	74.60248	72.91798
94.10659	62.39421	64.47254	81.76156	92.18516	96.41317
57.77241	39.6758	92.9219	5.945751	84.14239	11.32082
35.39472	6.655978	30.28363	21.49745	60.41897	69.60796
24.47074	26.65246	98.76739	93.42566	3.359297	26.57383
56.07815	19.49819	27.61706	68.02424	15.95704	98.02884
8.471042	67.12183	63.40346	76.31958	7.499641	98.89196
36.02855	29.87299	47.51455	55.36381	21.89627	17.16311
12.28189	62.84186	5.845769	92.22194	61.62257	10.19473

40.51257	98.28955	53.56659	92.3782	12.22714	96.71002
76.32432	84.00073	6.06483	65.61464	12.27131	35.47584
54.08769	29.12932	70.00469	61.97074	63.57334	61.65304
62.14152	12.38532	66.15649	86.79786	53.66333	52.50098
57.8284	22.03338	76.78519	26.2646	51.52273	17.63496
70.65976	43.83788	81.72875	66.97868	43.56208	46.06176
60.39709	43.44432	77.56971	9.066859	46.54014	88.65801
52.76118	7.251969	42.5117	26.34406	39.97722	83.22624
3.444353	22.82523	32.5076	83.01854	62.02138	65.90598
69.91396	2.525414	54.01181	9.874235	55.77849	35.48862
61.9681	55.68575	15.71388	85.90266	72.92635	45.59346
37.63208	97.2672	12.07805	18.45909	19.60334	70.31251
19.54157	16.05119	32.66149	10.44284	96.04197	57.13614
57.63634	3.953033	16.66153	86.77649	41.8413	75.3141
65.44285	32.69891	80.90811	26.51361	22.05917	33.02826
8.114725	48.43977	33.86643	63.16717	32.73458	35.19691
1.634822	61.80767	46.0516	42.70113	5.695554	2.960831
19.50505	73.2408	64.83035	31.8013	76.50759	71.98903
94.9902	47.16671	5.169942	87.92268	12.52716	73.11122
23.68288	79.2343	22.01436	87.93164	1.540252	80.73174

74.57541	93.85494	61.32147	23.0664	25.08304	30.41697
9.835806	44.00967	85.89734	20.73811	27.90105	85.10475
74.37677	57.71356	31.84105	70.91373	79.63492	95.49619
34.16765	42.95779	51.32948	99.73648	7.879868	71.10619
51.377	88.79055	21.92806	32.44484	60.69641	22.40618
71.39309	74.99438	60.77043	56.31654	72.62313	37.63231
35.45001	21.81576	18.45405	69.13149	99.2445	27.1637
72.51778	70.61403	7.337594	91.42944	99.44905	56.01488
92.00248	80.07568	68.14991	62.16851	25.88176	53.7102
84.2861	17.82299	9.543483	74.46896	48.55118	39.07696
36.72258	52.76329	24.21026	71.90721	35.63229	80.66926
96.37111	56.71162	91.76154	93.99127	14.20359	4.334116
22.6229	96.27114	30.82194	61.22735	88.71347	56.87183
25.44082	81.11525	80.83041	55.41769	56.02278	58.68635
79.21765	81.56594	52.01994	49.72683	2.071165	47.83236
56.50068	8.531767	38.40767	13.65648	76.17626	84.93043
99.10741	28.66121	26.70426	13.41646	94.99415	62.50001
66.81769	14.48088	54.61215	64.80637	93.25333	92.87561
46.44445	46.25485	58.82467	53.99985	90.44398	24.28279
39.87554	91.18102	35.7111	62.59234	30.25569	44.02209

42.41501	4.98632	66.5702	90.83091	62.24575	91.40014
74.22681	9.697948	7.473488	40.04638	69.44041	64.20259
46.45232	4.53894	28.85427	41.71844	56.68115	89.46926
18.17296	54.51711	22.50586	63.9256	56.25952	7.663289
80.52953	23.08483	8.042385	83.1823	86.30618	75.95979
70.38819	38.05641	28.91782	71.87912	56.80771	45.41046
66.33261	82.01337	90.21068	10.0548	47.09302	73.4335
34.5094	76.31217	33.71935	4.618773	20.88729	8.015561
41.71436	17.74461	31.6947	19.56411	81.08683	98.67901
16.64312	17.48506	56.64749	55.9339	76.72351	14.55144
5.034955	54.57899	36.20348	47.32674	91.80874	62.57262
49.20961	34.65327	68.65742	96.39453	54.57096	56.29435
70.52189	52.75622	53.80617	69.35938	60.3619	4.119653
92.44084	69.0336	28.90146	10.14241	16.55158	95.94741
33.39282	19.38662	20.96032	32.1969	1.689371	60.23222
64.78129	17.53023	5.282798	8.285195	91.82445	18.88882
44.92548	82.00726	30.26271	14.01735	56.3382	87.37037
71.08001	33.35891	28.79956	98.37689	20.37813	56.50343
29.68116	27.14496	84.5945	95.52364	15.60097	66.03609
44.63023	92.33403	73.38632	8.922338	13.19933	41.54886

29.17517	66.71529	30.79315	75.47971	75.19614	62.23497
98.75074	84.6075	25.20002	90.28695	66.08428	70.63816
28.97643	46.33521	56.00822	14.693	58.85138	19.28102
53.46196	72.79915	83.34223	72.93335	15.34047	81.69334
54.87027	16.17412	51.95016	57.48669	80.68774	40.18445
25.80506	39.42756	30.97945	24.10101	87.90833	69.58831
92.3856	31.75896	56.63665	48.46531	86.75028	81.39339
84.89869	40.35721	53.07175	83.53424	77.72449	44.1757
13.95925	33.51951	22.03577	1.216393	68.11877	53.34108
79.73053	55.65284	88.49178	57.66312	31.38584	55.281
44.41781	99.57523	8.270382	45.3396	79.14889	74.1567
35.18578	50.90491	88.03411	17.9382	52.00658	17.54112
51.50689	13.22863	32.30309	54.61136	57.04394	88.45713
60.07779	14.43457	94.82002	35.30248	9.613699	71.0616
84.88826	46.85821	44.38777	37.22607	91.18761	1.472624
10.50211	10.56117	70.15699	72.68061	8.18422	90.14317
84.10841	40.03584	64.88381	61.79462	16.84867	43.73993
73.60217	10.75694	12.84555	32.06957	38.14394	96.54399
49.80929	37.40522	68.55262	57.22247	59.82685	95.45879
19.99229	71.66878	70.05268	38.28399	86.00566	94.5543

54.2624	25.28286	12.93075	76.79156	88.86048	15.70801
96.01961	28.33462	86.18311	55.28526	42.4989	98.66404
35.46797	68.43256	66.11546	79.8918	44.33394	3.574221
50.82008	58.3449	94.21261	9.964261	48.93224	19.46237
46.92804	71.87347	1.302107	18.91731	64.81045	34.37374
37.19641	95.44513	36.58279	10.5492	51.62748	56.44148
96.875	12.6866	55.00368	49.02576	46.88937	53.46146
21.30009	49.96244	39.02586	45.94022	37.77553	42.4294
3.125287	10.10003	95.3289	83.05433	17.53485	50.67462
5.368575	4.410618	55.59602	25.41623	35.70984	50.26032
58.69532	93.54796	16.426	50.71151	69.63477	92.0127
70.63384	85.67269	91.37489	58.72237	39.35917	52.32335
3.852375	59.58133	60.19755	73.03732	46.46419	35.72301
18.09243	80.59526	22.96937	62.08743	21.57793	58.77153
81.63035	27.12258	62.74002	94.70205	64.70687	7.130993
90.63119	42.40103	28.47232	52.55865	93.42535	99.23988
80.8276	80.80067	60.29681	57.90642	44.88417	61.36371
27.82489	41.92675	23.56596	80.21758	75.80332	85.34276
30.19302	19.21186	86.64744	61.4267	66.50052	99.49603
22.54519	22.41296	42.63558	54.99511	63.90584	60.17973

81.0661	94.90984	26.44497	40.9422	56.23351	49.18575
95.84153	34.15723	48.03784	46.59633	46.5126	16.14833
68.54191	95.67369	4.259253	54.04102	98.74349	56.69307
51.0269	8.585651	72.60086	16.98348	80.7011	72.40422
98.06573	65.80011	51.77807	50.33035	88.28763	32.75454
33.4225	33.28931	38.22729	24.09356	14.77364	58.83702
59.26391	76.29385	51.8708	70.01773	91.02332	70.91467
11.77879	88.91138	20.60035	61.00675	1.221562	19.88449
49.38405	59.50493	2.842837	3.424829	76.16844	8.210518
1.719187	51.42171	15.48696	35.39303	7.909312	63.2705
56.05791	57.45328	49.58274	71.99001	56.83439	10.45955
7.675222	62.16363	76.93152	77.33272	57.58732	79.01908
41.27368	86.34583	69.36181	84.24922	70.48852	61.63732
44.68532	56.04672	95.71366	99.77872	26.77246	89.22803
88.43942	61.39877	89.23336	14.70715	98.88175	28.57498
38.48292	70.81946	44.81161	41.72262	97.7635	35.29136
59.68501	98.33885	42.786	47.21206	54.55391	86.89217
88.44074	88.96346	37.06653	9.320938	66.85069	73.58811
51.39955	10.79063	46.71933	66.48849	80.35535	42.86149
94.88516	95.58339	8.420972	39.28904	56.57436	30.7045

90.3711	93.07711	45.2542	32.44089	21.93114	62.68113
47.94285	11.34051	2.060979	46.79425	10.27764	57.59709
4.661752	75.94849	26.04462	69.18223	3.631947	31.26949
46.9866	1.558086	57.8819	2.083553	70.49223	98.07698
18.30136	44.94106	26.11653	82.33308	62.13269	70.04491
54.62691	60.9646	82.29251	59.62746	18.22619	9.290549
11.82949	65.40208	3.767303	73.60741	2.308904	6.668878
52.39079	57.97438	19.26617	25.96298	59.31856	53.51564
28.91581	87.0273	30.03484	53.05607	28.60507	69.31373
52.04887	8.093206	87.29397	75.03104	24.71651	93.78779
36.91242	94.84243	57.46129	29.25024	69.52278	81.09714
79.83104	1.971832	62.28455	76.51262	22.36163	33.44541
41.52458	86.31573	70.68065	67.6151	56.85162	80.68704
33.81709	33.32751	17.41101	22.43747	85.34086	99.51984
73.55425	58.26026	54.95226	39.02422	29.74923	20.09249
74.16364	23.28903	33.48044	34.31192	82.26073	44.52644
20.00885	13.1028	83.51499	86.66758	61.22016	18.07978
92.79225	56.46313	27.33565	76.31953	6.990629	49.89225
19.62046	42.71752	67.66163	18.78792	81.04604	94.11214
40.47189	13.24215	66.05384	68.69411	60.76291	81.43448

44.94046	1.450669	91.94081	72.62423	48.47193	52.74866
34.88748	78.50509	87.44233	46.9971	22.44122	23.10828
91.84144	40.36634	43.78359	43.59223	45.17522	48.72342
86.68456	47.62989	99.10383	31.63668	43.72552	67.25242
29.99907	58.90758	76.30568	69.02568	50.1496	95.18286
97.76986	34.83396	61.23726	87.02711	28.19278	79.19871
97.68209	68.41184	60.56912	59.20079	84.88859	13.73899
27.69046	94.51028	62.3877	99.48119	74.69928	33.5498
95.90367	22.51458	50.60302	93.14065	75.23706	68.10803
84.84585	46.90236	81.99666	25.10464	44.58417	85.04382
88.97219	53.29887	37.13163	54.68795	17.31042	24.52191
23.77761	63.63456	68.88772	81.22644	83.81948	8.052536
79.82998	83.87369	45.44952	69.66472	89.14245	12.93198
31.13127	88.8604	14.89133	26.65003	74.85712	98.71814
30.10016	5.797321	12.41437	54.48504	4.542607	64.86854
1.592555	10.82737	11.56364	15.47319	98.1476	45.50774
99.4002	47.39231	42.75671	56.5216	7.528511	85.42358
71.25977	20.94812	11.38855	77.85487	37.64601	57.37981
13.10776	21.01132	38.14392	96.31589	74.32247	94.88674
33.27991	96.54601	57.28607	90.39298	18.36215	57.60299

25.65537	20.22767	63.86062	12.06159	54.81034	31.28234
14.68382	28.81705	72.1607	50.19125	9.226122	26.66173
67.68433	90.8008	63.57176	46.13482	67.98427	19.4555
43.69759	4.407934	29.24197	87.34056	37.59995	1.075232
89.95522	67.77398	33.17156	69.80857	16.90817	34.07519
75.1441	34.39413	97.65057	15.18022	91.84405	13.3148
46.16317	86.52925	88.72851	6.663719	7.308011	97.8996
49.42747	84.90285	54.80776	5.931425	42.4505	19.29591
32.13703	21.07528	72.23842	21.45664	55.62959	58.08764
7.652712	42.67935	88.85086	20.18164	7.762067	3.181711
18.20342	64.50515	6.047513	93.54953	31.88566	13.95615
82.68685	49.24797	51.23889	2.107514	8.819489	92.12634
71.45142	13.67598	69.70893	28.28844	28.65263	41.40257
14.33524	23.55086	30.875	87.26096	47.81861	71.44223
10.33813	23.03627	26.09878	7.035728	96.80876	63.74202
57.71167	35.26108	97.96431	27.40933	7.926148	30.62486
13.22972	6.666328	32.92908	64.44801	38.83493	51.80152
42.96268	82.69121	15.30131	93.09155	88.01798	57.48036
99.43131	18.56486	68.38188	63.3341	88.11253	95.0413
79.8395	30.55388	2.609513	87.95041	86.87242	92.96312

Appendix H

PCA results of random number sets used in determining the level of confidence with which the results of the PCA analyses of the fallen clast data matrices of this study could be viewed.

Random Number Set 1

	Factor	Factor	Factor	Factor
Var1	-0.788550	0.111671	-0.445902	0.135101
Var2	0.439314	0.747197	-0.071081	-0.032553
Var3	-0.345247	0.769170	0.122730	0.464765
Var4	0.479210	-0.665791	-0.027453	0.539957
Var5	-0.726613	-0.146261	0.624917	0.009136
Var6	0.742958	0.320525	0.254674	0.039274
Expl.Var	2.243598	1.729802	0.675078	0.528498
Prp.Totl	0.373933	0.288300	0.112513	0.088083

	Eigenvalue	% Total	Cumulative	Cumulative
1	2.243598	37.39330	2.243598	37.39330
2	1.729802	28.83003	3.973400	66.22333
3	0.675078	11.25130	4.648478	77.47463
4	0.528498	8.80830	5.176976	86.28294

Random Number Set 2

	Factor	Factor	Factor	Factor
Var1	-0.769387	0.051598	0.301137	0.402355
Var2	0.626279	-0.378018	0.211586	0.502951
Var3	-0.428088	-0.341956	0.619310	-0.417172
Var4	-0.414189	0.574478	-0.457794	0.016732
Var5	0.592205	0.593802	0.277859	-0.308165
Var6	0.021041	0.776873	0.481702	0.257553
Expl.Var	1.690144	1.548652	1.037814	0.750460
Prp.Totl	0.281691	0.258109	0.172969	0.125077

	Eigenvalue	% Total	Cumulative	Cumulative
1	1.690144	28.16906	1.690144	28.16906
2	1.548652	25.81087	3.238796	53.97993
3	1.037814	17.29690	4.276610	71.27683
4	0.750460	12.50767	5.027070	83.78451

Random Number Set 3

	Factor	Factor	Factor	Factor
Var1	0.626755	0.401070	0.026635	0.472276
Var2	-0.742341	-0.270234	0.177923	-0.255387
Var3	-0.505466	-0.346444	-0.124426	0.730768
Var4	0.051252	-0.155171	0.950995	0.204257
Var5	0.654996	-0.567046	0.124015	-0.261246
Var6	-0.300760	0.823674	0.257603	-0.147757
Expl.Var	1.721490	1.377965	1.033977	0.954092
Prp.Totl	0.286915	0.229661	0.172330	0.159015

	Eigenvalue	% Total	Cumulative	Cumulative
1	1.721490	28.69150	1.721490	28.69150
2	1.377965	22.96609	3.099455	51.65759
3	1.033977	17.23295	4.133432	68.89054
4	0.954092	15.90154	5.087525	84.79208

Random Number Set 4

	Factor	Factor	Factor	Factor
Var1	0.512074	0.584589	-0.514848	0.189772
Var2	0.117462	-0.880010	0.240571	0.150966
Var3	0.742775	-0.020156	0.149082	-0.590808
Var4	-0.709125	0.170611	-0.083885	-0.589470
Var5	0.600577	0.437888	0.578103	0.017735
Var6	-0.573637	0.563100	0.491656	0.182576
Expl.Var	2.020343	1.654503	0.928135	0.788982
Prp.Totl	0.336724	0.275750	0.154689	0.131497

	Eigenvalue	% Total	Cumulative	Cumulative
1	2.020343	33.67238	2.020343	33.67238
2	1.654503	27.57505	3.674846	61.24743
3	0.928135	15.46891	4.602980	76.71634
4	0.788982	13.14970	5.391962	89.86603

Random Number Set 5

	Factor	Factor	Factor	Factor
Var1	0.578163	0.047292	-0.246891	-0.615794
Var2	0.358455	0.735333	-0.109184	0.421131
Var3	-0.140780	0.815135	0.020513	-0.369168
Var4	-0.228210	0.120270	0.899263	-0.226417
Var5	-0.755041	0.191406	-0.161114	0.260752
Var6	-0.737586	0.005701	-0.363810	-0.404440
Expl.Var	1.648782	1.258530	1.040286	0.975666
Prp.Totl	0.274797	0.209755	0.173381	0.162611

	Eigenvalue	% Total	Cumulative	Cumulative
1	1.648782	27.47970	1.648782	27.47970
2	1.258530	20.97550	2.907312	48.45520
3	1.040286	17.33810	3.947598	65.79330
4	0.975666	16.26110	4.923264	82.05440

Random Number Set 6

	Factor	Factor	Factor	Factor
Var1	0.357194	-0.607430	0.569056	-0.138071
Var2	0.479105	-0.702859	-0.353388	-0.048378
Var3	-0.545451	-0.400692	-0.579679	-0.313765
Var4	0.596609	0.417982	-0.385363	0.134763
Var5	-0.432822	-0.342854	-0.037416	0.824411
Var6	0.802806	-0.077990	-0.169934	0.221443
Expl.Var	1.842420	1.321877	0.963518	0.866704
Prp.Totl	0.307070	0.220313	0.160586	0.144451

	Eigenvalue	% Total	Cumulative	Cumulative
1	1.842420	30.70700	1.842420	30.70700
2	1.321877	22.03128	3.164297	52.73828
3	0.963518	16.05864	4.127815	68.79692
4	0.866704	14.44507	4.994519	83.24199

Random Number Set 7

	Factor	Factor	Factor	Factor
Var1	0.357194	-0.607430	0.569056	-0.138071
Var2	0.479105	-0.702859	-0.353388	-0.048378
Var3	-0.545451	-0.400692	-0.579679	-0.313765
Var4	0.596609	0.417982	-0.385363	0.134763
Var5	-0.432822	-0.342854	-0.037416	0.824411
Var6	0.802806	-0.077990	-0.169934	0.221443
Expl.Var	1.842420	1.321877	0.963518	0.866704
Prp.Totl	0.307070	0.220313	0.160586	0.144451

	Eigenvalue	% Total	Cumulative	Cumulative
1	1.847640	30.79400	1.847640	30.79400
2	1.481946	24.69910	3.329586	55.49310
3	1.097767	18.29612	4.427353	73.78922
4	0.739273	12.32121	5.166626	86.11043

Random Number Set 8

	Factor	Factor	Factor	Factor
Var1	0.564452	-0.575520	0.212226	-0.465522
Var2	0.009528	-0.888402	0.199939	0.132454
Var3	-0.620526	0.032635	0.181416	-0.694333
Var4	0.788781	0.139191	0.209523	0.134637
Var5	-0.227674	-0.555057	-0.681860	0.107472
Var6	0.583186	0.201317	-0.565226	-0.430531
Expl.Var	1.717867	1.489537	0.946240	0.931386
Prp.Totl	0.286311	0.248256	0.157707	0.155231

	Eigenvalue	% Total	Cumulative	Cumulative
1	1.717867	28.63111	1.717867	28.63111
2	1.489537	24.82562	3.207404	53.45674
3	0.946240	15.77067	4.153645	69.22741
4	0.931386	15.52311	5.085031	84.75052

Random Number Set 9

	Factor	Factor	Factor	Factor
Var1	0.712754	-0.485207	-0.273605	-0.061223
Var2	0.468425	-0.118631	0.725166	0.470584
Var3	-0.146606	-0.815995	0.254616	-0.120087
Var4	0.429495	0.680147	0.386952	-0.337546
Var5	0.852971	-0.175499	0.016338	-0.371816
Var6	0.635218	0.219372	-0.452561	0.421463
Expl.Var	2.064461	1.456872	1.020365	0.669434
Prp.Totl	0.344077	0.242812	0.170061	0.111572

	Eigenvalue	% Total	Cumulative	Cumulative
1	2.064461	34.40768	2.064461	34.40768
2	1.456872	24.28119	3.521333	58.68888
3	1.020365	17.00608	4.541698	75.69496
4	0.669434	11.15724	5.211132	86.85220

Random Number Set 10

	Factor	Factor	Factor	Factor
Var1	0.623507	0.342072	-0.530124	-0.250281
Var2	-0.695471	0.093292	-0.589283	-0.216027
Var3	0.152690	-0.737874	-0.461055	0.449946
Var4	-0.869534	0.219626	-0.033442	-0.034330
Var5	-0.759001	-0.287023	0.060261	0.062393
Var6	0.078326	-0.799415	0.099127	-0.579447
Expl.Var	2.234062	1.439857	0.855434	0.652589
Prp.Totl	0.372344	0.239976	0.142572	0.108765

	Eigenvalue	% Total	Cumulative	Cumulative
1	2.234062	37.23437	2.234062	37.23437
2	1.439857	23.99761	3.673919	61.23198
3	0.855434	14.25723	4.529353	75.48921
4	0.652589	10.87648	5.181941	86.36569