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The distribution and characteristics of deep-seated palaeo-mass movements in the northern and central Drakensberg, South Africa.

by

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Declaration

I, ... declare that the thesis, which I hereby submit for the degree Master of Science at the University of Pretoria, is my own work and has not been previously been submitted by me for a degree at this or any other tertiary institution.

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Abstract

Evidence for large deep-seated palaeo-mass movements are found within the Drakensberg. However, the distribution and origin of these movements are not fully documented or understood. By studying the distribution and geomorphic characteristics of palaeo-mass movements in the Northern and Central Drakensberg, this study set out to understand the formation of these large deep-seated palaeo-mass movements. The method was divided into three phases; detection, verification and mapping. Thirty-three possible mass movements were located through the use of a criteria-based searching method of satellite imagery, topographic maps and geological maps. The criteria consists of geomorphic features associated with known international and national palaeo-mass movements. Confirmation consisted of infield verification of the features identified in the criteria and thirteen sites were verified. In the third phase, confirmed sites were mapped, a morphological analysis was conducted and a relative age was estimated. Three important facts were confirmed. Due to the distribution of mass movements within the sandstone formations and close relation to dolerite sills, the geological characteristics, such as weaknesses in the sandstone formations, are considered major predisposing factors. The geomorphic characteristics of the mass movements have a large variety in appearance, size, age and types. This indicates that one single trigger event is an unlikely cause to the movements in this area. This study proposes that the main cause for large deep-seated mass movements in the Drakensberg was the Neogene uplift, which caused deeply incised valleys that led to the ideal conditions for the occurrence of these movements.

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Chapter 1: Introduction

Introduction

As a perpetual form of Earth's topographic change, mass wasting (a form of denudation) plays an important role in shaping mountainous landforms. The diverse instability processes influencing slopes on a large scale results in a variety of different forms of mass wasting (Crosta *et al.*, 2013), superficial mass movement being the most common. These processes also lead to deep-seated forms of mass movements, including rotational rockslides to lateral rock spreads, which can occur at different velocities. Generally, these mass movements occur at a larger scale than their superficial counterparts and, due to their size, are subjected to a large variety of factors in the forming process. The slopes experience different forms of triggering and controlling factors such as seismic activity, over-steepening, different weathering processes, long-term climatic changes and extreme rainfall events (Zerathe *et al.*, 2014), which all lead to a variety of deep-seated slope movement events.

The central Drakensberg plays host to large deep-seated palaeo-mass movements observed by Boelhouwers (1992) in the Bushman's River valley, by Bijker (2001) in the Injisuthi river valley, Singh *et al.* (2008) in the Meander Stream valley and by Singh (2009) in the Mahai valley. Little is known about the distribution of palaeo-mass movements throughout the rest of the mountains, although Sumner and Meiklejohn (2000) stress the significance of lithology and the role it plays in their distribution. The same geomorphological processes that occurred millions of years ago, shaping a large variety landscapes, are still occurring today – the only difference lies in the intensity and magnitude of the processes. It is important to understand the forming processes and conditional factors that lead to large deep-seated palaeo-mass movements in the Drakensberg. Unfortunately, mass movement research in southern Africa is limited (Hardwick, 2012). Thus, to fully understand the occurrence of deep-seated mass movements throughout the Drakensberg, a crucial step would be to identify the number of palaeo-mass movements in the region and document the characteristics. Compared to their newer counterparts, locating and identifying palaeo-mass movements is not an easy task. Nevertheless, their identification is important (and possible) in order to understand valley evolution and subsequent landscape development. Although large deep-seated movements have been noted by Boelhouwers (1992), Bijker (2001) and Singh *et al.* (2008), few have been classified and geomorphologically mapped in southern Africa. Mapping these movements has a practical application: due to safety concerns produced by the large deep-seated mass movements, morphological maps will contribute to landslide susceptibility maps as well as landslide inventory maps produced in the Drakensberg region.

Mass movements can also have potentially catastrophic impacts on the environment, economy and safety of individuals (Azañón *et al.*, 2005; Alexander, 2008; Alimohammadlou *et al.*, 2013). The abundant scars and impacts of recent and palaeo, as well as shallow and deep-seated mass movements are visible in mountainous regions worldwide, and reveal the influence mass movements have on the evolution of landscapes (Guzetti *et al.*, 1999). Due to the extreme hydromatic conditions needed to form or activate deep-seated landslides palaeo-mass movements can often be used as geomorphological indicators of previous climate conditions (Pánek *et al.*, 2008).

This study aims to assess the distribution and characteristics of palaeo-mass movements throughout the northern and central Drakensberg, and will describe their distribution in relation to geological and geomorphological settings. The discovery of palaeo-mass movements was made possible by accumulating identifiable features in a set of criteria (typically common geomorphic features found on previously identified mass movements throughout the world) and using these criteria on satellite imagery to locate the movements. The sites are classified and a further assessment of this study is to map each mass movement to provide a broad overview of the controlling factors leading to the separate events.

Defining deep-seated palaeo-mass movements

A mass movement can be defined as a downward and outward movement of slope-forming material under the influence of gravity, sometimes including a transporting medium such as water, air or ice (Goudie, 2004). Over time this mass movements becomes more integrated into the landscape and will then be typically described as a relict, dormant or palaeo-geomorphic feature. The term 'large deep-seated palaeo mass movement' is often ambiguous and used without consideration of its morphometric, type, and age it imposes on the characteristics of landslides. The term 'large' refers to the size of the landslide or area of slope material affected, and for the purpose of this study is defined by Van Schalkwyk and Thomas (1991) as 100 000 m^2 to 1 000 000m^2. 'Deep-seated' refers to the material and depth of the landslide. The majority of landslides occurring in the Drakensberg today are shallow landslides that involves only soil as a source material, usually caused by rainfall events (Paige-Green, 1989; Singh *et al.*, 2008). Therefore, it can be understood that the material involved with a deep-seated landslide contains both soil and bedrock and occurs at a greater depth than their shallow counterparts. The term palaeo implies that the landslide is not a recent event and that the landslides are in a dormant or inactive state, consequently referring to the age of the movement itself. Mather *et al.* (2003) revised a system (Appendix A), first created by Dikau *et al.*

(1996), for defining the active state of a landslide and summarizes possible identifiable geomorphic characteristics. The system is divided into sections based on the state of movement. The first division is whether the landslide is still active. If not, it can be considered dormant. Dormant landslides can further be divided into young, mature, old and ancient. According to this system an ancient landslide is a landslide that is inactive and includes the following criteria; the cause of the movement unknown, the main scarp of the landslide may be partially if not completely removed by erosion, as well as the lateral margins, and the internal morphology is fully integrated into the existing topography (Mather *et al.*, 2003). Relict or palaeo-mass movements can thus be classified in a broader sense, as movements or slope failures that were modified by erosion, stream incision and development of slope profiles, losing some of its identifiable features and creating a fossil footprint of the previous geomorphic and climatic actors in the region. Figure 1.1 is an example of a rotational palaeo landslide that is found in the Drakensberg which was mapped by Singh (2009). It is clear that some of the features whereby a mass movement can be readily identifiable become less observable over time.

Figure 1.1: Meander mass movement in the southern Drakensberg (outline in black) (Singh, 2009).

Sumner and Meiklejohn (2000) described possible occurrences of palaeo-mass wasting features in the Drakensberg as rotational sliding and slumping that incorporate bedrock, translational sliding and soil creep, forming stepped micro-relief in the shape of terraces. Even though possible causes for large deep-seated palaeo-mass movements in the Drakensberg are still uncertain, Sumner and Meiklejohn (2000) note that increased fluvial incision resulted from rejuvenated streams in the Drakensberg causes slope over-steepening that leads to deep-seated mass movement events. In the study done by Azañón *et al.* (2005), it was explained that active tectonic regions are usually characterized by high local relief with incised valleys and moderately inclined hill slopes. Erosion in such areas, except at very high elevation, is dominated by fluvial process, and Azañón *et al.* (2005) thus suggested that mass movement activities are one of the main processes that sculpt the landscape. Previous studies by both Bijker (2001) and Singh (2009) found that palaeo-mass movements can be extremely large, for example, an entire slope in the lower Injisuthi valley (approximately 2,4km in length), has been noted by Bijker (2001) as a palaeo-landslide zone. Tectonic uplift, directly or indirectly, can result in deep-seated mass movement events. Singh *et al.* (2008: 39) argue that recent landslides can be triggered by anthropogenic influences, but are 'mainly small to medium-sized features triggered by high intensity, prolonged rainfall events'. This suggests that deep-seated mass movement events, indicated by Boelhouwers (1992), Bijker (2001), Singh *et al.* (2008) and Singh (2009), may be the result of a large-scale phenomenon, such as a tectonic uplift.

Another possibility as to how these palaeo-mass movements could have occurred is given by Bijker (2001: 17), who states that 'one of the major causes of deep-seated palaeo landslides that involve bedrock and major rational slumping in the Injisuthi valley is the position of dolerite sills and dykes'. Both Sumner and Meiklejohn (2000), Bijker (2001) and Singh (2009) suggest that the role of the dolerite intrusions cannot be ignored and thus the lithological control of these mass movements also needs to be studied in order to fully understand the causes of the deep-seated mass movements.

Motivation

Palaeo-mass movements played an important role in the formation of the Drakensberg landscape and are a fascinating result of the formation of the Drakensberg and the southern African escarpment (Singh *et al.*, 2008). The central and northern Drakensberg have been geologically mapped, but little attention was given to the existence of these palaeo-mass movements (Singh *et al.*, 2008). Due to the presence of palaeo-mass movements in the Drakensberg, identifying the location and geomorphologically mapping the palaeo-mass movements are the first steps in understanding the formation of the Drakensberg landscape (Boelhouwers, 1992). Mapping the distribution and geomorphic characteristics of these movements may provide critical information on how and why they occurred. As a result, if the formation of palaeo-mass movements is understood and dating could be achieved to a certain accuracy, the palaeo-mass movements could serve as a possible climate proxy and can be considered as geomorphological indicators of a palaeo environment, which could provide useful information for future climate change research. Geomorphological features, such as the remains of a mass movement and understanding the responses of the physical environment, are relevant in environmental change studies (Sumner and Meiklejohn, 2000).

Currently the impact of mass movements is significantly underestimated, even though safety issues have been well documented and indicate that mass movements pose a continuing threat to socio-economic activities throughout the world (Blaschke *et al.*, 2000; Alexander, 2008). According to the Disaster Statistical Review of 2012 (Guha-Sapi *et al.*, 2013), geophysical disasters (earthquakes/tsunamis, volcanoes and dry mass movements), caused 63.7% of deaths, globally, related to disasters from 2001 to 2011, which is an average of 8.1 million victims annually. Over a seven-year time period, 2004 to 2010, 2620 fatal landslides were recorded causing 32 322 fatalities globally (Petley, 2012). In southern Africa, the immediate threat of mass movement is less pronounced, but in the Drakensberg palaeo-mass movement deposits often provide a relatively horizontal area in relation to the surrounding steep areas. It is not uncommon for infrastructure and settlements to have been developed in these areas or used as farm land. Guzetti *et al.* (1999) argued that population growth and expansion of settlements over hazardous areas are increasing the impact of natural disasters. It is accepted that palaeo-mass movements appear to be stable, but could still develop into hazardous environments. New and smaller movements, as well as gully erosion, are prone to occur on these older sites (Singh *et al.*, 2008) and could in the future reactivate further large-scale movement. Furthermore, mass movement failures influence the topographical, geological and hydrological settings on the slope and can reduce the stability of the slope (Guzetti *et al.*, 1999). Reactivation of large landslides causes massive changes in the slope morphology and, together with scarp retreat, can cause substantial damage to infrastructure and socio-economical activities (Borgatti *et al.*, 2006). It is thus important to determine the locations of palaeo movements. This knowledge can provide valuable information on safety and hazardous environments and contribute to hazard zoning as well as future mass movement susceptibility maps in the Drakensberg.

Aims and Objectives

The aim of this study is to determine the distribution and characteristics of deep-seated palaeo-mass movements features in the Drakensberg, in order to identify the extent of and the influence of deep-seated mass movements on the Drakensberg landscape. Important issues for consideration were the identification of palaeo-mass movements, as well as the type, relative age and influence of the sites throughout the central and northern Drakensberg. In addition, it is necessary to create diagnostic criteria by which one can evaluate the possible sites and which can also be used in further studies. At each site it was thus crucial to provide enough clear geomorphological evidence to confirm the sites as palaeo-mass movements, through in-the-field research. The study also aims to examine the possibility that these large mass movements were the product of massive uplifts that occurred during the Miocene and Pliocene epochs.

Objectives

1. To locate various mass movements through interpretation of aerial photography using diagnostic criteria.
2. To conduct in-field confirmation and identification of each possible movement, also through the use of a set criteria.
3. To provide detailed geomorphological site maps of the palaeo-mass movements.
4. To examine and discuss the possible origins of deep-seated palaeo-mass movements in the Drakensberg.

Thesis Outline

In Chapter two, the literature review, both national and international classification methods are discussed. Another focal point is on type of mass movements, conditioning and triggering factors for large mass movement events. After the literature review, chapter three focuses on the study area, including the geological and climatic history of the area. Chapter four focuses on methods used to identify mass movements and includes the explanation of the criteria. The results are shown in Chapter five. The results are discussed according to location, where the mass movements are described and a map of each mass movement event can be found. Chapter six contains the discussion and the conclusion is contained in Chapter seven.

Chapter 2: Literature review

Introduction

This chapter focuses on defining the term 'mass movement' by referring to the classical mass movement types (Varnes, 1958) and previously used classification systems such as Hungr *et al.* (2001) and Hungr *et al.* (2014). The chapter will continue on the initiation and conditioning events leading to mass movements and recent research on deep-seated palaeo-mass movements both internationally and in the southern African environment will be discussed.

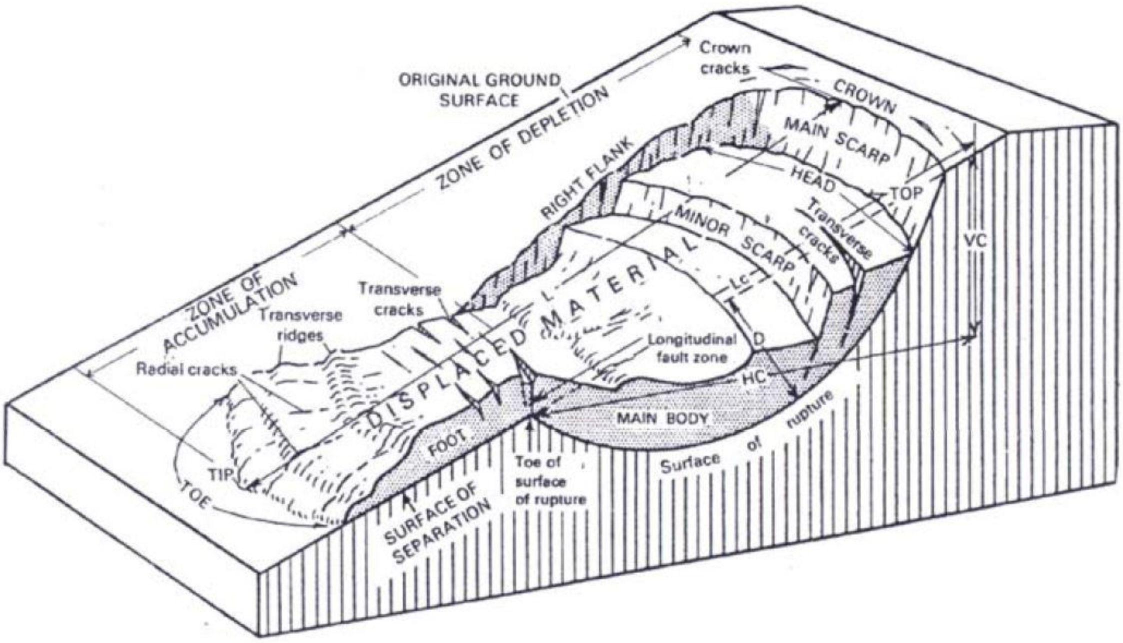
Mass movement types

Varnes (1958; 1978) set the framework for future type and classifications models. Even though the Varnes (1978) classification was modified in 1996 by Cruden and Varnes, the 1978 version has become the universally accepted classification of mass movements. The basic different forms identified by Varnes (1958; 1978) are falls, topples, slides, spreads and flows which are differentiated mainly by type and rate of failure, as well as the type of material. There have been various expansions and adaptations to these forms by different authors such as Hungr *et al.* (2001), Hardwick (2012) and Hungr *et al.* (2014). However, the classification is usually modified to suit the specific studies due to the complexity of mass movements (Hungr *et al.*, 2014).

In this study the following five types are acknowledged: falls, topples, slides, spreads and flows. Taken into consideration are the types and forms identified by Varnes (1978) and Hungr *et al.* (2014). The following section provides short descriptions of different types of mass movements, although it does not include variations such as relict mass movements or the effect of weathering on the form of the movement itself. Although rock falls are included in the classification, it has been excluded as a type of movement looked for in this study.

Nomenclature, types and classification of mass movements

Due to the variety of classifications and characteristics of mass movements it is necessary to define a set terminology to describe the different features of movements. Figure 2.1 shows the nomenclature used to describe a rotational mass movement (Varnes, 1958). This nomenclature is adapted from Varnes (1958) to suit different types of movements.



General nomenclature according to Varnes (1958) adopted for description of different mass movement types.

Main Scarp: A steep surface on the undisturbed ground around the periphery of the slide, caused by the movement of slide material away from undisturbed ground. The projection of the scarp surface under the displaced material becomes the surface of rupture.
Minor Scarp: A steep surface on the displaced material produced by differential movements within the sliding mass.
Head: The upper parts of the slide material along the contact between the displaced material and the main scarp.
Top: The highest point of contact between the displaced material and the main scarp.
Toe of Surface of Rupture: The intersection (sometimes buried) between the lower part of the surface of rupture and the original ground surface.
Toe: The margin of displaced material most distant from the main scarp.
Tip: The point on the toe most distant from the top of the slide.
Foot: The portion of the displaced material that lies downslope from the toe of the surface of rupture.
Main Body: That part of the displaced material that overlies the surface of rupture between the main scarp and toe of the surface of rupture.
Flank: The side of the landslide.
Crown: The material that is still in place, practically undisplaced and adjacent to the highest parts of the main scarp.
Original Ground Surface: The slope that existed before the movement which is being considered took place. If this is the surface of an older landslide, that fact should be stated.
Left and Right: Compass directions are preferable in describing a slide, but if right and left are used they refer to the slide as viewed from the crown.
Surface of Separation: The surface separating displaced material from stable material but not known to have been a surface of which failure occurred.
Displaced Material: The material that has moved away from its original position on the slope. It may be in a deformed or unreformed state.
Zone of Depletion: The area within which the displaced material lies below the original ground surface.
Zone of Accumulation: The area within which the displaced material lies above the original ground surface.
Runout: The horizontal travel distance achieved by a landslide

Figure 2.1: Nomenclature of an idealised mass movement (Varnes, 1978), obtained from Singh (2009).

Falls

Falls are rocks that detach from a steep slope or a near vertical slope (Cruden and Varnes, 1996); the boulders descend rapidly, falling through the air, leaping and rolling downslope. These are usually rapid to very rapid movements (Cornforth and Cornfroth, 2005). With steep vertical sides or overhangs, the movement occurs quickly until it reaches the foot of the slope where the material will accumulate. The distance of the movement is controlled by the topography of the slope and the movement can be caused by earthquakes, rainfall, freeze and thaw cycles or weathering of rock material (Agliardi and Crosta, 2003). Within bedrock, separation usually occurs at weaknesses within the rock itself. Shear surfaces form along joints, faults and bedding planes that are weathered and enlarged by erosional processes. Rock falls are usually individual or fragmental falls and occur in mountainous regions if there are steep escarpments, cliffs or rock walls (Tanarro and Muñoz, 2012). Therefore, rock falls occur in the basalt and Clarens scarps in the Drakensberg (De Lemos, 2013). Rock falls can also subsequently occur during or after a mass movement such as a slide. It may be considered then either as a part of the movement or as a separate event.

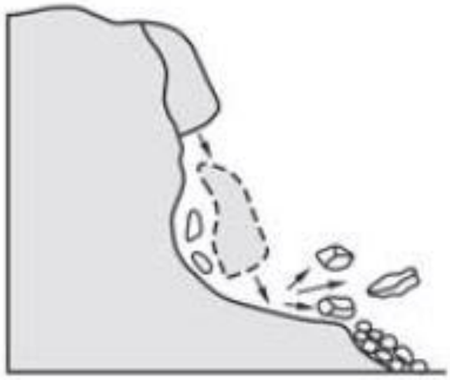


Figure 2.2: The displacement of a rock from a steep slope due to undercutting, forming a rock fall (Varnes, 1978).

Topples

Topples are a forward rotation of slope material around a pivot point or a hinge below the centre of gravity of the displaced mass. This occurs under the action of gravity and forces exerted by adjacent units in the slope or fluids in cracks formed in joints. The resulting loose material may fall, roll and bounce downslope, but a key feature is the main movement that it tilts before it detaches and collapses (Parise, 2002). Brideau and Stead (2010) stated that toppling is more complicated and further discussed toppling in three distinct methods depending on the material; block, flexural and block-flexure. Multiple rock block-toppling can occur with sliding in a strong but jointed material (Hungr *et al.*, 2014). Two different mechanisms are involved in the formation of a topple. Shown in Figure 2.3 A, is a detached mass that collapses forward. However, secondary topples can occur due to a previously formed deep-seated mass movement, as shown in Figure 2.3 B. An example can be seen in Nichol *et al.* (2002) with regards to Mount Breakenbridge and Mystery Creek in British Columbia, Canada. Similar to falls, toppling would occur in the steep basalt and Clarens escarpments (De Lemos, 2013).

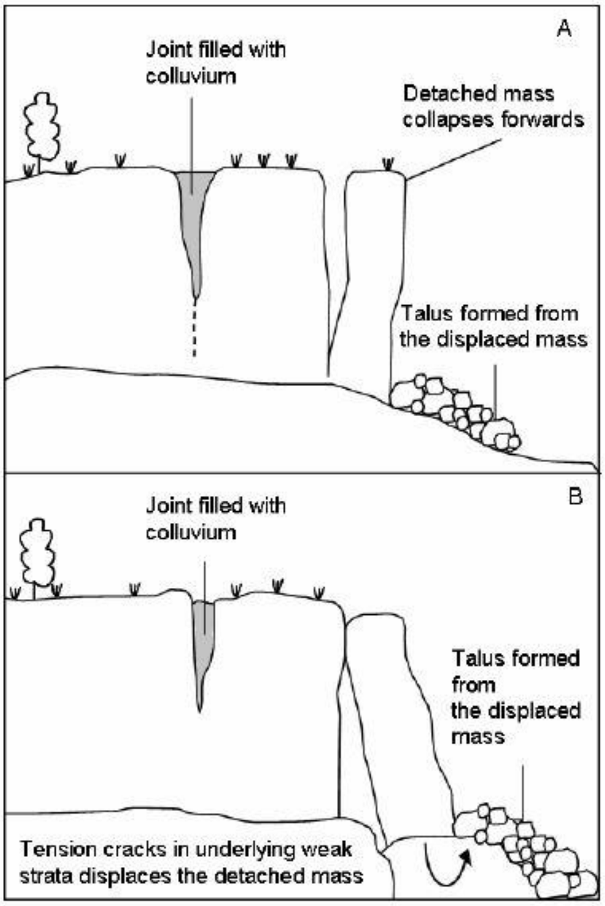


Figure 2.3: Two different mechanisms are found in the formation of topples. Figure A shows the rotation of a rock mass around the base of the slope, separated along a joint. Figure B shows possible rock mass that has been tilted due to a deep-seated rotational slide at its base (Cruden and Varnes, 1996).

Slides

All movements that occur and move downslope along a recognisable shear surface or a surface of rupture are considered to be slides. It is possible that a slide may progress into a flow or more than one type of mass movement. These are known as complex or composite slides (multiple or series of movement events) and usually have longer run-out lengths than a single slide. Movements such as rock-falls and -slides may trigger debris flows or debris avalanches of saturated talus or soils (Hungr *et al.*, 2014), such as the devastating Oso landslide that transitioned into a debris flow in 2014 (Wartman *et al.*, 2015).

In the classical classification, Varnes (1978) identifies two different types of slides according to the geometry of the slide’s rupture surface, namely rotational (Figure 2.1) and translational (Figure

2.4) landslides. Hungr *et al.* (2014) identified another type of slide mostly found in bedrock loads, namely the compound slide. There can be more than one style of movement due to changes in material behavioural properties, justifying the need for a complex landslide.

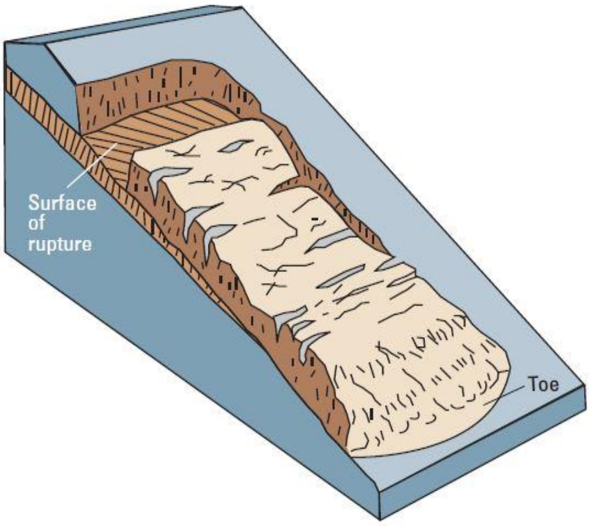


Figure 2.4: A shallow translational landslide (Highland and Bobrowsky, 2008) adapted from Cruden and Varnes (1996)

Rotational slides are often referred to as slumps or slips. According to Hungr *et al.* (2014) rotational slides (Figure 2.1) occur in weak rock masses often capped with a harder rock. The surface of rupture on a rotational slide has a concave curved shape and the motion of material is rotated. It is usually also characterised by a prominent main scarp, a titled 'bench' or terrace (Hungr *et al.,* 2014*),* and the displaced mass experiences little deformation. Terraces can be angled or dipped. The majority of deposited material will move vertically downwards from the main scarp as the upper surface rotates backwards toward the scarp (Highland and Bobrowsky, 2008). The event will usually occur moderately slowly. Rotational slides are common features and many examples are reported in the literature, such as the Collinabos landslide (Van Den Eeckhaut *et al.*, 2007), and in the Drakensberg, Boelhouwers (1992) identified the Bushman's River Valley rotational slide.

Translational slides occur on a planar shear surface characterised by a steep scarp, often U-shaped, where the slide head may separate from the stable rock along a deep, vertical tension crack. Hardwick (2012) argues that translational slides are usually shallow, but Hungr *et al.* (2014: 174) states that 'some of the largest and most damaging landslides on Earth are translational slides'. The movement usually occurs in a fast motion, depending on the weakness of the rock and the angle of the shear surface. The slope angle can vary from 11˚ to 50˚ and if the angle is large, the deposited material and the velocity of the slide will be higher than a typical rotational slide. The material may consist of loose, unconsolidated soils to extensive rock slabs, usually both. Failure usually occurs along faults, joints or contact zones between different layers of rock (Highland and Bobrowsky, 2008). Translation slides are also common in the literature, such as the Mocatán Landslide in Spain (Mather *et al.*, 2003) and the slide from Mt. Granier (Cruden and Antoine, 1984).

The compound slide differs from the translational and rotational slide as it consists of several shear surfaces or a surface of uneven curvature. Common features are horsts-and-grabens at the main scarp and significant distortion, as well as hummocky terrain in the accumulation zone. According to Hungr *et al.* (2014), the compound slide frequently occurs when the material rests upon a gently inclined to near horizontal plane of weakness, such as a weak layer in the stratigraphy. 'The shape of the shear zone may be bi-linear or curved but noncircular' (Hungr *et al.*, 2014: 175), including a steep main scarp that can form part of the rupture surface. Figure 2.5 is an illustration of a compound slide in the cretaceous shale in Liard Plateau, British Columbia.

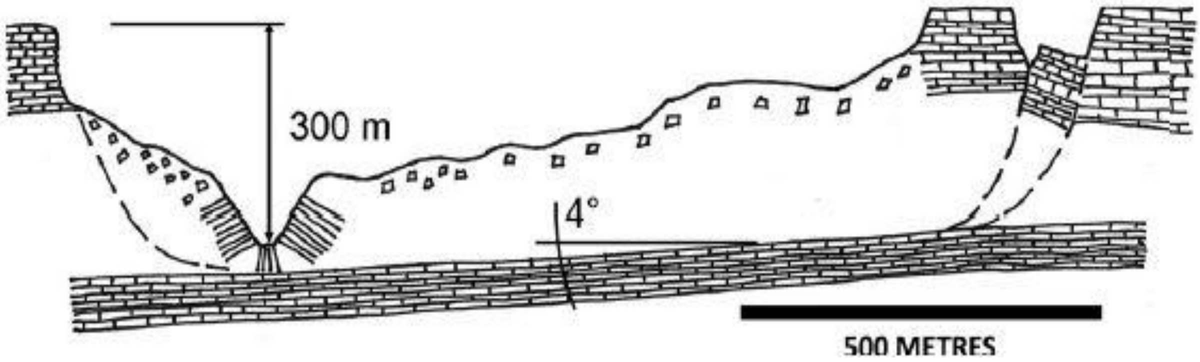


Figure 2.5: A compound landslide, with the horst-and-graben features on the right (Gerath and Hungr, 1983)

Flows

Flows can be defined as having a liquid property. The displaced mass represents a viscous liquid and moves as fluid over rigid beds (Singh, 2009), but in some cases the amount of water within the movement can be negligible (Davies *et al.*, 2013). The material properties can lead to different forms and results of flows; strong stiff plastic flows can lead to thick lobes, while more fluid flows can lead to fans and levees that could mould around rigid structures (Wilford *et al.*, 2004). Hungr *et al.* (2001) divides flows into a further ten categories depending on the material, water content, velocity and certain conditions such as flooding or excess water pore-pressure. Although most recent flows in the Drakensberg are superficial, there are rock avalanches and it is possible that a large rockslide can develop during movement downslope into a very fast flow of fragmented rock. Deep-seated flows often happen first as a landslide and then develop further as a flow extending long distances (Hungr *et al.*, 2014). Hungr *et al.* (2001: 226) elaborates on a flow slide and states that in a flow, collapsed material exists that would maintain significant moisture content: 'After an initial deformation, or as a result from earthquake shaking, the metastable structure collapses and the material liquefies, with a dramatic reduction in strength'. These deep-seated flows are among the most dangerous movements and can displace material more than 2km away from the depletion zone. Figure 2.6 illustrates a superficial flow in the Drakensberg. Flows are frequent forms of denudation, such as the debris flows in the Cederberg mountains (Boelhouwers *et al.*, 1999).

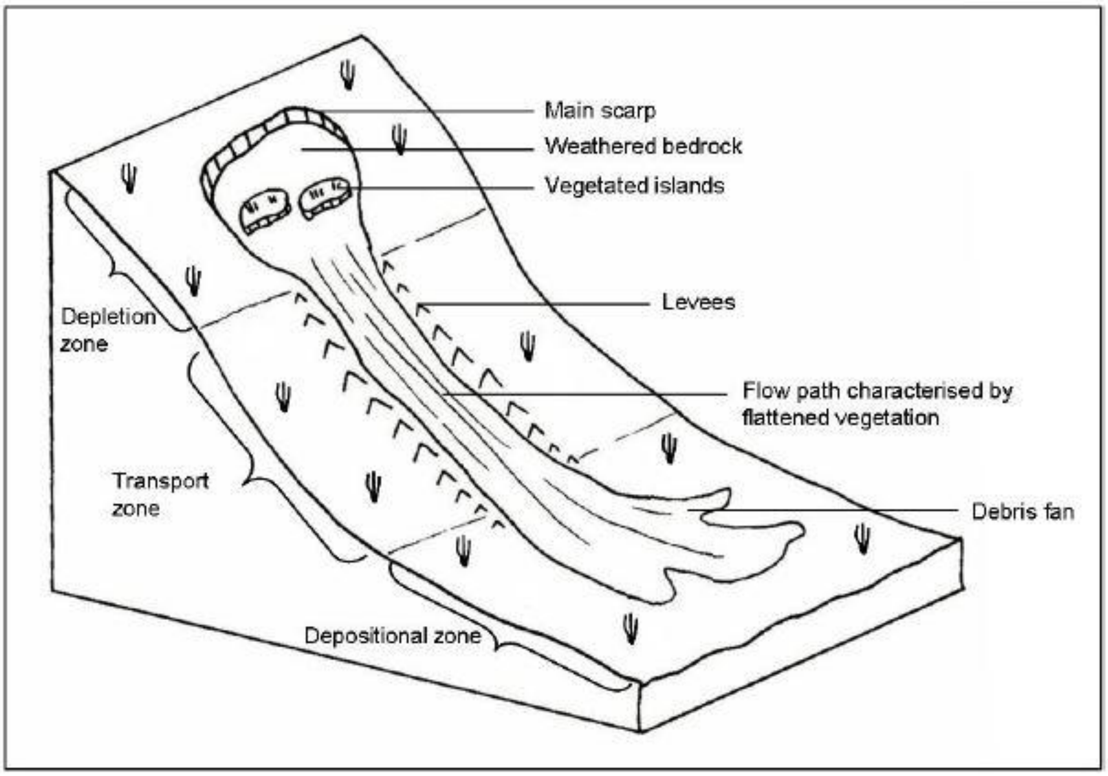


Figure 2.6: A superficial flow, typically a few meters in length but can reach to longer lengths depending on the slope and velocity (Hardwick, 2012).

Spread

Spreads can be categorised under slides due to the fact that there is a surface of rupture that are distinctive of slides in soil or rock over a very gentle inclined terrain or slope (Singh, 2009). Hungr *et al.* (2014), however, describes a spread as an elongation or stretching mass of coherent blocks or rocks due to plastic deformation of a weak underlying rock layer. When the shear surface is distinct, either a thin shear or a thin shear band, it refers to a compound slide. The defining feature of a spread is multiple retrogressive sliding failures over a single weak horizon. There are various forms of spreading depending on the material and formation of the softer underlying material. These include block spreads, liquefaction spreads and lateral spreads (Highland and Bobrowsky, 2008). Clear instances are observable in British Columbia, west of Mount Gunnel and Halden Creek (Geertsema and Cruden, 2009).

Overview of classifications of mass movements

Landslide classifications systems are essentially descriptive tools that reflect the needs of the user (Singh, 2009). Therefore, a large selection of different classification methodologies exists, based on different aspects, and dependant on each user's needs. Hungr *et al.* (2001) explains that a classification system can be either taxonomic or typological. Taxonomic classification is based on 'a hierarchy of descriptors to form a branching structure' (Hungr *et al.*, 2001: 222), while the typological classification, as Hungr *et al.* (2001) explain, is similar to a filing system based on certain attributes. Therefore, common defining attributes are the mechanism, material type and velocity of the movement. The most commonly accepted international classification method is the Varnes method (Varnes, 1978) (Table 2.1) which has been used in various landslide inventory maps (Van Den Eeckhaut *et al.*, 2011). Hungr *et al.* (2014) adapted this classification and broadened the types of movements by classifying them according to type of movement as well as type of material. This classification has also been used in various modern studies to identify palaeo-mass movements (Kojima *et al.*, 2015), but it is difficult to isolate and determine one single cause for the failure of the movement by which you can classify the event (Duncan and Wright, 2005). In many studies, the term 'landslide' is commonly used, but one defining factor in international palaeo studies is the existence of a slip surface, and not many more classifying categories. Therefore, the term 'landslide' is very broad and encompasses a large variety of different aspects, although the surface of rupture is usually clearly explained and defined (Pánek *et al.*, 2014). These aspects carry over to palaeo-mass movements and as a result are hard to classify.

Table 2.1: Varnes' (1978) classification of mass movements.

Type of movement	**Type of material**				
	Bed rock		**Bed rock**	**Engineering soils**	
				Predominantly coarse	**Predominantly Fine**
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	Rotational	Few units	Rock slump	Debris slump	Earth slump
			Rock block slide	Debris block slide	Earth block slide
	Translational	Many units	Rock slide	Debris slide	Earth slide
Lateral spread			Rock spread	Debris spread	Earth spread
Flows			Rock creep	Debris flow	Earth flow
			Deep creep	Soil creep	
Complex	Combination of two or more principle types of movement				

Many large deep-seated palaeo-mass movements consist of first, second and even third separate movement events. In such cases, it is necessary to distinguish the different movements in a more complex manner and look at the movement itself more completely than most classifications are capable of. The term 'slide' or any other single type will not be sufficiently discernible in most large palaeo-mass movements that occur in the Drakensberg. Hungr *et al.* (2014) suggested that the material type should be expanded and reworked to include more complicated mass movements into a single classification, as per the Cruden and Varnes (1996) classification.

Hardwick (2012), Singh *et al.* (2008) and Singh (2009), adapted the classical classification of Varnes (1978) (Table 2.1) to different types of mass movements for the South African context. Table 2.2 illustrates the classification Singh *et al.* (2008) adopted, where the main discerning factor is the type of movement: fall, topple, slide, spread or flow. Secondary factors include the type of material that discerns between bedrock and soil, dividing the latter into material size; coarse or fine.

Table 2.2 Singh's *et al.* (2008) adopted classification of mass movements in South Africa.

	Type of material		
Type of movement	**Bedrock**	**Engineering Soils**	
		Predominately Coarse	**Predominately Fine**
Fall	Rock fall	Debris fall	Earth flow
Topple	Rock topple	Debris topple	Earth topple
Slide	Rockslide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Rock flow	Debris flow	Earth flow
Undifferentiated	Type of movement not qualified		

In addition, Singh *et al.* (2008) and Singh (2009) identified the need to distinguish the movement further by size (Table 2.3) and age. Table 2.3 shows adescriptive elements compared to size, therefore any mass movement larger than 1 000 000m^2 will be classified as very large, with categories of large, medium, small and very small as the size of the movement decreases.

Table 2.3 Singh's (2008) adopted classification of a mass movement by areal extent and size (after Schalkwyk and Thomas (1991)).

Size of mass movement	**Description**
0.01-10.00 m^2	Very small
10.01-1000.00 m^2	Small
1000.01-100 000.00 m^2	Medium
100 000.01-1 000 000.00 m^2	Large
>1 000 000.00 m^2	Very large

The classification for mass movement in the Drakensberg, as proposed by Hardwick (2012), is based on movement type, the primary discerning factor, while the coherency of displaced material and style of activity is used to create subclasses. To be suitable for the Drakensberg region, Hardwick's classifications were adapted from Cruden and Varnes (1996) as well as Hutchinson (1988), and identified the following types of mass movements: falls, topples, slides and flows, classifying spreads under flows. Table 2.4 shows the suggested classification proposed by Hardwick (2012). According to this classification, it is possible to have a multiple or a single event slide. For the use of palaeo research, a time-scale is a necessary attribute in the classification system, and due to the fact that one was not included in the classification proposed by Hardwick (2012), the classification will need to be adapted to be suitable for palaeo-mass movements.

Table 2.4: Hardwick's proposed classification (2012: 78).

Material with the behavioural properties of a:	Type of movement	Style of movement
Solid (rocks and boulders, consolidated soil mass)	**Fall** Displaced material moves down and away from its original position, may freefall, bounce or roll.	**Single** Movement occurs as a single event.
Plastic (particles of varying sizes, capable of being remoulded)	**Topple** Displaced material displays a pivot action and rotates forward before moving down and away from its original position.	**Multiple** Repeated events of the same type of motion in the same general location and along the same shear surface.
Liquid (particles of varying sizes where cohesion is less)	**Slide** Displaced material moves along a shear surface that is easily identifiable as either a: *Translational slide* – movement is forward and parallel to a planar shear surface, or a *Rotational slide* – movement is backward and along a curved shear surface.	**Composite** Two or more types of movement occurs simultaneously or as a result of an initial movement.
	Flow Material moves along a shear surface and parallel to the slope at a velocity dependent on the coherency of the mass. The plastic-liquid limit of the displaced material determines whether the flow occurs as a: *Creep flow* – displaced material shifts downslope in sheets and has a curved wave-like form. *Surficial flow* – displaced material flows over the surface of the slope, depositing displaced material as it flows downslope. *Incised flow* – displaced material has gouging effect on slope material, removing slope material as it flows downslope.	

Conditioning and trigger factors leading to mass movements

Large deep-seated palaeo-mass movements do not occur linearly over time, but usually occur in separate distinct phases which results in clusters of mass movements. The first is a pre-failure phase which can last up to 10^4 years and is followed by a triggering phase (Zerathe *et al.*, 2014). Crosta *et al.* (2013) further divided the pre-failure phase and triggering phase for deep-seated mass movements into three important sections: predisposing, preparatory and triggering. Each section plays an important role in the stability and control of the slope. The pre-failure phase consists of a series of cause and effect events or a series of preparatory or conditioning factors that leads to an increase of shear stress or reduction in shear strength, increasing the likelihood of a mass movement event. Although mass movements develop due to a series of pre-emptive conditions, they require a trigger mechanism as an initiation event which directly leads to an abrupt response in a slope movement. Predisposing factors include lithology, rock mass characteristics, tectonic stress regime, valley geometry and the structural domain. The geological setting both determines and controls the type of the movement (Borgatti *et al.*, 2006). Preparatory factors include deglaciation rates, topographic stresses, weathering, increases in the load of the slope or changes in the loading forces, changes in the valley geometry and uplift rate. Triggering factors include climate changes, water level changes, seismic activity and excessive rainfall events (Crozier *et al.*, 1995; Schmidt and Beyer, 2002; Schuster and Wieczorek, 2002; Prokešová *et al.*, 2013). The orientation of the slope is an important factor as well, since 48% of all landslides occur in the equator facing slopes. This can be attributed to the higher and greater insulation, wetting and drying cycles, soil cracking, infiltration and pore-water pressures leading to valley asymmetry (Mills, 2006). 'Generally, slope stability is related to the balance between the stimulating factors (that increase shear stress) and the parameters that supply the soil mass resistance against sliding' (Alimohammadlou *et al.*, 2013: 220). Ultimately, slope instability occurs when the shear stress of the slope is greater than the shear strength of the slope, causing the equilibrium between shear stress and shear strength to falter. This occurs either by a decrease in shear strength or an increase in shear stress (Duncan and Wright, 2005).

Factors that increase shear stress

Factors that increase shear stress include load increase of slope material on higher parts of the slope, as well as overloading soil or rock weight by water. If cracks at the top of the slope are filled with water it loads the slope increasing the weight. Water pressure in the cracks increases the hydrostatic water pressure, which also increases shear stress. Removal of lateral support at the bottom of the slope ultimately increases the effective height and angle of the slope, which can either be caused by natural processes or by human activities, and ultimately leads to an increase in shear stress (Duncan and Wright, 2005). In terms of large deep-seated palaeo-mass movements, it is possible that human activities can lead to reactivation of the movement. Slope angle is an important factor and can increase due to tectonic uplifts where the secondary result of the uplift is a rejuvenation in river processes. This results in renewed stream incision that increases vertical erosion and leads to steepening of valley sides (Sumner and Meiklejohn, 2000), and undercutting of the slope material leads to a progressive increase in shear stress (Crozier *et al.*, 1995).

Factors that decrease shear strength

Shear strength of a slope is the resistance factor of the slope. The weathering of rocks reduces the strength of the slope as a whole and chemical processes can change the composition into a completely different material with different properties (Duncan and Wright, 2005). Vegetation removal can also lead to a decline in shear strength. Slope material that has inherently weak characteristics or discontinuities has low strength properties and can easily weaken under weathering and other external stresses. If the initial state of material changes due to chemical weathering, the resulting shear strength weakens considerably (Hardwick, 2012). For example, clayey rock material that is naturally weak will soften and hydrate, or desiccate, crack and disintegrate if changes are brought onto the original state of composition, texture or lithology of the slope materials.

Trigger events

The most common trigger events are rainfall, snowmelt, water level changes, volcanic eruptions and seismic events (Prokešová *et al.*, 2013). It is, however, evident from historically documented case studies that rainfall is the most prominent trigger of mass movements (Eisbacher and Clague, 1984; Gruner, 2006). Higher pore-pressure leads to large slope movements by increasing seepage forces and lowering the effective stresses (Bonzanigo *et al.*, 2000). 'It also accelerate[s] the velocity of subcritical crack growth (Atkinson and Meredith, 1987) and reduce[s] the friction angle of weathered and water saturated rock surfaces, which is generally lower than that of dry and unweathered ones' (Prager *et al.*, 2008: 392). Links are found between both landslide occurrences and extreme rainfall events, as well as landslides and long-term rainfall seasons (Prokešová *et al.*, 2013). High intensity, short duration storms are commonly described as mass movement trigger events in the Drakensberg (Bijker, 2001), but large deep-seated events would require a long duration and a large quantity of water in order for a whole slope and entire valley slope to be affected. It is a known fact that frequent or large earthquakes are also a leading cause of landslide events (Crozier *et al.*, 1995); the repeated seismic shaking can reduce the shear strength within a slope and cause changes in the hydraulic conductivities (Prager *et al.*, 2008). Climate change over periods can also influence the frequency and magnitude of mass movements, such as increases in precipitation, deglaciation, glacial debutressing, permafrost degradation and changes in sediment supply (Trauth *et al.*, 2000; Stoffel and Huggel, 2012). Pánek indicates that humid climatic phases played an important role in the formation of a series of large landslides found in the Flysch Carpathians (Pánek *et al.*, 2014).

The resulting different initiating triggers cause mass movements to occur at different scales, rates and magnitudes. A very large sudden soil block slide in the Bogd Fault, Mongolia, could have been triggered by seismic activities (Philip and Ritz, 1999), while the Waitawithi Landslide Complex was most likely triggered by fluvial incision (Lacoste *et al.*, 2009), proving a variety in mass movements events. Pánek *et al.* (2010) found that most recent mass movements in central Europe occur during high rainfall events and are presented in the form of shallow instabilities. There is, however, evidence of concentrated relict/palaeo deep-seated mass movements of which the origins can be related to major palaeo-geographical changes experienced in the region. Deep-seated mass movements are common in the Drakensberg (Boelhouwers, 1992) and other mountainous regions, even medium to low relief areas, as in Arroyo de Gor, Spain, where a series of rotational landslides occurred due to river incision (Azañón *et al.*, 2005). Borgatti and Soldati (2010) argue that under specific conditions, such as fluvial undercutting related to stages of landscape evolution, concentrated events are produced.

Previous studies

The focus of international studies on mass movements has predominately been on recent events, which typically involve the prevention and prediction of mass movements and the assessment of hazardous environments. Table 2.5 indicates recent topics of movement research. Mass movement studies include broad fields, such as geo-informatics and the use of remote sensing techniques, slope hydrology, geology and the use of various methods such as carbon dating to assist with the research. Often, studies such as that of Tanarro and Muñoz (2012) on rock-falls, Crosta *et al.* (2013) on deep-seated gravitation deformations, Wartman *et al.* (2015) on the catastrophic Oso landslide and Champati Ray *et al.* (2016) on the Kedarnath landslide, focus on the causes of recent large events or a series of shallow events where the characterization and classification, as well as influences of various elements associated with the trigger of the event, are assessed. Multiple studies on the mechanics of landslides and the triggers causing slope stability failures have been done, such as Dang *et al.* (2016) that studied the mechanism of rapid long-runout landslides triggered by the Kumamoto earthquakes. There has been developments and improved methods of 'morphological characterization, observation of dynamics, kinematic modelling and geochronological dating to better understand landslide processes' (Lebourg *et al.*, 2014: 1). The development of new technology, increasing quality and improvement of LiDAR DEMs and satellite imagery (Santangelo *et al.*, 2015), as well new technologies such as electrical resistivity tomography (EMT) (Pánek *et al.*, 2014) have largely contributed to improved research on mass movements. Furthermore, new methods increase the quality and output of detecting methods, susceptibility and inventory maps, leading to development with an ever-increasing accuracy in recent years. The development of landslide inventory and susceptibility maps form part of an important section of landslide research (Bishop *et al.*, 2012), including landslide hazard zonation, evaluation and mapping of a recent landslide events (Parise *et al.*, 2016). Studies done by Abdulwahid and Pradhan (2016) and by Ciampalini *et al.* (2016) are good examples. Abdulwahid and Pradhan (2016) used LiDAR to create a landslide susceptibility map for the Ringlet area of Cameron Highlands in Malaysia and Ciampalini *et al.* (2016) used permanent scatterer interferometric synthetic aperture radar data to improve a landslide susceptibility map of the Messina Province in Italy. Studies such as Hattanji and Moriwaki (2009) and Tien Bui *et al.* (2016) used new techniques to critically assess relict landslides in order to predict the outflow of future events. Various studies, such as Fabris and Pesci (2005) and Martha *et al.* (2010), have focused on automated detection of new landslides.

Table 2.5: A list of international studies on mass movements since 2010.

Topic	Authors
Geomorphological and structural characteristics of palaeo-mass movements and dating mass movements	Pánek *et al.* (2010), Šilhán and Pánek (2010), Chen *et al.* (2012), Pánek *et al.* (2012), Lebourg *et al.* (2014), Migoń *et al.* (2014), Pánek (2014), Zerathe *et al.* (2014), Bilcher *et al.* (2016).
Geomorphological and structural characteristics of individual recent landslide events	Aucelli *et al.* (2012), Crosta *et al.* (2013), Kojima *et al.* (2015), Wartman *et al.* (2015), Champati Ray *et al*. (2016)
Landslide susceptibility maps using DEM, LIDAR and remote sensing techniques	Van Den Eeckhaut *et al.* (2011), Abdulwahid and Pradhan (2016), Ciampalini *et al.* (2016)
Classification	Alimohammadlou *et al.* (2013), Hungr *et al.* (2014)
Landslide detection, prediction and monitoring	Fabris and Perci (2005), Martha *et al.* (2010), Tien Bui *et al.* (2016)
Landslide distribution and inventory mapping	Van Den Eeckhaut *et al.* (2011), Guzetti *et al.* (2012), Santangelo *et al.* (2015)
Climate change	Borgatti and Soldati (2010), Huggel *et al.* (2012), Stoffel and Huggel (2012), Gariano and Guzzetti (2016)
Triggers and mechanics	Verachtert *et al.* (2012), Davies *et al.* (2013), Prokešová *et al.* (2013), Dang *et al.* (2016)

Palaeo-mass movements

A relatively smaller component of mass movement research is the investigation of palaeo-mass movements. Studies done on palaeo-mass movements internationally are fewer than those on recent events, due to the fact that landslides will over time become more deteriorated and eroded which makes it hard to identify in field, or with aerial images and maps (Mather *et al.*, 2003).

The geomorphological and structural characteristics of individual or a series of palaeo-mass movements have been a frequent topic in palaeo-mass movement research. Examples of such studies were done by Philip and Ritz (1999), Mather *et al.* (2003), Azañón *et al.* (2005), Pánek *et al.* (2010; 2014), Aucelli *et al.* (2012), Lebourg *et al.* (2014), Migoń *et al.* (2014), and Kojima *et al.* (2015) to name a few. Further research topics on palaeo-mass movements include mis-interpretations of landforms, reactivation of relict movements (Prokešová *et al.*, 2013) and causes or trigger factors of large or palaeo-mass movement zones (Crozier *et al.*, 1995). It is, however, difficult to identify a specific trigger for a large deep-seated palaeo-mass movement (Lebourg *et al.*, 2014). Historical studies demonstrate a method of researching older movements, but are relatively uncommon for palaeo events in unpopulated areas and events stretching back further than a few hundred years. Climate change has been investigated as a trigger event and research has also been undertaken on the influence of climate change on the frequency and magnitude of mass movements (Gariano and Guzzetti, 2016). Several studies have found positive correlations between changes in weather patterns, such as deglaciation and an increase in water levels (Trauth *et al.*, 2000; Schmidt and Beyer, 2002; Huggel *et al.*, 2012; Stoffel and Huggel, 2012). Furthermore, there has been some discussion on the role palaeo-mass movements plays as a climatic indicator. A study done by Borgatti and Soldati (2010) focuses on palaeo-mass movements as a record of climate variability, and argues that studying old mass movements would provide valuable climate proxy data. Bichler *et al.* (2016) used dated palaeo landslide deposits within a valley as markers of glacial retreat. Between seismic and climatic events there is still uncertainty about which form of trigger plays a larger influencing role in the formation of landslides (Zerathe *et al.*, 2014). Therefore, Lebourg *et al.* (2014) argue that, due to the complex nature of deep-seated landslides, they need to be discussed in terms of their spatial context, temporal frequency and weathering conditions, as well as geological and geomorphological conditions.

More frequent and specific studies on palaeo-mass movements have been conducted in the European Alps, New Zealand, Poland and Russia, the U.K., Spain, Japan (Kojima *et al.*, 2015) and also China (Chen *et al.*, 2012). An important study, which has a correlation with the focus of this dissertation, was carried out by Mather *et al.* (2003). Mather *et al.* (2003) investigated the features and classification of a relict mass movement in the Sorbas Basin in Spain, while Philip and Ritz (1999) studied the occurrence of a 50km^3 palaeo landslide in Gobi-Altay. Pánek *et al.* (2010) studied the chronology of the largest long run-out landslide that occurred in the transitional late glacial period during the Holocene, found in the Western Flysch Carpathians (Slovakia). Other studies include the topic of gravitational slope deformation (Crosta *et al.*, 2013) and 'gigantic low-gradient slides' (Pánek *et al.*, 2008: 449).

South African studies on mass movements

In southern Africa, only a few studies focus specifically on mass movements and studies on palaeo-mass movements are even fewer (Singh *et al.*, 2008). In the early 1980's , Reynhardt (1979), King (1982), Paige-Green (1989), Van Schalkwyk and Thomas (1991) did a number of studies on mass movements in southern Africa (Table 2.6.), while Olivier (1980), Boelhouwers (1992), Garland and Olivier (1993), Sumner (1993), Singh *et al.* (2008) and Singh (2009), have done research on mass movements in KwZulu-Natal. In the 1970's, Humphreys (1971) developed four land-use zones in which the Drakensberg can be divided: the wilderness heart, landslide zone, trail zone and threshold zone. The landslide zone indicated in Figure 2.7 involves the Clarens sandstone escarpments and are depicted at 2000m and 1500m. This was one of the first studies that discussed landslides in the Drakensberg.

Topic	**Authors**
Palaeo-mass movements	Singh *et al.* (2008), Singh (2009)
Classification	Singh (2009) *MSc Thesis,* Hardwick (2012) *PhD Thesis*
Inventory, prediction and susceptibility maps	Paige-Green (1985), Garland and Olivier (1993),Bijker (2001), Paige-Green and Croukamp (2004), Singh (2009) *MSc Thesis*, Diko *et al.* (2014), Tyoda (2014) *MSc Thesis*
Landslides	Reynhardt (1979), King (1982), Paige-Green (1989), Van Schalkwyk and Thomas (1991), Sumner (1993), Sumner and Meiklejohn (2000)
Mudflows/mudslides	Boelhouwers *et al.* (1998)
Debris flows	Humphreys (1971), Hanvey *et al.* (1986), Lewis and Hanvey (1988), Illgner (1995), Lewis (1996), Boelhouwers *et al.* (1998; 1999), Sumner and Meiklejohn (2000).
Rock falls	Gupta (2001), De Lemos (2013) *MSc Thesis,*
Solifluction and gelifluction	Harper (1969), Nicol (1973), Lewis (1988) Boelhouwers (1991; 1994; 2003), Grab (1999; 2000) (Boelhouwers *et al.*, 2002), Kück and Lewis (2002), Boelhouwers and Sumner (2003), Mills and Grab (2005) and Mills *et al.* (2009)

Table 2.6: Literature on mass movements in southern Africa.

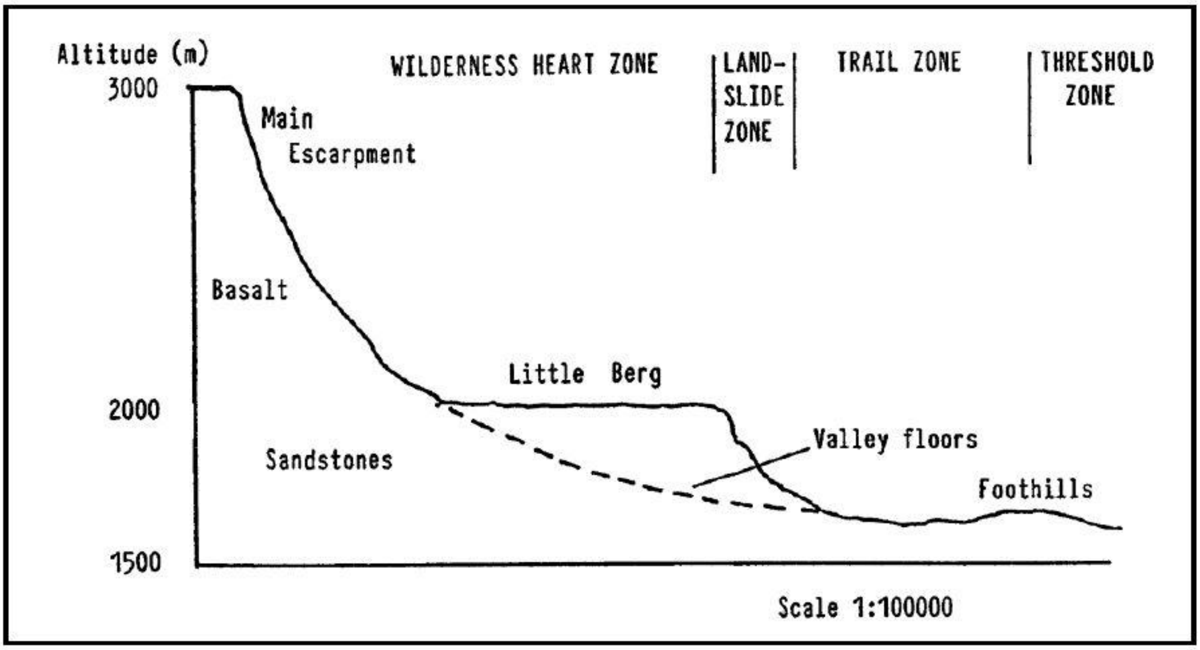


Figure 2.7: The different land-use zones in the Drakensberg, depicted by Humphreys (1971)

Solifluction formation and terracing in the Drakensberg and Lesotho highlands have been extensively reviewed in literature. Initial studies on solifluction lobes in the Lesotho highlands were conducted by Harper (1969), Nicol (1973), and Lewis (1988). Research was later continued by Boelhouwers and Meiklejohn (2002), Boelhouwers (1991; 1994; 2003), Grab (1999; 2000), Boelhouwers *et al.* (2002), Kück and Lewis (2002), Boelhouwers and Sumner (2003) and Sumner (2003). Mills and Grab (2005) and Mills *et al.* (2009) discussed the possibility of periglacial landforms such as solifluction and gelifluction lobes, and contributed to the argument of glaciation in the high Drakensberg, as well as the different factors that result in valley asymmetry found in both the high Drakensberg and below the escarpment.

Boelhouwers (1992) documented the geomorphology of the central Drakensberg in general, however, in the same study a relict mass movement features in the Bushman's River Valley (Giant's Castle Game Reserve) has been identified. The major rotational landslides that have been measured by Boelhouwers (1992) range from 140m to 300m in width, and the deposits are between 25m to 50m. Sumner (1993) did a study on a surficial mass movement complex, whereas Boelhouwers *et al.* (1998; 1999) focused on the Du Toit's Kloof and Cederberg Mountains in the Western Cape, and completed studies on debris flows. Prior to Boelhouwers *et al.* (1998; 1999), Hanvey *et al.* (1986), Lewis and Hanvey (1988), Illgner (1995), Lewis (1996) completed studies on debris flows across Eastern and Western Cape regions. Van Schalkwyk and Thomas (1991) completed a study about landslides produced by floods in KwaZulu-Natal in 1987 and 1988. Gupta (2001) continued research in the Du Toit's Kloof on the geomorphological controls of landslide activity and De Lemos (2013) did a study on the distribution of rock-falls in Golden Gate Royal National Park. Furthermore, a recent study done by Diko *et al.* (2014) focused on the role of soil properties and ongoing anthropogenic activities in increasing susceptibility of slope movement in the Dzanani area (Limpopo).

Although research on specific mass movements in South Africa is limited, susceptibility maps were produced and are frequently studied. Paige-Green (1985) created a synoptic hazard map for South Africa, which was later expanded by Garland and Oliver (1993) and again by Paige-Green and Croukamp (2004). Bijker (2001) and Singh (2009) both produced susceptibility maps or models for landslides in the Drakensberg area, whereas Tyoda (2014) created a susceptibility map for an area in the Western Cape and studied the role of remote sensing in the detection and classification, monitoring, and prediction of slope failures. The Engineering Geoscience Unit within the Council of Geoscience has been actively engaged in landslide inventory and susceptibility mapping in the Western Cape, Limpopo and KwaZulu-Natal (Diop *et al.*, 2010). Another study on mass movements is the research done by Hardwick (2012), which focused on creating a specific classification for identifying predominately shallow mass movements in southern Africa.

South African studies on palaeo-mass movements

Bijker (2001) expanded on the research done on palaeo-mass movements in the Injisuthi river valley (Central Drakensberg). These were not mapped or characterised, but she stated that the Injisuthi valley is intruded extensively by dolerite dykes and sills of which the strike direction is predominately north-west and south-east, and can be linked to the formation of palaeo-mass movements in the area. Bijker (2001) identified the whole valley as a palaeo landslide zone susceptible to superficial landslides. However, the only studies that concentrated purely on palaeo or relict-mass movements within the Drakensberg were done by Singh *et al.* (2008) (see Table 2.6) and Singh (2009). Singh *et al.* (2008) found that a high number of large and wide palaeo landslides have not been recognised or mapped by geologists. The high number of movements that occurred thousands of years ago in the region indicates the important influence that relict landslides had on slope development (Singh *et al.*, 2008). Singh (2009) noted that within the Kwa-Zulu Natal region, geology plays an important role in the type of movement, such as falls linked to bedrock that are resistant to deep weathering, focusing on fault lines, whereas flows and slides are common in bedrock and are susceptible to deeper forms of weathering. The role of dolerite in the formation of large deep-seated mass movements is also highlighted by Singh (2009), due to the weathering between contact zones of the dolerite and sedimentary rocks. Dolerite intrusions changes the dip of the surrounding rocks and that the jointing within the dolerite creates areas of increased groundwater flow (Singh, 2009). Singh (2009) geomorphologically mapped and classified the following palaeo mass movements in KwaZulu-Natal, the Bushman's Valley rotational slides first identified by Boelhouwers (1988), the Mount Currie landslide, Knostrope Landslide, Meander Stream Rotational Landslide, Gobela Landslide, Mooihoek Landslide, Poplars Landslide and the Mahai Valley mass movement which falls within the study area. The Mahai Valley palaeo landslide, as classified by Singh (2009), is a large debris flow palaeo landslide characterised with hummocks that spread laterally, a long runout and a prominent toe. The landslide flowed 1750m into the valley floor and covered an area of approximately 0.69km^2.

Age estimation

Estimating the precise age of a mass movement event is often difficult, as materials used for dating are relatively scarce and can sometimes result in distorted versions of the age. However, due to the increasing availability of dating methods there has been an increase in the number of dated landslides in the world (Pánek, 2014). A variety of methods provide more options to date mass movements specifically. Each method would either provide a relative age or would determine a more absolute date. The most basic method is making use of historical data such as aerial photographs and old maps, or even recollections of catastrophic events that hold valuable information concerning the development of slope formation. Another method is the proposed active state by Mather *et al.* (2003) (introduced in Chapter 1) and Santangelo *et al.* (2015) where they approached dating from a relative point of view, by considering the appearance of the landslide morphology. The presence or absence of vegetation, fluvial activity and erosion processes can give an indication of age, although it is heavily dependent on variables such as the nature of the geology and weathering rates of each study area, and may also differ from study to study. Absolute dating provides a clear and sometimes precise date of the event, whilst relative dating provides a wider possible time-scale in which the event could have happened.

Over the past 10-15 years, the number of methods available to define a landform's age has increased significantly (Lang *et al.*, 1999; Pánek, 2014). Classical methods such as radiocarbon, lichenometric and dendrochronological dating have been used in various studies, even in southern Africa. Boelhouwers *et al.* (1999) applied relative dating techniques, such as the Schmidt Hammer to debris flow deposits in the Cederberg Mountains, whereas Singh *et al.* (2008) identified the age of Holocene mass movements in the Drakensberg by using radiocarbon dating on peat and bogs, establishing the minimum age of the events. Internationally ^{14}C dating has been regularly used in various studies to date specifically mass movements (Prager *et al.*, 2008; Chen *et al.*, 2012). In ^{14}C-dating remnants of organic material that were overridden by regolith gives a maximum date of the event. Organic material trapped and obtained within the regolith of the landslide gives the relative or proxy age of the event, while organic material that accumulates in landslide dams or bogs, ponds or lakes situated at the back scarp of the movement gives a minimum age (Prager *et al.*, 2008). This method has been used by Singh *et al.* (2008) and Singh (2009) to date five palaeo landslides in KwaZulu-Natal, the oldest minimum age obtained was 3420 years before present from the Meander Stream rotational landslide. However, using ^{14}C dating on much older landslides proves difficult and is not used often. New absolute dating methods such as Cosmogenic nuclides, Uranium's series, Ar-Ar, Optically-Stimulated Luminescence and Alpha Record track dating exists (Lang *et al.*, 1999) but have not been used in mass movement studies in the Drakensberg.

Chapter 3: Study area

The study area is located in the northern and central Drakensberg, KwaZulu-Natal. The area covers a national park, private land and a game reserve (see Figure 3.1). Royal Natal National Park forms the northern boundary. Ndedema and Monk's Cowl are in the central regions of the study area and Injisuthi is an area within the northern part of the Giants Castle Game Reserve. Injisuthi forms the southern boundary of the study area. Included in the study area, between the park and reserve, is an historically tribal land, called Mweni. The study area stretches across the lower valleys of the Drakensberg towards the great escarpment forming the boundary between South Africa and Lesotho.

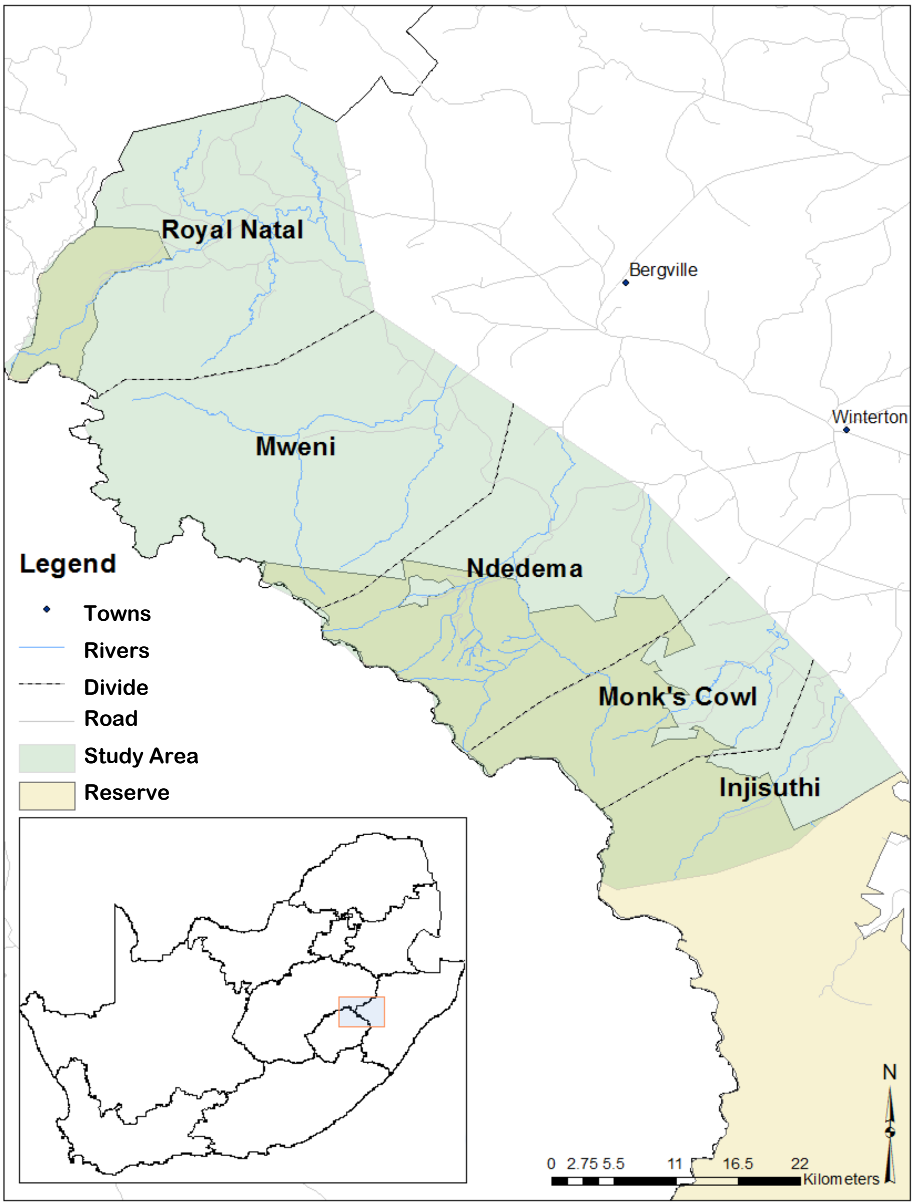


Figure 3.1: Location map of the study area.

The geological and geomorphic history of southern Africa

The formation of the major geological units in the lithostratigraphic sequence and time frames are essential to understanding the geomorphology of southern Africa (Maud, 2012), thus a summary of the major geological stages in southern Africa will be presented below.

Previous to Partridge and Maud (1987), King (1944) attributed the origin of the great escarpment in southern Africa to uplift and erosion. King explained that the existence of bevelled surfaces and rejuvenated streams was due to periods of erosion and uplift leading toward incision and planation surfaces. King identified five periods of uplift and four planation surfaces in the Drakensberg area, but Partridge and Maud (1987) contested this and instead identified two periods of uplift and three periods of erosion.

The geological evolution of southern Africa started with stabilisation of the granitic Kaapvaal Craton, forming the structural basement of the subcontinent, approximately 2 600Myr (Maud, 2012). The following eons experienced a series of extensional and compression periods that gave rise to the Namaqua-Natal mobile belt on the southern side of the Kaapvaal Craton 2 000 to 1 000Myr. To the north-west the Kalahari Craton stabilised 1 000Myr. This resulted in a combination of orogenic belts that created swells and intracratonic basins up to 600Myr. These swells were repeated throughout the Phanerozoic rejuvenating uplift, which persisted into the Neogene epoch. The uplift spread from the intracratonic mobile welts to large areas, and affected the whole craton (Maud, 2012).

Around 500 Ma in the Palaeozoic, a passive margin developed along the southern edge of Gondwana, resulting in the sedimentation of the Cape Supergroup. Afterward, giving rise to the Cape Fold Mountains, a margin was activated around the end of Permian (250 Ma). This also resulted in the basin that formed north of the Cape Fold Mountains, named the Karoo Basin, which extended well beyond present day margins and into adjoining areas of Gondwana. Sediments of the Karoo Basin, which forms part of the Drakensberg, reached a thickness of up to 7 km in some areas. On top of the sediments, the Karoo Basin ends with extensive basalt outpourings from 180 Ma, which currently forms the Drakensberg Escarpment. According to Maud (2012), together with this outpouring additional rifting began to form the later southern sub-continents. When the volcanism ceased most of southern Africa was covered by the Karoo supergroup (Maud, 2012). Southern Africa stood high within the basalts, reaching 2 400m in Lesotho and approximately 1 500m in the western interior.

Due to a rising mantle plume beneath Gondwana, rift faulting started to occur, which led to the breakup of Gondwana 130 Ma ago, and resulted in an uplift along the axis roughly parallel to the

Indian ocean (Moore *et al.*, 2009). The break-up occurred along faulted rifts that are associated with the Pan-African welts. High elevations of the interior resulted in a substantial escarpment, which is called the Great Escarpment, and reached up to an elevation of 2 000m (Hardwick, 2012). However, Moore *et al.* (2009) dispute the plume model, stating that there are three southern African flexure axes represented by major drainage divides, including the escarpment, which is parallel not only to the ocean but to the surrounding ocean spreading ridges. Moore *et al.* (2009) also suggest that a correlation between the initiation of these axes and major drift sequences exists, suggesting that there is a correlation between the flexure axes and plate reorganisations, and therefore to the topography of southern Africa. According to Grab and Knight (2015), further dating of land surfaces across southern Africa are needed to evaluate the competing theories.

The most extensive geomorphic features in southern Africa were formed after the breakup of Gondwana and form an important phase of southern African geomorphology. Soon after the continental break, the escarpment experienced severe erosion by a major early Cretaceous erosional event, all of which was achieved by eastward scarp retreat across the region and rivers working headward from the new ocean coastlines. The first period of accelerated denudation in the early Cretaceous (140-120Myr) was followed by a second Mid-Cretaceous (100-80Myr) and a late period of acceleration between 80-60Myr (Kounov *et al.*, 2009). This led to the removal of a large volume of Karoo rock over the central elevated portion of the subcontinent, except in areas of the main Karoo Basin. A period of accelerated denudation during the Late Cretaceous removed around 3km of crustal section at a mean rate of 95m/Myr (Brown *et al.*, 2002). This rate has been disputed by Kounov *et al.* (2009)*,* suggesting a 5km crust removal in the Late Cretaceous and 2-3km Cenozoic denudation, which is at least an order of magnitude lower than during the Cretaceous. Furthermore, they suggested that the accelerated denudation rate in the Cretaceous could have been caused by a regional uplift, with climate-driven erosion as a secondary factor. The Mid-Cretaceous was most likely the period where most of the present day southern African high-elevation topography was formed (Kounov *et al.*, 2009).

As the escarpment retreated from the coast, erosion to the oceanic region cut a gently sloping bench across the coastal hinterland and at the same time erosion was proceeding inland at the elevated plateau. This resulted in two vast erosion surfaces above and below the Great Escarpment, known today as the African surface. Above the African surface a number of mountain massifs were preserved, including the Drakensberg (Partridge, 1998).

On the southern African uplift

Maud (2012) stated that during the Neogene, the Drakensberg experienced two separate tectonic uplifts, which could have resulted in the initiation of deep-seated mass movements 20-30Myr ago. The uplift is necessary to account for the Pliocene marine sediments that are found 400m east of Port Elizabeth, Eastern Cape. The profiles of major east-draining rivers convex upward and show, according to Partridge (1998), the maximum uplift for the Neogene period (Moore, 1999; Moore and Blenkinsop, 2006). In Figure 3.2, the axis on which the maximum uplift occurred along the Drakensberg is called the Ciskei-Swaziland axis (C-S Axis); it is situated roughly 50km to 80km inland and runs almost parallel to the eastern coast of southern Africa. The first uplift took place during the Miocene epoch and had an uplift of approximately 200m. The second uplift took place during the Pliocene epoch with an estimated lift of roughly 600m to 900m (Partridge, 1997; 1998). Moore and Blenkinsop (2006:605) further state that geomorphic evidence supporting the Neogene uplift is clear, since 'Geomorphological characteristics of the east coast drainages also provide clear testimony to the uplift recognized by Partridge'. Western rivers flow in an extremely meandering manner, 'but to the east of the C-S axis, they have incised spectacular deep valleys' (Moore & Blenkinsop, 2006: 605). Therefore, the uplift resulted in a renewal of rivers flowing to the east coast, which in turn caused the rivers below the escarpment to be deeply incised (Partridge and Maud, 1987).

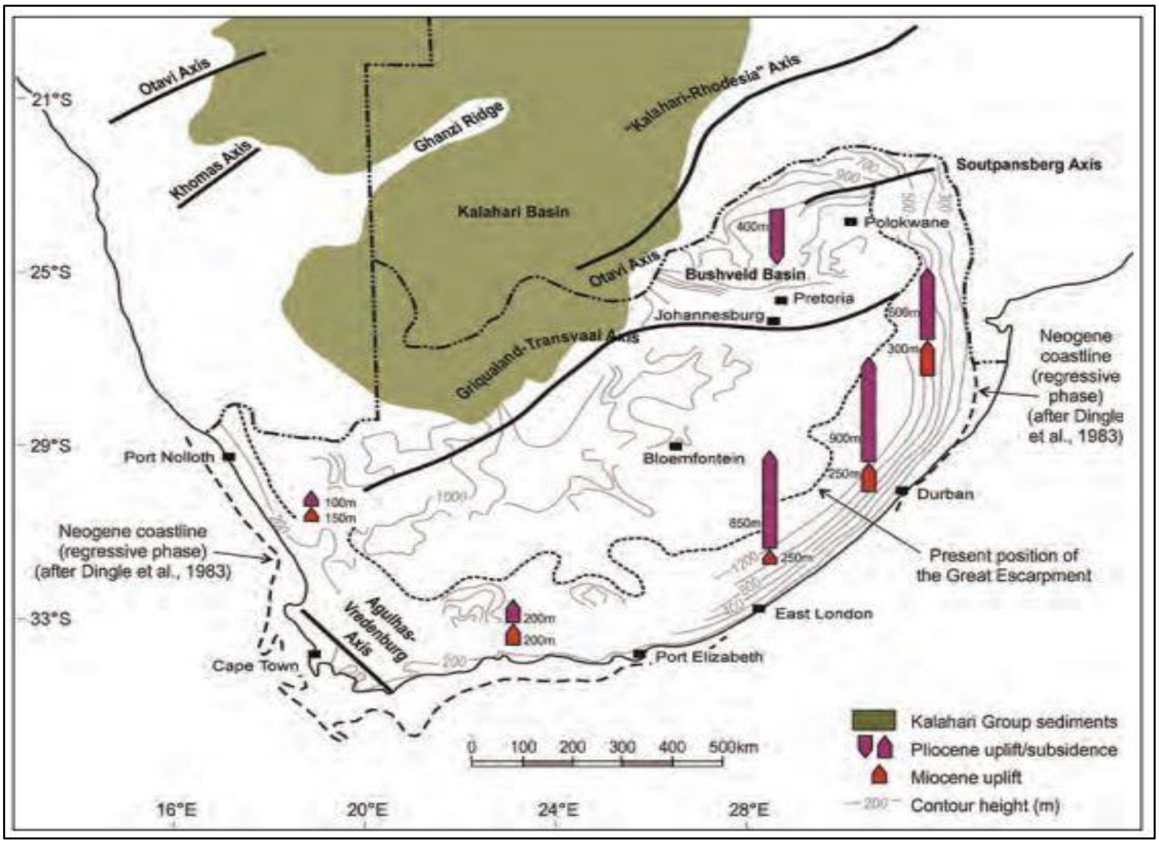


Figure 3.2: The Neogene uplift (after Partridge and Maud, 1987), red arrows indicate the amplitude of the Miocene uplift, the purple arrows indicate the Pliocene uplift (Maud, 2012).

Geology

The Drakensberg's lithology belongs to the Karoo Supergroup and is characterised by horizontally bedded sedimentary strata, overlain by basalt flows. The series of layers are also intruded by a network of dolerite dykes and sills (see Figure 3.3). The strata are mostly flat, only dipping slightly towards the south and south-west. The geology of the Drakensberg can be divided by their topographical shape and composition into two parts, the Main Berg and Little Berg. Figure 3.3 illustrates a cross-sectional diagram of the Drakensberg geology, clearly indicating the Main Berg as well as the Little Berg. The Main Berg forms the summit area, comprised out of volcanic basalts and peaks over 3000m.a.s.l. The basalts, known as the Drakensberg Group, overlay a series of sandstones, the Clarens, Elliot and Molteno formations, which together form Little Berg (Eriksson, 1983; Boelhouwers, 1992). The layers of the Little Berg are distinguished by the amount of mud and clay contained within the sandstone formations. The Clarens Formation consists of sandstone, while the Elliot Formation consists of red mudstone and lenses of sandstone, and the Molteno Formation of sandstone and grey mudstone forming shale (Boelhouwers, 1992). The series of layers has been deposited from a dominantly fluvial (Molteno) to an aeolian environment (Clarens) (Grab *et al.*, 2011). Figure 3.4 illustrates the general geology of KwaZulu-Natal.

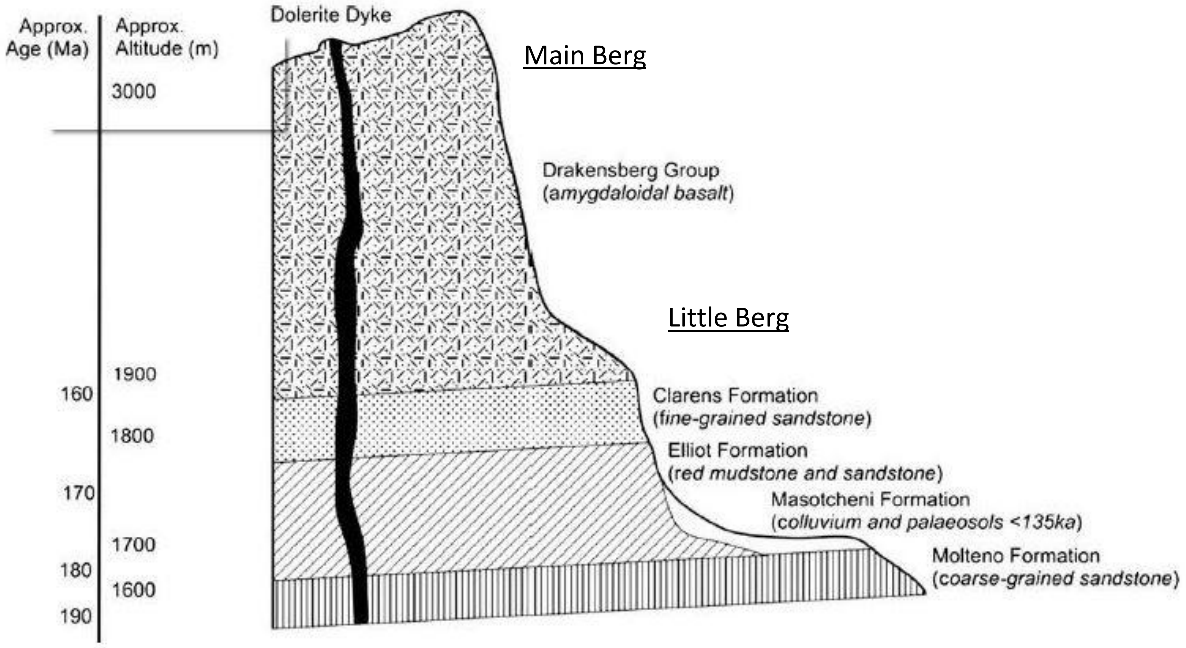


Figure 3.3: An east to west cross-section of the Drakensberg geology (after Eriksson (1983)).

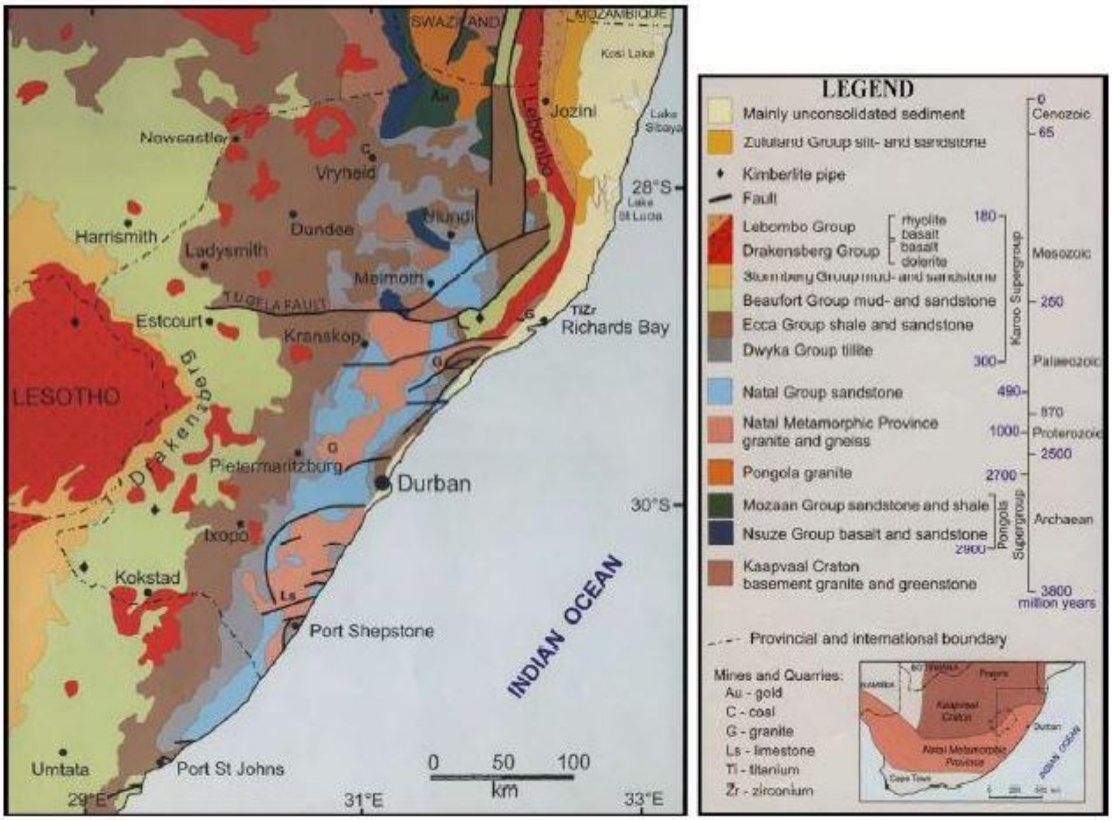


Figure 3.4: The regional geology of KwaZulu-Natal (Whitemore *et al.*, 1999).

The Drakensberg Group

The Drakensberg Group, consists of lava flows which solidified to basalt, are a dark grey to purplish-red colour with a thickness of 1400m, forming the Main Berg escarpment. These lava flows occurred 180Ma ago (Marsh *et al.*, 1997), before the breakup of Gondwana. Not all the basalts are uniform, some contains pipe amygdales. The central part consists of thick flows, with only scattered amygdales perpendicular to the flow contacts. Individual flows vary in size, some less than 1m thick and others to more than 50m, with an average thickness of 6m. Evidence is clear that the succession of lava outpourings was relatively quick, indicated by the tight contact between different flows (Sumner *et al.*, 2009).

Clarens Formation

The Clarens Formation is formed out of pale creamy to white coloured fine sandstones and siltstones, forming the top layer sedimentary rock in the Karoo sequence, laid down between 200 and 160 million years ago (Eriksson, 1983). Discolouration occurs due to chemical weathering from water sources and turns from a white to the pale creamy colour (Grab *et al.*, 2011). The grains show moderately good sorting, while the grain shapes are sub-rounded to sub-angular and fine and medium grained sandstone. There are siltstone with mudstone horizons towards the lower base of the formation (Sumner *et al.*, 2009). The formation has been deposited in mostly arid, aeolian conditions (Johnson *et al.*, 1996). Exposed rock escarps exist in the central Drakensberg, reaching 300m in thickness, commonly called Little Berg. Weathering and erosion of the structurally weaker, closely jointing sediments results in caves and overhangs (Sumner *et al.*, 2009).

Elliot Formation

There is a presence of iron oxide and salt pans that indicate that the original environmental setting was seasonally flooded ephemeral pans. Thus, the Elliot Formation was formed out of floodplain sediments deposited by meandering rivers (Johnson *et al.*, 1996) with a thickness of 70-250m (Schlüter, 2008). The red colour in the formation is due to the iron oxide and the sandstone is predominately yellow to white when exposed as outcrops. Characterised by massive red silt- and mudstones with lenses of fine to coarse sandstone. Different deposition processes and source material led to differences in the sorting and grain shapes. Red to purple argillite is common at the contact zone between the Molteno and Elliot Formations, and due to the lack of resistant sandstone outcrops the slopes underlain by the Elliot Formation are relatively smooth (Eriksson, 1983; Boelhouwers, 1988).

Molteno Formation

With a thickness that ranges from 15-300m and deposited by large perennial rivers with established floodplains, the Molteno Formation was formed during the Middle Triassic under warm and humid climatic conditions (Johnson *et al.*, 1996). The formation is a series of light coloured, fine to very coarse sandstones with layers of argillaceous sediments and conglomeritic sandstones. Shales and mudstones found in the formation are grey or blue, when weathered it appears yellow, while the sandstones have a sparkling appearance due to the deposition of silica upon the quartz grains (Eriksson, 1983). The grains are rounded to sub-rounded and sometimes sub-angular, composed of quartz and feldspar (Eriksson, 1983). Argillaceous sediments are typically overgrown with vegetation if found on a ledge or on a terrace (Boelhouwers, 1988; Hardwick, 2012).

Dolerite sills and dykes

Dolerite dykes intrude through all the sandstone layers and throughout the Drakensberg Group. Due to the manner of intrusion and rapid cooling experienced by the dolerite, it is highly jointed and displays hexagonal to rectangular and smaller horizontal joints. Mass movements, tectonic activity or shrinkage may lead to slickenside surfaces, but at deep depths the joints are too tight for major water seepage processes, but these joints in the upper region may develop into topples (Hardwick, 2012). Dykes and sills in the area are more resistant than the sandstone layers and vary in size from tenths of meters thick, which can form scarps, to more than 30km in length (Moore and Blenkinsop, 2006).

Strength and geomorphic properties of the Karoo Supergroup

This section will look at the various geological and topographical factors of the study area. The valley aspect has been discussed by Meiklejohn (1994), Grab (1999) and by Boelhouwers (2003), and they concluded that the high Drakensberg, and areas below the Main Berg escarpment have clear valley asymmetry and asymmetrical slope development processes. The north-facing slopes are often longer with lower gradients, and the south-facing slopes are shorter and steeper. This is a result of variable ground climates leading to different types of slope processes, weathering intensity and rates above and below the escarpment (Boelhouwers, 2003). Therefore, the steeper south-facing slopes generally have higher moisture content and organic matter.

Main Berg

The basalts with amygdales are susceptible to weathering and can act as an aquifer supplying water to springs. During the cooling stages of the lava, sills and vertical dykes formed. The basalts are more susceptible to thermal fatigue than the underlying sandstones (Sumner *et al.*, 2009). Thin fine grained and more brittle zones occur on both the top and bottom sides of the basalt flow contacts. These zones are more likely to fracture under stress conditions.

Mechanical fracturing, flaking and spalling are reported in basalts caused by environmental conditions such as temperature and moisture differences. When exposed to moisture, the volume of the rock changes, ultimately leading to micro-fissuring, jointing and fissuring that increases the porosity of the rock. In all the basalts deuteric alteration possibly occurred in the later stages of solidification, transforming the original glass and olivine crystals to swelling clays. The behaviour of clays can be seen as an interaction between the clay particles where water fills the voids and spaces between the particles themselves. It is accepted that the main cause of deterioration is the expansion of swelling clay minerals and active zeolites within the rock mass. Chemical alteration and physical erosion both increase the vulnerability of the basalts to erosion (Sumner *et al.*, 2009). Mass movements that typically form in the basalt escarpment are due to weathering along the joints and weakness in the rock, resulting in rock falls in higher altitudes. Moon and Selby (1983) found that in the Royal Natal (northern Drakensberg) basalt outcrops are uniform in strength; cracks and joints are either horizontal or vertical, tightly closed and non-continuous, leading to the conclusion that weathering is only slight. Various forms of debris flows and creeps are noted in the Lesotho highlands, with relation to solifluction lobes and sheets (Boelhouwers and Meiklejohn, 2002). According to Hardwick (2012), falls and topples occur in soft or brittle rocks like the basalt and dolerite formations found in the Drakensberg. Similar to falls, relict or palaeo topples are not easy to identify. A source area may be identified, but are not easily found with the use of aerial and satellite images.

Little Berg

Slope instability in the valleys below the escarpment is largely due to differences in permeability between the sandstone and the mudstone layers. The Karoo sequences conformably overly each other and, except for the contact between the basalts, it is sometimes difficult to identify the boundaries between them. The sandstones weather non-uniformly so that dense layers may be underlain by less competent layers (Hardwick, 2012), consisting of 35%-90% quartz, up to 20% feldspar with a matrix of 10-60%. The silica and calcite that are forming as cementing agents will weather at different rates (Sumner *et al.*, 2009).

The larger the content of active clay minerals in a layer of rock the greater swelling, strain softening and changes in behaviour (Duncan and Wright, 2005). Duncan and Wright (2005) continued further by stating that slicken sided surfaces develop in clays, especially highly plastic clays, as a result of shear on distinct planes of slip. It is also possible that clay minerals leach from the overlying sandstone and become deposited as a layer of clayey sand on the mudstone.

It is expected that sandstone is more durable than mudstone, but the compressive strength of the Clarens sandstone varies between moderately strong to extremely strong, and where the grains are loosely packed and clay content is high; rapid weathering can be expected, which is most likely caused by wetting and drying cycles (Sumner *et al.,* 2009). An unusual property of the Clarens and Molteno Formations is that they shrink and swell excessively with changes in moisture content, even though they are composed of predominantly kaolinite clay particles, which has, according to Hardwick (2012), a non-expanding lattice structure. This leads to the assumption that sandstones are susceptible to wetting and drying cycles (Sumner and Loubser, 2008). Sandstones are more permeable than mudstones and moisture accumulates, increasing pore pressure at the contact zones with the mudstones, including between the basalts and the Clarens Formation. An increase in moisture enhances the weathering at the contact zone between layers and in between the pores of the sandstones, widening the area and pores until the material disintegrates. Seepage can occur along joint lines into the sandstone massif where the mudstones are exposed and weathers easily. This leads to a decrease in basal support and eventually collapse of the Clarens sandstone escarpments (Meiklejohn, 1997). Weathering of the sandstones leads to overhanging shelters or caves in the lower formations, where Meiklejohn (1994) found higher weathering rates due to the consistency of moisture within in the caves.

Therefore, in the Clarens and the lower formations large slides are possible, due to the weakness between the contact zones of mudstone and sandstone layers, creating preferential weathering due to the sandstone's susceptibly to weathering. This geological region forms a landslide susceptibility zone (Figure 2.7) identified by Humphreys (1971), and discussed in Chapter 2. Although various slides at various depths are prominent in this region, rock falls are also common in the steep slope overhangs of the sandstones (De Lemos, 2013).

Dolerite intrusions

Dolerite sills and dykes play an important role in slope stability, due to the contact metamorphism and shattering results of the intrusions. Bijker (2001) suggests that relict major rotational landslides in the Injisuthi valley are associated with dolerite dykes, and Singh (2009) found an association between dolerite and large mass movements over the Holocene landslide in KwaZulu-Natal. According to Moon and Selby (1983) sandstone and dolerite slopes fall within the strength equilibrium envelope, whereas argillaceous slopes do not. Preferential seepage can occur along the intrusions and faults, leading to higher moisture conditions in the contact zones and ultimately higher weathering rates. The intrusions can alter the dip of bedding planes of the adjacent geology so that the dip is similar to the slope gradient. Differential weathering between dolerite and sedimentary rock created steep topography and areas of high relief (Singh *et al.*, 2008). As a result, large to very large mass movements may form along the intrusions. The Meander Stream large rotational landslide (Figure 1.1) is found within the Elliot Formation, but the cliff line on the southern eastern margin corresponds with a thin dolerite dyke higher up on the southern hillside (Singh *et al.*, 2008; Singh, 2009).

Climatic history of southern Africa

Climate has a dramatic influence over geomorphic features and on the processes that create landforms. Mountainous areas are especially vulnerable to climatic changes due to high altitudes, high slope gradient, generally higher precipitation, poorly developed soil and sensitive vegetation. These changes will manifest themselves quickly in the form of changing geomorphic processes (Sumner and Meiklejohn, 2000). For example, a periodical change in the duration of precipitation can lead to deep-seated mass movements (Trauth *et al.*, 2000). It is therefore important to know the climatic condition of the Drakensberg before the onset of these mass movements, as well as during and after the period of activation. Palaeo climate is controlled by various factors: major tectonics, including the above mentioned uplift, global climate changes as well as orbital changes of the earth (Trauth *et al.*, 2000; Zachos *et al.*, 2001) and over the last 65Myr (Cenozoic) the climate has changed from extreme warmth and ice free poles to extreme cold and massive continental ice sheets and polar caps (Zachos *et al.*, 2001).

According to $\delta^{18}O$ and $\delta^{13}C$ ice core records the most pronounced warming trend of the Cenozoic era occurred in the early stages of the era during mid-Palaeocene (59Myr) to early Eocene (52Myr) and peaked with the early Eocene Climatic Optimum (52-50Myr). This was followed by a 17Myr cooling trend over the middle, late Eocene and early Oligocene where there was a large expansion of ice sheets and caps and formed the *Oi-1* Glaciation (Zachos *et al.*, 2001). This first major continental ice sheet formed with the opening of the Tasmania-Antarctic and Drake passages in Antarctica (Maslin and Christensen, 2007). The ice sheets persisted throughout the Oligocene epoch until its latter stages (26-27Myr) when a warming trend reduced the extent of the Antarctic ice sheet (Zachos *et al.*, 2001).

From the early to middle Miocene epoch the ice volume remained low and temperatures peaked in the late middle Miocene forming the Mid-Miocene Climatic Optimum (17-15Myr) (Zachos *et al.*, 2001). Following this period, a global palaeo-geographical change led to the establishment of the circum-Antarctic current (Neumann and Bamford, 2015), which triggered the reestablishment and growth of the Antarctic ice sheet and arctic glacial climates (Majewski and Bohaty, 2010). During the mid-Miocene 16-11Myr a period of hyper-aridity was caused due to the collision of the African and Asian plate and the closing of the Tethys Sea (Neumann and Bamford, 2015). This dry period was followed by a period of decreasing temperatures from the mid to the late Miocene, known as the Middle Miocene Climate Transition. This is characterised by a long-term cooling trend that ended with major expansion of the Antarctic ice sheet (Majewski and Bohaty, 2010). The cooling trend continued throughout the late Miocene towards the early Pliocene (6Myr) (Zachos *et al.*, 2001). These climatic changes during the middle Miocene were pronounced in southern high latitudes, where significant cooling and hydrographic changes took place. Early Pliocene experienced a slight warming trend until 3.2Myr, following a cooling trend that formed the Northern Hemisphere Glaciation (Zachos *et al.*, 2001), and during the Pleistocene the climate globally cooled down even further (Majewski and Bohaty, 2010).

In the Quaternary period (2.7Myr) southern Africa experienced a succession of cold arid periods with interchanging warm wet climates. These glacial and interglacial fluctuating periods had a cyclical period of about 100 000 years (Sumner and Meiklejohn, 2000). However, this theory has been the focus of some debate. There is a possibility that alpine regions in southern Africa have been glaciated, but the lack of conclusive evidence for glaciations has left the debate unresolved and therefore it is accepted that the alpine regions of southern Africa were not permanently glaciated.

According to Fitchett *et al.* (2016) new quantitative approaches and dates of geomorphic features, such as moraines, gives more substantial evidence for spatially restricted Quaternary glaciation in the Drakensberg. Boelhouwers and Meiklejohn (2002) stated that during the coldest parts of the Quaternary the conditions were likely to be more arid and the data suggested that the precipitation was at such a low rate that glaciation could not be possible. Geomorphic features often related to glaciation could have been misinterpreted and could have resulted from fluvial incision and deposits derived from jointed bedrock. Under the warm, moist interglacial conditions, important landscape-forming processes were more active than in the cooler, dry periods.

Current climate

The climate of the Drakensberg during the summer months of November to January are wet, warm and humid, while the winter months of May to July are mostly cool and dry. More specific data has been collected by Sumner and Nel (2006) at Injisuthi, but general climatic conditions of the area record an average of 1050mm rainfall p.a. and 14˚C mean annual temperature. Temperatures rarely exceed 35˚C and is unlikely to fall below freezing point during the day. Nocturnal temperatures can fall as low as -12.5˚C, however rarely, during the winter. Precipitation occurs throughout the year and the Drakensberg is one of the least drought-prone areas in South Africa (Hardwick, 2012). This is due to the seasonal movement of pressure cells along the coast and over the interior of southern Africa.

Vegetation

Several authors identified altitudal vegetation zones for the Drakensberg, among the first was Humphreys (1971). Due to the topographical height differences, slope angle, aspect and edaphic gradients the area provides a large number of micro-climates in which diverse vegetation can exist. This includes both the mesic vegetation of the KwaZulu-Natal escarpment and the drier Eastern Cape Drakensberg and Lesotho interior.

Wetlands are found in the low valleys in the foothills of the Drakensberg. Rich with a diverse biodiversity, wetlands are protected areas and are also an important source for water capture (Pelser *et al.*, 2013). Evident in Figure 1.1 (pp. 3) is the meandering nature of the river upstream of the landslide. Large deep-seated mass movements play an important role in the development of wetlands. When the displaced soils are spilled into the river it forms a blockage, this blockage forces the formation of floodplains and wetlands.

Occupation and Infrastructure

Large areas in the study area are used for recreational purposes, including the larger parks or reserves such as Royal Natal National Park and the Giant's Castle Game Reserve, but various private hotels, camp sites, lodges and restaurants are also built within the area. If the land is not used for recreational purposes it is mostly used for subsistence farming near small villages. A smaller area is used for commercial farming, due to the steep topography. Some areas, such as Busingatha, are more densely populated and there are areas close to the villages which are demarcated as spiritual or culturally important land, such as Sandlwana river valley in Mweni.

Due to an increase in population, Mweni is expanding and small huts and houses are found deeper within the Drakensberg valleys. The flat topography which deep-seated palaeo-mass movements can provide is ideal for the construction of recreational or housing structures and provide areas for farming purposes, increasing the rate for erosion and the chance for natural disasters (Guzetti *et al.*, 1999).

Chapter 4: Methodology

The methods are structured in three phases. Firstly, the detection phase, which includes the use of a criteria to identify possible study sites in the research area. Secondly, the verification phase, which includes in-field mapping and verification of features identified in the first phase. Finally, the analysis phase consists of post-field work mapping, morphometric analysis and the classification of mass movements. This chapter will focus on explaining the methods used in these three phases.

First phase – Detection methodology and criteria

The first phase followed a process similar to the process used in most palaeo-mass movement studies, namely the analysis of aerial images to identify lineaments and typical topographic features found on mass movement affected slopes (Lebourg *et al.*, 2014). Mapping of mass movements is based on the recognition of distinct surface features, criteria specific to individual areas and the reliance on tools such as aerial imagery (Crosta *et al.*, 2013). Palaeo-mass movements are often misinterpreted as different landforms due to erosion processes that transform their original morphology (Šilhán and Pánek, 2010), and are sometimes missed altogether. Mather *et al.* (2003) indicated that mass movements older than 100 000y may be partially removed by erosion and will be integrated into the existing topography. This complicates identifying palaeo-mass movements, as features usually related to landslides, such as scars, are less visible. However, creating specific criteria for features that are usually consequential of mass movement is possible.

Detection methodology

Satellite imagery was used in the process of identifying possible sites. Google Earth's imagery proved to be very effective; the resolution is more than satisfactory and the easy manner in which the images can be viewed is useful. In a study aimed at identifying deep-seated gravitational slope deformations, Crosta (2013: 16) explains: 'Google Earth is an interactive geographic data browser allowing a highly accurate remote navigation in a three-dimensional virtual environment and the possibility to examine slope geometry with a variable resolution from different points of view and by relief enhancement'. Topographic maps were used in combination with Google Earth and satellite imagery obtained from the Department of National Geospatial Information (NGI). The topographic maps were used specifically to identify possible sites by combing over contour lines and indentifying the directional flow of river segments. These maps were useful to identify features and determine the dimension of the sites. Following the initial processes, aerial photography and geological maps were used to determine further possible sites. Once a site was identified, a more detailed inspection was completed by examining the different maps and images mentioned previously.

Due to the size of the study area, a logical and chronological methodology was needed to assist in the process of locating possible sites. First, the whole study area was divided into five smaller areas (as shown in Figure 3.1, Chapter 3) according to the main valleys, namely Royal Natal, Mweni, Ndedema, Monk's Cowl and Injisuthi. Each main valley was scanned, followed by searching second and third order rivers and tributaries of the main river. Lastly, the escarpment area was examined.

Criteria

Aerial photography was mainly used in past studies, even though success is dependent on the skill of the viewer and, unlike recent mass movement events, there is no concrete method of identification by remote sensing or any other automated method other than manually scanning the photos. Thus, the need for criteria specifically created to identify palaeo-geomorphic features. The criteria was compiled by examining various internationally and locally published studies, such as Mather *et al.* (2003) and Pánek *et al.* (2008) (see further Table 4.1), that identified and mapped palaeo-mass movement events. Common geomorphic features found on these movements, or as a resulting consequence, were identified and used as indicators for past mass movement events. The criteria is divided into main topics or groups where specific features such as rotated geology or misplaced boulders were placed. The groups are as follows:

- the topographic shape of the slope.
- valley constraint or river pinching caused by the landslide event.
- deranged drainage patterns and upstream meandering of the valley river.
- hummocky terrain and topographic undulations.
- incised flanks.
- recent forms of erosion such as newly or active landslides.
- form of sediment displacement.

An explanation of each criterion can be found within Table 4.1, together with further features which can be used to verify the criteria. Rock falls and topples were not considered due to the fact that it is extremely difficult to discern evidence of these events occurring from satellite imagery.

Criteria	Description	Features	Author Citation
Topographic shape	The terrain below the escarpment moving towards the toe of the mass movement could have features that distinguishes the area from the surrounding valley side, such as a subtle anomalous variation in the geological dip and bedding orientation. The escarpment itself has an uncharacteristic, undulated shape commonly associated with stream erosion, but with no direct source. Therefore, rills can form across the head scarp and the head scarp can remain steep. Terraces may also form due to rotational or translational sliding, but will usually be accompanied by a rise from the back scarp.	Convex toe shape, Anomalous dip, Arc or flat shape escarpment, Rise in height of the toe, Steep head scarp, Terraces	(Sumner and Meiklejohn, 2000; Mather *et al.*, 2003; Azañón *et al.*, 2005; Pánek *et al.*, 2008; Singh *et al.*, 2008; Pánek *et al.*, 2012; Pánek *et al.*, 2014)
Valley constraint and deflection	The formation of regolith deposits of a mass movement, if the runout was deposited onto the valley floor, is typical of large movements in the Drakensberg, will result in valley constriction. Usually deflecting the direction of the river around the toe. It is possible to use this feature to identify palaeo-mass movements, although due to the age of some movements, it can be problematic because erosion and river incision can make visibility difficult. Damming of rivers as well as the meandering of the upstream river can possibly indicate a mass movement event.	Valley constraint, River deflection, Irregular river direction, Damming of rivers, Meandering of rivers	(Philip and Ritz, 1999; Mather *et al.*, 2003; Azañón *et al.*, 2005; Singh *et al.*, 2008; Pánek *et al.*, 2010; Van Den Eekchaut *et al.*, 2011)
Hummocky terrain and topographic undulation	The terrain below the escarpment moving towards the toe of the mass movement may consist of hummocky terrain caused by the movement event and further erosion. The type of movement greatly influences the topographic shape of the deposits. Often, due to this obstruction caused by the hummocky terrain, water bodies or wetlands can be found at the foot of the escarpment, showing a difference in vegetation. "Older slides are recognisable by their vegetation pattern, which reflects the hydrological condition of the slide." (Hardwick, 2012: 65)	Undulations, Hummocky terrain, Water bodies, Change in vegetation	(Pánek *et al.*, 2008; Singh *et al.*, 2008; Lacoste *et al.*, 2009; Pánek *et al.*, 2012; Hardwick, 2012; Pánek *et al.*, 2014)
Valley side river derangement	Together with pond or wetland formation, the topography of the deposited material obstruct natural flow of river segments, resulting in the segment flowing in a non-regular direction. Differences in the river direction, such as anti-typical flow direction of river segments, can indicate a mass movement event. Mass movements events can form damming of rivers or even cause ponds on the valley side due to river derangement. Soil pipes may form as well. Such features form important clues to discovering palaeo-mass movement events.	Bog, pond or wetland formation upslope, Irregular river segment direction, Soil pipes	(Mather *et al.*, 2003; Azañón *et al.*, 2005; Singh *et al.*, 2008; Lacoste *et al.*, 2009; Pánek *et al.*, 2010; Van Den Eekchaut *et al.*, 2011; Hardwick, 2012; Pánek *et al.*, 2012)
Deeply incised flanks	When a mass movement occurs, it leaves the sides of the body and scarp vulnerable to further erosion through incision. Typically a small tributary forms on the boundaries of the mass movement that could lead to further erosion, possibly resulting in gully formation or deeply incised flanks. This could be used to denote the area of the mass movement in combination with other features as criteria. A good example is the Dilston Slide in the Umkomaas Valley (Singh *et al.*, 2008: 42). The scarp can also become susceptible for rill and gully erosion.	Gullies Side valley streams	(Mather *et al.*, 2003; Pánek *et al.*, 2008; Singh *et al.*, 2008; Hardwick, 2012; Pánek *et al.*, 2012; Verachtert *et al.*, 2012)
Active or recent mass movements	On various palaeo-mass movements the change in geology structure initiates weaknesses within the first mass movement. These weaknesses in the slope could result in secondary movements on the first mass movement. This usually does not consist of the same area, intensity or volume and are most of the time small, but can be distinguished separately from the first mass movement. The area can subsequently be termed as a palaeo-mass movement zone. Sliding produces a disrupted, anomalous drainage pattern.	Small and recent movements	(Pánek *et al.*, 2010; Hardwick, 2012; Pánek *et al.*, 2012; Verachtert *et al.*, 2012)
Sediment displacement – type and form	The shape of the accumulation zone portrays important clues; large rotated blocks within the sediment can indicate a movement. Thus, it is important to look at sediment displacement, especially close to the valley floor. If geologic strata is are disturbed by boulders or out of place dips it can indicate a mass movement event. Stair-stepped patterns of displaced backward rotated blocks.	Rotated blocks, or out of place boulders, Lack of geological structure or strata, Reverse slopes	(Lacoste *et al.*, 2009; Pánek *et al.*, 2010; Van Den Eekchaut *et al.*, 2011; Migoń *et al.*, 2014; Pánek *et al.*, 2014)

Table 4.1: Criteria used to identify and confirm mass movements (derived from international and national studies of mass movements).

The weathering and erosion of the geomorphic features following a mass movement over time, as suggested by Mather *et al.* (2003) and Verachtert *et al.* (2012), is shown in Figure 4.1. The flanks of the movement force the drainage towards it, leading to incised river segments. The reverse slopes act as dams, or material that obstructs flow downslope and causes the collection of water and the development of soil pipes. A common feature in the Drakensberg, soil pipes can be clearly identified as lines of thicker green vegetation on satellite imagery, especially in the winter (Hardwick, 2012). Mass movements alter the hydrological conditions of the slope and trigger soil pipe development (Verachtert *et al.*, 2012), as seen in Figure 4.1. Created by Mather *et al.* (2003) and developed further by Verachtert *et al.* (2012), Figure 4.1 shows the development of a soil pipe system initated by a mass movement. However, it is important to note that mass movements are not a necessary condition for the development of soil pipes. Therefore, pipe formation on a slope cannot be considered as conclusive evidence but can be an indicator to a mass wasting event.

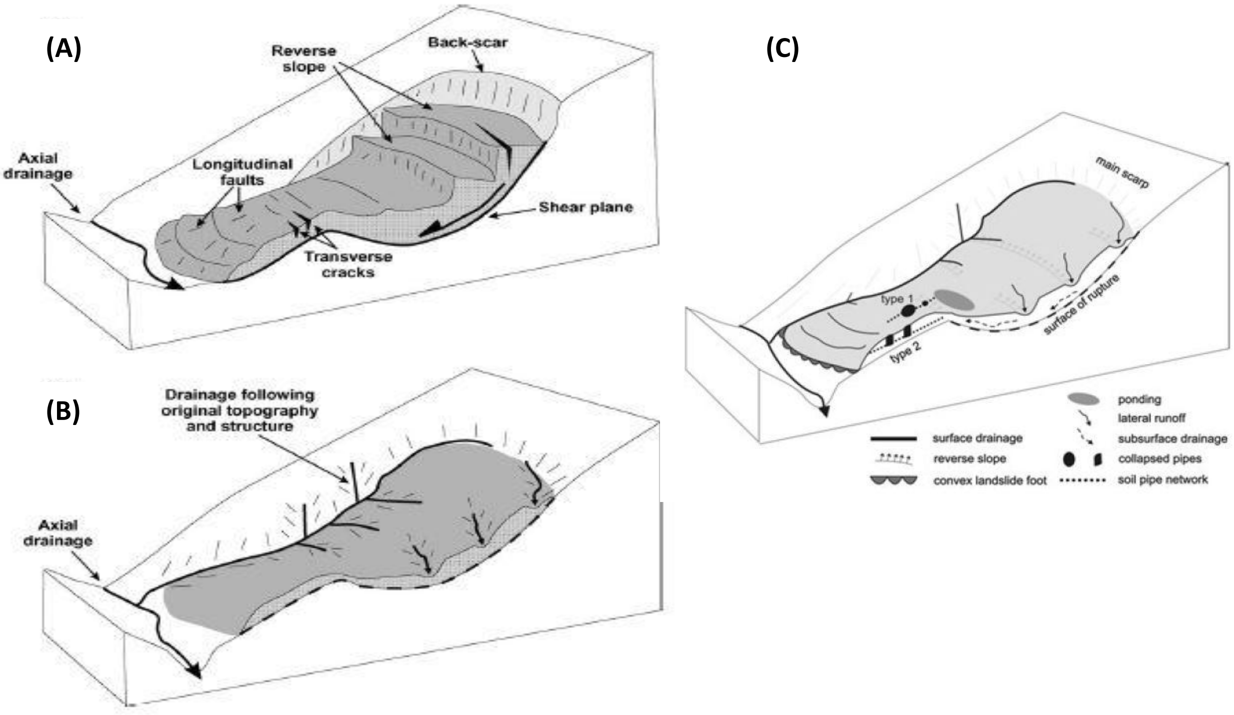


Figure 4.1: The typical weathering and erosion following a mass movement over time. (A) Directly after the event with clear and distinct features visible. (B) and (C) indicates geomorphic features after the area has been allowed to erode and integrate back into the landscape (Mather *et al.*, 2003; Verachtert *et al.*, 2012).

Seen on the palaeo-mass movement mapped by Pánek *et al.* (2012), Figure 4.2, are clear indications of geomorphological features, such as deeply incised sides leading to gullies which indicate the two flanks of the movement. A feature commonly found in the Drakensberg and indicated on the map, is small and recent superficial movements with smaller secondary movements on the flanks. Erosional slopes, less fragmented landslide blocks and topographic undulations are clearly indicated. Figures 4.3, 4.4 and 4.6 are previously identified deep-seated palaeo-mass movements in the Drakensberg and KwaZulu-Natal. These mass movements were discussed and mapped by Boelhouwers (1992), Singh *et al.* (2008) and Singh (2009) and are the Bushman's River rotation slide (Figure 4.3) identified by Boelhouwers, the Meander stream rotational slump (Figure 4.6) mapped by Singh *et al.* (2008) and Singh (2009), and the Mount Currie Complex landslide (Figure 4.4) also mapped and dated by Singh *et al.* (2008) and Singh (2009).

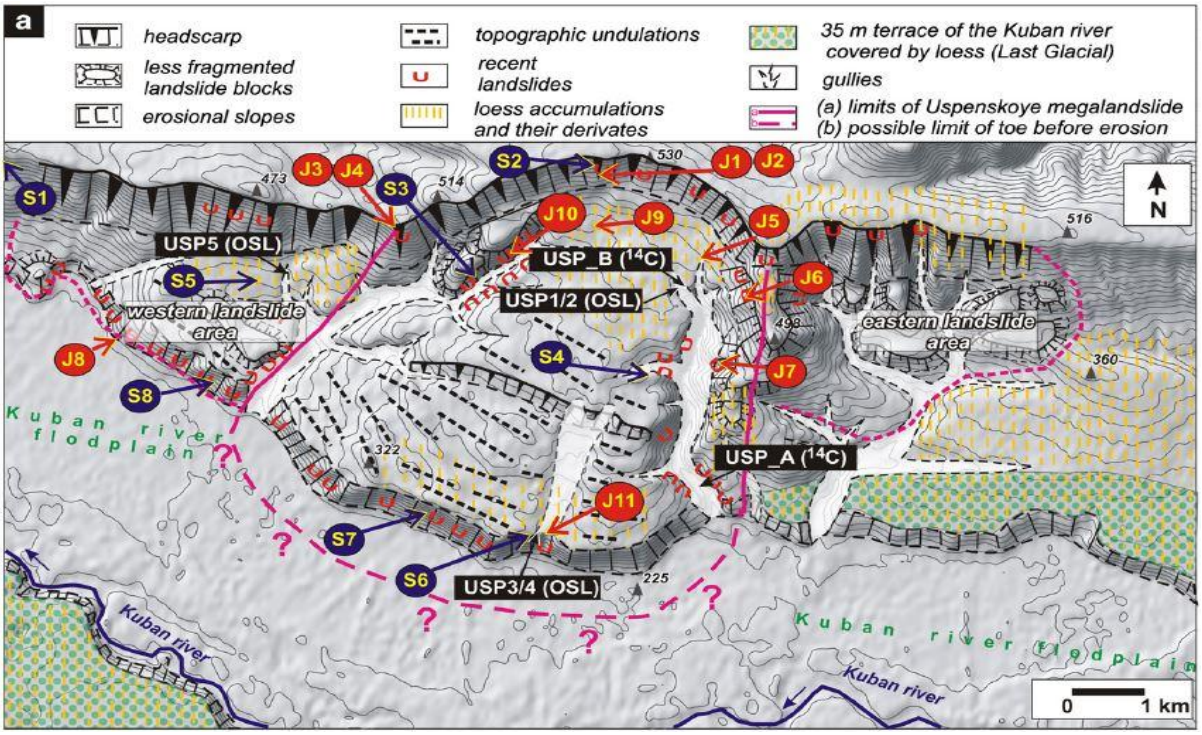


Figure 4.2: Example of a geomorphic map indicating a palaeo landslide in the Kuban Valley, Northern Caucasus (Russia) (Pánek *et al.*, 2012).

The Bushman's River rotational slide (Figure 4.3) has clear river deflection visible and as a result valley pinching occurs. Clear river derangement can be noted on the slope of the movement, as the streams are forced to flow around the main deposition where point heights are visible. Clear rotation of the bedrock is visible, and the back scarp is populated with vegetation.

In Figure 4.4, the Mount Currie landslide, hummocky terrain is prevalent leading to river derangement, gully formation, as well as bog or pond formation. This leads to clear vegetation changes throughout the slope as also seen in Figure 4.5. In Figure 4.6, the Meander stream rotational landslide, a bog or pond below the main scarp developed, and incised flanks, derange river segments and river deflection are clearly visible. The meandering of the river in the valley is also a clear indication of palaeo-mass movement.

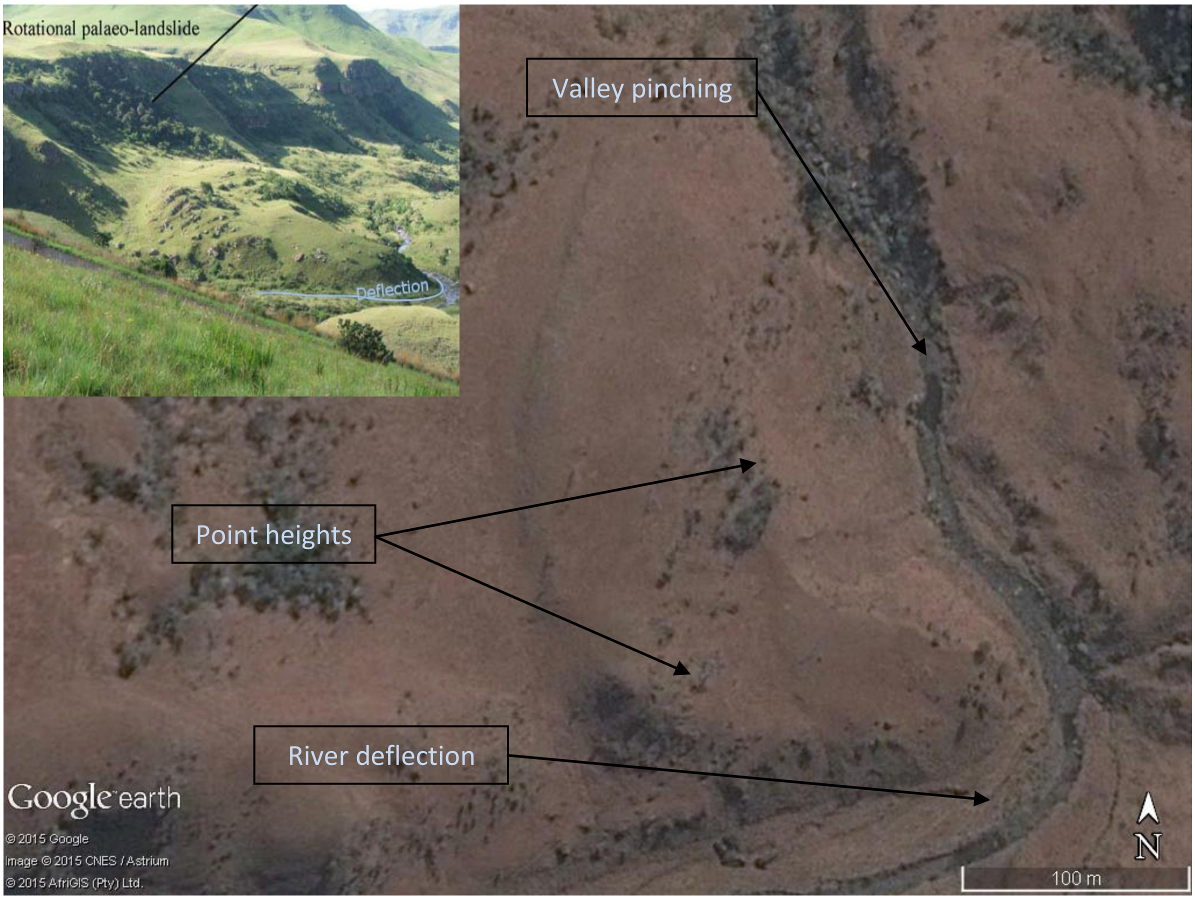


Figure 4.3: Satellite image of the Bushman's River rotational slide indicating typical geomorphic features associated with palaeo-mass movements. The insert is a photo of the site taken from across the valley (Singh, 2009).

These features, as seen in Figures 4.1 to 4.6, and explained in Table 4.1, are typical features whereby large deep-seated palaeo-mass movements can be identified from aerial imagery, aerial photographs, geologic and topographic maps. However, in order to prevent the false identification of sites, most of the features must be visible or identifiable in a study site; one feature cannot solely identify a mass movement.

It is therefore necessary to do a thorough inspection of the individual study sites in order to classify the type of movement and confirm the features identified. As Mather *et al.* (2003) explains, not all characteristics necessarily indicate a mass movement event and that detailed knowledge of each study site is necessary and will only then allow for identification of the feature as a landslide.

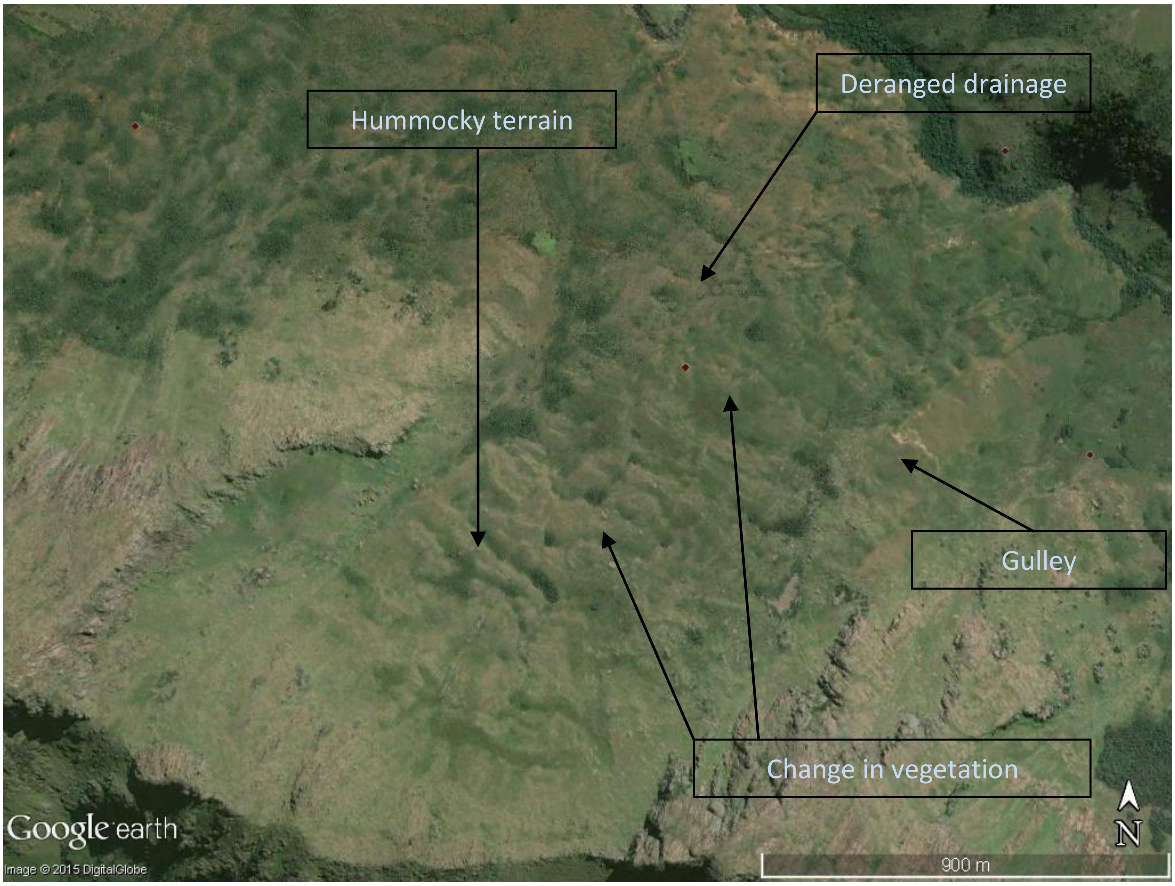


Figure 4.4: A satellite image of the known Mount Currie landslide (Singh, 2009), indicating typical geomorphic features associated with palaeo-mass movements.

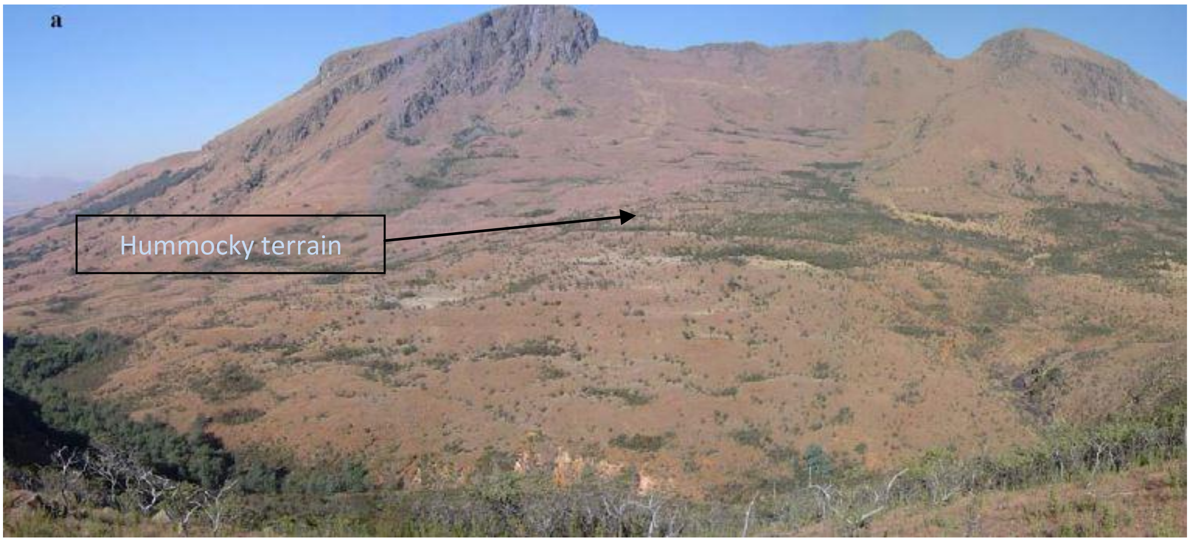


Figure 4.5: A view from the toe of the Mount Currie landslide (Singh, 2009) looking towards the back scarp (Singh, 2009).

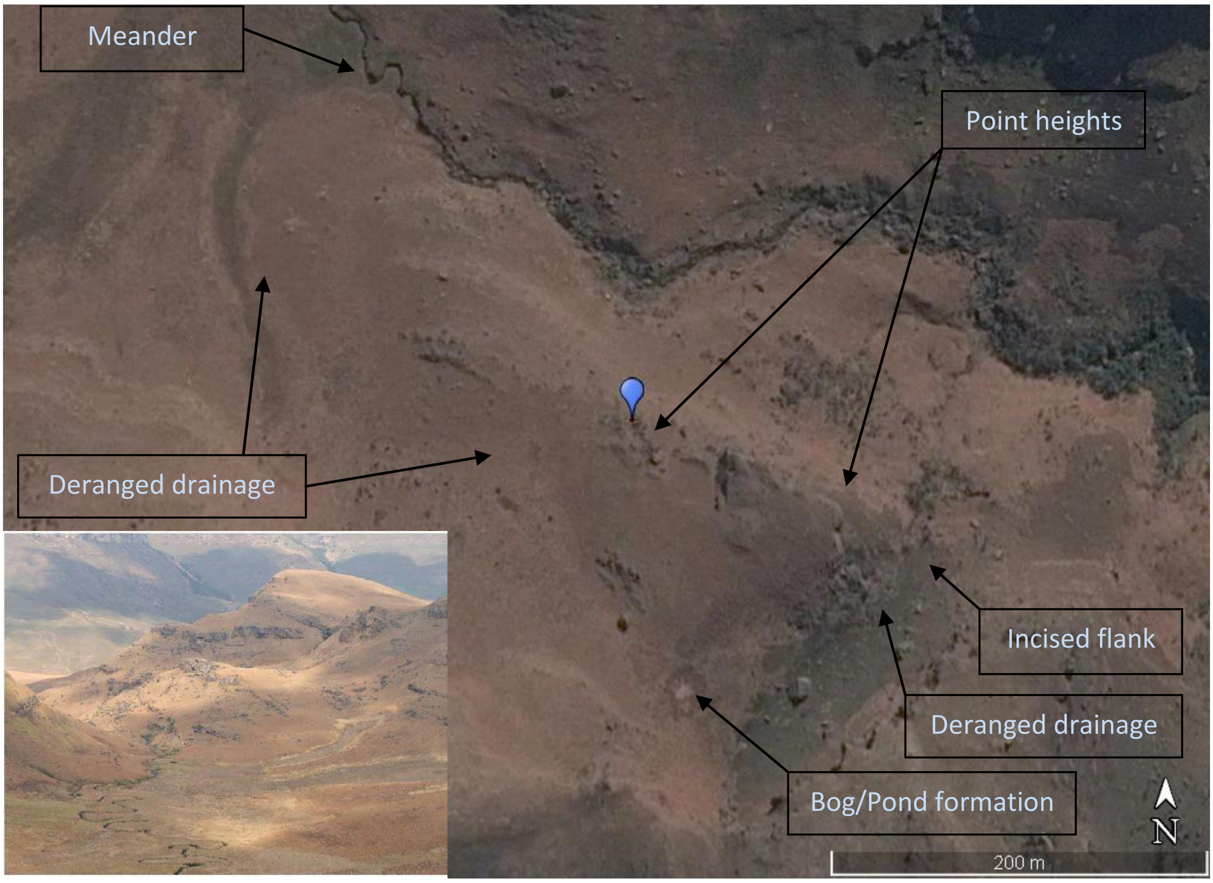


Figure 4.6: A satellite image of the known Meander stream rotational landslide, indicating typical geomorphic features associated with palaeo-mass movements. The insert is a photo of the site taken from across the valley (Singh, 2009).

Second phase – In-field verification

In-field verification is an important process that leads to the verification of the results found in the first phase. Each valley was visited and the possible sites were explored. Features identified in the first stage were documented and the landscape was visually interpreted. If possible, spot heights were taken with the use of a global positioning system (GPS). Most sites were within a reachable walking distance, although some could not be visited physically due to their remote location. Aerial observation was limited to the Monk's Cowl, Dedima and Mweni valleys only, while other unreachable sites were solely reliant on the interpretation of aerial imagery. Appendix B is a summary of verification possibilities at the individual sites.

Dating

Absolute dating methods would be beneficial to the study and would have been considered if not due to the lack of availability. Dating using Uranium series or Ar-Ar dating is limited to a few studies, and therefore there was a need for a different approach. Dating of the study sites could be a relative estimation only, a correlation between the movement itself and fluvial terraces, and by the general appearance of the landslide. If the movement spilled into the valley floor, an indication would be expected to be visible and it could then be determined whether the movement developed after the formation of fluvial terraces found in the valley. If this was not clearly definable, the condition of internal morphology, lateral margins and main scarp could give some indication. Each mass movement have been dated by the proposed activity state (Appendix A) introduced by Mather *et al.* (2003). This system of Mather *et al.* (2003), defines a fossil category which has been disregarded and the term 'fossil' has been adapted to 'ancient'. This was due to the term 'fossil' describing the state of geomorphic features rather than giving an indication of age, determined by the appearance of the features. Therefore, each movement can be classified as either young (100-5,000yrs), mature (5,000-10,000yrs), old (10,000-100,000yrs), and ancient (>100,000) by the appearance and the condition of the main scarp, lateral margins and internal morphology (eg. Hummocky terrain, drainage network and pond formation). In this study, the term, palaeo, as discussed in chapter one, is a term explaining a broad sense of the age movement, including the terms 'relict' and 'fossil' which is regarded to have the same implication and meaning. Palaeo, therefore, describes a mass movement falling into any these categories. Mass movements younger than 100yrs are not considered as palaeo-mass movements. They are however considered as dormant landslides, and lack the characteristics defined in the criteria set out by Mather *et al.* (2003) to be considered as palaeo-mass movements.

Classification derived for mass movements

Table 4.2 illustrates the classification derived for this study, adopted from Singh (2009), Hardwick (2012) and Hungr *et al.* (2014), although various adjustments were needed to include different aspects of palaeo-mass movements. Movement type is the main discerning factor, classified as fall, topple, slide, flow or spread. Slide is further divided into subcategories: rotational, translational, compound and complex. Secondary factors include movement style, behavioural properties, size as derived from van Schalkwyk and Thomas (1991), material type, geology type and age. Movement style discerns between single, multiple and composite. Behavioural properties focus on the material itself and distinguish between solid, plastic and liquid. Material type discerns between the physical properties of the mass, dividing it between bedrock, debris or earth. Geology type specifically distinguishes between the geology layers in the Drakensberg, namely the Drakensberg basalts or the sandstone formations, while size is divided into five separate categories defined by Singh (2008).

Table 4.2: Modified classification for palaeo-mass movements

Movement type	Movement style	Behavioural properties of the material	Size	Material type	Geology type	Age
Falls	Single	Solid	0.01-10.00 m^2	Bedrock	Sandstone	Young
Topple	Multiple	Plastic	10.01-1,000.00 m^2	Debris	Basalt	Mature
Slide: Rotational Translational Compound Complex	Composite	Liquid	1,000.01-100,000.00 m^2	Earth		Old
Flow			100,000.01-1,000,000.00 m^2			Ancient
Spread			>1,000,000.00 m^2			

Third phase – Mapping methodology and morphometric analysis

Mapping methodology

Due to the differences regarding the notation of geomorphic features, previous geomorphological maps were examined, features identified and a style adapted that would clearly define the study areas. The visual aspects of the geomorphic maps were produced following a comparison between various international (Pánek *et al.*, 2010; Guzetti *et al.*, 2012; Otto and Smith, 2013) and South African geomorphic examples, with special relation to the Drakensberg and mass movements (Singh *et al.*, 2008; *Singh*, 2009). The map design is intended to focus on defining the outline and extent of each movement and to indicate geomorphic features found in the criteria (Table 4.1), such as the escarpment, terraces, imbedded boulders, gullies, streams, rivers and floodplains. The features, associated with the criteria, have been digitised from satellite imagery as spatial layers and overlay an aerial image. If a specific item could be located on the aerial photograph, it was digitised as a point feature. If the feature formed part of a larger area or extended into a recognisable area, it was digitised as a polygon. This process was completed and the maps were produced using ArcMap.

Morphometric analysis

The morphometric analysis provides the geometric dimensions of the different movements and helps define various characteristics and properties of the movement itself. The morphometric analysis, which has been adapted from Hardwick (2012), includes aspect, the length and height, as well as secondary lengths of escarpments and terraces. This was obtained from a Digital Elevation Model (DEM) of the area and some spot heights that were taken in-field. The analysis distinguishes between the zone of depletion, transportation and deposition with measurements in length for each section. The measurements were done in ArcMap, on rectified satellite imagery and 5m contours, obtained from National Geospatial Information (NGI).

Chapter 5: Results

In this Chapter, the results for each phase as indicated in Chapter 4, are presented. The results of the first phase show all possible sites found. Phase two defines between the possible sites and confirmed sites. Phase three includes a morphological map, description followed by a summary of the criteria and morphometric measurement of each confirmed site.

First Phase

In the first phase, 33 possible mass movements were identified with their location indicated in Figure 5.1. All of the possible sites were viewed from satellite imagery, topographic and geologic maps. Sites that were chosen showed some indication of matching the criteria, seen in Table 5.1.

Figure5.1: Possible mass movement study sites identified during phase one. Royal Natal indicates the Mahai Valley Landslide

Table 5.1: Criteria of the possible sites identified during the first phase of detection. Each criteria has been classified under the following: NI – Not identifiable, SI - To some extent identifiable, CI – Clearly identifiable.

Mass movemnt name	Topographic shape	Valley constraint and deflection	Hummocky terrain and topographic undulation	Valley side river derangement	Deeply incised flanks	Active or recent mass movements	Sediment displacement – type and form
Drifters	SI	NI	CI	CI	SI	CI	SI
Clifford Chambers	SI	NI	SI	CI	SI	NI	SI
Mahai Valley	CI	CI	CI	CI	SI	SI	CI
Tendele	CI	CI	CI	CI	CI	SI	CI
eBusingatha	SI	CI	SI	CI	SI	SI	SI
MMS19	SI	CI	SI	CI	CI	NI	SI
MMS8	SI	NI	NI	SI	SI	SI	NI
MMS5	SI	CI	NI	CI	CI	SI	SI
MMS13	SI	SI	SI	SI	SI	SI	CI
MMS17	SI	CI	SI	SI	NI	NI	SI
MMS18	SI	CI	SI	CI	CI	SI	SI
MMS2	SI	CI	CI	SI	SI	NI	SI
MMS22	SI	SI	NI	CI	CI	CI	SI
Mweni	SI	SI	CI	CI	SI	NI	CI
Misgunst	SI	NI	SI	SI	CI	SI	SI
Sandlwana	SI	CI	NI	SI	SI	NI	SI
MMS6	CI	CI	SI	SI	SI	NI	NI
MMS1	SI	CI	SI	SI	SI	NI	SI
Baboons Rock	CI	SI	CI	CI	CI	SI	CI
Didema	SI	SI	CI	SI	NI	SI	NI
The Climb	CI	SI	SI	SI	NI	SI	SI
Mushroom Rock	CI	CI	CI	CI	CI	SI	CI
Xaxavithi	SI	CI	SI	SI	SI	CI	SI
Ndedema	SI	SI	SI	SI	NI	NI	NI
Mtoti	SI	CI	SI	CI	SI	NI	NI
Hospital Spruit 1 + 2	CI	CI	SI	SI	SI	NI	SI
Dingaans Cave	SI	SI	NI	CI	SI	SI	SI
Maartenspiek	CI	NI	SI	CI	CI	CI	CI
Wonder Valley	SI	SI	CI	CI	SI	SI	SI
Catarack Valley	CI	CI	CI	CI	SI	NI	CI
Injisuthi	CI	CI	CI	CI	SI	NI	CI
Little Tugela	CI	CI	CI	CI	CI	CI	CI
Copulation Rock	CI	CI	CI	CI	SI	NI	SI

Second Phase

During this phase of verification, 13 of the possible study sites were confirmed in the field and were identified as mass movements or had a high likeness to features identifiable with mass movements. Six of these sites were previously mapped or speculated on, of which four lie in the Injisuthi River valley and have been discussed by Bijker (2001), but have not been examined in detail. The Mahai Valley landslide, mapped by Singh (2009) fell within the study area and has been remapped as well. These six sites were subjected to the same criteria, Table 4.1 (pp. 42), as the other possible sites. Within Table 5.2, type of movement is identified. Not all movements were categorised within the idealised nomenclature shown in Figure 2.1 (pp. 8) and therefore each zone (depletion, transportation and accumulation) was only documented if it is distinct and clearly recognisable. As discussed in Chapter 4, a movement with an unrecognisable form is classified as a complex landslide. Furthermore, style of movement indicates weather it is a single, multiple or composite movement. Table 5.2, summarises further the behaviour, size, type of material, geology and age of each identified movement.

Table 5.2: Summary of the second phase, classification adapted from Singh (2009) and Hardwick (2012) as discussed in Chapter 4.

Mass movement name	Type of movement	Style of movement	Behavioural properties of the Material	Size	Type of material	Type of geology	Age
Drifters	Complex landslide	Composite	Solid and plastic	Very large	Bedrock	Basalt, sandstone and dolerite	Ancient
Mahai Valley	Complex landslide	Composite	Solid and plastic	Very large	Bedrock	Sandstone	Old
Tendele	Rotational landslide	Single	Solid	Large	Bedrock	Sandstone	Mature-old
Mweni	Rotational landslide	Single	Solid	Large	Bedrock	Sandstone	Mature
Sandlwana	Landslide	Single	Solid and plastic	Large	Bedrock	Sandstone	Old
Maartenspiek	Landslide	Single	Solid	Very large	Bedrock	Sandstone	Old
Wonder Valley	Rotational landslide	Single	Solid	Large	Bedrock	Sandstone and dolerite	Old
Mushroom Rock	Rotational landslide	Single	Solid	Very large	Bedrock	Sandstone	Old
Baboon Rock	Compound landslide	Multiple	Solid and plastic	Very large	Bedrock	Sandstone	Old
Cataract Valley	Rotational slump	Single	Solid	Large	Bedrock	Sandstone	Old
Little Tugela	Complex landslide	Composite	Solid and plastic	Very large	Bedrock	Sandstone and dolerite	Old
Injisuthi	Landslide	Single	Solid	Large	Bedrock	Sandstone	Mature
Copulation Rock	Rotational landslide	Single	Solid	Very large	Bedrock	Sandstone	Old

Not all of the 33 possible sites could be visited infield, the more remote sites were viewed from afar or by aerial observation. Appendix B shows the type of observation that was done in order to identify and characterise each study site (refer to Chapter 4, Second phase). The confirmed mass movements are divided into five areas, also according to Figure 5.1. In the Royal Natal section the following mass movements have been identified: Mahai, Tendele and Drifters. The Mweni section consists of two movements: Sandlwana and Mweni, while the Ndedema section consists of Baboons' Rock and Mushroom Rock. The Monk's Cowl section consists of Maartenspiek and Wonder Valley and the Injisuthi section consists of four movements: Cataract Valley, Copulation Rock, Little Tugela, and Injisuthi.

Third phase

In the subsequent sections all the positively identified sites within each area, according to Figure 5.1, by drawing attention to their features and reasons why they are considered as palaeo-mass-movements has been discussed. Each site is identified and a map is presented with a description of the event, while each section contains a figure indicating the local geology of the area. These geological maps were obtained from the Council of Geoscience (2928 Drakensberg Geological Survey, 1981; 2828 Harrismith Geological Survey, 1998). The figures are only sections of the whole map. A complete legend can be found in Appendix C. Following the description of the sites is a morphometric summary.

Royal Natal

This study area is situated in the Northern Drakensberg of KwaZulu-Natal. Three main sites are located within this area. The first site, the Mahai Valley mass movement, and the second, Tendele mass movement are located within the Royal Natal National Park boundaries. The Mahai Valley movement and the Tendele movement were previously considered as palaeo-mass movements by Singh (2009) but only the Mahai Valley landslide has been geomorphologically mapped. The third site, Drifters mass movement, is a very large event situated further north of the park boundaries towards the Free State, see Figure 5.1. Figure 5.2 shows the geology of the Royal Natal National Park. Typically of the Drakensberg, the study area has basalt capped Clarens escarpments, with dolerite sills occurring across the region. Table 5.3 is a summary of the criteria of each confirmed mass movement found within this area, followed by a discussion of each mass movement.

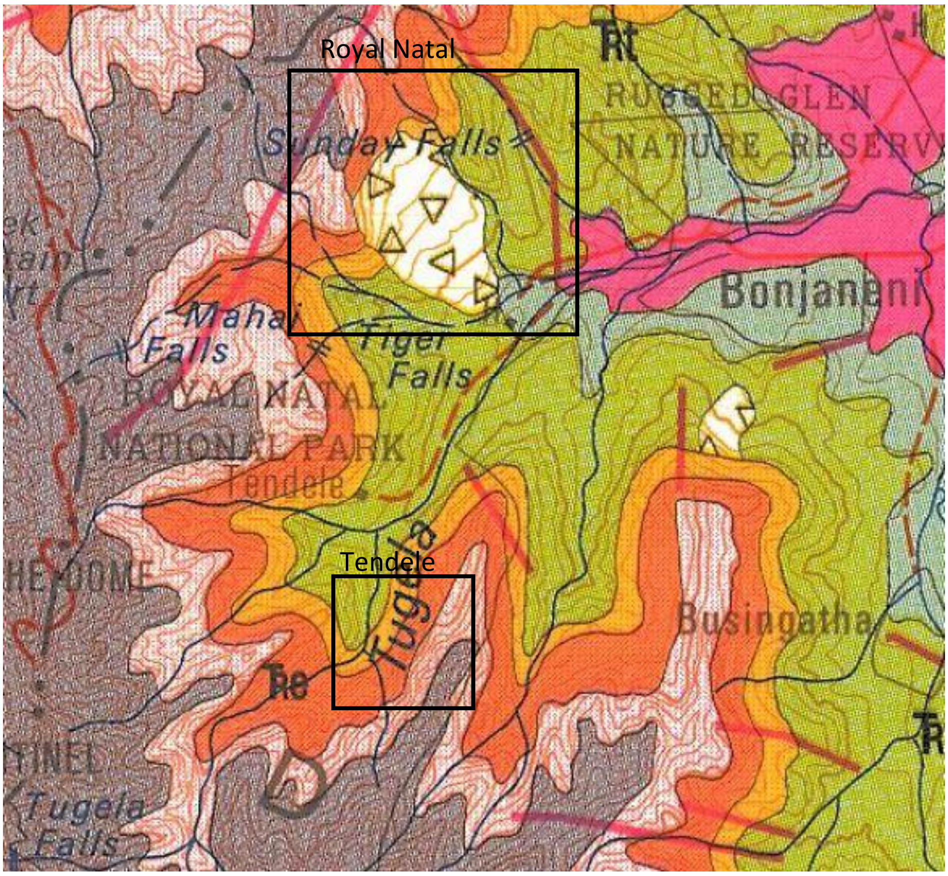


Figure 5.2: Geology of the Royal Natal National Park, see Appendix C for map key.

Table 5.3: The criteria of the movements found in the Royal Natal area.

	Mahai Valley Landslide	Tendele Landslide	Drifters Landslide
Criteria	**Features**	**Features**	**Features**
Topographic shape	Rise in height of the toe Indication of terraces that have unconforming geological structure.	Rise in height of the toe. Terraces and spot heights.	Rise in height of the toe. Indication of terraces that have unconforming geological structure. Spot heights. Rotated geology.
Valley constrain and deflection of valley	Valley constrain. River deflection.	Valley constrain. River deflection.	Valley constrain. River deflection. Irregular river direction.
Hummocky terrain and topographic	Undulation. Hummocky terrain. Changes in vegetation.	Undulation. Hummocky terrain. Changes in vegetation.	Undulation. Hummocky terrain. Changes in vegetation. Water bodies.
Valley side river derangement	Bog pond. Wetland. Irregular river segment.	Bog pond. Wetland. Irregular river segment.	Bog pond. Wetland. Irregular river segment.
Deeply incised flanks.	Deeply incised valley streams.	Deeply incised valley streams.	Deeply incised valley streams and gullies.
Active or recent mass movements.	Small movements.	Small movements.	Small and recent movements on edges and streams.
Sediment displacement, type and form	Out of place boulders. Lack of geological structure.	Out of place boulders. Lack of geological structure.	Out of place boulders. Lack of geological structure.

Mahai Valley mass movement

This movement was first identified and mapped by Singh (2009). Field observations suggest that the movement is larger than originally defined by Singh (2009). The movement's length, from the main scarp (2030m.a.s.l.) towards the toe (1400m.a.s.l.) is 2.681km. The movement spans across an area of 281ha and can be considered as a very large mass movement according to the classification. The width of the toe spans 0.983km and the transportation zone of the movement, where it is considered to be pinched, spanning 0.730km. The main scarp spans 0.977km, although this could vary due to the uncertainty involving the origin of the movement. On the geology map of the area a clear dolerite sill, which is situated along the back scarp of the movement, is visible and could have played a pivotal role in the formation of the movement.

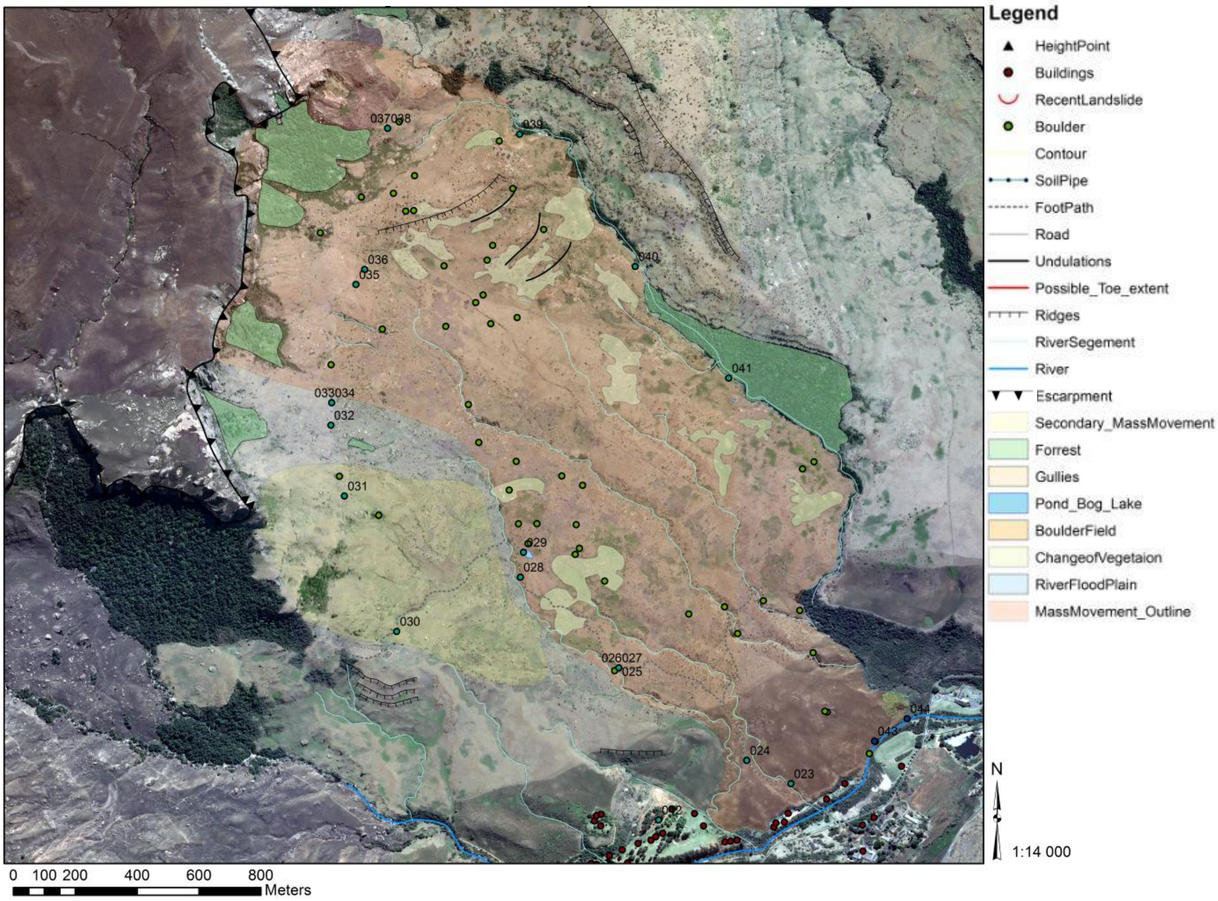


Figure 5.3: The layout of the Mahai Valley complex slide imposed over a satellite image.

Observations from the toe indicate that features on the southern flank of the toe represent an unmoved geological structure. This consists of an area that did not move during the event, consequently pinching the downward flow of debris and regolith of the movement around the Mahai campsite and onto the valley floor. Further evidence is found in the valley symmetry between the unmoved structure and the opposite valley bedrock, an ongoing geological structure across the river follows a continuous structure on the study site. The main body and the zone of accumulation supply the following evidence: topographic undulations, deeply incised streams, changes in the vegetation, and large boulders within the regolith. Point 028, on Figure 5.3 also seen in Figure 5.4, indicates deeply incised streams with deflection around boulders, which probably mark the edge of the mass movement. Evidence of moved structure and the continuation of displaced material down slope are visible. Areas with bogs and ponds are visible within the accumulation zone.

Figure 5.4: A section of the accumulation zone (foreground) and the left flank of the Mahai landslide.

On the southern side of the movement, raised step-like topography indicates its flank or edge. On both flanks of the movement, the opposing geology seems to correlate and is on the same level, showing cross-valley symmetry as seen in Figures 5.5 (Right). The distinct layers seen in Figure 5.5 are also visible on the opposite side of the valley. This step-like geology is not part of the mass movement, but below and also across the main scarp secondary movements occurred as indicated in Figure 5.3. Rock falls are in abundance along the main scarp, while down slope towards the toe, hummocky terrain is visible. The main body of the slide shows no signs of structured bedrock and boulders are scattered throughout the body and the direction of the displaced material changed during the occurrence.

Figure 5.5: (Left) Bog developing due to restriction of water flow down slope. In the background large imbedded boulders are visible. This feature can be found at point 29 on Figure 5.3. (Right) A view from the left flank of the movement towards the right flank of the movement. There is a clear lack of geology over the main body of the landslide. Also evident is the turned regolith flow towards the river from the main scarp and on the far side is the remainder of a dolerite sill.

There is some indication that the initial movement occurred closer to the upper north side of the slope, located near Castle Rock, with secondary movements along the escarpment. Located at the main scarp of the movement is a drop in height that develops down slope into a rise. This forms the minor scarp of the movement where the rest of the movement flows out towards the valley floor. Height difference in this area is vast, with a 500m difference in the main scarp and the minor scarp has approximately 200m height difference. The minor scarp accounts for river deflection and the strange derangement pattern at the base of the main scarp. Changes in vegetation develop from a forested to a wetland area, from where the river incised through the geology and formed a steep valley.

The north-eastern side of the movement is characterized by a deeply incised river, the colour of the exposed rock is reddish brown and the sandstone with different grain sizes. The layers vary in thickness and are set at different angles. The rock formation on the opposite side of the stream has a grey-brown colour. Figure 5.2 indicates the geology of the region, the slope indicated on the map shows some form of palaeo-soils and scree, supporting the argument that the slope is a form of palaeo-mass movement. Along the length of the western escarpment and northern flank of the movement are clear dolerite sills.

Due to the size and various features, this mass movement can be defined as a very large complex landslide. Although it could have occurred as a rotational movement, there is no clear substantial rotation surface of rupture visible or easily identifiable. The age of the movement is disputable, some valley pinching and river deflection are evident, indicating that the movement must have occurred afterwards the current valley floor had been formed. The toe of the movement forced the river to create a new path around it, suggesting that the nature of the movement was in a flow-like manner, supported by Singh (2009). The condition of the main scarp is dissected and vegetated, with an unclear lateral margin, except at the incised valley on the right side of the movement. There are deeply incised streams over the main body which have irregular direction of flow. According to these observations and relative eroded nature of the features visible on the main body, the movement is classified as old.

Tendele mass movement

The possibility exists that this mass movement formed during two separate events, indicated in Figure 5.6, a larger first and a smaller second movement. The second movement is more recent, due to the fact that the second movement features are more clearly visible and the large event would have covered and conceal the smaller event. The rise of the toe is not as prominent, but still visible. Both movements are believed to be rotational landslides while the length of the main movement (measured in the direction of movement) is approximately 0.89km. Width at the toe, middle and escarpment are 0.556km, 0.455km and 0.269km respectively. The toe on the valley floor is situated at 1580m.a.s.l, while the crown is at 1923m.a.s.l. and the top at 1756m.a.sl. This mass movement covers and an area of 54.113Ha and can be classified as a large movement. The second event has a length of 0.425km, width at toe level is 0.494km, in the middle it has a width of 0.376km and the main scarp with a width of 0.191km.

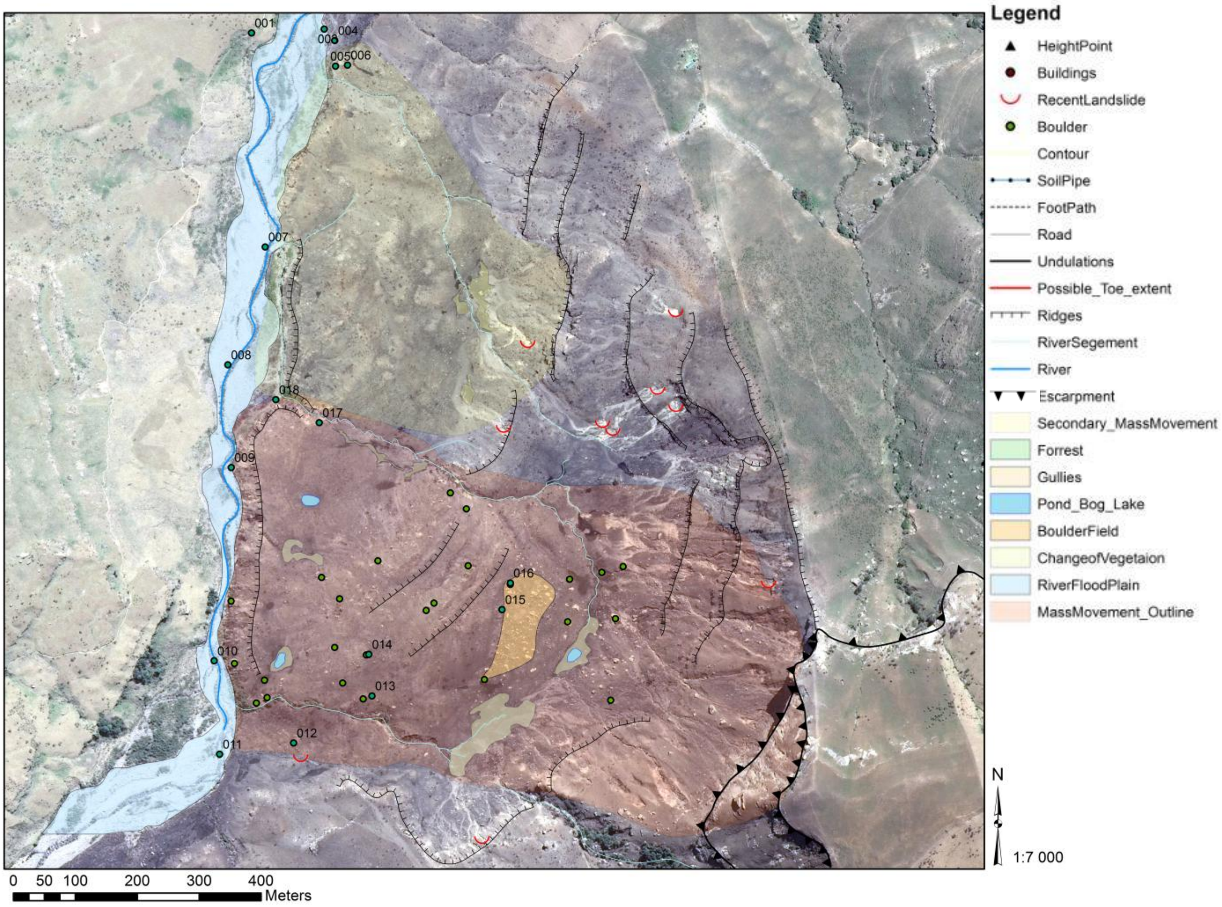


Figure 5.6: The layout of the Tendele rotational landslide imposed over a satellite image.

The southern edge of the movement is well defined and an incised stream indicated the extent. Incised streams are a common feature as proposed by Mather *et al.* (2003). Figure 5.7 shows the river segment deflection on the valley side. Towards the main scarp there is a clear lack of bedrock on the southern side. There is discontinuation of geology from the right, across the incised river, to the left in the body of the movement. Observations in-field, suggest that the movement moved onto a floodplain where it pinched the river and forced the river to flow around it. There is an approximate 2m drop in difference between the current river bed and the previous floodplain where the movement has spilled onto and another meter difference between the colluvial and fluvial material. Large boulders within and erosion of the toe can be seen in Figure 5.8.

Figure 5.7: On the right flank river segment deflection is against normal gravitation directed pull, which formed around step-like topography. Note the change in vegetation in this area as well.

Figure 5.8: (Left) Weathering and erosion of the toe near the left flank exposes angular boulders within the soil which indicate a colluvial disposition. (Right) Massive boulders are located within the regolith on the toe of the movement near the right flank.

Clear river deflection, together with wetland formations and associated changes of green vegetation are visible on the edges of the movement. Large rotated boulders are found throughout the whole slope. Non-conforming valley symmetry is evident, which is a clear indication for the mass movement. The slope can be described as step-like. Four steps are clearly visible, with spot heights on each step creating minor scarps. Each step increase in height from the main scarp to the spot heights, indicating a rotational surface of rupture. At each level there is river derangement around the scarp, thus in each layer different vegetation and river deflection occur on the slope as seen in Figures 5.7 and 5.9. On the northern edge of the movement bedrock is visible, with deeply incised flanks. Figure 5.2 indicates the bedrock of the slide, and shows that the movement occurred within the Clarens Formation and the underlying sandstone formations.

Figure 5.9: The Tendele landslide viewed from across the valley, clearly visible is the heavily eroded toe and step like topography of the movement.

Due to the geomorphic signs in the study area, this mass movement can be considered as mature to old. Rills and incised river segments are present on the main scarp but is vegetated and the lateral margins are clearly identified with incised streams and tributaries. The internal morphology of the mass movement is characterised by undulating topography and disrupted drainage patterns.

Drifters mass movement

This movement occurred over a very large area and includes a large number of features. At the toe of the movement (Figure 5.10) is a small rise and at the base of this rise hummocky, incised terrain persists with embedded boulders. Three different areas occur over the movement and the extent of this very large south-facing mass movement is indicated in Figure 5.11, reaching a total area of 813.38ha, with a length of roughly 4km. The main escarpment is 2173m.a.s.l. with second terraces ranging in heights of 1800m.a.s.l. From the escarpment downwards there is a step-like portion of bedrock, which has some indications of rotational movement (Figure 5.10). Similar features to those in the first area is within the second part which is another step-like area (Figure 5.12). The third area of the movement consists of the major regolith spill and placement of material down slope. On the eastern flank of the movement, adjacent to the stream, are clear bedrock, also on the western side. Deeply incised streams can be found on both flanks of the mass movement. Point 052 (Figure 5.10) indicates the point height located at the toe of the movement. The movement might have spilled into the river level and pinched the entire river, but it is questionable and without clear data it is debatable whether the stream formed after the initial event. At the toe of the movement there is no indication of bedrock, but on the opposite side of the river bedrock structure is visible. River deflection is therefore possible if the movement reached river level. There are also massive boulders both on the mass movement side and on the other side of the river but fewer are noticeable on the non-mass movement side and at a smaller scale. Superficial mass movements into the stream are visible.

Figure 5.10: (Left) An incised section of the lower body movement, viewed from the toe towards the back scarp. (Right) A small secondary rotational movement at the main scarp.

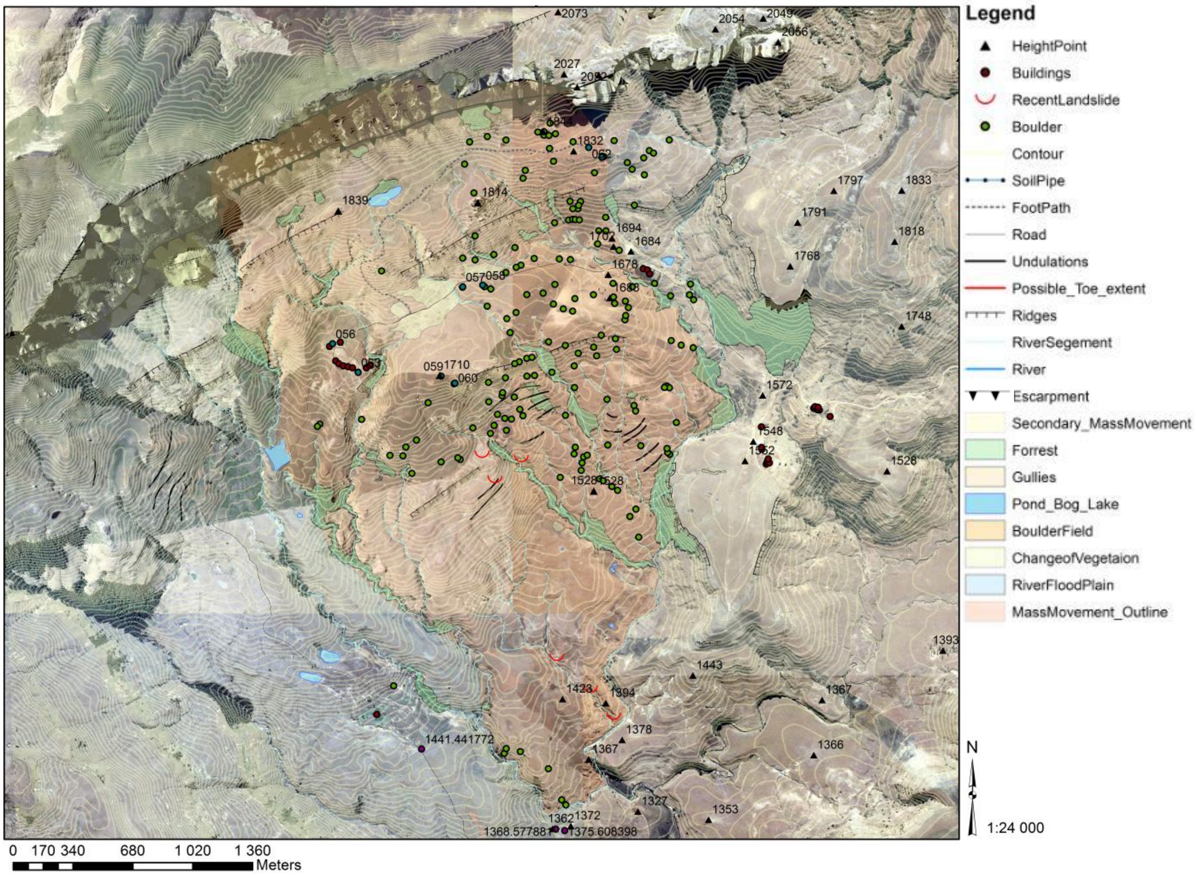


Figure 5.11: The layout of the Drifters complex slide imposed over a satellite image.

Leading up towards the escarpment from the toe of the movement are different point heights. River deflection and pond formation with deranged river segments are common features along the western flank of the movement. On the far western side the bedrock (or ridge) dividing the two zones seems to be an almost horizontal formation, indicating either the edge of the movement or a non-rotational movement.

River deflection is visible around the first and second terrace, where the Drifter Lodge is located, this deflection is around the ridge itself. Between the stream and the second terrace is an area covered with grassland. This area tilts upwards towards the foot of the movement. Big boulders are littered throughout the accumulation area and at the point heights. There are bog and pond formations throughout the entire movement. Most of the structure is covered with vegetation, therefore to attain 100% certainty of geological rotation through observation is not possible but some indication is visible in Figure 5.12.

Figure 5.12: Rotated bedrock in the first minor scarp, rotation shown at A, viewed from the left flank.

Formed and flowing around the point heights, on the well-defined terraces, are ponds, bogs and wetlands, with river derangement clearly evident. The accumulation zone is highly deranged. There is no steep escarpment present at the secondary terrace, instead a moderately inclined slope that is littered with boulders (Figure 5.13). Below the minor scarps, in the accumulation zone towards the river, evidence of hummocky terrain increases together with massive boulders, bogs, ponds, wetland, deranged river segments and incised river streams up towards the rise in height at river level. Multiple superficial movements occur on the sides of the incised streams.

Furthermore, visible on the geological map (Figure 5.14), the entire slope has been mapped as a form of scree or rather, newly undefined geological layer. Several dolerite sills are present, most notably the sill existing parallel to the escarpment that have played an important role as a control in the formation of the movement. The size of this event can be credited to the dolerite sill intrusion. A feature that is common in other study sites are the proximity of an event to the valley floor or a major incised river. This site has tributary streams only, which are deeply incised on the flanks. Every feature of this slope falls into the criteria set out to determine whether this feature is a mass movement. Owing to these facts, there is a strong possibility that this slope has had some form of down-slope movement but the size and extent complicate its classification.

Figure 5.13: The secondary minor scarp viewed from right flank of the movement, littered with boulders present on the main dispositional area of the movement as well.

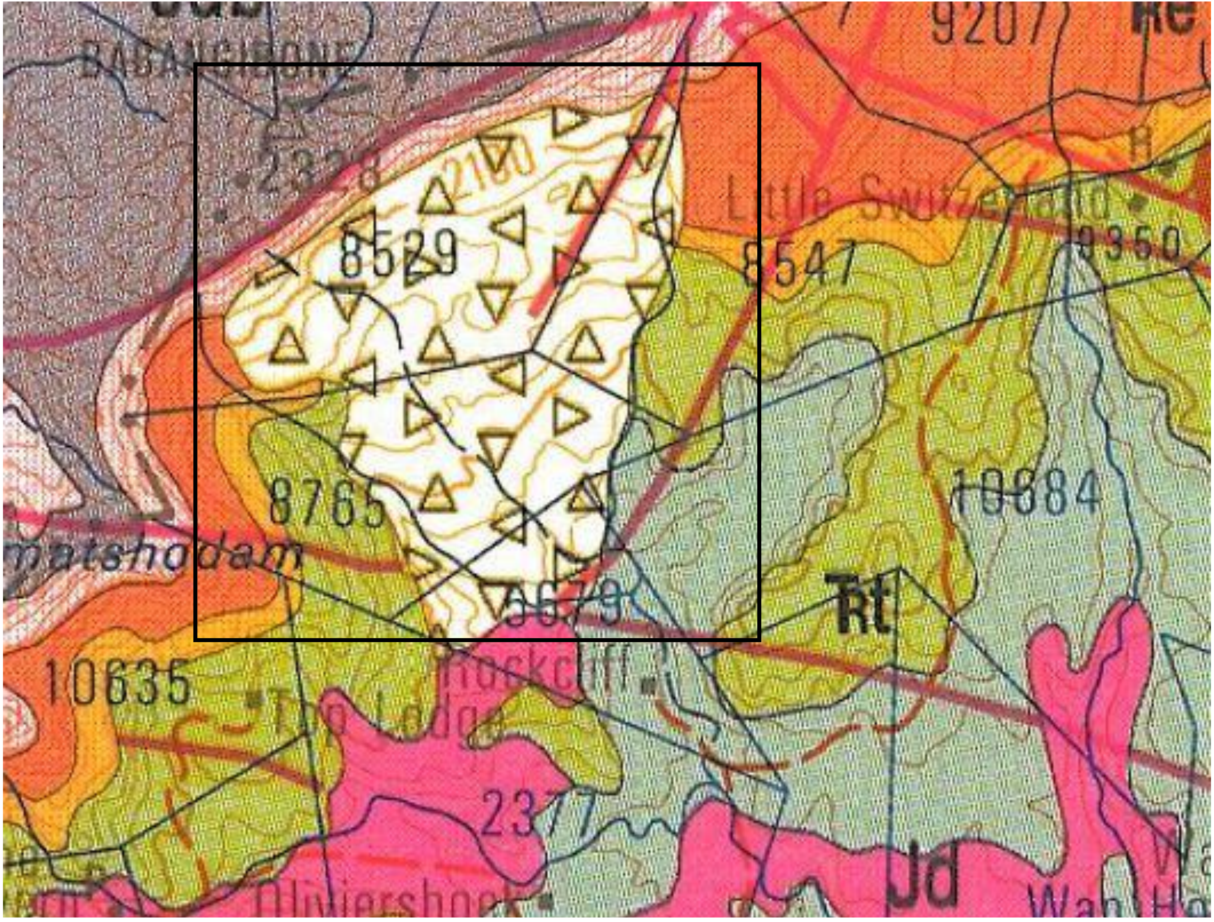


Figure 5.14: Geology map of the Drifters area. The black square indicates the location of the movement. See appendix C for map key.

Due to the geomorphic features of the mass movement this site is classified as an old to ancient very large mass movement. The features on the terraces are smooth and integrated into the landscape. The scarp is vegetated, except on steep edges, and dissected. The lateral margins are difficult to identify. Drainage patterns show both disrupted and normal stream patterns but where there are disruptions, the streams are deeply incised.

Mweni Valley

Mweni is a large open valley south of Royal Natal National Park. The lower valley comprises Clarens sandstone escarpment topped with basalts, with large valleys and steep slopes and wide river flood plains towards the east. This area, being cultural farm land, is scattered with huts and houses and some areas suffer severe erosion from gullies initiated by hiking and animal trails. Two palaeo mass movements were confirmed in this area, shown in Table 5.4, namely Mweni and Sandlwana. Figure 5.15 indicates the geology of the area, followed by a discussion of each mass movement.

Table 5.4: The criteria of the Sandlwana and Mweni mass movements.

	Sandlwana Landslide	**Mweni Landslide**
Criteria	**Features**	**Features**
Topographic shape.	Toe shape is fan-like. Two terraces that are unconfirmed with geological structure. Clear depletion zone.	Toe shape indefinable. Escarpment is concave. No rise in height. Indication of terraces that are unconfirmed with geological structure
Valley constrain and deflection of valley.	River deflection, pressed against the opposite slope.	Almost none. Some deflection. Irregular river direction. No damning developed due to lack of valley pinching.
Hummocky terrain and topographic undulation.	Undulations and hummocky terrain present along the deposition zone. Clear changes in vegetation.	Undulation. Hummocky terrain. Changes in vegetation.
Valley side river derangement.	Bog and ponds visible in the deposition zone. Derange river drainage.	Bog, pond and wetland visible. Irregular flow of river segment.
Deeply incised flanks.	Gully present.	Gullies, possible cause other than the movement. Clear side valley streams
Active or recent mass movements.	Recent small movements present on the flanks.	No recent movements.
Sediment displacement. Type and form.	Buried boulders in the deposition zone. Non-conform valley symmetry.	Rotated blocks, body of movement is littered with boulders. Change in geological structure. Unconformity towards continuing slope.

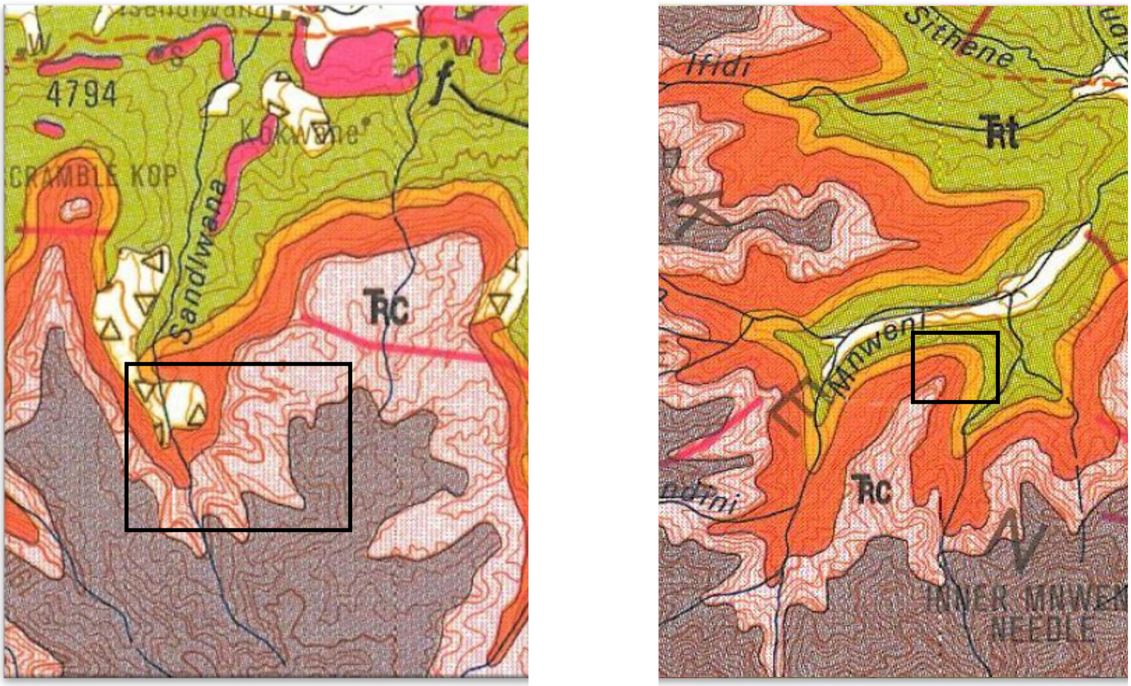


Figure 5.15: Geological sections of the Sandlwana (Left) and Mnweni (Right) valley, the rectangles indicate the location of the different mass movements. See appendix C for map key.

Sandlwana mass movement

This site was observed from an aerial perspective, with no in-field observations. Indicated in Figure 5.16 is the dimension of the possible mass movement taken from an aerial perspective. The movement spans 78.9ha, with a length of 1.106km. The width at toe, middle and escarpment level are 0.67km, 0.642km and 0.331km respectively. The features are indicated in Figure 5.17.

Figure 5.16: Sandlwana rotational slide, aerial view from a north to south perspective. Indicated on the photo is the zone of accumulation and depletion.

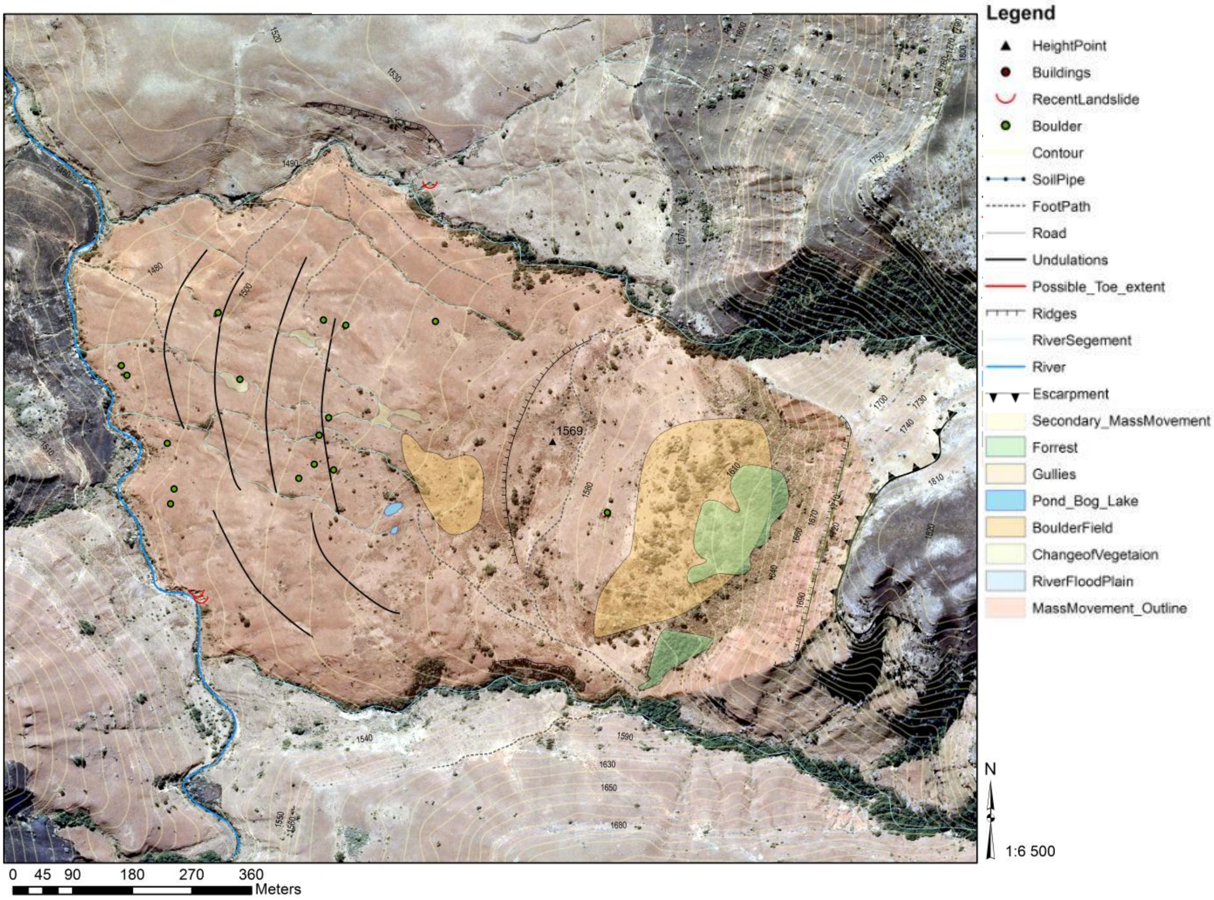


Figure 5.17: The layout of the Sandlwana rotational slide imposed over a satellite image.

Both flanks of the escarpment have deeply incised streams flowing from Little Berg downslope to the Sandlwana river. Forestation growth is visible below the main scarp. Boulder fields did not only develop close to the main scarp, but further downslope and single boulders imbedded in the regolith are sprawled out over the body of the movement. There are various vegetation changes across the body, most likely caused by streams deflecting around lithological obstructions. There are several of these streams flowing down the body of the movement, and some areas are severely eroded by animal trails. Various gullies are found throughout the movement, but can be contributed to overgrazing of the slope. Along the flanks some superficial movements took place and similar features are found at the toe. The movement spread out in a fan-like topography at the bottom of the valley. There was no valley pinching due to the incised nature of the river, but there is some evidence for river deflection around the toe and valley asymmetry is clear.

Although only aerial observations where used, this site can be classified as a slide. Further detail and additional investigations are necessary to identify the movement type accurately. Figure 5.15 indicates the geology of the area, it is shown on the map that the site is regarded as palaeosoils scree and not bedrock. This contributes to the argument that the site is a mass movement feature.

Due to the characteristics of the geomorphic features, the site can be classified as mature to old. Although there is derangement of river around the terraces, some streams flow over the deposited material in a normal pattern into bogs and ponds and are sometimes disrupted by undulations. The main scarp is vegetated and there are indications of the formation of new rills and streams which form on the shear face.

Mweni mass movement

In-field observation indicated that this movement, Figure 5.18, was a single event which did not form part of a whole range or a palaeo-mass movement zone in the valley. The movement is found on the upper slopes of the Molteno Formation and Clarens Formation (Figure 5.15). From the main scarp towards the toe, it has a length of 0.48km and is 0.3km wide and the movement spans roughly 24.1ha.

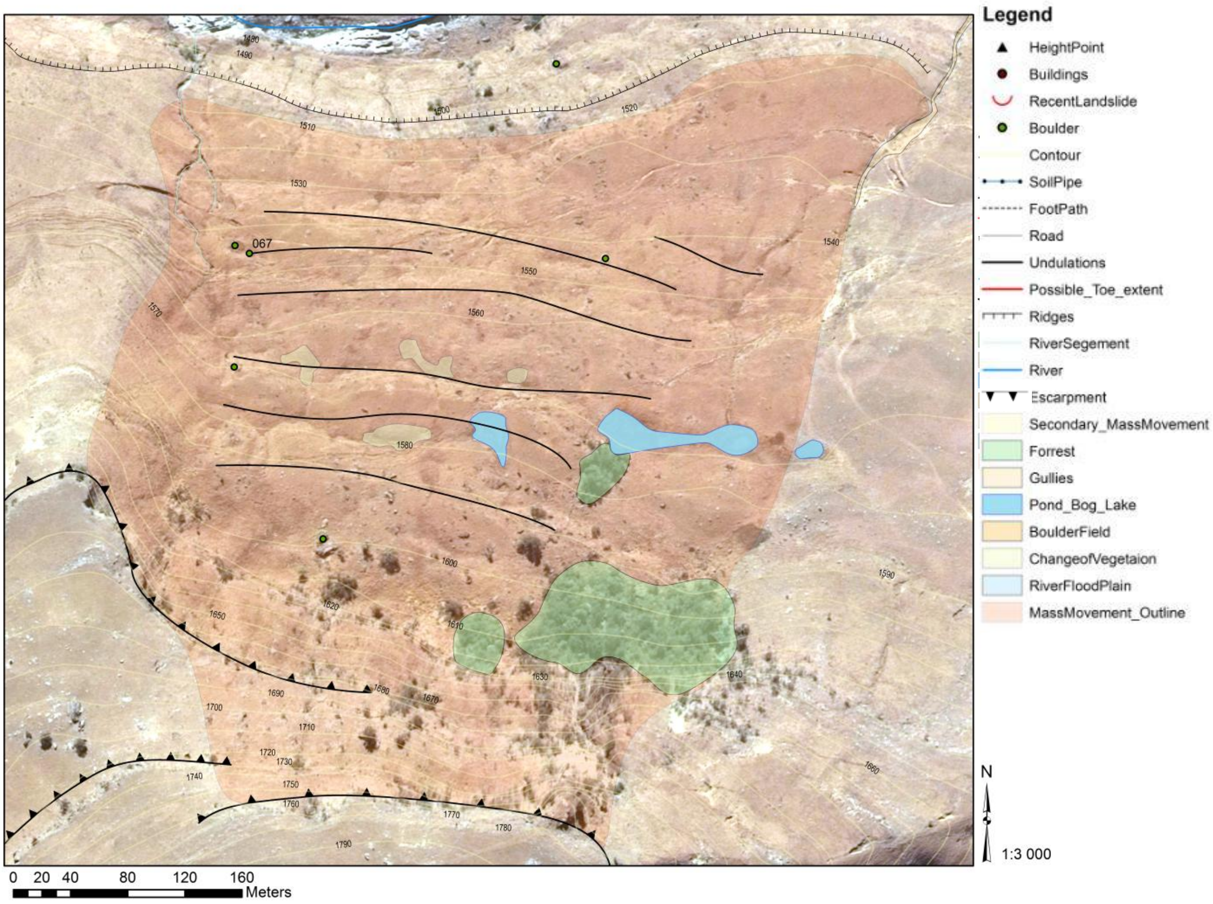


Figure 5.18: The layout of the Mweni rotational mass movement imposed over a satellite image.

Evident on the movement is the step-like topography obstructing and deranging natural flow of steams. Clear changes in the vegetation are visible and the formation of bogs are common throughout the entire slope. Visible on Figure 5.19 and throughout the slide various angular boulders are imbedded within the soil (Figure 5.19). On the left-hand side of the movement, close to the toe, are incised streams leading to gully formation, indicated on Figure 5.20 (Left). A clear drop in height downslope from the toe of the movement towards the river is evident. This could possibly be due to new river incision, or the fact that the movement did not spill into the valley floor and consists only of a series of slumping blocks. Although no clear rotations are plainly visible, the formation of bogs and ponds is an indicator of a rotational surface of rupture. There is also some indication of soil piping visible from aerial photos. The zone of depletion is evident at the main scarp, Figure 5.20 (Right). Natural forestation close to the main scarp is also visible.

Figure 5.19: Boulders are buried within the deposition, and an incised flank is visible on right side of the movement.

Figure 5.20: (Left) The incised left flank leads towards a gully. (Right) The main scarp with the zone of depletion below.

The whole slope is on a steep angle with the valley river deeply incised. This incision would have led to the over-steeping of the entire slope, resulting in the relatively new formation of the movement. The movement can be classified as a large rotational slide. Due to the clear hummocky terrain and the disrupted drainage network of the internal morphology, this movement can be classified as young to mature. The clear lateral margins, shown by streams and partially vegetated tension cracks are clear indications of a younger age.

Ndedema

The Ndedema Valley is an open valley leading towards the Cathedral Peak Hotel, and Ndedema Resort. Figure 5.21 indicates the geology of the region and the valley has fewer dolerite sills and dykes than typically found in this region. Two sites are confirmed in this region, the rotational slide, Mushroom Rock, and the more complex composite sliding of the southern facing slope, called Baboon Rock. Table 5.5 is a summary of the criteria, followed by a discussion of each mass movement.

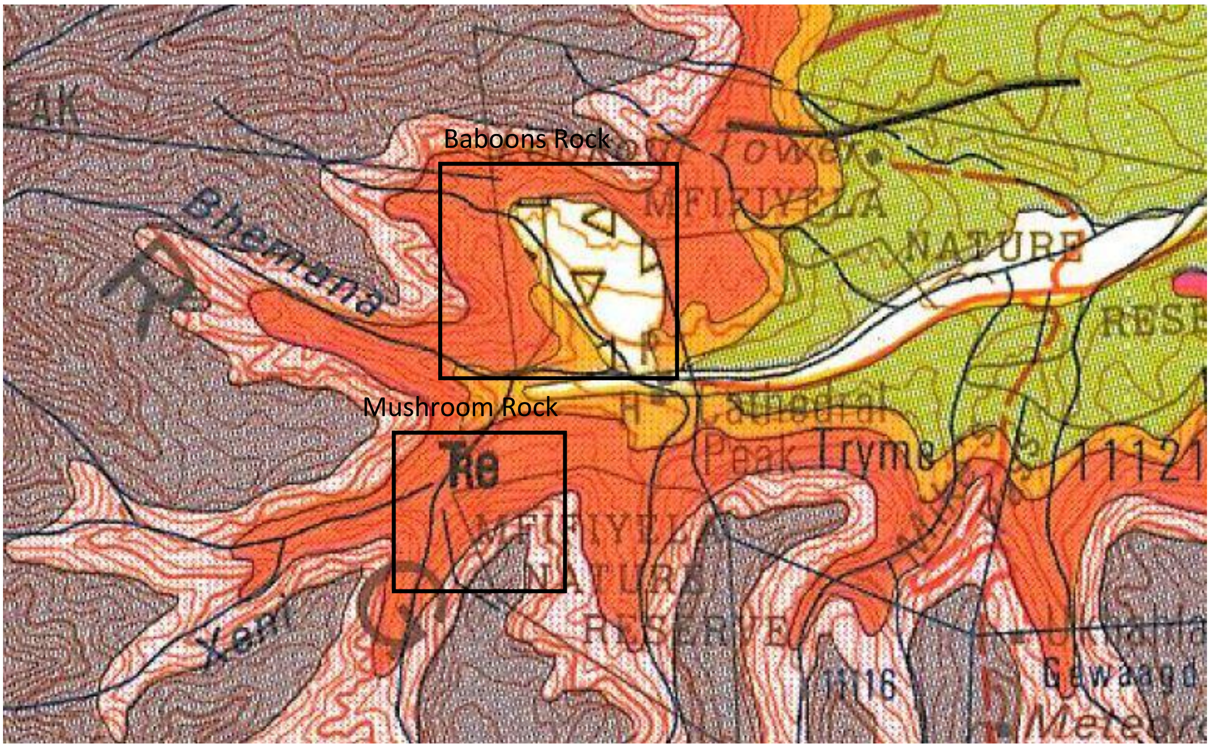


Figure 5.21: Geology sections of the Ndedema region. The black squares indicate two separate mass movements in this region. See appendix C for map key.

Table 5.5: The criteria for the mass movements in the Ndedema area.

	Baboon Rock	**Mushroom Rock**
Criteria	**Features**	**Features**
Topographic shape	Toe spill into the valley river and into the side streams in separate events. Rotated geology at the main scarp.	Rise in height of minor scarp and along the toe., Flat straight main scarp. Indication of terraces that are unconfirmed with geological structure.
Valley constrain and deflection of valley.	Some river deflection.	River deflection.
Hummocky terrain and topographic undulation.	Heavy undulations at main scarp. Hummocky terrain over majority of slope. Water bodies evident. Changes in vegetation over whole body of movement.	Undulations and rises within the deposited material. Hummocky terrain visible. Water bodies. Changes in vegetation, due to obstruction of slope hydraulics.
Valley side river derangement.	Irregular river segment direction at the main scarp, Bogs, ponds and wetland on the body of the movement.	Irregular flow of river segments.
Deeply incised flanks.	Incised flanks.	Gullies and pipe formation on the flanks.
Active or recent mass movements.	Recent flow along side.	Small recent mass movements.
Sediment displacement, type and form.	Rotated geologic layers. Out of place boulders in between undulations.	Lack of geological structure and valley symmetry. Out of place boulders.

Baboon Rock mass movement

The main scarp has a height of 1710m.a.s.l. and reaches down to toe level at 1383m.a.s.l. with the main movement covering 154ha. Close to the main scarp are clear rotational movements. Point 082 in Figure 5.22 indicates the edge of the movement. Hummocky terrain and undulations are found throughout the whole movement, while the terrain on the right are smooth and has less indication of hummocky terrain. Hummocky terrain spreads over the inclining slope, with the most severe undulation forming at the backscarp. Visible on the western flank of the movement, close to the main scarp, is evidence of rotated bedrock. The rotated geology can provide an answer for the extreme hummocky terrain found towards the middle of the slope and close to the main scarp.

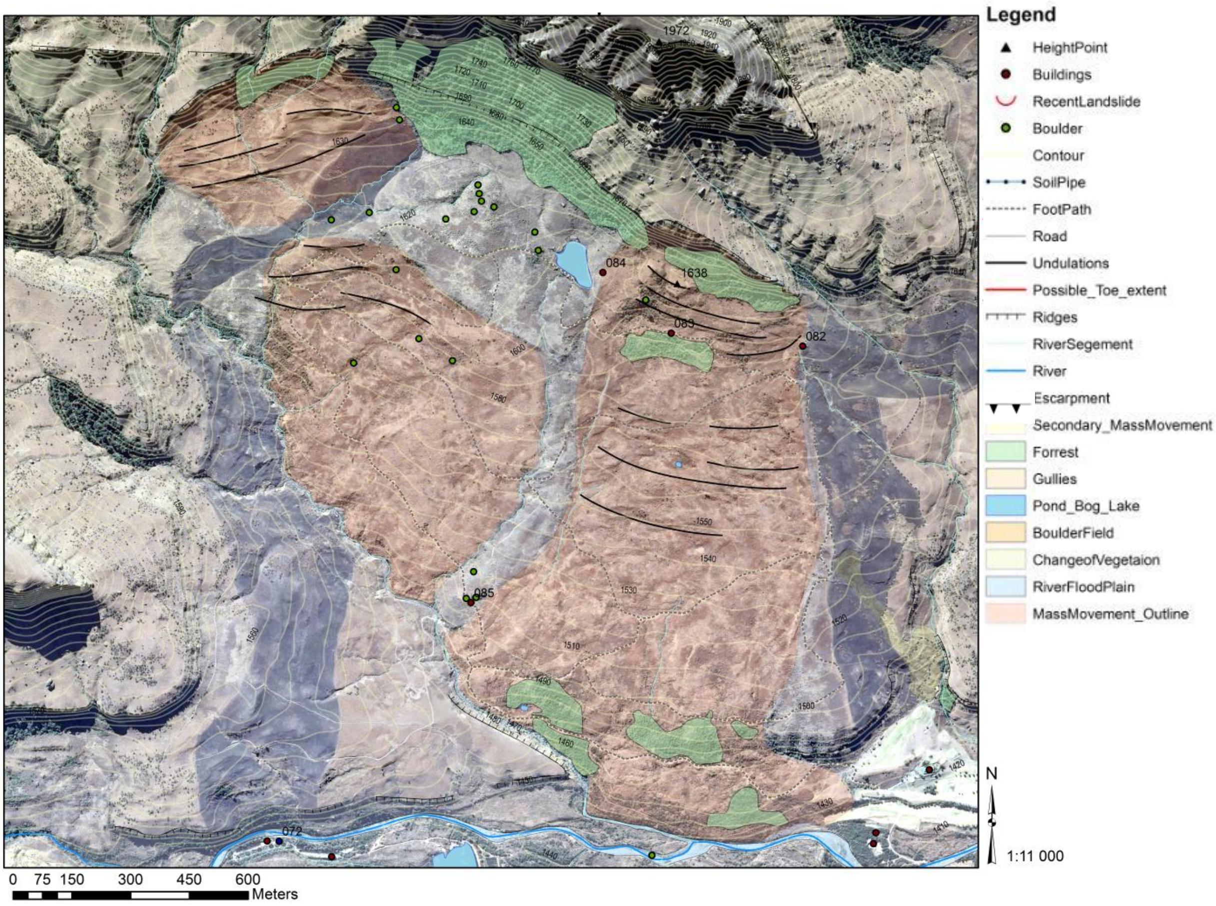


Figure 5.22: The layout of the Baboon Rock complex slide imposed over a satellite image.

At the main scarp, forestation is visible and point heights and deranged drainage is evident. In Figure 5.23, one can see that a part of the main scarp is detached from the escarpment, with an incised stream between the two sections. The mass movement could have provided a sufficient weakness in the slope for it to be exploited by stream erosion.

As mentioned, the region in front of the main scarp, is extremely hummocky, but more striking is the change in height between the different spot heights and the adjacent low lying areas. Figure 5.24 (left) shows the terrain in this area; clearly visible are angular boulders among steep rises at the foot of the main scarp and the material consisting of loose soil, boulders and rubble. Some boulders are imbedded within the soil.

Figure 5.23: Hummocky terrain located at the main scarp.

Figure 5.24: (Left) Imbedded between the undulations located at the main scarp are angular boulders. (Right) Rotated geology located at the back scarp of the movement, indicated by A.

The extent of the rotational movement downslope does not reach the valley floor; downslope from the point heights and undulated terrain are less severe hummocky terrain where bog formation is evident and changes in the vegetation are more severe. Also, on the west side of the slope is the renowned natural Lake William, which is an indication of some form of rotational movement. On the right or eastern flank of the movement is evidence of a more recent flow that spilled into a deeply incised river segment.

Observations on the western flank and toe indicate that the regolith spilled into the side valley river, the body of the western flank remains hummocky although not as distinct as below the escarpment. There are various changes in vegetation and there is evidence of embedded boulders with point heights scattered throughout the area. There is also a lack of valley symmetry, as defined ridges are visible across the river that is missing in the study area. Figure 5.25 shows the body of the movement on the western flank.

Figure 5.25: The image shows displaced material located in the main body and towards the western flank of the Baboon Rock mass movement.

Close to the hotel there are clear signs of undisturbed bedrock, due to the lack of imbedded boulders closer towards the valley floor and middle region of the slope. There is no clear sign of structured bedrock at the river level, but there is some similarity to the deposited regolith as seen in Figure 5.26. The geological map indicates the area as palaeo soils that contributes to the discussion that the slope forms part of a mass movement feature (Figure 5.22). Evident throughout the area is the low angle at which the bedrock is dipped and where a spread can be formed. Further investigation will be needed to identify if there is a slip surface for translational sliding or deformation of a weak underlying layer that can lead to spreading. Soft clay layers within in the sandstone formation are often surfaces where spreading can occur.

Figure 5.26: The toe of the Baboon Rock movement viewed from across the river in a northern direction.

With clear rotation visible at the main scarp and features associated with spreading visible throughout the body of the movement, identification of the mass movement is complicated. It is possible that the slope deformed in a manner identified by Hungr *et al.* (2014) and that it can be classified as a compound landslide. However, it is also suggested that the whole slope is a palaeo-mass movement zone, consisting of various rotational slides at the main scarp and with lateral spreads along the main body of the movement.

This movement will be classified as mature to old, due to the internal morphology consisting of clear disrupted drainage patterns, hummocky terrain and clear undulations. The escarpment is vegetated, but clearly identifiable.

Mushroom Rock mass movement

The main scarp is located at 1766m.a.s.l., while the minor scarp is at 1607m.a.s.l. The total distance of the movement is 0.87km, the toe is roughly 0.69km in length and the whole mass movement constitutes an area of roughly 10.7ha. Figure 5.27 is an aerial photograph showing the possible extent of the movement, which is then defined in Figure 5.28.

Figure 5.27: Aerial photo of the Mushroom Rock mass movement with the outline of the movement taken from a north to south view point.

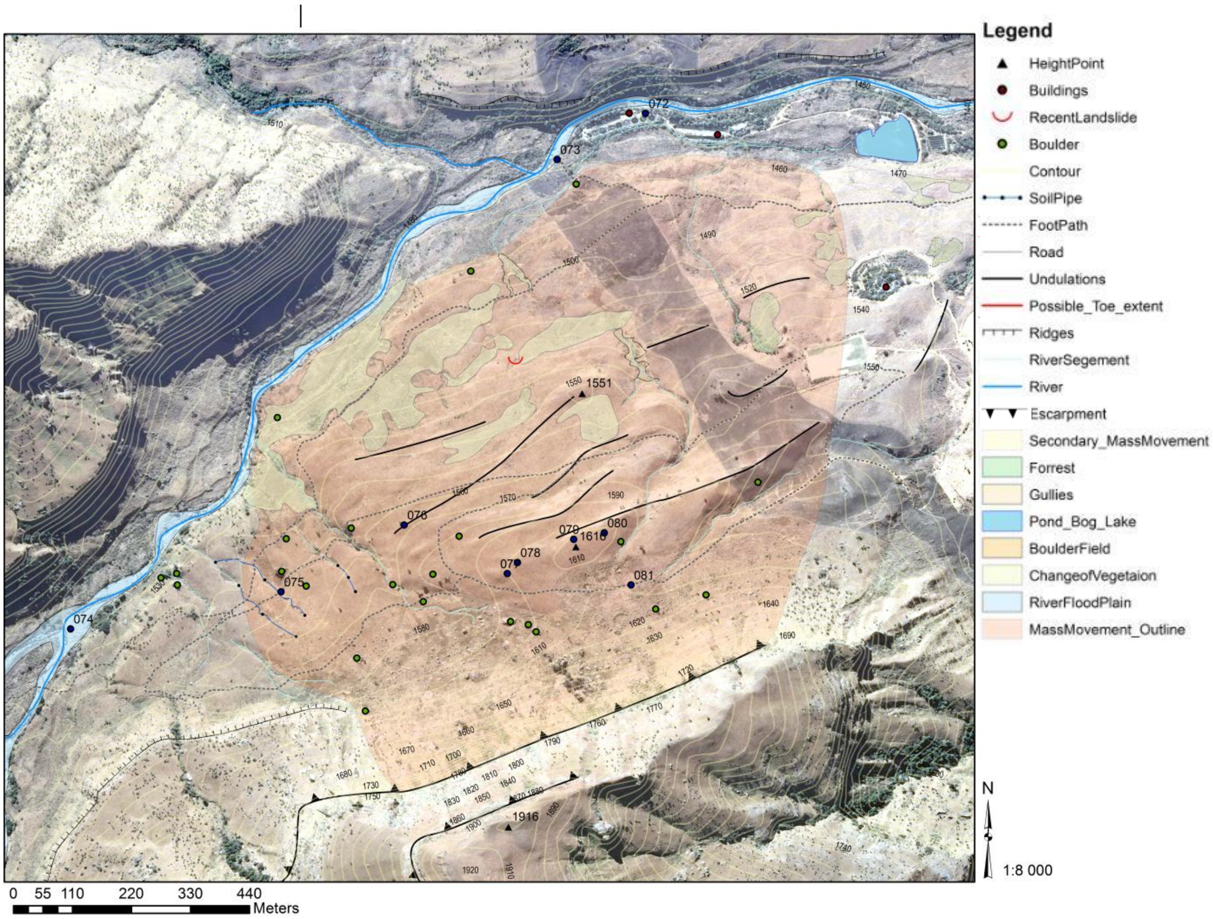


Figure 5.28: The layout of the Mushroom Rock rotational slide imposed over a satellite image.

Similar to the geological structure of the Drakensberg the bedrock is visibly angled or dipped, although within the ranges of what will commonly be found in the Drakensberg. It is important to take this dipped bedrock into consideration, due to the fact that the angled bedrock can create similar features to those that are used to identify mass movements in the criteria. Figure 5.22 is the geological map of the area and illustrates that the mass movement is primarily within the Clarens Formation and the underlying sandstone layers.

There is evidence that the movement spilled into the river on the right side of the site; angular rocks are visible higher up in the soil matrix, while rounded rocks are visible lower down due to erosion by the river. On the left side of the toe, the river bank shows fluvial eroded rock throughout the soil matrix. It is possible that the movement did not spill into the river itself in this area, or that the toe of the movement has been eroded away, as shown at point 073 on Figure 5.28. Figures 5.29 and 5.30 show the main body of the movement found in the accumulation zone.

Figure 5.29: The main deposition of the Mushroom Rock mass movement seen from the left flank towards the right. The body of the movements is heavily undulated and incised.

Figure 5.30: Clearly seen is the undulated terrain of the Mushroom Rock mass movement which causes changes in the river segment direction, viewed from the toe towards the main scarp seen in the background.

At the western edge of the movement, there is a continuation of Molteno Formation across the valley and also upstream into the valley. As shown in Figure 5.31 (Left), the Molteno Formation cuts away and is not visible on the western flank towards the main scarp, which indicates a clear depletion zone.

Figure 5.31: (Left) A collapsed soil pipe found on the left flank of the Mushroom Rock movement. (Right) A view from the left edge of the movement towards the back scarp.

Due to the rise of the minor scarp, shown in Figure 5.32, deranged river patterns and change in vegetation are visible at the base of the main scarp. In fact, the whole body of the movement is covered with vegetation that change due to obstructions caused by the topographic undulation that resulted in deranged drainage patterns. Various bog formations are also a result thereof. On the right flank of the movement, the topography is less steep or gentler and not clearly populated with undulating or hummocky terrain. Instead, more boulders are visible with signs of soil piping and gully erosion. Valley pinching and boulders of various sizes with colluvial origin are found lower and closer to the river. These boulders are also found upslope but are imbedded in the soil. Figure 5.31 (right) also shows a collapsed soil pipe found at point 075 on the map (Figure 5.28).

The mass movement can be classified as a rotational old landslide. The age of the movement is indicated by the lack of clear margins. Although the undulated terrain is clearly visible, it is smooth and vegetated with a normal stream pattern on the right flank. In the accumulation zone, the drainage pattern remains disrupted by the undulating terrain and reverse slopes. The main scarp is dissected and vegetated.

Figure 5.32: Viewed from the back scarp towards the toe, is the rise of the minor scarp. A change in vegetation and the deflection of river segments around the rise are visible in the foreground.

Monk’s Cowl

Monk’s Cowl is situated in the Champagne Valley in the central Drakensberg. The valley, similar to the general geology of the area, has steep Clarens escarpments leading up to the main basalt escarpment. Various dolerite dykes and sills are found within in this area, as seen in Figure 5.33. A summary, Table 5.6, is included in this section that show the criteria of each mass movement.

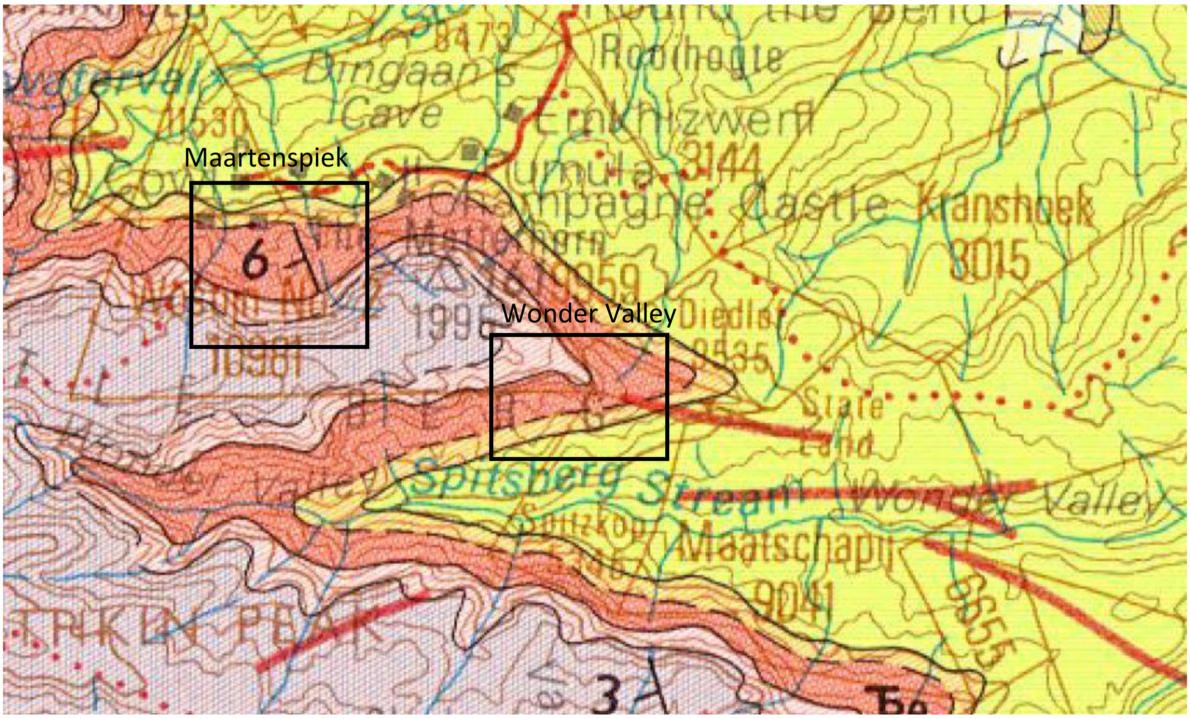


Figure 5.33: Geology section of Maartenspiek and Wonder Valley. The black rectangles indicate the separate mass movements in this area. See appendix C for map key.

Table 5.6: The criteria for the mass movements in the Monk's Cowl area.

	Maartenspiek	**Wonder Valley**
Criteria	**Features**	**Features**
Topographic shape.	Rise in toe height, and clear spot heights. A clear minor scarp. Indication of terraces that are unconfirmed with geological structure.	Arc shape escarpment.
Valley constrain and deflection of valley.	No valley constraint of river deflection, movement is formed away from river.	
Hummocky terrain and topographic undulation.	Little undulations, but some changes in vegetation indicate changes in slope and hummocky terrain.	Heavy undulated. Hummocky terrain. Changes in vegetation.
Valley side river derangement.	Upslope irregular river segment flow direction. Changes in vegetation due to obstructions in slope hydraulics.	River segment derangement.
Deeply incised flanks.	Deeply incised flanks and streams along the body of the movement.	Gullies. Incised streams.
Active or recent mass movements.	Small and recent slides visible.	
Sediment displacement, type and form.	Out of place boulders. Lack of geological structure along the main scarp and no clear valley symmetry.	Rotated geology. Out of place boulders. Lack of geological strata at main scarp.

Maartenspiek mass movement

Situated near the Monk’s Cowl camp site and close to the Champagne Castle Hotel, Maartenspiek has a large and clear depletion, transportation and accumulation zone. The height of the main scarp reaches 1967m.a.s.l., while the minor scarp reaches 1774m.a.s.l. The total length of the movement is aproximately 1050m, although the toe could have been eroded back up slope. The length of the transportation zone is 720m and it is 200m wide, while the deposition zone has a length of 713m and is 413m wide. Maartenspiek (Figure 5.34) can be classified as a complex landslide, covering 106ha.

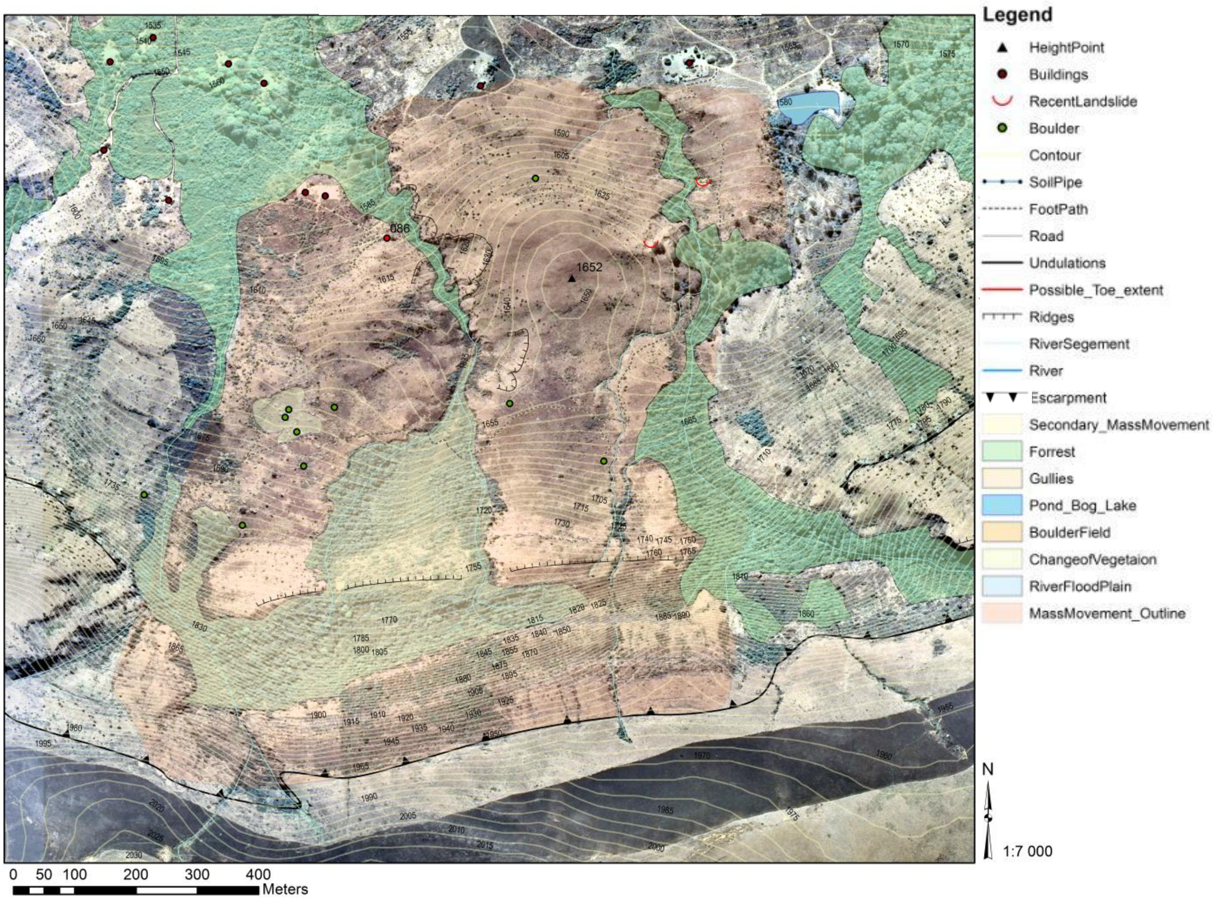


Figure 5.34: The layout of Maartenspiek complex slide imposed over a satellite image.

At the back scarp there is forrestation, as seen in Figure 5.35, and changes in vegetation due to the deflection of water around geologic obstructions. Downslope the streams are incised into the bedrock, creating steep ridges where small and superficial mass movements can occur. There are two distinct rises at the toe, with streams separating each one. A minor scarp, located close to the main scarp influences the river segment drainage pattern, causing it to flow around the scarp and resulting in deranged drainage patterns. There is, however, no valley pinching or river deflection due to the fact that the movement did not spill onto the current valley floor. Towards the deposition area, there are more changes in vegetation and bog formation. Another indication is the lack of valley symmetry, the main scarp itself is straight but on the right and left side is a large cut back or regresion zones. The main scarp depletion zone can be clearly identified.

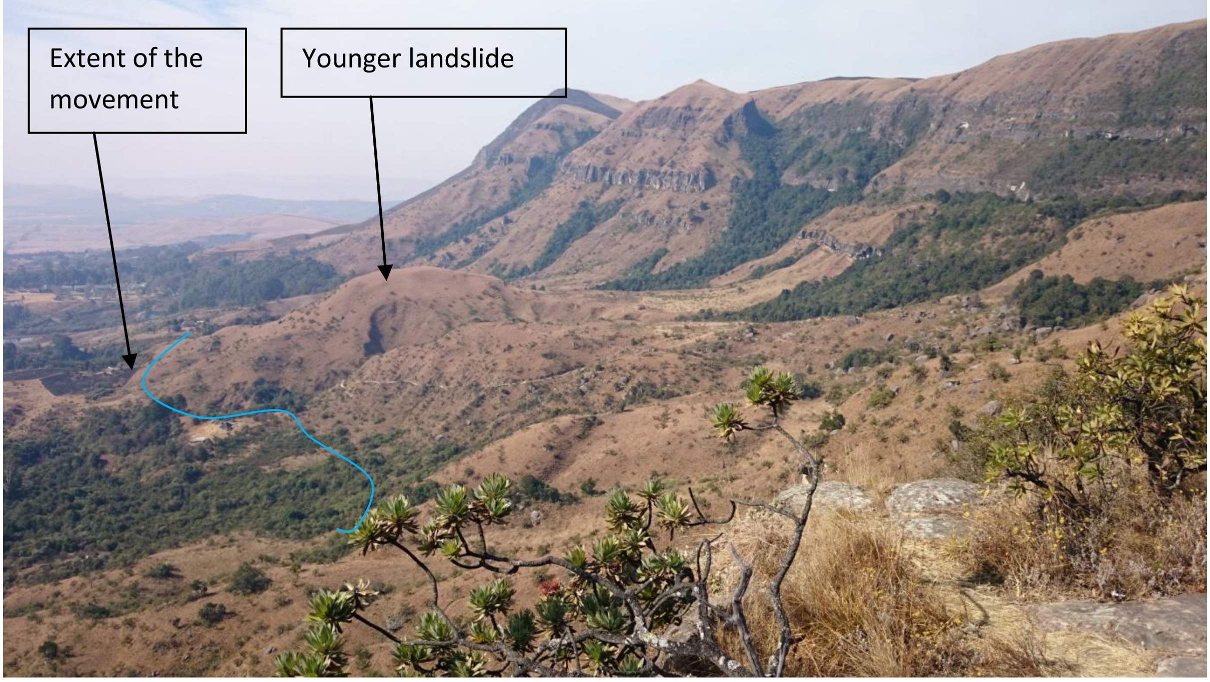


Figure 5.35: View of Maartenspiek from the west flank towards the east, clear indication of the extent of the movement. Note the young and smaller landslide scars in the foot of the movement.

Initial observations derived from a topographic map suggest that this is a possible landslide due to the rise away from the backscarp (1650m.a.s.l.), as seen in Figure 5.35. Figure 5.33 illustrates the geology of the area, which indicates that there are no intrusions depicted on the site. On the footpath leading up towards Maartenspiek a white grey sandstone is visible with characteristics of the Clarens Formation (figure 5.36). As shown in Figure 5.33, Maartenspiek is situated in Clarens Formation lithology and within the subsequent sandstone layers. It is derived, according to the features discussed, that Maartenspiek is quite clear and has a very distinctive mass movement affected slope. Figure 5.36 shows an aerial view of the mass movement in which the deposited material and main scarp depletion zone are evident.

Figure 5.36: (Left) Aerial view of Maartenspiek. (Right) Rock samples at the left is on top of Little Berg (Clarens Formation) and the sample on the right is located in the deposition zone of the movement.

Due to the appearance of the geomorphic features on this study site, it is suggested that the movement can be classified as an old to ancient landslide. The features of the movements are almost completely eroded back into the landscape, and while there are clear indications of its margins, the deeply incised streams are the only indication of a deranged stream pattern. Apart from the terraced obstructions, the terrain is smooth and not undulated. The main scarp is identifiable, but vegetated.

Wonder Valley mass movement

The geology of the area is indicated in Figure 5.33 and the movement itself occurred in Elliot Formation lithology and the subsequent sandstone layers. Depicted on the geological map is the presence of a dolerite sill, which could possibly play a role in the formation of the mass movement and the surface of rupture.

The Wonder Valley movement, shown in Figures 5.37 and 5.38, is characterised with clear rotation and heavily undulated areas below the main scarp. The river segment is deflected around this rotation on the left side of the mass movement. Forestation is evident, as well as the deep incision of the river segment. Embedded boulders are evident near the toe. Below the house, hummocky and undulating terrain can be observed. Further downslope, although few, hummocky terrain and deranged river segments with some incision are apparent. However, it is inconclusive if the movement’s toe is spilled onto the valley river floor level. Therefore, the movement will be classified as a large rotated landslide consisting of an area of 22.36ha. The movement is roughly 400m from the main scarp to the end of the rotation.

Figure 5.37: View of the Wonder Valley slide in a northern direction across the valley.

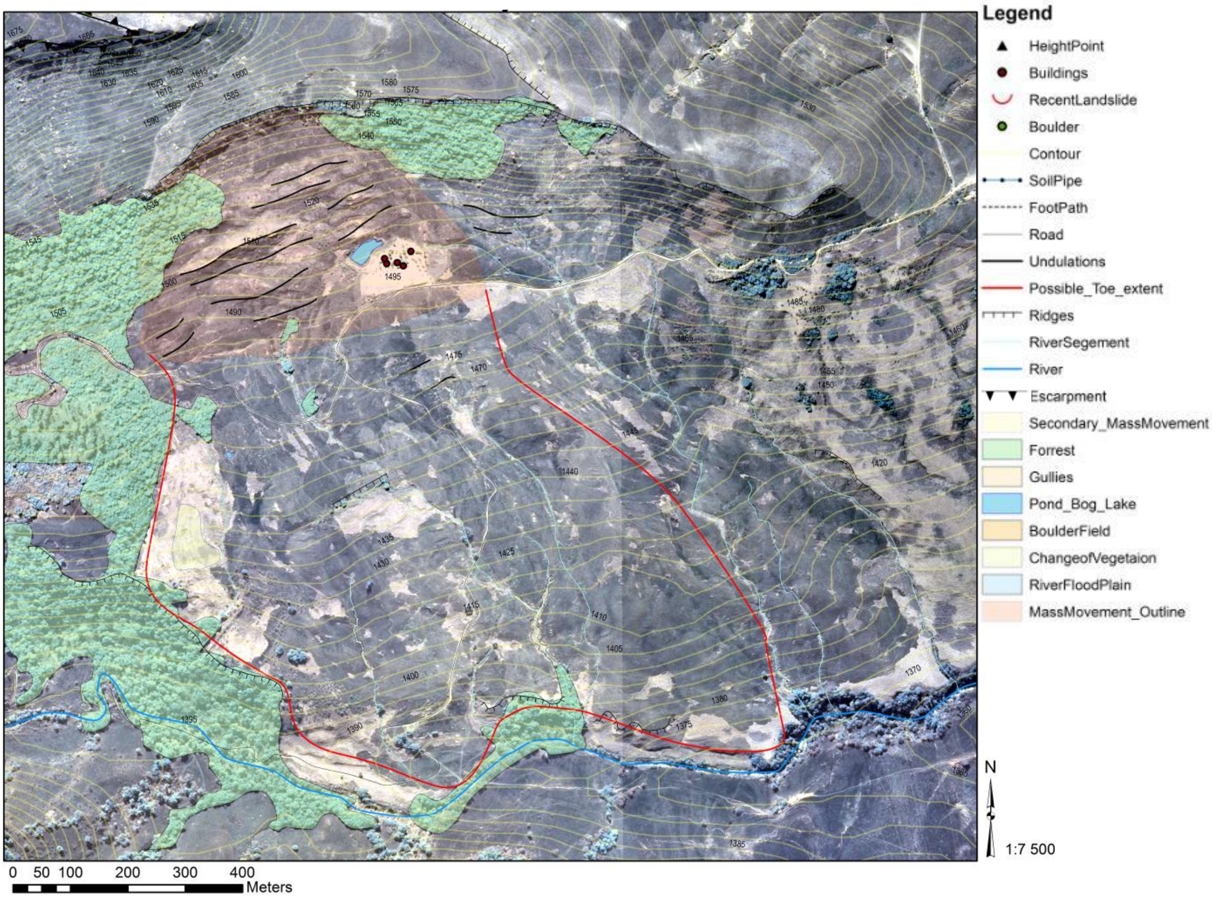


Figure 5.38: The layout of the Wonder Valley rotational slide imposed over a satellite image.

From observations the slide can be characterised as mature. The clear indication of hummocky and undulating terrain, with reversed slopes close to the main scarp supported by deranged river patterns contribute to this suggestion. However, if the zone of accumulation is located at the valley floor, it can be suggested that it is an old landslide, due to the vague margins. Further in-field research will be needed to identify an absolute age of the movement and to clarify the extent of the movement itself.

Injisuthi

Injisuthi is a valley situated in the Giant’s Castle Game Reserve in the Central Drakensberg. This deep valley has large Clarens scarps capped with overlying basalts. The valley, as seen in Figure 5.39, has several dolerite sills intruding through the sandstones. A summary of the features found is included in Table 5.7.

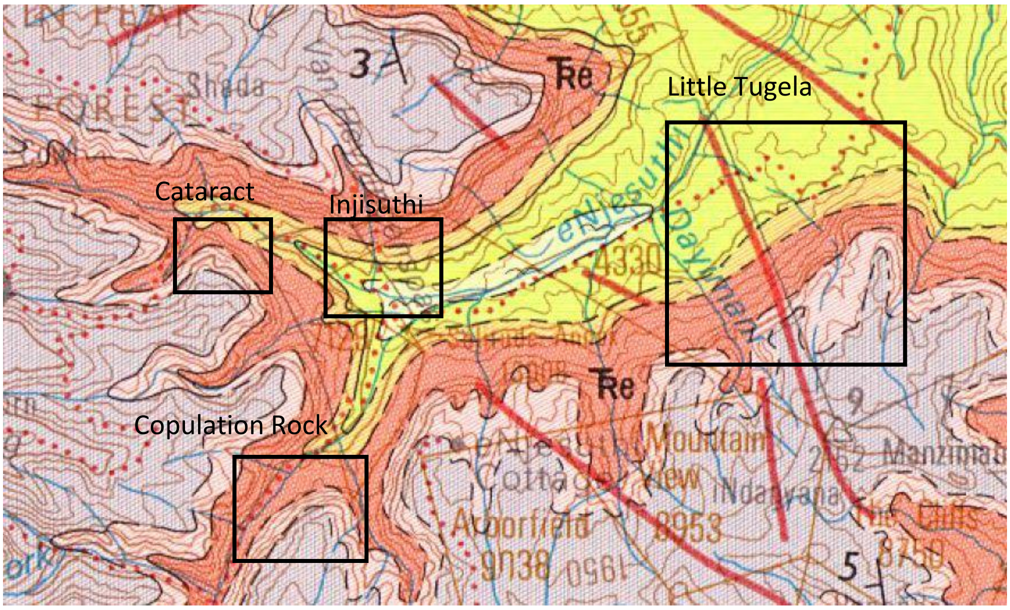


Figure 5.39: Geology map section of the Injisuthi Valley, the black squares indicate the mass movements in this area. See appendix C for map key.

Table5.7: The criteria for the mass movements in the Injisuthi area.

	Cataract	**Copulation Rock**	**Little Tugela**	**Injisuthi**
Criteria	**Features**	**Features**	**Features**	**Features**
Topographic shape.	Rise in toe height and spot heights, Valley unconformity.	Indication of terraces that are unconfirmed with geological structure. Rise in height of deposition zone.	Indication of terraces that are unconfirmed with geological structure.	Rise in the height of the toe.
Valley constrain and deflection of valley.	Valley constrain. River deflection. Meandering of river on valley floor.	Valley constraint. River deflection.	Clear valley constraint and pinching. River deflection. Meandering upstream.	Clear river deflection around the toe of the movement.
Hummocky terrain and topographic undulation.	Undulations. Hummocky terrain. Changes in vegetation.	Change in vegetation.	Undulations. Hummocky terrain. Changes in vegetation. Water bodies.	Some undulations. Some hummocky terrain.
Valley side river derangement.	Bog, pond and wetland formation. Deranged and irregular direction of flow of river segments.	Wetland formation at the base of the main scarp. River segment has irregular direction of flow.	River segment derangement throughout the whole movement. Bog, pond and wetland formations occurrences throughout the movement.	River segment derangement, forced around deposited material.
Deeply incised flanks.	Some incision.	Some incision.	Deeply incised flanks. Formation of gullies and soil pipes evident.	Flanks are incised streams.
Active or recent mass movements.			Secondary movements along the edges.	
Sediment displacement, type and form.	Out of place boulders within the regolith.	Out of place boulders embedded within the soil.	Lack of geological strata and valley symmetry. Rotated and out of place boulders which are imbedded within the soil.	Out of place boulders imbedded in the soil. Lack of bedrock in transportation and depletion zone.

Cataract mass movement

As shown in Figure 5.40, this movement's main scarp is located within the basalts layer, although the majority of the movement is situated in the sandstone layers. The movement has an approximate length of 475m from the main scarp to the end of the regolith deposits. Its toe reaches down to the river level at approximately 1542m.a.s.l. and extends 850m along the Delmhlwazini river. The main scarp reaches approximately 600m in width at 1740m.a.s.l., and the mass movements spans roughly 29.4ha. Figure 5.39, the geological map of the area, indicates that there are no dolerite influences over this movement.

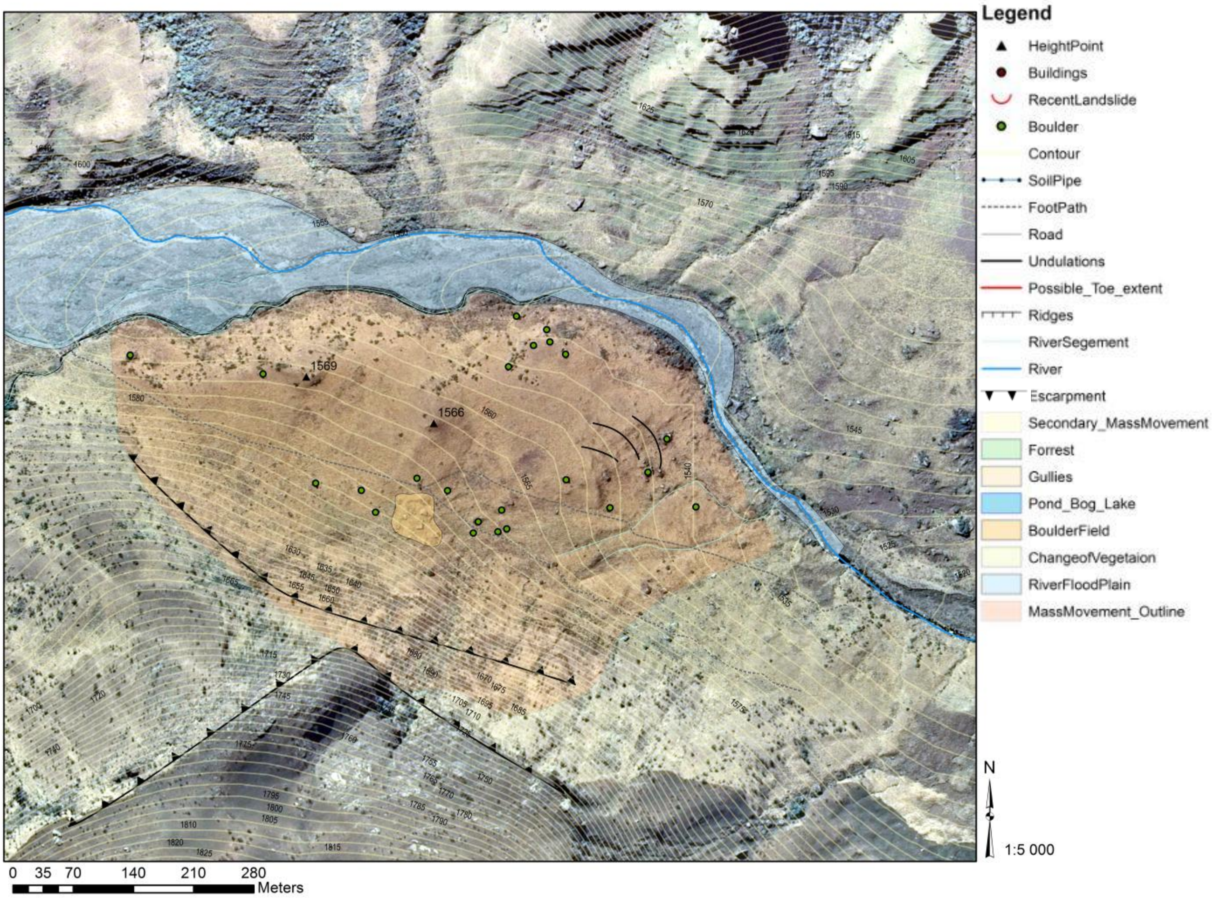


Figure 5.40: The layout of the Cataract rotational slide imposed over a satellite image.

The movement appears to have occurred in a single motion onto the valley floor and is classified as a large rotational landslide. Indications of the event include the hummocky terrain visible at the toe of the mass movement, as well as the regolith deposits that formed into two small cone-shaped mounds indicated as spot heights on the map (Figure 5.40) and is shown in Figure 5.41. There is an incline at the base of the main scarp towards the toe of the movement, which leads to deranged drainage. Furthermore, clear river deflection and modest valley constraint are visible on the western side of the movement. The regolith itself lacks bedrock structure and contains large boulders that would have been deposited with the movement itself. Small river segment flows are obstructed by the nature of the regolith and flow around the main deposit. Figure 5.42 indicates the depletion and accumulation zone of the movement. Due to the morphologic features visible on the slide, such as the smooth vegetated margins, this movement will be classified as mature.

Figure 5.41: The toe and one spot height viewed from the left flank towards the right of the Cataract movement.

Figure 5.42: Aerial view of the Cataract movement. Depicted on the photo is the accumulation and depletion zone.

Copulation Rock mass movement

Situated close to the Battle Caves, this mass movement's toe reaches down to the river level at approximately 1570m to 1512m.a.s.l. and extends 1400m along the Njesuthi River. The main scarp reaches approximately 1843m.a.s.l. and stretches 730m. From the main scarp to the end of the regolith deposits, the movement is roughly 475m in length. It is possible that the main scarp lies within the basalts or that the entire movement formed within the subsequent sandstone layers in a non-complex manner. The site can be identified as a very large rotational landslide. Figure 5.43 indicates the extent of the movement and it spans roughly 107.7ha.

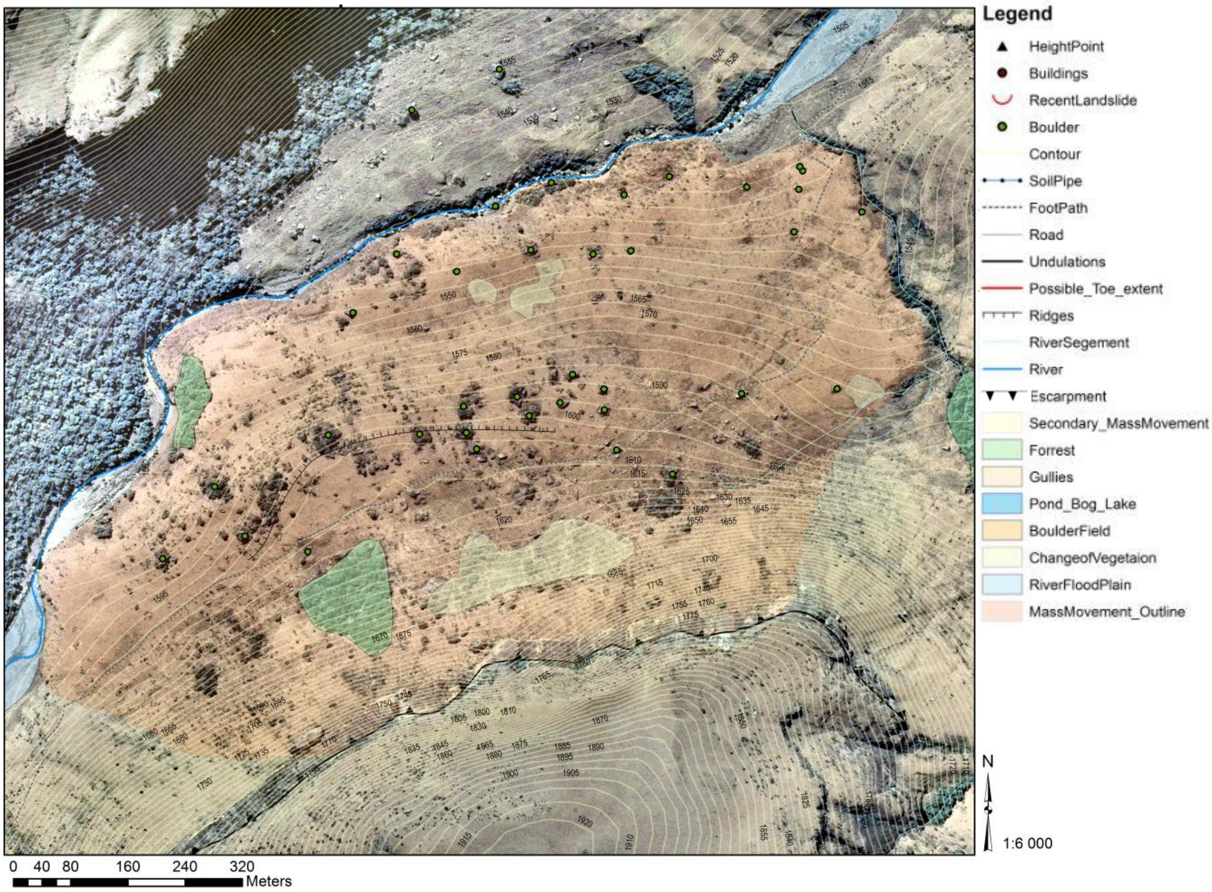


Figure 5.43: The layout of the Copulation Rock rotational mass movement imposed over a satellite image.

As shown in Figure 5.44, the regolith deposits form a severely constrained river valley along the toe of the mass movement and river deflection is also present. The directions of small river segments leading towards the main river along the mass movement are against the general valley direction, and flow around the secondary scarp. Close to the main scarp is evidence of river derangement and areas of vegetation change. Sag ponds are also visible across the movement, which is a common feature in palaeo-mass movements and rotational slumps (Singh *et al.*, 2008). Figure 5.45 shows the length of the movement, in which valley pinching and the large number of boulders within the regolith can clearly be seen.

Figure 5.44: View from backscarp towards the left flank and foot of the movement. Clear valley pinching is visible.

Figure 5.45: Side view of the Copulation Rock mass movement, viewed from the right flank towards the left.

This movement will be classified as mature to old, due to the smoothness of the accumulation zone. The lateral margins are clearly visible on the floodplain.

Little Tugela mass movement

The movement's regolith deposits reach down to river level at approximately 1320m.a.s.l. and spreads almost 1400m across in width. The main scarp is 1950m.a.s.l. and roughly 1475m wide. From the main scarp to the end of its deposits at the river, the movement is approximately 2400m in length. This site most likely formed in the sandstone layers beneath the basalts in a complex manner involving more than one type of movement between two large dolerite sills that can be seen in Figure 5.39. It is therefore classified as a very large complex landslide. Seen in Figure 5.39, is a large dolerite sill stretched across the body of the movement, which could have played a role in the formation of the movement. The extent of the movement is indicated in Figure 5.46 and it spans roughly 318.3ha.

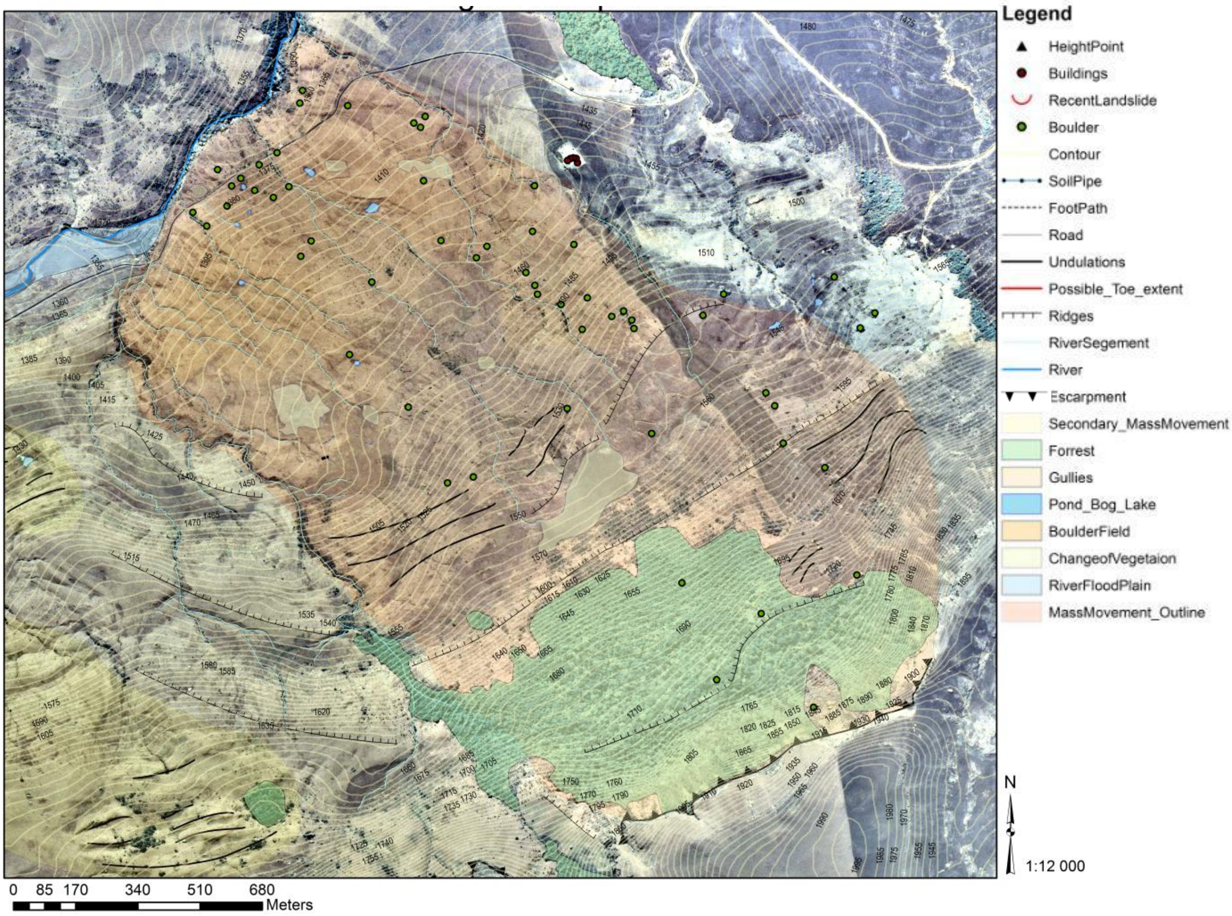


Figure 5.46: The layout of the Little Tugela complex landslide imposed over a satellite image.

The nature of the bedrock surrounding the site shows a clear discontinuity and an observable curvature backwards toward the main scarp of the movement, forming the depletion zone. This accounts for the lack of valley symmetry. There are three identifiable terraces. Furthermore, the main and minor scarp are covered with forests. Within the regolith are extremely large boulders, which indicate the sheer scale and velocity of the occurrence (Figure 5.47). In the accumulation zone and depletion zone are areas of vegetation change, formation of ponds and bogs (Figure 5.47) as well as clear stream derangement. The flanks of the movement are characterised by deeply incised streams whose tributaries show signs of soil piping and gully formation. The toe of the movement constrains the river valley, which also results in the meandering nature of the river upstream and can be clearly seen on Figure 5.47.

Figure 5.47: (Left) A pond located near the toe of the mass movement. (Right) The back scarp viewed from the right flank, close to the toe. Hummocky terrain, terraces and imbedded boulders are visible.

This movement is the largest movement in a series that forms part of a palaeo-mass movement zone. Although it was suggested by Bijker (2001), further research of the site was not undertaken. The internal morphology of the slide is undulating, with hummocky topography, with a relative normal stream pattern, especially in the zone of accumulation. There are, however, clear signs of previous deranged drainage patterns seen in Figure 5.47. The lateral margins are indicated by incised streams. However, the condition of the geomorphological features suggests that the feature is a mature slide, it will be classified as an old slide due to the size and general extent of eroded features.

Injisuthi mass movement

Formed in the sandstone layers beneath the basalts in a singular movement, this mass movement can be classified as a translational landslide. However, due to the unclear surface of rupture a clear definition would require more detailed investigation. The depletion, transportation and deposition zone are clearly definable. Its toe reaches down to the river level at approximately 1420m.a.s.l. (seen in Figure 5.48) and is almost 780m wide, while its main scarp is 1800m.a.s.l. and roughly 550m wide. From the main scarp to the end of its toe at the valley floor, the movement is 1130m in length. Figure 5.49 shows the extent of the movement which spans roughly 45.5ha.

Figure 5.48: (Left) Imbedded boulder within the regolith at the toe of the movement. (Right) The toe of the movement and back scarp viewed from across the valley in a northern direction.

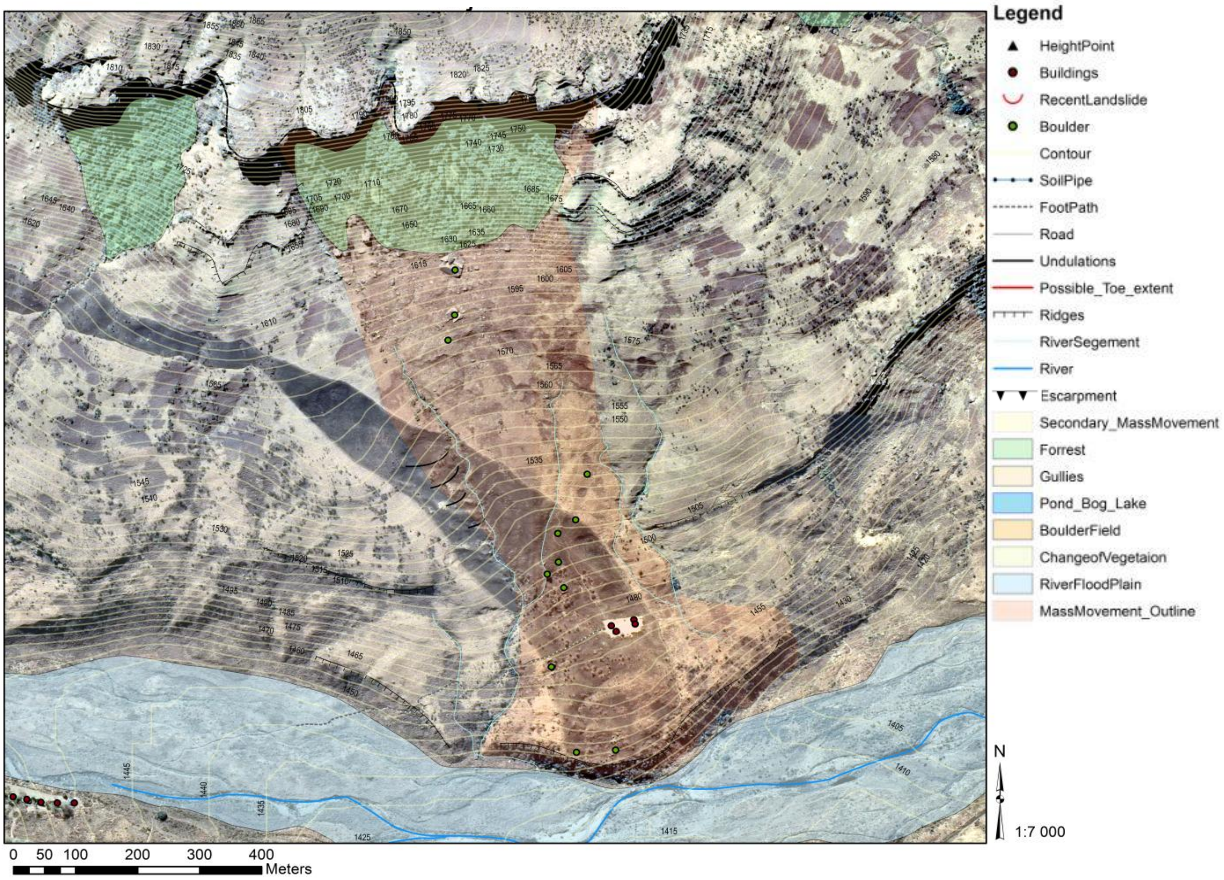


Figure 5.49: The layout of the Injisuthi landslide imposed over a satellite image.

The bedrock structure is discontinued across the site surface, clearly indicating the path of movement that took place during this mass movement. There is clear deranged drainage on top of the movement and further evidence can be found in the river deflection caused by the regolith deposits on the valley floor (Figure 5.48), including segments of streams flowing in the opposite direction of the general slope towards the river. Similar to the previous site, the movement’s regolith contains large boulders, as indicated in Figure 5.48, which could have travelled down slope only in such an event as a deep-seated landslide. A few small houses have been built on top of the deposition of the mass movement, which are visible in Figure 5.49. It is possible that the area will be susceptible to gully formation and slope failure, if erosion develops further.

Due to the morphometric and geomorphological features, this slide will be classified as mature. The condition of the scarp is dissected and it is vegetated in the moderate inclines areas. The lateral margins are clearly visible by lateral streams, with some tributaries flowing into the streams, and by the relative hummocky terrain that disrupted drainage patterns.

Morphometric summary

While Table 5.2 (pp. 52) presents the classification of the identified sites, Table 5.8 provides a summary of the morphometric measurements. The roughness of the terrain and the size of the movements led to the fact that in-field measurements for all the study sites were improbable. Therefore, the measurements were taken on ArcGIS after the site had been mapped with the use of a DEM (constructed out of 5m contours), which could lead to errors and inaccuracy. Table 5.8 summarises the extent and size of the mass movements according to an idealised shape (refer to nomenclature discussed in Chapter 2) of a mass movement and indicates the large variety that can be found throughout the Drakensberg.

Table 5.8 Summary of the morphometric measurements of verified study sites as discussed in Chapter 4, adapted from Hardwick.

Site Name	MSh	STh	Sw	Sd	Th	Tw	Tl	Dw	Dl	Size	LM	Aspect
Drifters	2173	1813	1809	360	**	**	**	2035	3230	813.82	4073	South
Mahai Valley	2030	1725	977	305	1600	730	1279	983	768	281	2675	South-east
Tendele	1923	1580	429	343	**	**	**	551	502	54.11	870	West
Mweni	1761	1581	279	80	-	-	-	371.56	302	24.1	480	North
Sandlwana	1768	1605	205	163	**	**	**	730	980	78.9	1110	North-west
Maartenspiek	1967	1774	802	193	1730-1650	722	204	713.3	413.6	106	1050	North
Wonder Valley	1567	1531	329	36	-	-	-	520	314	22.36	400	South-east
Mushroom Rock	1766	1607	654	159	-	-	-	1072	687	10.7	873	North
Baboon Rock1	1710	1590	357	120	-	-	-	646	1383	154	1470	South
Cataract Valley	1752	1565	400	188	-	-	-	740	301	29.4	475	North
Little Tugela	1900	1610	1560	290	**	**	**	1077	1340	318.3	2152	North
Injisuthi	1800	-	452	**	1620-1490	322-192	559.24	485.62	308	45.5	1145	South
Copulation Rock	1730	1535	615	95	-	-	-	1147	438	107.7	643	North

MSh	Main scarp Height (m.a.s.l.)	**Tw**	Width of transport zone parallel to contour (m)
STh	Secondary terrace height (m.a.s.l.)	**Tl**	Length of transport zone perpendicular to contour (m)
Sw	scarp width parallel to contour (m)	**Size**	Area of the whole movement in ha
Sd	escarpment height difference (m)	**Dw**	Width of deposit parallel to contour (m)
Th	Height of transport zone (m.a.s.l.)	**Dl**	Length of deposit perpendicular to contour (m)
LM	Length of movement (m)	**Aspect**	Aspect or slope facing direction

-The mass movement does not have this morphometric feature.

**Taking into consideration the complexity of some movements, which is difficult to define and classify, depletion, accumulation and transportation zones are difficult to define as well. Thus, in some aspects the morphometric measurements are limited as well and do not distinguish clearly between the different zones.

Chapter 6: Discussion

This chapter aims to summarise the classification and discuss the shared and uncommon features found on the various mass movements in the study area. Its aim is not only to discuss the common identifying features found in the criteria, such as the hummocky terrain found virtually over every mass movement, but to discuss small differences between the movements and to highlight features that contribute to identifying the causes of the mass movements. The criteria will also be discussed with regards to its success in identifying mass movements from various cartographic sources used. The discussion will further develop into a possible cause for the shared features and the resulting distribution of the mass movements.

Classification

Classifying movements to a single category has proved to be difficult, with movements such as Baboon Rock, Drifters, Mahai Valley and Little Tugela showing features identifiable with more than one type of movement. Therefore, these mass movements have been classified as complex landslides in accordance with Mather *et al.* (2003) and Hunger *et al.* (2014), except Baboon Rock, which is classified as a compound slide, and more additional research should be undertaken in future in order to identify a clear surface of rupture. Table 6.1 is a summary of notable features of the mass movements found in this study.

Table 6.1: Summary of important features found in the results

Mass movement	Type of movement or rotational feature	Toe on valley floor, or spilled in the river	Size	Type of geology	Aspect
Drifters	Complex landslide, rotational features	Unclear	Very large	Basalt, sandstone and dolerite	South
Mahai Valley	Complex landslide, rotational features	Yes	Very large	Dolerite, sandstone	South-east
Tendele	Rotational landslide	Yes	Large	Sandstone	West
Mweni	Rotational landslide	No	Large	Sandstone	North
Sandlwana	Landslide	Yes	Large	Sandstone	North-west
Maartenspiek	Landslide	No	Very large	Sandstone	North
Wonder Valley	Rotational landslide	Unclear	Large	Sandstone and dolerite	South-east
Mushroom Rock	Rotational landslide	Yes	Very large	Sandstone	North
Baboon Rock	Compound landslide, rotational features	Yes	Very large	Sandstone	South
Cataract Valley	Rotational slump	Yes	Large	Basalts and sandstone	North
Little Tugela	Complex landslide, rotational features	Yes	Very large	Sandstone and dolerite	North
Injisuthi	Landslide	Yes	Large	Sandstone	South
Copulation Rock	Rotational landslide	Yes	Very large	Sandstone	North

By observing mass movements according to this specific classification, it can be concluded that there are four important broad categories by which to view and analyse a mass movement: size, type, geology and age. The movements in this study do not have any correlation in size, type and age, and vary in each of the categories.

Shared and common features

The deep-seated palaeo-mass movements identified in the previous chapter share some similar features. They are large to very large and three of the movements cover more than 200ha, consisting of the whole valley slope, which indicates the extent of palaeo-mass wasting in the Drakensberg. Another important result was that most of the movements, with the exception of Drifters, Mahai Valley and Cataract Valley, were found below the Drakensberg basalts and lie within the sandstone formations. There is no particular favour to size or aspect. Valley symmetry processes play little to no role in the distribution of these movements, although positioning of the movements within the sandstone is a repeated feature. Although rotational surface of rupture are found on many movements, there are various mass movement types. Some of the behavioural properties of mass movements in the study area indicate that a solid structure ripped from the slope, but formed a flow or continued in a plastic manner and spilled onto the valley floor (such as Injisuthi and Mahai Valley).

It is clear that the majority of the movements found in this study are distributed along the Little Berg. Due to this distribution of the sites, the role of lithology in the formation of palaeo-mass movements in the Drakensberg cannot be ignored (Sumner and Meiklejohn, 2000; Bijker, 2001; Singh *et al.*, 2008; Singh, 2009). A common defining feature is a rotational surface of rupture, with ten out of twelve movements showing indications of some sort of rotation at the back scarp that develops further down slope into a flow (Sandlwana, Baboon Rock), or the whole body of the movement (Cataract, Tendele) being rotated. The very large movements tend to have occurred over various rupture surfaces while the small movements occurred over a single rupture. This could also be due to secondary movements that occurred consequently due to the first movement. However, rotated bedrock is much more evident than a translation movement after a period of erosion (creating much more obvious terraces), and this common feature can be as a result of the easily identifiable nature of rotated geology from aerial photography, satellite imagery and topographic maps.

Criteria

The criteria are based on identifying features from previously classified deep-seated palaeo-mass movements in the studies by Boelhouwers (1992), Singh *et al.* (2008) and Singh (2009), as well as international studies such as Azañón *et al.* (2005), Šilhán and Pánek (2010), Pánek (2010) and Lebourg (2014) , see Chapter 4. Features found in these movements were identified and used to find more mass movements in the study area, based on the features as universal signs of previous movements. The criteria performed well, identifying thirty-three sites that resulted in thirteen verified deep-seated palaeo-mass movements. The following features proved to be reliable and can be used to positively identify mass movements. The features include change in the vegetation and hummocky terrain. Reverse slopes usually indicate some form of rotational movement on a surface of rupture and foster pond and swampy areas where greener vegetation may flourish. Distinct fan or circular toe features that leads to river deflection are also clear indicators. Deranged river patterns on the slope are another common feature, and if imbedded rock boulders can be identified, it would provide further evidence. Incised flanks can be used to identify the extent of the movement (Mather *et al.*, 2003).

One of the major concerns of using these sort of criteria stems from the finding of features using aerial photos, satellite imagery and topographic maps, which is dependent on the skill of the observer. This could lead to missed features or the erroneous identification of slope movement features. It is therefore believed that there may be more deep-seated mass movements within the study area. One relatively clear indicator of past movements used to identify features, is the fact that mass movements may spill onto fluvial plains, pinching rivers, with fluvial actors being the apparent trigger. This could lead to the reduced possibility of finding slope failure features with regard to colluvial actors or seismic triggers, this includes deep-seated gravitational deformations, resulting in criteria specifically set up to find fluvial-formed mass movements. In spite of these complications, the criteria are set up in a manner to be used not only in the Drakensberg region, but in other mountain regions as well and can be adapted to suit site specific criteria. This is supported by the fact that the criteria are created according to features found not only in the Drakensberg but also in international studies.

Conditioning and trigger factors

Mass movements form due to a series of events that lead the slope to become more susceptible to mass movement, i.e. more unstable, until the movement is activated by a trigger event (Crozier *et al.*, 1995). This process, as discussed in chapter two, is named 'conditioning factors' and the Drakensberg had to experience its own form in the past far more substantial than it currently experiences to answer for the large number and magnitude found in the study. Events that would cause direct changes in slope angle, orientation and length, curvature and elevation are the most common conditioning factors that lead to an increase in shear stress of the slope. While increased rainfall is the most common trigger to overcome slope stability (Hardwick, 2012). The distribution of palaeo-mass movements in this study supports the following statement made by Sumner and Meiklejohn (2000: 313-314): 'Larger landslide events and rock falls, although evident in the basalt, are primarily associated with the underlying Clarens Formation sandstones and the transition to the lower Elliot Formation shales'. According to Borgatti *et al.* (2006) large complex landslides, with elements of rotation and flows, are common in mountainous regions where there are weak clayey rock mass outcrops which are similarly found in this study. The composition of the sandstones in the Drakensberg is a combination of rough to fine sandstones with intermittent layers of clay and shale, as described in Chapter 3. Rock seepage and absorption concentrate on the clay layers, while water moves through the rock at weaknesses and the intermittent clay layers. This movement forms passages for the flow of the water, which results in pathways of increased weathering and a lowering of the overall shear strength of the slope, possibly leading to a surface of rupture. The weaknesses of the various geological layers (discussed in Chapter 3) indicate a clear preparatory and condition factor, which leads to the higher magnitude and more frequent mass movement events in the Clarens, Elliot and Molteno Formation lithology.

The magnitude and size of the palaeo-mass movements found in the research area suggests that some form of major preparatory and conditioning factor or a large-scale trigger must have taken place, other than the susceptibility created by the geology. If the mass movements in the study area experienced, or are under the influence of the same predisposing factors such as the geology, it can be argued that the four classification categories (size, type, geology and age) would be similar and vary less and less between study sites. Also, if the mass movements are similar the greater the likelihood is that there is one single cause or trigger for all of the movements, for example, the rotational slumps in the Arroyo de Gor area in Spain (Azañón *et al.*, 2005) which form due to an incised valley. There are at least three types of possible causes that need to be discussed and considered for palaeo-mass movements in the Drakensberg: major trigger events such as heavy rainfall, seismic activities and a preparatory factor, such as incision.

Seismic events

In order to discuss seismic activities as a possible cause, two scenarios must be debated; the first scenario is that a single seismic event occurred during the later stages of the Neogene or upwards till the Holocene, and the second scenario is that a series of seismic events occurred before and during the Holocene. Therefore, this discussion is discerning between a single and a series of events. If a single seismic event during the Neogene uplift was a direct cause for a series of deep-seated mass movements, the four categories would show similar signs and there would be distinct features visible on the movement. Therefore, if all the large deep-seated mass movements were caused by one single seismic trigger event, they would display similar attributes in the four identified categories. A seismic event would likely lead to a correlation in distribution, type, size and importantly age. The toe of each movement would most likely be eroded due to the renewed incision, if the event occurred closer to the Neogene (Lacoste *et al.*, 2009), and all of the movements would then indicate a similar age or the same stage of degrading of identifiable features. If, however, the movements occurred over a significant period, due to a series of separate seismic events, some of the movements would likely show intact toes overlaying the floodplains and incised valleys of the mountain range, which are shown in the various mass movements. The geomorphic features on the mass movement would also indicate various ages (Mather *et al.*, 2003). Although the argument is speculative, it is unlikely that one single seismic event is the cause for the all movements in the study site, due to the fact that some movements have clearly intact toes, differing ages and are different types. Once absolute age has been established on the identified palaeo-mass movements these movements can be related to different proxy data and to past seismic events.

Rainfall

Two scenarios must be considered; the first a single rainfall event and second, a period of heavy rainfall. The magnitude of a rainfall event that would lead to mass movements of this size would be immense. It is not unreasonable that such extraordinary environmental conditions could have occurred during the interglacial periods of the Quaternary. Although, a single heavy rainfall period would once again lead to mass movements having a similar age, size, type, and distribution and once again the variety characteristics found in the mass movements shows this as unlikely. The interglacial climatic changes that occurred over a period of time, as suggested in Chapter 3, can lead to size, age, type and distribution differences which coincide with the results of the study. Rainfall and climatic changes cannot be disregarded as a trigger event for these movements, only that a single rainfall event must be excluded. Not only does the rain effect the structure of the slope, it adds mass and decreases the strength of the slope. Increased slope angle and height coupled with an increase in moisture and rainfall, accelerate the weathering and erosion conditions, increasing the shear stress and decreasing the shear strength of the slope. The role of climate change in the development of mass movements in the Drakensberg can be considered as both a conditioning factor and a trigger factor. The interglacial periods experienced during the Quaternary (Sumner and Meiklejohn, 2000) can contribute to the instability of massive slope deformations noted in the Drakensberg, with linkages found internationally between long rainfall events and mass movements (Bonzanigo *et al.*, 2000; Prokešová *et al.*, 2013). However, Singh (2009) compared the ages of five palaeo mass movements in KwaZulu-Natal to the palaeo climate proxy record from the Cold Air

Caves speleothem and found no clear association between the formation of the movements and the warmer wetter periods. This suggests that climatic events are not the sole cause for deep-seated mass movements in the Drakensberg.

Increased incision

As discussed in chapter 3, the Neogene uplift is a major conditioning factor that took place in the Drakensberg (Sumner and Meiklejohn, 2000). The uplift, as argued by Partridge (1998), could have induced circumstances for the extreme large events to take place. Such uplift would result in deeply incised valleys with over-steepened slopes (Bijker, 2001), increasing the shear stress of the slope and leading to favourable conditions for deep-seated mass movements to occur, but there would still be a need for a trigger for large to very large events. As a result of the uplift, the mass movements would be located in a valley, and their regolith would have been deposited onto the valley floor. In the examination of the movements found in the region, instances of river deflection and a clear indication of colluvial deposits within the valley flood plain were evident. Twelve movements are found within the incised valleys of Little Berg and nine out of thirteen mass movements identified spilled onto the floor, with river deflection and valley pinching apparent, refer to Table 6.1. This clearly indicates the role incision has played in the location as well as the formation of mass movements found in this study. Azañón *et al.* (2005) stated that localised stream incision and steep valleys can lead to a concentrated distribution of mass movements, which is also evident in the distribution of the mass movements found in this study. Therefore, the results link stream incision to be a consequential factor in the distribution of the movements. There is, however, a need for more absolute age reconstruction of the movements to confirm the role of the Neogene uplift on mass movements in the Drakensberg.

Dolerite intrusions as preparatory factor

A major conditioning factor, where the majority of mass movements are located, is the susceptible sandstone geology and steep Clarens scarps. One movement that should be discussed separately is the largest movement found in the research area, the Drifter’s movement, which showed fewer signs of the involvement of river incision. The size and massive volume of material displaced could have changed the hydrological and topographical dynamics of the entire slope, burying any indications of the involvement of incision. However, the most defining aspect of this movement is the clear and distinct dolerite sill that runs along the main scarp of the movement, causing further weakness in the geology. This can be considered as an inherent conditioning factor (Moon and Selby, 1983; Bijker, 2001; Singh *et al.*, 2008; Singh, 2009) and a leading preparatory cause for the Drifters movement. Other large movements in the region have spilled onto the floodplain, but dolerite intrusions are also present in their formation. The Mahai Valley and Little Tugela movements are both classified as very large, and both have clear dolerite sills running along the back scarp and along the edges of the movement. Therefore, this association suggests that dolerite intrusions within the back scarp can lead to the formation of very large deep-seated movement (Singh, 2009), although it is not a necessary condition for deep-seated mass movements.

The age of the movements and the role it plays in the Drakensberg environment

Palaeo-mass movements themselves are proxy data of previous conditions experienced in the region and can be considered as a result of conducing climatic conditions occurring in a certain period. Therefore, landslides may contain clues regarding longer term variations of precipitation patterns (Prager *et al.*, 2008; Borgatti and Soldati, 2010). The relative age of the movements were provided (Table 5.1, pp. 51) and all of the movements have been dated to the Holocene and towards the late Pleistocene, according to the condition and appearance of the morphological features (Mather *et al.*, 2003), see Chapter 4 and Appendix B. It is, however, necessary to determine an absolute age for these movements in order to clarify a clear cause and due to the fact that Singh *et al.* (2008) and Singh (2009) dated landslides in the Drakensberg to a much younger date. The age of the movements defined in this study suggest that the movements occurred over a wider period of time, and not a small range associated to clusters of movements which can be linked to a specific trigger as discussed earlier in this chapter.

If the mass movements indicated in this study were initiated by periods of rainfall or seismic activity and if they were facilitated by extensive undercutting or fluvial incision as suggested, it can be expected that the undercutting of slopes would likely operate at different rates and different areas of the catchment due to slight differences in the geology and micro-environmental conditions (Crozier *et al.*, 1995). This would result in a large age difference in the movements, which coincides with the findings. The age of the movements can also be estimated based on the shape of the toe. Deep valley incisions lead to the continuous removal of the down slope buttresses leading to regularly activated slides through time and preventing the conservation of any compressional distal toes (Lacoste *et al.*, 2009). This suggests that features with distinct toes are slightly younger if the area experienced a degree of renewed incision. Therefore, if there is a significant indication of a toe at a study site, the mass movement would most likely have occurred a long period after the incision reached its peak. Some of the landslides studied in this region have no significant toe or fan-like features, including Mushroom Rock and Baboon Rock, and must therefore have occurred before or during the period when stream incision was still relatively strong and exposed to renewed incision. Movements with clear river deflection and an indication of a relatively untouched toe, such as

Injisuthi and Cataract Valley, would most likely occurred after the period of strong incision and can be perceived as younger movements.

The influence of palaeo mass movement on the environment

One of the important roles that these movements play in the Drakensberg, is the formation of wetland and large widespread flood zones which usually occur upstream from the mass movement. The Bushman's River rotational slide (Boelhouwers, 1992), the Meander Rotational slide (Singh *et al.*, 2008) and the Little Injisuthi complex landslide give extraordinary examples of such a flood plain development. The large floodplain in the Injisuthi Valley, forming part of the Giant Castle Nature Reserve, formed as a direct result of the deposition of the Little Injisuthi complex landslide by obstructing the natural flow of the river. This resulted due the deposition of material in the stream, diverting drainage (Knight and Grab, 2015) and the eventual formation of a new flood plain. Very large deep-seated palaeo-mass movements, therefore plays an important role in the formation of wetlands and the biodiversity of the Drakensberg.

Hazard and risk factors

The movements found in this study show no significant signs of recent activity or reactivation. It has, however, been noted that some of these movements have been subjected to increased erosion or lead to more superficial landslides, such as Baboon Rock. On the following movements, including Mahai Valley, Drifters, Mushroom rock, Maartenspiek, Wonder Valley and Injisuthi, people are currently living or have various vacation facilities, activities or hotels that have been built on the relative gentler slopes provided by the palaeo-mass movements. It is in the opinion of this study that these areas are not in immediate risk or danger but the areas can be more susceptible to severe erosion, due to the fundamental changes in the structure of the slope. As more areas in the Drakensberg are used for anthropogenic purposes, such as farming and construction of homes or vacation facilities, slopes influenced by deep-seated mass movements are more exposed and vulnerable to geomorphic processes. Future changes in climatic conditions can lead to reactivation of mass movements and therefore these areas should be taken into consideration in newly developing hazard notation maps.

Chapter 7: Conclusion

The study set out to understand the distribution and characteristics of large deep-seated palaeo-mass movements in the Drakensberg. Referring to research objectives one and two, it is concluded that deep-seated palaeo-mass movements are features associated with the incised valleys in the lower Drakensberg. After identifying the size and magnitude of these movements their important role in the formation of the Drakensberg landscape is clear and the number found in the study area serves as a quantitative example.

To identify palaeo-mass movements in the Drakensberg, and complete the first phase, this study set out to compile diagnostic criteria. The objective was met with relative success in the study area and provided a platform for deep-seated palaeo-mass movement criteria to be used in future research. This criteria can be used not only in the Drakensberg but also in other mountain regions across the world. Within the first phase, thirty-three possible sites were selected, out of which thirteen were positively identified in the second phase and matched the criteria that was set out in Chapter 4. These movements were mapped and described in Chapter 5.

The movements found in the study area share some characteristics. A rotational rupture surface is a common feature which is observed in different areas within the Drakensberg (Boelhouwers, 1992; Singh *et al.,* 2008; Singh, 2009). Characteristics used to identify the movements in the first phase; including distinct toe features, rise in the toe height, together with changes in vegetation are shared features in the movements. Palaeo-mass movements impact the slope hydrology which can be clearly seen by bog and pond formation and by the deranged river patterns. These features are universally found across the mass movements. There are however geomorphological and morphometric differences between mass movements in the study area, such as aspect, size, age and the behavioural properties of deposited material, which leads to the conclusion that there are different triggers of each mass movement.

The location of mass movements found in this study can mainly be attributed to two different factors. First, lithological control played an important role in the distribution of the movements, due to the fact that all the palaeo-mass movements were found within the sandstone formations. Weaker layers of mudstone and sandstone within the formations are considered conditioning factors. Three of the sites, including two of the largest, are directly linked to dolerite sills located in the main scarp. The presence of the dolerite significantly weakened the slope in order for very large deep-seated movements to form (Bijker, 2001; Singh, 2009). Therefore, the role of dolerite cannot be ignored as a contributing factor, but it is not the main cause of large deep-seated mass movements in the Drakensberg.

There is, however, an explanation needed to establish a reason as to why these movements have occurred. Due to the distribution and identifiable features of the deep-seated mass movements found in this study, it is proposed that there is no clear evidence for one large-scale trigger that led to the development of all of the mass movements. Increased rainfall, or periods of rainfall, in the intermitted warm and wet period of the Quaternary could have triggered these movements, and this period could have led to multiplying the incision force of streams that lead to the formation of deep seated-mass movements. However, Singh (2009) found little to no correlation between rainfall and palaeo-mass movements in KwaZulu-Natal. Separate seismic events could also be a trigger for the deep-seated mass movement events, but a single trigger event must be excluded from the debate due to the different apparent ages shown by the mass movements found in the study. It is clear that these mass movements occurred as separate events over a long time period and due to different triggers. An important conditioning factor and a second reason as to the distribution pattern, is the Neogene uplift. Eleven of the mass movements in the study were found on the valley floor, showing signs of valley pinching and river deflection. Indicating that valley incision played a role in their formation. Steeper slope profiles after the Neogene era represent a rejuvenation of rivers which led to an increase of incision (Partridge and Maud, 1987; Bijker, 2001). The physical increase of height of the mountain range led to an increase in size and frequency of deep-seated mass movements in the Drakensberg. Therefore, the large frequency, magnitude and the distribution of the palaeo-mass movements has to be credited to the initiation of processes that resulted directly from the uplift, even if different triggers were subsequently involved, and the preparatory condition stipulated by the geology.

The movements identified in this study show no significant signs of re-activation and are relatively stable. This study suggests that these areas are not in immediate risk or danger but can be susceptible to severe erosion, due to the fundamental changes deep-seated mass movements have caused in the structure of the slope (Guzetti *et al.*, 1999). Seen on the mass movements in this study, are smaller and new landslides, which could cause severe damage to any infrastructure or buildings. As more areas in the Drakensberg are used for anthropogenic purposes such as farming and construction of homes or vacation facilities, slopes influenced by deep-seated mass movements are exposed and vulnerable to geomorphic processes. Therefore, the movements identified in this study should be taken into consideration in newly developing hazard notation maps.

Palaeo deep-seated movements play a valuable role in the development of wetlands. As discussed in Chapter 6, deep-seated palaeo-mass movement deposits block the river and initiate the creation of a floodplain, as seen in the Little Tugela mass movement.

The following points serves as a summary of the findings in this study:

- Thirteen large deep-seated palaeo-mass movements has been verified and mapped.
- The Neogene uplift created a perfect environment for the formation of large deep-seated mass movements in the Drakensberg and can be credited to the formation of these movements.
- The characteristics of the geology plays an important role in the distribution of the movements found in this study, due to the fact that all the palaeo-mass movements were found within the sandstone formations.
- The role of dolerite sills and dykes is a contributing factor, but it is not the main cause of large deep-seated mass movements in the Drakensberg.
- The movements identified in this study should be taken into consideration in newly developing hazard notation maps.
- The criteria was relatively successful and can be used in future research for identifying deep-seated palaeo-mass movements, not only in the Drakensberg but also in other mountainous regions across the world.

Limitations

Most of the limitations in this study were experienced in meeting the first two objectives. First, the criteria and the use of the criteria is reliant on the skill of the interpreter of the aerial images and photos, which could result in uncertainty as to whether all of the movements in the area have been found. Furthermore, clarifying and identifying each site amounts to an enormous field task, which is both expensive and time consuming. Therefore, a more observational method was chosen in identifying and classifying the sites.

Recommendations

Improvements to the criteria are essential for further studies. The criteria are based on previous studies where one can see clear and defining features and are used to identify possible sites. The criteria can be improved to include a more comprehensive model of mass movements, such as slope deformations. More intensive and site-specific research for each study site should be conducted, where soil samples and clear indication of geology can be sampled and the surface of rupture can be identified. More intensive research should be conducted on dating of these mass movements, possibly looking into new methods of dating and into other methods of verification, such as electrical resistivity tomography (Pánek *et al.*, 2014). The role of palaeo-mass movements on wetlands should also be studied further as well as the role palaeo-mass movements play in the initiation of other slope processes which can be studied as a result of this thesis. Questions such as "Does deep-seated palaeo-mass movements increase current soil erosion on affected slopes or induce certain geomorphological features such as soil pipes and recent mass movements in the Drakensberg?" should be answered. If this can be defined, it would be possible to identify the role palaeo-mass movements play in mass movement susceptibility and soil erosion maps. It is suggested that further investigation should be done to clarify the role of palaeo-mass movements as previous climate indicators, with specific reference to the Drakensberg area.

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Appendix

Appendix A

The identification of stage and age proposed and adopted by Mather *et al.* (2003).

Activity state	**Identification of causes of movement**	**Condition of main scarp**	**Condition of lateral margins**	**Internal morphology**	**Estimated age**
Active- currently moving (includes landslides, inactive landslides that have been reactivated)	Causes of movement identifiable and active	Sharp; unvegetaded	Sharp; unvegetated; streams at edge	Hummocky; fresh scarps; reverse slopes; undrained depressions; fresh tension crack	<100 (historic)
Suspended- moved within the last 12 months and likely to move again	Causes of movement identifiable and likely to occur again	Sharp; unvegetated	Sharp; unvegetated; streams at edge	Hummocky; fresh scarps; reverse slopes; undrained depressions; identifiable tension crack	<100 (historic)
Dormant – young	Cause of movement still identifiable and could re-occur	Relatively sharp; partially vegetated	Relatively sharp; partially vegetated; lateral streams fed by small tributaries flowing of the main body of the slide	Hummocky; relative sharp and fresh scarps; reverse slopes; undrained depressions; tension cracks closed but vegetated but marked by small depressions	100 – 5000 (Late Holocene)
Dormant – mature	Cause of movement still identifiable but not likely to re-occur	Smooth; vegetated	Smooth vegetated; lateral streams fed by tributaries flowing of the main body of the slide	Smooth rolling topography; disrupted and disjointed internal drainage network	5000 – 10 000 (Early Holocene)
Dormant – old (inactive) or relict	Cause of movement may be inferred but associated with different climatic and geomorphological conditions	Dissected; vegetated	Vague lateral margins; no lateral drainage	Smooth undulating topography; normal stream pattern	10 000 – 100 000 (Late Pleistocene)
Fossil (inactive) or ancient	Cause of movement unknown but associated with different climatic and geomorphological conditions	May not be identifiable; likely to be at least partially if not completely removed by erosion	May not be identifiable; likely to be at least partially if not completely removed by erosion	Fully integrated into existing topography and very little indication of the former landslide morphology remains	>100 000

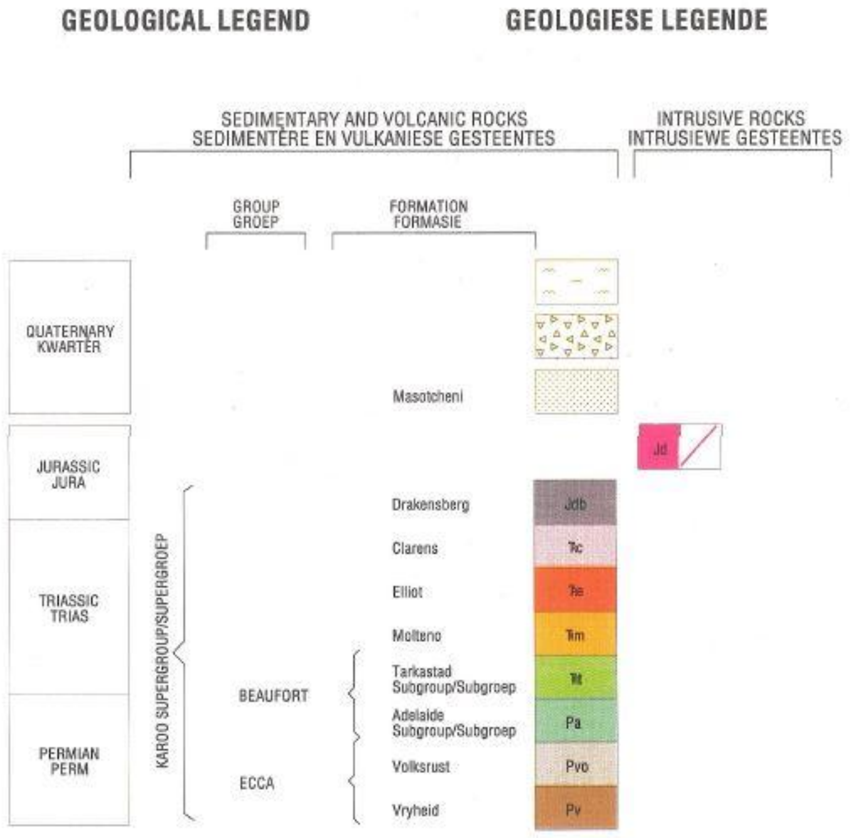
Appendix B

Appendix B shows the various types of observations that was done at study sites identified in phase one.

Mass movement name	Topographic/Satellite	In-field observations	Aerial observation (Helicopter)	Previously known or speculated	Possibility of mass movement event
Royal Natal					
Clifford Chambers	Yes	Yes	No	No	No
eBusingatha	Yes	No	No	No	No
Drifters	Yes	Yes	No	No	Yes
Mahai Valley	Yes	Yes	No	Yes	Yes
Tendele	Yes	Yes	No	Yes	Yes
Mweni					
MMS1	Yes	No	Yes	No	No
MMS5	Yes	No	Yes	No	No
MMS6	Yes	No	Yes	No	No
MMS8	Yes	Yes	Yes	No	No
MMS13	Yes	No	Yes	No	No
Mweni	Yes	Yes	Yes	No	Yes
MMS17	Yes	No	Yes	No	No
MMS18	Yes	Yes	Yes	No	No
MMS19	Yes	No	No	No	No
Sandlwana	Yes	No	Yes	No	Yes
MMS22	Yes	No	Yes	No	No
Monk’s Cowl					
Dingaan’s Cave	Yes	Yes	Yes	No	No
Hospital Spruit 1	Yes	No	Yes	No	No
Hospital Spruit 2	Yes	No	Yes	No	No
Maartenspiek	Yes	Yes	Yes	No	Yes
Misgunts	Yes	No	Yes	No	No
Mtoti	Yes	Yes	Yes	No	No
Ndedema					
Ndedema	Yes	No	Yes	No	No
The Climb	Yes	No	Yes	No	No
Wonder Valley	Yes	Yes	No	No	Yes
Xaxavithi	Yes	No	No	No	No
Mushroom Rock	Yes	Yes	Yes	No	Yes
Baboon Rock	Yes	Yes	Yes	No	Yes
Didima	Yes	No	Yes	No	No
Injisuthi					
Cataract Valley	Yes	Yes	No	Yes	Yes
Little Tugela	Yes	Yes	No	Yes	Yes
Injisuthi	Yes	Yes	No	Yes	Yes
Copulation Rock	Yes	Yes	No	Yes	Yes

Appendix C

The complete legend for the geological maps of the various study sites.



LITHOLOGY
LITOLOGIE

~	Alluvium Alluvium
△	Scree Glooiingspuin
░	Partly consolidated fine-grained sediments with silcrete nodules Gedeeltelik gekonsolideerde fynkorrelrige sedimente met silkreetknolle
Jd	Dolerite; dolerite dyke (╱) Doleriet; dolerietgang (╱)
Jdb	Basalt Basalt
Ŧrc	Yellow to pale-red, fine-grained sandstone Geel tot ligrooi, fynkorrelrige sandsteen
Ŧre	Red and purple mudstone; interbedded yellow to grey siltstone; fine- to medium-grained sandstone Rooi en pers moddersteen; tussengelaagde geel tot grys sliksteen; fyn- tot middelkorrelrige sandsteen
Ŧrm	Medium- to coarse-grained glittering sandstone; gritstone; subordinate green and red mudstone; carbonaceous shale Middel- tot grofkorrelrige glinsterende sandsteen; grintsteen; ondergeskikte groen en rooi moddersteen; koolstofryke skalie
Ŧrt	Fine- to medium-grained sandstone; red, green and blue mudstone Fyn- tot middelkorrelrige sandsteen; rooi, groen en blou moddersteen
Pa	Grey mudstone; dark-grey shale (carbonaceous in places); siltstone; sandstone Grys moddersteen; donkergrys skalie (koolstofhoudend op plekke); sliksteen; sandsteen
Pvo	Blue-grey to dark-grey shale Blougrys tot donkergrys skalie
Pv	Medium- to coarse-grained sandstone; micaceous shale; coal Middel- tot grofkorrelrige sandsteen; glimmerryke skalie; steenkool

(2828 Harrismith Geological Survey, 1998)