University of Ballarat

School of Science, IT & Engineering - Geology

LANDSLIDE MAPPING AND PROCESSES IN THE GRAMPIANS, VICTORIA

Honours Research Thesis, Bachelor of Applied Science (Honours) - Geology, University of Ballarat, Victoria, Australia

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DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition , I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Ballarat and where applicable, any other partner institution responsible for the joint award of this degree.

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ABSTRACT

Uncharacteristically high rainfall in January 2011 caused extensive landslides in the Grampians Ranges, particularly on the east facing slopes of the Serra-Wonderland-Mt Difficult ranges. The landslides affected mostly National Park as well as private property and municipal infrastructure costing the region financially, environmentally and economically.

To mitigate future landslide hazards and risks the landslides have been mapped to determine the nature and extent (spatial and temporal), the contributing factors and the processes related to the landscape features. Using GIS 176 landslides and 274 failure points were mapped.

The failure points were noted to occur at a mean azimuth of 113.2 on slopes averaging 34.3˚ gradient. Four geological formations (Silverband Formation, Serra Sandstone-Sandstone, Wartook Sandstone and Major Mitchell Sandstone) comprised 70% of the total failures due to an average rainfall of 227.6mm. Five representative landslides were examined to have common morphological characteristics, recorded as zones: zone A (failure and erosion); zone B (erosion and transport); zone C (transport and minor deposition); zone D (minimal transport and significant deposition); zone E (remaining deposition and run-out). The landslides often had total lengths tens of times that of their width and hundreds of times the depth.

The underlying landscape and surficial environment are major controls on the spatial distribution of the landslides. These conditions are compounded by an influx of water, both surficial and sub-terrigenous, from significant rainfall to the point of failure.

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1.0 INTRODUCTION

Landslides pose a significant risk to people and municipal infrastructure; not withstanding numerous fatalities, the total estimated socio-economic cost in Australia to 2008 is $500 million dollars (Leventhal & Kotze, 2008) and billions of dollars annually on a global scale. To mitigate future risks to population it pays to have an informed objective view of landslides, which should include: a landslide inventory, hazard assessment and finally risk assessment and risk management (AGS, 2007). This thesis discusses the landslides which occurred in the Grampians Ranges (Gariwerd) associated with the extreme rainfall event that occurred in January 2011 for the state of Victoria causing extensive flooding in the study area.

The project has been completed under the supervision of Peter Dahlhaus, Stuart Brown (University of Ballarat) and Anthony Miner (A.S Miner Geotechnical). The project contributes in part to the Grampians Natural Disaster Research Project undertaken by the University of Ballarat for the Northern Grampians Shire (NGS) Council. It may inform the NGS Landslide Contingency plan drafted by the NGS. Other stakeholders include: Department of Environment and Primary Industries, (DEPI); Parks Victoria; Glenelg Hopkins Catchment Management Authority (GHCMA); Victorian Police (VicPol); State Emergency Services (SES); Country Fire Authority (CFA) and VicRoads.

1.1 Aim and Objectives

The aim of this project is to construct an understanding of the landslide processes in the Grampians Ranges (Gariwerd) to largely determine the:

- Nature and extent (spatial and temporal) of landslides in the Grampians Ranges (Gariwerd)
- Contributing factors to the landslide events, particularly focussing on January 2011
- Landslide processes and their relationship to the landscape features in the Grampians (Gariwerd).

This Honours research project should contribute to the larger research project by adding an understanding of the landslides and their contributing factors, developing a foundation for future studies to ultimately reduce the impact to local communities.

1.2 Location

The Grampians Ranges (Gariwerd) is predominantly a National Park, one of the largest in the State of Victoria, and is located approximately 230 kilometres west of Melbourne (Figure 1.1). The ranges stretch for 90 kilometres north and 50 kilometres west covering 1,681 km^2 (Elliot, 1984) excluding the: Black Range State Park; Mt Arapiles-Tooan State Park; and the Deep Lead Flora and Fauna Reserve (ParksVic, March 2003). The Grampians are a prominent feature of Victoria's Western Uplands (Joyce *et al.*, 2003) and a popular tourist attraction.

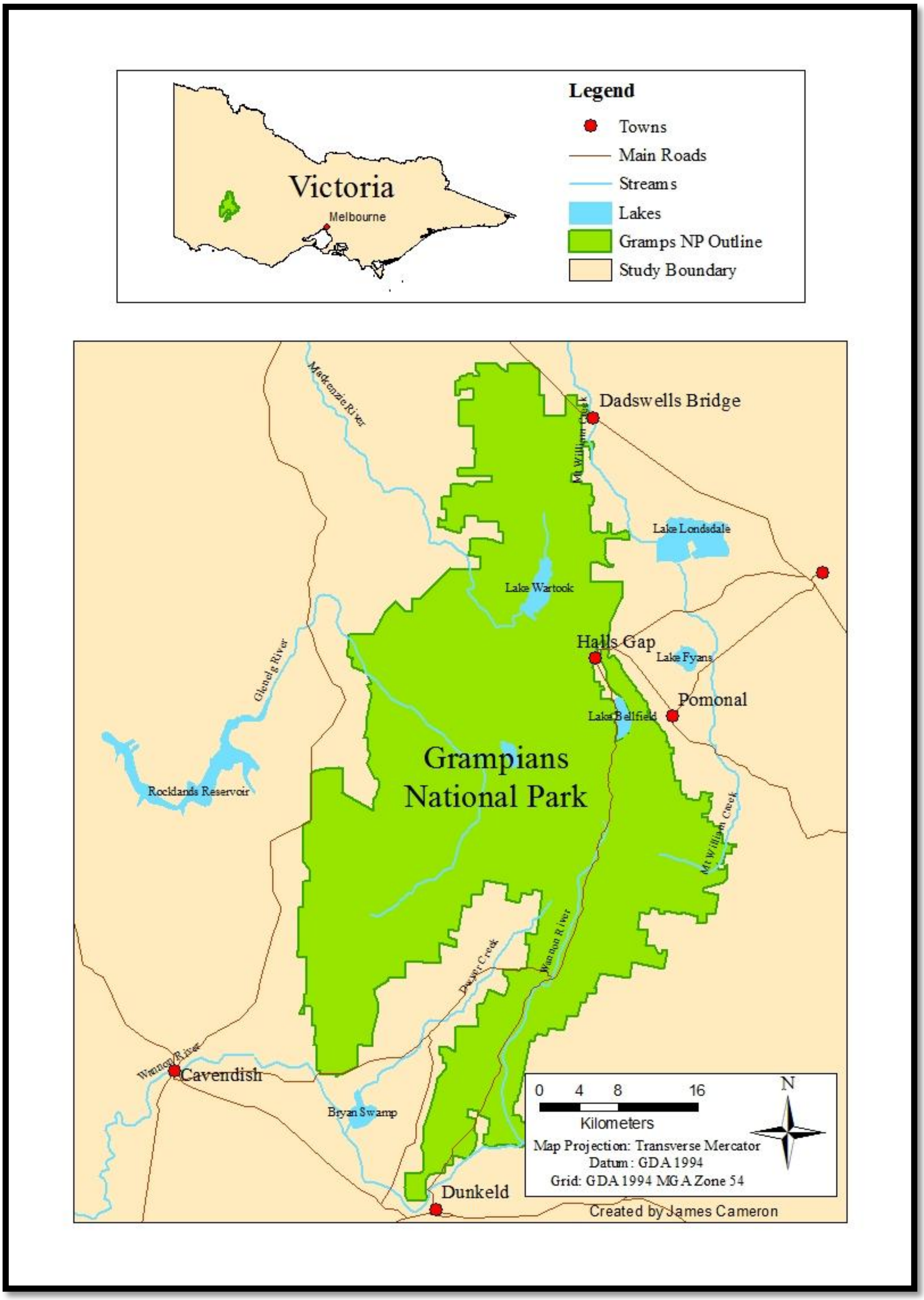


Figure 1.1 Location Map of the Grampians National Park, Victoria.

1.3 Climate

The climate of southwest Victoria is heavily influenced by the prevailing weather patterns of the Southern Ocean that characteristically progress from west to east. The weather patterns remain a constant alternation between high pressure and low pressure systems (DPI, 2013), that move southward in summer and northward in winter. The Grampians region has a temperate climate with warm dry summers and cold wet winters (BoM, 2013). The main axis of the Grampians Ranges is situated perpendicular to the prevailing weather systems, with an elevated topography that greatly contrasts to the surrounding table lands and consequently the area experiences a higher rainfall (Calder, 1987) (Figure 1.2).

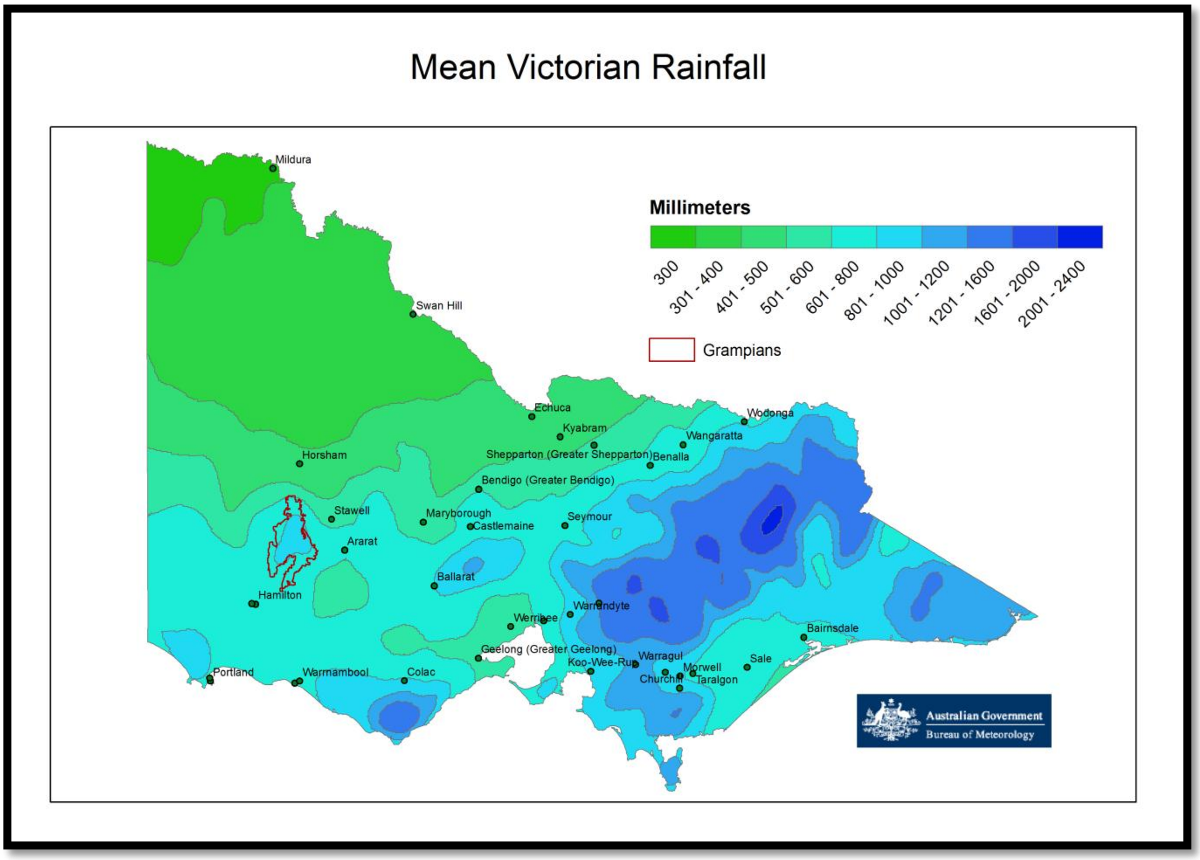


Figure 1.2 Victorian average annual rainfall (modified from BoM, 2013).

Despite normally drier summers, south eastern Australia occasionally experiences abnormal east coast low-pressure weather systems that linger in the Tasman Sea. These can provide westward moving moist air masses that can cause significant rainfalls in a single episode (DPI, 2013).

1.4 Physiography

With a reasonably stable geological and ecological environment the landscape evolution of the Grampians Ranges is fairly slow due to the erosion resistant nature of the rocks (Sherbon-Hills, 1960). Differential weathering has dominated the profile of the Grampian Ranges when compared to the surrounding table lands and plains, creating a cuesta-and-vale topography (Joyce *et al.*, 2003). The only episodic factors that decrease the stability are bushfires and landslides that are closely linked to the climate of the area. Against the skyline the mountains are an iconic landscape of western Victoria with steep east facing scarps along the Serra-Wonderland-Mount Difficult and Mount William Ranges with scree slopes and alluvial deposits at the base. The back side of the ranges are more gentle slopes that are parallel to the strike of the formations with dips of less than 45°(Joyce *et al.*, 2003).

Drainage of the Grampians Ranges is strongly influenced by the lithology and structural geology of the Grampians Group, where strongly developed jointing controls the positions of smaller streams and valleys (Joyce *et al.*, 2003). The major streams accumulate the run-off and generally drain northward into the Wimmera River via the Mount William, Fyans and McKenzie creeks, and southward into the Wannon and Glenelg rivers (Calder, 1987). In the northern end, the Wartook syncline has produced a shallow catchment in which the Wartook Reservoir has been constructed along the McKenzie River (Figure 1.1) (Joyce *et al.*, 2003; Sherbon-Hills, 1960). The local river basins are depicted in Map 1; Debris Flow

Inventory. The Grampians are the head waters for large portions of two of western Victoria's larger rivers: the Glenelg and Wimmera rivers.

1.5 Vegetation

Over a thousand species of flora including trees, shrubs and wildflowers (Elliot, 1984), approximately a third of Victoria's entire indigenous flora, are found in the area including several species which are unique to these mountain ranges (Costermans, 1981). The ranges are relatively isolated with respect to the species of flora that cover the slopes and the fact that no geologically similar rock formation exists for hundreds of kilometres around only further isolates the area (Costermans, 1981). Keeping this fact in mind it becomes especially apparent that there is a relationship of the flora to the geology and symbiosis between flora.

Within the Grampians, plants can be grouped into identifiable associations and communities that are indicative of different soil types, slope and drainage, aspect and the general availability of water (Calder, 1987). These physiological characteristics are closely linked to the climate, geomorphological processes and vegetation and each of those unto each other. Many Ecological Vegetation Classes (EVC), have been mapped in the Greater Grampians Region. Generally the EVC's are grouped into the Broad Vegetation Types (BVT) which closely relate to the geology and geographic locations. ParksVic (March 2003) describe seven BVT's as follows (DEPI, 2008, 2013):

Heath Woodland Complexes – Tend to exist in areas of less than 500mm of rain in deep uniform infertile sand outwashes derived from quartz sandstone or quartzite, often underlain by 'coffee rock' where iron has leached out of the overlying soil. Vegetation consists of a predominantly Stringybark (Eucalyptus sp.) overstorey with a thick understorey of heathy shrubs with some sedge and grass ground cover.

Herb-rich Woodland Complexes – Make up the area between Heathy Woodlands (sandy soils) and Dry Foothill Forests (clayey soils) where there is better water availability of higher rainfall 500-600mm. The soil tends to have more loamy characteristics overlying clay subsoil. The over storey is comprised of tall eucalypts (Manna Gums and Yellow Box) with a minimal understorey and a dense ground cover of herbs.

Dry Foothill Forests – Similar to Herb-rich Woodland, with moderately fertile clay rich soils and a higher rainfall of 500-800mm, this BVT is characterised by a greater diversity with an over storey of Messmate and Brown and Red Stringybark, with a significant shrub layer and ground cover of grasses and tussocks.

Inland Slopes Woodland – (See Above, Dry Foothill Forests) – the distinction is that this BVT may exist in areas of higher rainfall.

Plains Grassy Woodland – Dominated by taller eucalypts (Yellow Box, River Red Gum and Grey Box) that grow in fertile silt to clay soils with a moderate rainfall of between 400-600mm. Minimal understory of wattles and heath with a perennial grass ground cover that grow on gently undulating plains.

Valley Grassy Forests – Gently undulating fertile alluvial soils where the rainfall is greater than 700mm allow tall trees, usually eucalypts, to dominate the overstorey with herbs grasses and sedges comprising the ground cover.

Grassland – Very sparse trees and shrubs with plains of alluvial silts and clays on which mainly perennial grasses dominate. These areas experience marginal rainfall (300-500mm) about the perimeters of the area.

1.6 Environmental & Land Use History

The Grampians Ranges were ‘discovered’ by Europeans in 1836 by Major Mitchell during his ‘Australia Felix’ journey (Elliot, 1984) and were described as ‘a sublime landscape’ that was ‘truly grand’ (Calder, 1987). The Grampians Ranges (Gariwerd) have been of even greater importance to the local aboriginals for more than 20,000 thousand years prior to European settlement (FoGG's, 2013). The aborigines however quickly disappeared with the arrival of graziers from 1839, especially the areas around Mt Zero and Victoria Valley (Elliot, 1984). For the remainder of the 19th century a continuous succession of gold rush’s and improvements to the infrastructure, for the growing proximal communities, was the norm. The State Rivers and Water Supply Commission was established in the early 20th century (Calder, 1987) and is listed among the regulatory bodies operating in the area. The Forests Department declared a State Forest which occupied a large proportion of the public land in the Grampians (Calder, 1987), now considered as the true beginnings of the Grampians National Park, which was formed on 1st July 1984 (Elliot, 1984; FoGG's, 2013; McCann, 1994). The declaration was preceded by moves of the State Development Committee in 1951, and the Land Conservation Council in 1981 recommending that the area, of significant environmental and social importance, become a National Park (Calder, 1987).

During the 19th and 20th centuries the Grampians Ranges were utilised for their vast natural resources most notably the hardwood timbers. The timber was used by the new townships for infrastructure including buildings and rail and even more significantly for many steam engines and tanneries that operated in the area related to the mining and leather industries (Calder, 1987). The last of the Forest Commission operations ceased timber production in 1985 after the establishment of the National Park (Calder, 1987).

Grazing has become subordinate in the Grampians Ranges especially since the institution of the conspicuous National Park boundaries. Farming still exists on adjoining land most prominently in Victoria Valley and the eastern foothills of the Mount William and Serra, ranges where large farming operations still exist. Asides from pastoral operations on adjoining land the National Park has returned to a more natural environment only sporting a tourist network of outdoor activities contributing more than $100 million to the local economy (ParksVic, March 2003). The tourism revolves around many outdoor activities such as bushwalking, camping, conservation and four-wheel driving.

1.6.1 Historic Landslides

No records or evidence are found of landslide events equivalent to those that occurred in 2011, on such a numerous or broad scale. However there have been a number of incidences where heavy rains have cause localised flooding and isolated occurrences of mass wasting. Some of the notable mass movements are:

- In October 1916 The Horsham Times reported that there was a large scale debris flow off the eastern side of Mt William at little Red Mans near Pomonal (Trove, 1916). A very wet month was recorded with almost twice the average rainfall with a 55mm fall over two days (BoM, 2013). Trove (1916) describes the event as the ‘highest recorded flood in white history’ causing a landslide comprised of mud, sand and rock a mile long from Little Red Mans to Long Gully. The power of which removed trees in an upright position where they were strewn to the peripherals of the debris flow (Trove, 1916).
- In November 1934 a debris flow affect the Mt Victory Scenic Rd that was primarily rock and earth (debris) (Trove, 1934). Like the previous event The area experienced

more than twice the monthly average of rainfall with 94mm over three days (BoM, 2013).

GHD (2011)[12] outlined a number of flooding a slope failures listed from historical accounts and anecdotal recollections by long-time residents.

- 1906 flood
- 1909 (27th Aug) flood - 'Delleys Bridge washed away, 150mm in 30 hours'
- 1910 flood
- 1915 (21st Sep) flood – 'Delleys Bridge badly Damaged'
- 1916 (24th Oct) landslide – 'Landslide near Bellfield, 140mm in 24 hours'
- 1917 flood 'Delleys Bridge'
- 1934 (8th Nov) landslide – 'Debris flow covered Archibalds orchid, 25-30mm in half and hour
- 1939 flood
- 1939 landslide at Pomonal post bushfires
- 1946 (20th Feb) flood – 'Road closed at Mokepilley Creek'
- 1956 flood
- 1970? Rockfall Sundial Peak
- 1992 (21st Dec) flood – 'Flash flooding of Stoney Creek, 134.2mm over three days'
- 1996 (30th Sep) flood – 'Minor valley floor flooding, 123mm over three days'
- 2003 (21st Feb) flood – 'Flash flood Stoney Creek, 147mm over two days'
- 2005 (14th Jun) flood – '136.2 over 5 days'

[1] This report is confidential and is the property of GHD who prepared the report for the Northern Grampians Shire (NGS); and may only be used and relied on by the NGS; and may only be used for the purpose for which it was intended.
[2] The project contributes in part to the Grampians Natural Disaster Research Project undertaken by the University of Ballarat for the NGS Council.

1.6.2 January 2011 Event

In January 2011 heavy rains and consequently extensive flooding triggered more than 190 landslides throughout the Grampians National Park (NGS, 2011). During the rainfall period of 12th, 13th and 14th of January, weather stations in the area recorded extreme rainfalls far greater than the average January rainfall and were a significant proportion of the average annual rainfall (extended explanation Section 5.1) (BoM, 2013). The 2011 January rainfall was in most cases a record breaker for the area, which has in excess of 100 years of records. The event has been referred to as a one in one hundred year rainfall episode, as outlined by the Halls Gap Community Safety Committee (NGS, 2011).

Slope failures brought on by the high rainfall included rockfalls, landslides and debris flows. The high water content provided a fluvial environment that entrained material including: clast sizes from clay to very large boulders and in some instances a high percentage of vegetation debris. The landslides caused extensive damage to roads; significantly the Southern Grampians Road, Silverband Road and Northern Grampians Road. Proximally to the township of Halls Gap, National Park and residential infrastructure was damaged including popular walking tracks.

1.7 Previous Studies

The first studies of the Grampians geology were undertaken to satisfy growing curiosities from the minerals industry. But it wasn't until the 1960's that a comprehensive study resulted in 'The Geology and Structure of the Grampians Area, Western Victoria' published as a Geological Survey of Victoria memoir, Spencer-Jones (1965). This seminal text was later superseded by the vast quantities of structural data which had become available and the tectonic history of Victoria was revised. In 1997 Cayley and Taylor published a revision of the Grampians Ranges geology and structure with 'Grampians:

Special Map Area Geological Report' that expanded and refined the work of Spencer-Jones (1965).

Mass wasting in the Grampians region has received little attention simply due to the lack of this type of event since European settlement, with only a few notable instances throughout the 20th century that were recorded (Section 1.6.1). Due to this fact, the absolute scale of the event in 2011 took authorities by surprise and initiated a number of post-debris flow investigations by Parks Victoria and Vic Roads, both in conjunction with the Northern Grampians Shire. Numerous geotechnical reports were completed regarding risk management for the local government and Vic Roads solely for the purpose of immediate remediation of municipal and State resources. In these reports a detailed preliminary evaluation of the debris flows affecting or posing imminent risk to people and infrastructure was provided to the mentioned authorities. These reports are the property of the consultants and are only for the use of those authorities.

2.0 LANDSLIDE CLASSIFICATION AND MAPPING TECHNIQUES

2.1 Introduction

Landslides are among the most devastating of the natural disasters that impact human civilisation, accounting for 17% of the mortalities from natural disasters (Alimohammadlou *et al.*, 2013). Yet the fact remains that landslides are an integral part of the geomorphology that shapes the landscape in the past and present. They are one of the most frequent natural processes occurring on a regular basis and are a key mechanism of erosion and material transport (Bianchini *et al.*, 2012). Given the high frequency of this natural process and the ever increasing human population that is encroaching on fragile landscapes that cannot support permanent residencies, it is vital that landslide risk management is undertaken. The risk management process should minimise the impact on people and include risk analysis, risk evaluation and risk treatment (AGS, 2000).

In this chapter, landslides and mass movement mechanisms will be reviewed in relation to hazard analysis (as precursor to risk management) using mapping techniques. The focus will be on creating landslide inventories that document on the spatial and temporal relationships of landslides so future studies can expand the acquired knowledge to produce landslide susceptibility, hazard and risk maps. To produce statistical maps GIS (Geographical Information Systems) techniques need to be used, as GIS programs can filter statistical data and create spatial and temporal associations between factors (Chacón *et al.*, 2006). Using GIS techniques, various data types (terrain, geology, and physiography) can be simulated in appropriate ways for the purpose of a study. For example many landslide events involve multiple landslides and high definition images can be used to locate and define specific landslide occurrences.

Landslide is a term that is often generalised to define any type of movement of earth material down a slope at any speed, but in fact the term mass movement is more accurately defined by this loose definition. Mass movements may fall, topple, slide, spread, flow and/or slump along a distinct plane or zone of sliding as a slide or creep (Walker & Fell, 1987). Mass movements occur when the stability of any slope has been compromised by a variety of preparatory causal factors and triggering causal factors but ultimately the driving force is gravity, creating a net movement of material downwards and outwards (Varnes, 1958). Principally but not exclusively, the material that is transposed from its original position is composed of regolith, which overlies more coherent bedrock (Scott & Pain, 2008), often accompanied by bedrock and fill (Walker & Fell, 1987). The process of movement occurs when the shear forces acting on the materials on a slope exceed the shear strength of the material, usually by an excess of slope gradient or mass. When the shear strength is surpassed it only requires a trigger to activate a landslide. More often than not water acts as a trigger because it infiltrates the subsurface, increasing the porewater pressure and reducing the shear strength.

2.2 Causal Factors

It has long been recognised what conditions influence landslide occurrence. Terzaghi (1950) originally proposed that there were two groups of causes: internal and external. Internal causes include mechanisms that reduced the shear strength of a earth mass, whereas external mechanisms are forces that overcome the reduction in shear strength and therefore induce mass movement (Bell, 1983). More recently views have altered slightly to two distinct groups of causal factors that contribute to landslide occurrence and these are standard for landslides on natural and man-made slopes. The two groups of causes that are responsible for landslides are: Preparatory Causal Factors – Terzaghis' internal mechanisms, and Triggering Causal Factors –Terzaghis' external mechanisms (Popescu, 2001). Popescu (2001) presented some causal factors, listed in Table 2.1, that are likely to contribute to landslide incidences in many cases, some of which may act as either preparatory causal factors or triggering causal factors subject to individual landslides (Popescu, 2001).

2.2.1 Preparatory Causal Factors (Geological/Geomorphical Conditions)

Preparatory factors are the underlying geological conditions or changes in the geomorphology to predispose a slope to be susceptible to landslides (Popescu, 2001) and are largely down to the properties of the earth materials. The geological conditions that may contribute to a reduction in shear strength are prehistoric properties and may include: material strength, presence of discontinuities (faults, joints, strata, sedimentary contacts or metamorphic foliations) and weathered material (Popescu, 2001). Whereas geomorphological conditions are likely to be relatively recent in the geological evolution of the land surface, such as erosion, which may increase the height or gradient of a slope and therefore increase the weight above the foot of the slope (Bell, 1983), and therefore increase the shear stress.

2.2.2 Triggering Causal Factors

Triggers are the final aspect of landslide occurrence. These are usually, but not exclusively, mechanical processes that rapidly change the conditions that keep the slope material stable. Water in one or other of its forms is the most likely agent to trigger landslides, but vibrations in the form of earthquakes or other shocks are also widely responsible for triggering them (Popescu, 2001).

A brief list of landslide causal factors
1. Ground conditions 1. Plastic weak material 2. Sensitive material 3. Collapsible material 4. Weathered material 5. Sheared material 6. Jointed or fissured material 7. Adversely oriented mass discontinuities (including bedding, schistosity, cleavage) 8. Adversely oriented structural discontinuities (including faults, unconformities, flexural shears, sedimentary contacts) 9. Contrast in permeability and its effects on groundwater 10. Contrast in stiffness (stiff, dense material over plastic material)
2. Geomorphological processes 1. Tectonic uplift 2. Volcanic uplift 3. Glacial rebound 4. Fluvial erosion of slope toe 5. Wave erosion of slope toe 6. Glacial erosion of slope toe 7. Erosion of lateral margins 8. Subterranean erosion (solution, piping) 9. Deposition loading of slope or its crest 10. Vegetation removal (by erosion, forest fire, drought)
3. Physical Processes 1. Intense, short-period rainfall 2. Rapid melt of deep snow 3. Prolonged high precipitation 4. Rapid drawdown following floods, high tides or breaching of natural dams 5. Earthquake 6. Volcanic eruption 7. Breaching of crater lakes 8. Thawing of permafrost 9. Freeze and thaw weathering 10. Shrink and swell weathering of expansive soils
4. Man-made processes 1. Excavation of slope or its toe 2. Loading of slope or its crest 3. Drawdown (of reservoirs) 4. Irrigation 5. Defective maintenance of drainage systems 6. Water leakage from services (water supplies, sewers, storm-water drains) 7. Vegetation removal (deforestation) 8. Mining and quarrying (open pits or underground galleries) 9. Creation of dumps of very loose waste 10. Artificial vibration (including traffic, pile driving, heavy machinery)
Table 2.1: Landslide causal factors (Popescu, 2001).

2.2.3 Processes

The processes by which landslides are produced are predominantly physical but can also be chemical. Gravity is the primary driving force by which landslides occur with a net movement of material downwards and outwards (Varnes, 1958), as the natural processes of erosion attempt to reach equilibrium. Movement occurs when the shear stress exceeds the shear strength either by height, weight or a change in lithostatic pressure. Causal Factors aid gravity in creating landslides by changes in:

Slope Gradient – An increase in slope gradient may occur via erosion or excavation at the foot of the slope (Zaruba & Mencl, 1982) and this ultimately increases the shearing stresses of a slope (Bell, 1983). Critical slope gradients can vary depending on material and structural conditions but generally slides will resist movement to much greater angles than earth flows and slumps (Walker & Fell, 1987).

Slope Height – An increase in slope height by vertical erosion or excavation relieves lateral stresses and can rapidly allow movement to occur (Zaruba & Mencl, 1982).

Loading Embankments – Natural deposition or excavations on top of a slope can increase the shear stresses and an increase in porewater pressure in finer grained soils and therefore decreases the shearing strength (Zaruba & Mencl, 1982).

Shocks and Vibrations – Earthquakes and volcanic eruptions are the usual sources of vibrations but may also include man-made explosions. Vibrations in any material produce rapid fluctuations in stress as cyclic loading and unloading can cause changes in pore pressure reducing shear strength (Walker & Fell, 1987). In soils and sands, vibrations decrease inter-granular bonds and generally rearrange the grains, which commonly produces loss of cohesion and in other cases spontaneous liquefaction (Bell, 1983).

Water Content – An increase in the water content in the ground generally increases the porewater pressure and this in turn decreases the shear strength by decreasing cohesion and friction between the grains (Bell, 1983). The source of water can be intense short periods of rain, prolonged periods of rain and melting snow. If the water impacts an area after a dry spell, rainfall can markedly increase landslide incidence due to infiltration of cracks in the previously desiccated soil (Zaruba & Mencl, 1982).

Groundwater –Flowing ground water can wash out soluble and fine particles and elements that may be cementing the greater mass together (Bell, 1983). Groundwater, if confined, can exert significant hydrostatic pressure upwards on overlying beds, and this dramatically decreases the frictional resistance (Zaruba & Mencl, 1982).

Frost Effects – Water that is present in joints and pores in the subsurface can freeze and subsequently expand. The expansion mechanically widens joints and further fractures the material and decreases the cohesion (Zaruba & Mencl, 1982). When the ice thaws the water may drain and leave behind less consolidated material which can move, and is only further compromised by the drainage of thawed ice, increasing water content (Bell, 1983).

Weathering – Generally weathering disturbs the cohesion of saprock (slightly weathered rock (Scott & Pain, 2008)) both mechanically and chemically (Zaruba & Mencl, 1982). As weathering processes act upon the rock, the rock will change chemically limiting cohesion and this could lead to mass movement.

Vegetation – Vegetation acts as a natural mechanical stabilisation as the roots penetrate the subsurface (providing additional tensile strength) and also assists in reducing water content by extraction and inhibition of aerial rainfall (Zaruba & Mencl, 1982). But it can also have adverse effects, contributing to weight on the slope in addition to transferring above ground forces (wind), dynamically to the ground. Vegetation may also increase infiltration by accentuating the roughness of the ground surface and desiccating the soil creating cracks (Walker & Fell, 1987).

2.3 Landslide Risk Management (LRM)

The total socio-economic cost of landslides in Australia during the 20th century is estimated to be $500 million (Leventhal & Kotze, 2008), and worldwide mass wasting accounts for billions of dollars of expenditure annually. Not with standing Australia's small percentage of the total global landslide events, the importance of minimising the actual cost to Australian society; including: social, economic and environmental costs is part of municipal and environmental planning. Following the Thredbo landslide in 1997 it was recognised by the Australian Geomechanics Society (AGS) and representatives from local governments, that there were shortfalls in the national LRM guidelines established in 1985, 2000 and 2002. To overcome this the interested parties proceeded to assemble the Natural Disaster Mitigation Programme (NDMP) to fund advances in the LRM (AGS, 2007).

The AGS established a framework for conducting the LRM within a defensible and rigorous set of guidelines and legislative requirements, to properly inform the implicated regulators and practitioners on a consistent approach (AGS, 2007). The framework, Appendix A, is nationally accepted and has been used as a basis for a recently convened Joint Technical Committee (JTC-1), chaired by Robin Fell of the AGS, which developed an International Landslide Zoning guideline. The framework includes the three guidelines outlined by the AGS: Landslide Zoning (AGS, 2007a), Practice Note (AGS, 2007c) and Australian GeoGuides (AGS, 2007e) (AGS, 2007).

2.4 Hazard Analysis

The process of hazard analysis, Appendix A , involves four distinct areas according to AGS (2007c) these are: data collection/collation, field investigation, hazard identification and frequency analysis.

2.4.1 Data Collection/Collation (Pre-analysis)

This component of the analysis is the preliminary research of site specific papers and relevant data, particularly terrain and geological data and aerial photographs, from which a concise view of the region in question can be gained. As part of the data collection the regional setting must be outlined in terms of the geology and geomorphology. These aspects are, in most cases, controls of landslides (as outlined in Section 2.) but also takes note of non-geological factors that may contribute to the overall occurrence and distribution of landslides. GIS techniques can be used to filter the large volumes of data collected, including factors of the natural and human environments. GIS has been available for 40 years (Chacón *et al.*, 2006) and has had time to evolve and become an incredibly useful statistical tool to produce quantitative results (Lee, 2009). Figure 2.1 is an example of how interpretable landslide susceptibility maps can be, especially for non-professionals.

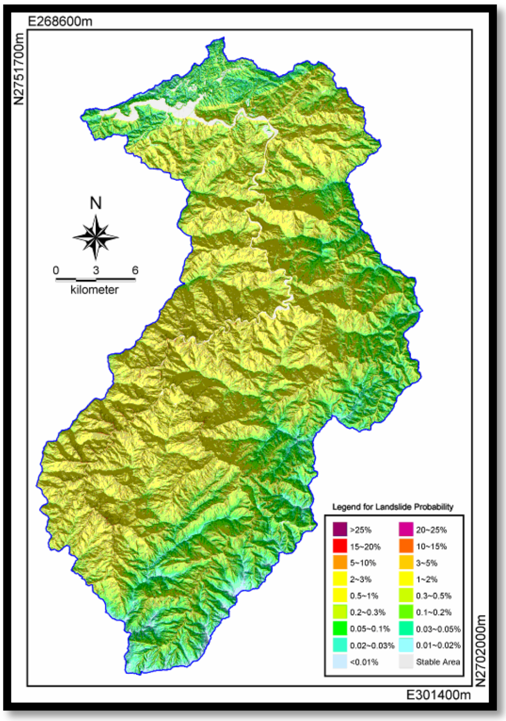


Figure 2.1: Probability map of typhoon Aere landslide event, Taiwan (Lee, 2009)

The GIS process involves a number of steps to identify and quantify landslide incidence. First a landslide inventory, which should include the "location, classification, volume, activity and date of occurrence of individual landslides in an area" (AGS, 2007a), must be compiled by either the regulator (often local governing bodies) or the practitioner (geological specialist). Depending on the scale of an inventory map the attributes recorded may vary to: only location for small scale maps, to large scale maps that "distinguish landslide sources from deposits, classify different kinds of landslide and show other pertinent data" (Chacón *et al.*, 2006). Naturally practitioners are able to produce more geologically specific and significant information required for larger scaled maps. Realistically inventory maps can be tailored to suit the purpose of the regulating body, for instance creating a temporal landslide inventory for a particular rainfall event which may be considered significant by the regulator.

As a means of locating landslide occurrences and extent various techniques can be used, including: interpretation of stereoscopic photographs taken soon after the event, visual or digital analysis of high-resolution digital elevation (Fiorucci *et al.*, 2011). Technological advances in remotely sensed data has increased the use of laser scanning methods (Rau *et al.*, 2012), both aerially (Airborne-based ALS) and terrestrially (Terrestrial-based TLS), with the former more useful, as it can cover greater areas more rapidly (Jaboyedoff *et al.*, 2012). Ultimately laser scanning cannot entirely replace field work with its current applications so field observations must be conducted to confirm at least landslide locations and dimensions (Jaboyedoff *et al.*, 2012).

Other remotely sensed techniques can be used for landslide identification and classification but they too have limitations, such as differential Synthetic Aperture Radar (SAR) interferometry which is conducted from space-borne platforms (Hervás *et al.*, 2003). SAR is somewhat restricted due to its distant nature having implications from direction of antenna illumination, loss of coherence between SAR data pairs in densely vegetated areas, unfavourable SAR illumination with respect to slope aspect and angle, atmospheric effects and insufficient spatial resolution (Hervás *et al.*, 2003).

High resolution images can be further used to recognise landslide causative factors such as: slope gradient, slope roughness, tangential curvature, relative and total slope heights and wetness index (Lee, 2009). With this data it is possible to enrich a landslide inventory map where different aspects of landslides can be measured using varying GIS layers such as topography and satellite images. Once a reasonable volume of data concerning the causative factors can be compiled, relying on the most influential factors, each factor can be appropriately weighted as of its subjective importance in terms of the landslide area (Bathrellos *et al.*, 2009). Once the factors have been weighted, usually the trigger such as rainfall has the highest coefficient and can be manipulated statistically to produce probability values using logistic regression (Lee, 2009).

2.4.2 Field Investigation

It is important to supplement a study on landslides that is primarily computer based, with contemporaneous field work to ensure that what is reported is as comprehensive as possible. In a field investigation geomorphic features and processes can be mapped in plan view (AGS, 2007c) using standard geological mapping methods and symbology such as those represented in Figure 2.2. A plan view may be complemented with a succinct but accurately scaled cross section on the landslide, which will be useful to characterise the earth movement later in the study (AGS, 2007c). Appendix B shows features common to most landslides that will likely be included in either the plan view, cross section or both.

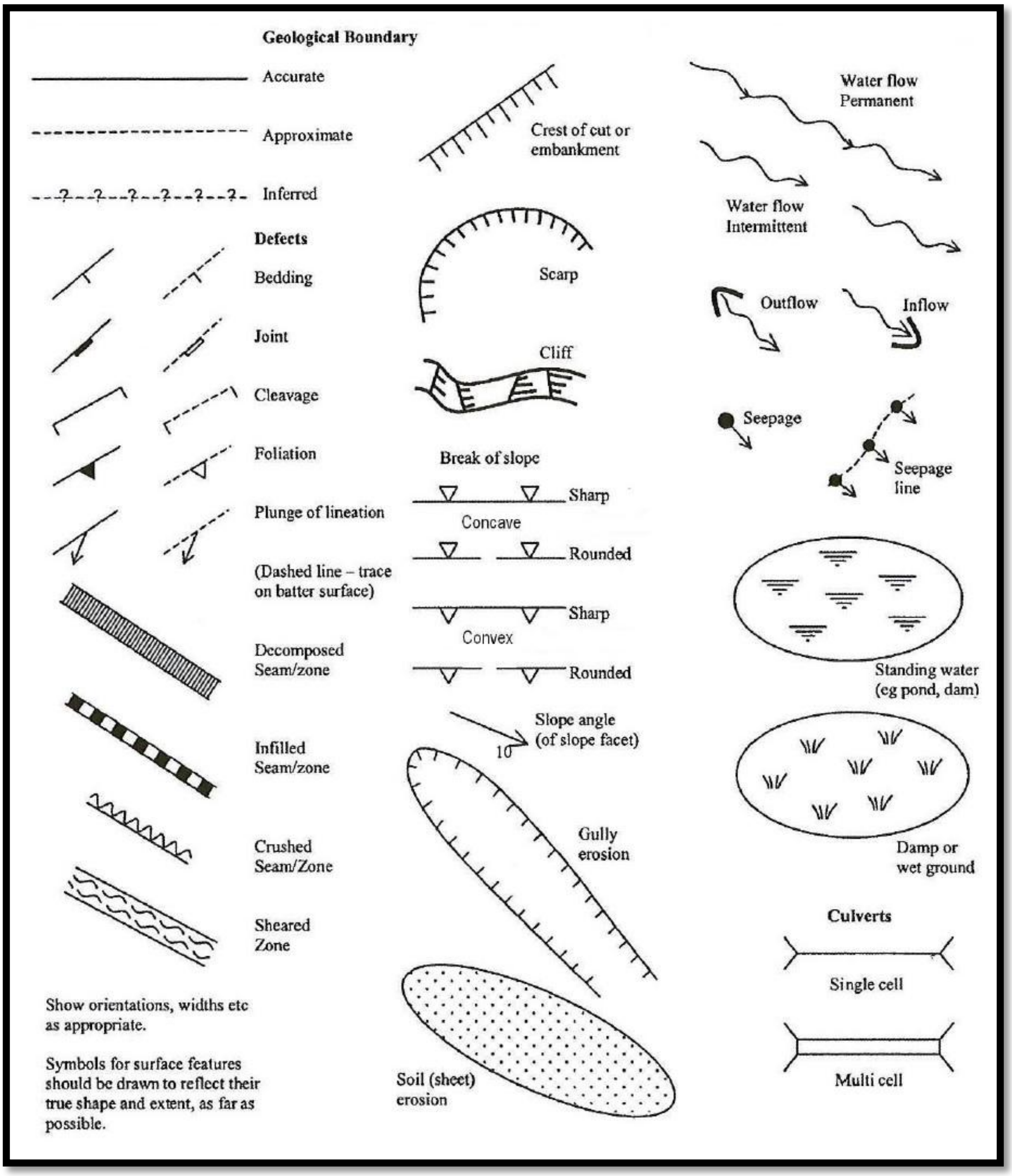


Figure 2.2: Geologic and geomorphic mapping symbols to be used during field mapping (AGS, 2007c).

2.4.3 Landslide Characterisation

Landslide characterisation (hazard identification) should ultimately describe a landslide or group of similar landslides using information collected during the preliminary desk work and field investigation and should include: the classification (movement type), extent of the landslide (location, area and volume), travel distance and rate of movement (creep, slow or fast) of the landslide(s).

2.4.3.1 Classification

There are numerous classifications of landslides with each tending to focus on a certain aspect of the landslide in terms of the geology, geomorphology and engineering (Scott & Pain, 2008). Such classifications may include: a simple classification that delineates the type of shear planes with a brief description of the material and the velocity of movement, or a geotechnical classification such as Table 2.2, which is useful when undertaking a geotechnical analysis, or a thickness-length ratio classification (D/L, where D is maximum thickness and L is maximum length of movement in the direction of slope) which can be useful to determine the landslide process groups such as in Table 2.3 (Walker & Fell, 1987).

Soil Fabric Conditions (affecting cohesion and internal friction)	**Pore fluid pressure conditions on slope surface (affecting pore fluid pressure)**

• First time slides in previously unsheared ground: soil fabrics tends to be random (or oriented as a result of depositional history) and shear strength parameters are at peak or between peak and residual values
• Slides on pre-existing shears associated with:
    ○ Previous Landslides
    ○ Colluvium
    ○ Periglacial Solifluction
    ○ Other Freeze-thaw Processes
    ○ Tectonics
    ○ Lateral expansion
• In these cases the soil fabric surface is highly oriented in the slip direction and shear strength parameters are at or about residual values.
	• Short-term (undrained) - no equalisation or excess porewater pressure set by changes in total stress.
	• Intermediate - partial equalisation of excess porewater pressures.
	• Long-term (drained) – complete equalisation of excess porewater pressures to steady seepage values.
	• Note that combinations of A, B and C can occur at different times in the same landslide; for example, a particularly dangerous type of slide is that in which long-term, steady seepage conditions (C) exist up to failure but during failure, undrained conditions (A) apply; that is a drained/undrained failure.

Table 2.2: Physical parameters for the Geotechnical classification (Walker & Fell, 1987)

Landslide Type	**D/L (%)**
Slides	5-10
Flows	0.5-3.0
Slumps	15-30

Table 2.3: Thickness-length Ratio classification (as percentages) according to (Walker & Fell, 1987)

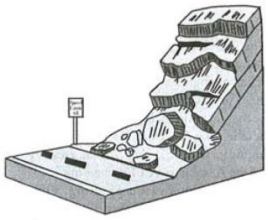
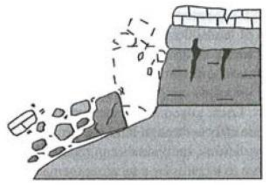
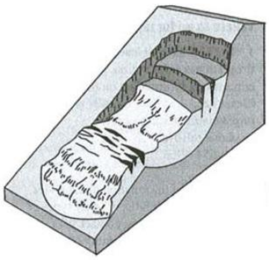
However to standardise the classification of mass movement, a simple process based on the movement type has been developed and this includes: falls, topples, slides (rotational and translational), lateral spreads, flows (in bedrock and soil) and complex slides (Varnes, 1978). Varnes (1978) also proposed that material type be included to further define landslides, including: Rock, Soil, Earth and Debris.

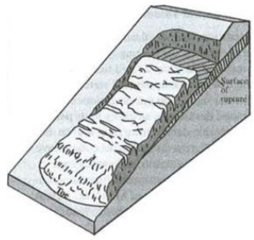
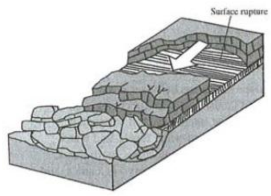
Rock is 'a hard or firm mass that was intact and in its natural place before initiation of movement.'

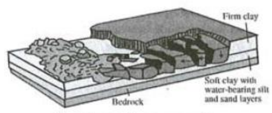
Soil is 'an aggregate of solid particles, generally of minerals and rocks that, either, was transported or was formed by the weathering of rock in place. Gases and liquids filling the pores of the soil form part of the soil.'

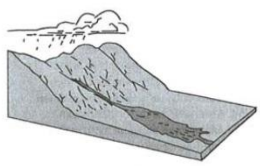
Earth is 'described as a material in which 80% or more of the particles are smaller than 2mm, the upper limit of sand sized particles.'

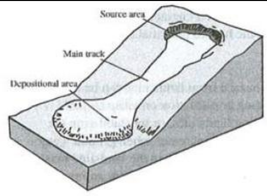
Debris 'contains a significant proportion of coarse material; 20%-80% of the particles are larger than 2mm and the remainder is less than 2mm.'(Varnes, 1978)

<table>
<tr><th>Type of Movement (Dominant)</th><th>Diagram (Material)</th></tr>
<tr><td>Falls
Falls are characterized by varying sizes or types of material, most commonly debris or rock that travels from a static position by free fall for the better part of the distance travelled, along with saltation or rolling with a high velocity and the potential to be highly destructive (Bell, 1983; Zaruba & Mencl, 1969). The Material is often singular rocks or enormous rock complexes that cause the debris to scatter far and wide at the base of the slope.</td><td>
Rockfall</td></tr>
<tr><td>Topples
Topples are caused by an imbalance between the position of the weight vector and the centre of gravity. If the weight vector falls outside of the centre of gravity and therefore the outward side of the base toppling can potentially occur (Zaruba & Mencl, 1969). The occurrence of toppling may be amplified ‘with increasing discontinuity angle and steep slopes in vertically jointed rocks’ (Zaruba & Mencl, 1969).</td><td>
Topple</td></tr>
<tr><td>Slides-Rotational
Homogenous clayey soils and rocks (clays, claystones, argillaceous shales) are common mediums for rotational slides or slumps which begin with tension scars in the upper area of a slope that form concentrically and parallel to the main scarp (Figure such such) where by failure occurs at an inclined angle to head area and movement transpires along a curved surface. (Bell, 1983). This produces an accumulation of transported material at the foot of the slope (Zaruba & Mencl, 1982). The degree of weathering of the overconsolidated clays will determine how circular the rotational failure will be, the more weathered, the less circular. Slumps tend to act retrogressively with each successive rotational slide developing in a head ward direction along a common basal shear surface.</td><td>
Rotational landslide</td></tr>
</table>

<table>
<tr><td>Slides-Translational
Translational slides more often or not occur along a bedding plane of clays and soils that have been weathered down to a plane often a change in lithology or bedrock but can also occur in solid rock where consolidated lithology overlies planar features that act as a sliding agent. Sliding surfaces have a coefficient of friction that is proportional to the roughness of the surface, but the friction can be reduced by the hydrostatic pore pressure (Zaruba & Mencl, 1982).
Movement comes about due to a combination of gravitational forces, a slip surface and weakness at the upper extremities of the earth mass surpassing the total resistance forces of the shear surface. The slip surface is all but parallel to the ground surface and may be very extensive and occur at lesser slope angles than rotational slides.</td><td>
Translational landslide</td></tr>
<tr><td>Rock Slides
Rock slides are equivalent in behaviour to translational slides but water and hydrostatic pore pressure are not common causal or trigger factors and are more likely a result of mechanical weathering such as freeze-thaw action wedging the rock free of its bonds. Unlike translational slides rock slides require a much higher incidence angle to the underlying planar surface.</td><td>

Block slide</td></tr>
<tr><td>Lateral Spreads
Lateral spreads tend to have a high pore water pressure that allows the clays, quick clays and particularly varved clays (alternating light and dark thin sediment layers formed in cold climate lakes (Boggs, 2011)) to flow concentrically outwards (Bell, 1983). The resulting landslide is likely to occur fairly rapidly due to the high porewater pressure.</td><td>

Lateral spread</td></tr>
<tr><td colspan="2">Flows-Bedrock
Bed rock flows may be conceptualized as plastic deformation occurring largely in intact bedrock as surficial and deep creep. This type of movement happens extremely slowly with little acceleration (Zaruba & Mencl, 1969).</td></tr>
<tr><td>Flows-Soil, Debris and Rock
Flows tend to have a high fluid content giving them fluidal motion principally composed of fine-grained soils. The high water content also allows the flow to travel across surfaces with relief angles</td><td>
Debris flow</td></tr>
</table>

between 5° to 15°, and possibly as flat as one degree or less, and tends to follow drainage paths such as valleys, streams or gullies (Bell, 1983). But it is also possible to have dry flows. Dry flows consist of rock fragments, these flows usually originate as rock falls or rock slides that develop a larger movement of rock/debris but are primarily composed of silt and sand, and are often referred to as rock flows or avalanches (Bell, 1983).	 **Earthflow**
Complex Slides Complex slides are not a standalone type of landslide but will display characteristics of two or more mass movement types (Zaruba & Mencl, 1982). In fact many landslide occurrences may not display just one type of mass movement and could be categorised as complex slides.	
Figures 2.3 The types of landslide movements according to Varnes' classification (USGS, 2004)	

2.4.3.2 Extent and travel distance of landslides

The extent and travel distance of landslides simply refers to the dimensional attributes of an individual episode of mass wasting. The extent of a landslide refers specifically to the location, area and volume; which for the best part can be determined remotely using aerial or satellite images, or during the field investigation using a handheld Global Positioning Device (GPS) that can be walked around the edge of the landslide. Once the area has been deduced, either DEM comparison (before and after the event) or thickness estimation in the field can determine a volume approximation (Chang *et al.*, 2005). The travel distance, which may also be known as the run-out distance, is the linear distance from the base of the landslide to the front of the landslides final position (Chacón *et al.*, 2006). Furthermore a description of the landslide can be enhanced using Table 2.4 where Cruden and Varnes (1996) include other aspects of the slide such as the: state and distribution.

Activity		
State	**Distribution**	**Style**
• Active	• Advancing	• Complex

• Reactivated • Suspended • Inactive ○ Dormant ○ Abandoned ○ Stabilised ○ Relic	• Retrogressive • Widening • Enlarging • Confined • Diminishing • Moving	• Composite • Multiple • Successive • Single

Description of Movement			
Rate	**Water Content**	**Material**	**Type**
• Extremely Rapid • Very Rapid • Rapid • Moderate • Slow • Very Slow • Extremely Slow	• Dry • Moist • Wet • Very Wet	• Rock • Soil • Earth • Debris	• Fall • Topple • Slide • Spread • Flow

Table 2.4: This table is an extension of the classification by description (Cruden & Varnes, 1996)

2.4.3.3 Rate of movement

The rate of movement is quite simply the average speed at which the movement of a slope is occurring. To gauge the rate of landslide movement Cruden and Varnes (1996) developed a key, Figure 2.4, that has values or ratings of movement velocity assigned to likely destruction.

Velocity Class	Description	Velocity (mm/sec)	Typical Velocity	Probable Destructive Significance
7	Extremely Rapid			Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
		5×10^3	5 m/sec	
6	Very Rapid			Some lives lost; velocity too great to permit all persons to escape
		5×10^1	3 m/min	
5	Rapid			Escape evaluation possible; structures; possessions, and equipment destroyed
		5×10^{-1}	1.8 m/hr	
4	Moderate			Some temporary and insensitive structures can be temporarily maintained
		5×10^{-3}	13 m/month	
3	Slow			Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
		5×10^{-5}	1.6 m/year	
2	Very Slow			Some permanent structures undamaged by movement
		5×10^{-7}	15 mm/year	
	Extremely SLOW			Imperceptible without instruments; construction **POSSIBLE WITH PRECAUTIONS**

Figure 2.4: Key to determine the rate of which a landslide moves (Cruden & Varnes, 1996).

2.4.4 Frequency Analysis

The preceding sections in hazard analysis are primarily focussed towards the spatial relationships of landslides to each other and the likely causative factors. But it may be possible to deduce the temporal relationship of a singular landslide or landslide event to a significant point in time or to local history. If what has triggered a landslide event is clear, it may be possible to develop a maximum threshold for which a standard can be made (Glade *et al.*, 2000). For example if a landsliding event has been triggered by exceptionally large rainfall and is not often recorded, it may be possible to delineate a value with respect to time such as a one in one hundred year rainfall event. The susceptibility of a slope can then be measured in relation to a maximum threshold of the triggering factor. To properly manage this, historical information about landslides is invaluable with appropriate dates, triggers and active stages of landslides, this ensures the most accurate temporal assessment (Chacón *et al.*, 2006).

Hazard and risk analysis is the next step, but first it must be made clear the difference between the two. Landslide hazard maps ‘delineate areas within which there is a finite probability of occurrence of being affected by slope instability in the time period relevant to the site’ whereas landslide risk maps ‘attempt to quantify the vulnerability of the area, either in terms of the probability of occurrence, or the expected damage to population and property’ (Walker & Fell, 1987). So the element of risk can be included much like any of the other factors and simply be assigned a coefficient by which it is multiplied and this will produce data that is weighted in terms of risk.

2.5 Conclusion

Given the destructive nature of landslides it is in man’s best interest to educate ourselves to predict scenarios where certain landslide types may occur. The AGS LRM provides key methods for landslide hazard analysis using data collection, field investigations, landslide classification and hazard frequency analysis. This framework is the basis for the research methods adopted in this project.

GIS methods will be used to recognise the spatial and temporal relationships between environment, triggers and landslide events. Advances in laser scanning imagery make the application of landslide hazard identification easier, as inventories can be compiled more rapidly.

3.0 REGIONAL SETTING

As is with most occurrences of mass wasting, those in the Grampians Ranges are largely influenced by the underlying geology and geomorphology. The Grampians geology has been the focus of many investigations due to their unique nature, in particular their striking physiography amongst the surrounding plains.

In this chapter the geologic evolution of the Western Uplands which includes the Delamerian Orogen and Western Lachlan Fold Belt will be assessed with an in depth view of the geology and geomorphology of the Grampians group. As well as past geomorphic evolution, present day processes must be acknowledged as the primary forces that are shaping the ranges now and into the future.

3.1 Geologic Evolution (Late Neoproterozoic and Palaeozoic)

The Grampians region has had a very complex geologic evolution which has occurred over the last half a billion years during which the western majority of the Australian continent was part of the supercontinent Gondwana (Li & Powell, 2001). Between the Late Neoproterozoic and the Early Carboniferous the Tasman Orogenic System, an accretionary orogen on the margin of Gondwanaland (Cayley *et al.*, 2011), was taking shape and this was responsible for much of eastern Australia as it appears today (Gray & Foster, 2004; Keep, 2003). Cratonisation of the Tasman Orogenic System against the Tasman Line, involved three extensive deformational events occurring in an eastward direction as the Delamerian Orogen (550-470Ma), the Lachlan Orogen (540-340Ma) and the New England Orogen (310-210Ma) (Gray & Foster, 2004). Only the Delamerian and Lachlan orogenies have played any significant part in the formation of the Grampians Group and the Grampians Ranges in their current state.

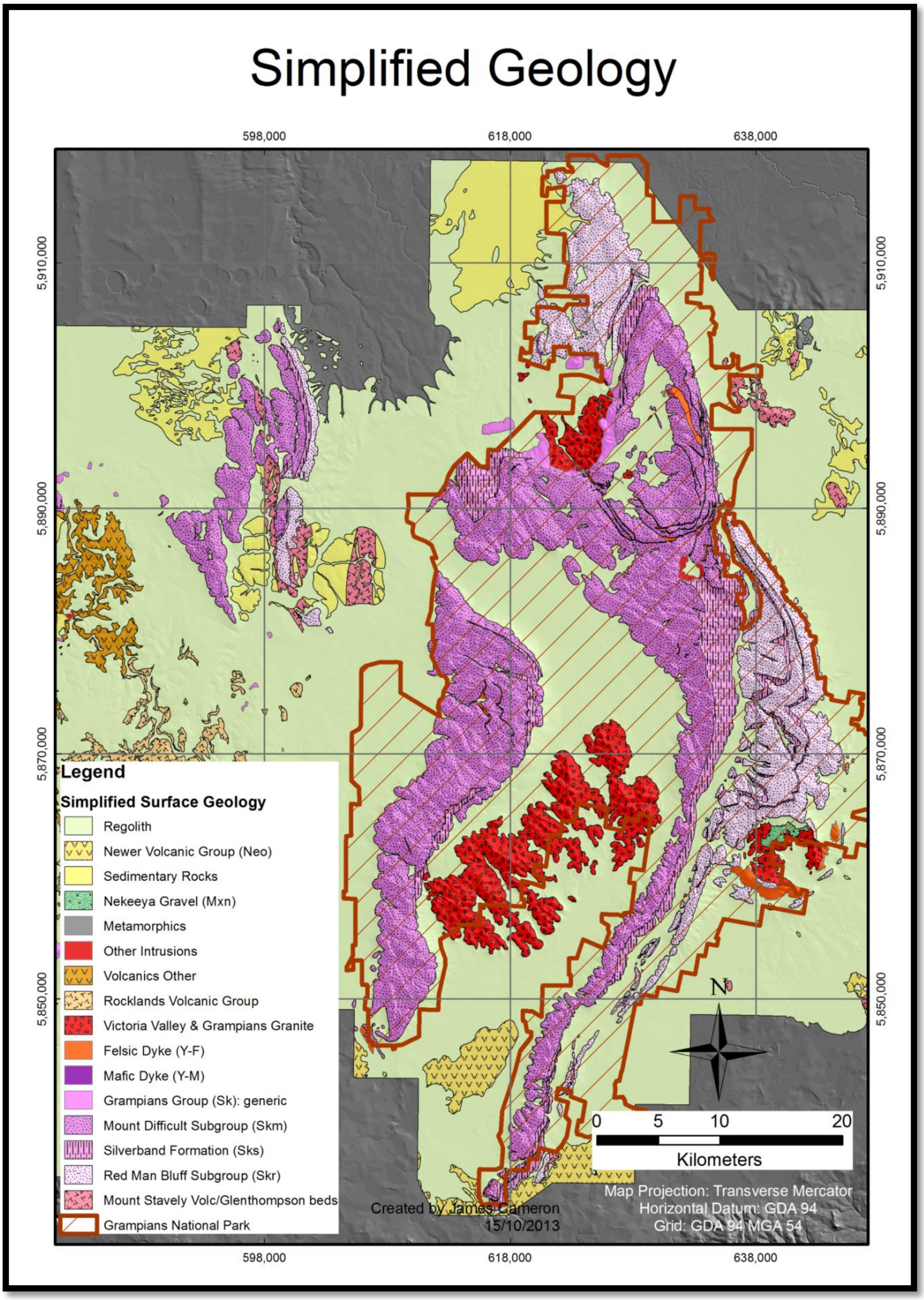


Figure 3.1 Map: Simplified Surface Geology. Colours basically represent the geologic age (light red-Cambrian, pinks –Ordovician/Silurian, dark green –Mesozoic, yellow-Tertiary, light green-Quaternary and Various igneous bodies).

3.1.1 Early-Late Cambrian (The Delamerian Orogeny)

Recent research into the geology of the basement, Delamerian Orogen, has increased our understanding of the geologic evolution of the Grampians region. The Delamerian is often poorly represented in the region due to the overlying sedimentary and volcanic rocks and weathered material limiting outcrops (Gray & Foster, 2004). However it is known that the Moyston Fault represents the eastern most exposure at the surface where the Delamerian is thought to be fore-arc ophiolite fault slices in the upper crust (Cayley *et al.*, 2011). A recent study, as described in Cayley *et al.* (2011), used the latest seismic analysis to confirm the structural nature of the underlying bedrock and has proved the Moyston Fault is east dipping and that it is most likely the boundary between the two tectonic complexes. The lowest of the succession of the Delamerian is likely ultra-mafic to felsic submarine volcanics overlain by hemipelagic black shales and turbidites (Cayley & Taylor, 1997). These rocks experienced the first episode of protraction in the Delamerian Orogen, and as a result were shortened by west dipping thrust fault belts. This was responsible for the deformation of the Glenelg River Complex (Cayley & Taylor, 1997). Following the initial period of deformation submarine volcanism produced the final Cambrian volcanic event extruding calc-alkaline andesites to dacites and shoshonitic basalts such as those of the Stavely Volcanic Complex (Squire et al. 2006). A fault boundary separates the Stavely Volcanic Complex from the overlying Glenthompson Sandstone that is thought to have once existed as an unconformity due to volcanic detritus in the sandstone (Cayley & Taylor, 1997). Syn-deformation deposition of the formation is suggested and confirmed by the sediments that are turbidites of micaceous terrigenous type (Cayley *et al.*, 2011). Extensive granite plutonism occurred across the Delamerian Orogeny para-contemporaneously with the final sediment deposition of the Glenthompson Sandstone and coincidently marks the end of the Delamerian deformation (Cayley *et al.*, 2011; Cayley & Taylor, 1997; Kemp & Gray, 1999).

3.1.2 Ordovician to Devonian (The Lachlan Orogeny and Grampians Group)

The Lachlan Orogeny is the second of three compressional sequences associated with the Tasman Orogenic System. The Lachlan Orogen can itself be divided into sub provinces of deformation, these are: the western, central and eastern sub provinces; of which only the western is relative to the formation of the Grampians (Gray & Foster, 2004). The sub provinces can in turn be separated into structural zones for example in the western sub province exists the: Stawell, Bendigo and Melbourne zones (Miller et al. 2005). The western margin of the western sub province (Stawell zone) is delineated by the Moyston Fault, but the area that lies between the Moyston and Stawell-Ararat Faults (Moornambool Metamorphic Complex) is contentious due to its ambiguous relationship to both the Delamerian and Lachlan Orogenies (Gray & Foster, 2004).

The western sub province consists of turbiditic sandstones and mudstones that structurally verge eastward with reverse faults and tight to isoclinal folds (Miller *et al.*, 2005). The Moornambool Metamorphic Complex which lies immediately adjacent to the Stawell Zone is comprised of ‘amphibolite-grade equivalents of the Cambrian Magdala Volcanics and the thick Cambrian-Ordovician turbidites of the St Arnaud Group (Korsch et al., 2002). The superposition of the turbidites over the volcanics is documented in the hanging wall of the first order faults: Moyston, Avoca and Mt William (Cayley *et al.*, 2011) and supports the theory of a normal thrust fault boundary between the two orogenic systems at the Moyston Fault. The significance of the Moornambool Metamorphic Complex is that it provides approximate time frames of metamorphism and exhumation during the Ordovician (Miller *et al.*, 2005), which coincides with much of the deposition of the

Grampians Group. In this time the erosion of the bedrock, formed in the Delamerian Orogen to the west, transported Quartz-rich sediment fluvially east into an ocean basin to deposit the Stawell and Bendigo zones (Cayley & Taylor, 1997). The Grampians Group is thought to have been deposited in a marginal marine equivalent but in structural basins adjacent to the source (Cayley & Taylor, 1997). Gouramanis *et al.* (2003) postulated that the research conducted on the Major Mitchell Subgroup ichnofacies is suggestive that the Grampians Group in general was not marine due to the species of organisms and sedimentology of the subgroup. A contraction, due to the continuing Lachlan Deformation, of the Grampians Group in a north-west / south-east direction caused thin skinned deformation during which thickening occurred as thrust stacking, thrust faults and later folding (Cayley & Taylor, 1997).

3.2 Geology of the Grampians Group

The Grampians Group includes the: Mount William, Serra-Wonderland-Mt Difficult and Victoria ranges (Spencer-Jones, 1965) that are consequently separated by valleys from which the Fyans and Dwyer creeks and the Wannon and Glenelg rivers drain. The depositional environment has been contested from low relief braided plains Jones (1993), to tidal processes George (1994) (Gouramanis et al.2003) but regardless of any contention there is a consensus; the succession is characterised by quartz-rich sandstone, siltstone, mudstone, and minor conglomerate (Douglas & Ferguson, 1988) fluvial to shallow-marine deposits (Cayley & Taylor, 1997). Cayley and Taylor (1997) describe the Grampians Group as having several sequences that overlie one another and consist of: a quartzo-feldspathic to micaceous sandstone suite (Red Man Bluff Subgroup), overlain by a micaceous mudstone dominated suite (Silverband Formation) and finally quartzose sandstone suit (Mount Difficult Subgroup); their relationship to each other can be seen in

Table 3.1 and Figure 3.1. These sequences can be further divided into formations and members (beds) that are easily traceable along strike, mostly uninterrupted or altered.

The following sub-sections are simplified descriptions of the subgroups that constitute the Grampians Group, using the most recent and widely accepted description proposed by Cayley and Taylor (1997) who have refined work previously undertaken by Spencer-Jones (1965).

3.2.1 Red Man Bluff Subgroup

The Mount William Range, Mount Stapylton-Roses Gap area and parts of the Black Ranges account for the outcrops of the Red Man Bluff Subgroup. The Thermopylae Conglomerate (Skrt) is notably the lowest formation in the Red Man Bluff Subgroup and consequently the lowest of the Grampians Group, and lies on a fault contact with the underlying bedrock. This formation, along with all but the Major Mitchell Sandstone (Skra), poorly outcrops with limited exposures, particularly on the flanks of Mount William.

Lithologies grade from quartzo-feldspathic conglomerate (Skrt) and sandstones to more quartz rich massive sandstones such as those of the Kalymna Falls and Major Mitchell Sandstones. Lesser beds of siltstone appear interbedded among coarse to medium grained quartzo-felspathic sandstones in the Gariwerd, Watgania and Murray Hill Sandstones, which are often cross bedded to massive. Pebbly lags of sandstone and quartz vein clasts occur in all formations most conspicuously in the Murray Hill Sandstone, which also incorporates the Pohlner Conglomerate. The Pohlner Conglomerate, like the Thermopylae Conglomerate is a polymictic conglomerate with gravel-cobble-sized sub rounded clasts of sandstone and vein quartz, but differs with inclusions of smaller clasts of siltstone, chert, mafic and felsic volcanics.

The Major Mitchell Sandstone, which is overlain by the Silverband Formation, forms the majority of the Mount William Range and is responsible for prominent cliffs along strike at the top of the range. On the western dipping slopes of the Mount William Range both the Major Mitchell Sandstone and the Silverband Formation appear due to sub-levels of thrust sheets primarily above the Salamis Fault.

3.2.2 Silverband Formation (Sks)

In between the Red Man Bluff Subgroup and the Mount Difficult Subgroup the Silverband Formation defines a marked change in the sort of deposition and therefore sediment type. Though the contact with the underlying Major Mitchell Sandstone is conformable the transition is gradual with an indefinite boundary between the two with the sand gradually grading into mudstone. The formation is largely comprised of thinly laminated red-bed mudstone with thin interbeds of fine-medium grained micaceous quartz sandstone and occasional coarse-grained quartz sandstone. The red-bed terminology can be ascribed to a distribution of fine grained iron oxide, haematite.

A prominent feature of this formation is the presence of soft-sediment sedimentary structures such as: symmetrical ripples, mud cracks in filled with sand, raindrop imprints and bioturbation.

Two sandstone members are included in the Silverband Formation both of which are quartz sandstone (Table 3.1).

3.2.3 Mount Difficult Subgroup

The Mount Difficult Subgroup is the most extensive of the three sequences forming the bulk of the Serra-Wonderland-Mount Difficult Range (SWMD) chain, the Victoria Range and the Black Range. The relatively pale-coloured sandstone-dominated subgroup conformably albeit sharply overlies the Silverband Formation as the Serra Sandstone

(Skms1&2), which is recognisable on the jagged SWMD Range ridge line, most of the Victoria Range and parts of the Black Range. The Serra, Moora Moora and Wartook formations comprise most of the subgroups outcrop and are very geologically similar. All formations display a general fining upwards with intermittent gravel lags and thin interbeds of siltstone. The Serra Sandstone is divided into two branches of the formation by the Teddy Bear Conglomerate (Skmst), the lower of which is a coarse grained to pebbly quartz sandstone and the upper a finer grained sandstone with abundant trace fossils. The distinction of the sandstones may be purely down to the lack of observation of outcrops in the field and the relative discontinuity of the formations between ranges, however they are very traceable throughout the Grampians and Black ranges. The Teddy Bear Conglomerate is distinguished from other coarse grained polymictic conglomerate rocks due to the larger angular to sub angular clasts of mudstone and, vein quartz and medium-grained sandstone.

Stratigraphy of the Grampians Group			
Adaption of Cayley and Taylor (1997) Stratigraphic table for the Grampians Group			
	Subgroup	**Formation/Member**	**Thickness (m)**
Youngest	Mount Difficult Subgroup	Wartook Sandstone (Skmw)	250+m
Grampians Group		Daahl Sandstone Member (Skmwd)	(10-20m)
		Moora-Moora Sandstone (Skmm)	200-500m
		Serra Sandstone (Skms1)	350-500m
		Teddy Bear Conglomerate Member (Skmst)	(4-15m)
	(Silver Band Formation)	Silverband Formation (Sks)	750m
		Glen Hills Sandstone Member (Sksg)	(350m)
		Wannon Sandstone Member (Sksw)	(30m)
	Red Man Bluff Subgroup	Major Mitchell Sandstone (Skra)	300-450m
		Kalymna Falls Sandstone (Skrk)	450m
		Murray Hill Sandstone (Skrm)	300m
		Pohlner Conglomerate Member (Skrmp)	(2m)
		Watgania Gap Sandstone (Skrw)	200m
		Gariwerd Sandstone (Skrg)	300m
Oldest		Thermopylae Conglomerate (Skrt)	300m
Minimum total measured thickness: (excluding members)			3700m

Table 3.1 Stratigraphy of the Grampians Group.

3.3 Geomorphic Evolution of the Grampians Group

The Grampians Ranges morphology is due to a very complicated structural evolution, which in turn has greatly influenced the erosion and morphological changes to create the iconic cuesta-and-vale topography of the SWMD range, Wartook syncline and the Mitchell Plateau. As previously mentioned, the Grampians Group experienced thin skinned thrust stacking and thrust fault thickening (Section 3.1.2), the result of this deformation were some major structural features.

Thrust Faulting - The first significant structural feature that impacted the Grampians Group was the thrust faulting that occurred during the initial compression by the Lachlan Fold Belt. These thrust are bedding parallel that are noticeable by intense zones of fracturing brecciation, the porphyry dykes have intruded in these areas of weakness (Cayley & Taylor, 1997). The thrust faulting has displaced the sequence significantly enough that the sequence is in fact repeated in places; low in the Red Man Bluff Subgroup (Thermopylae Fault), high in the RedMan Bluff Subgroup (Salamis Fault), and within the Silverband formation (Leuctra Fault) (Cayley & Taylor, 1997). Most other numerous faults can be attributed to one of these major thrust faults.

Folding - Folds generally occurred after most of the thrust faulting and transpired in generations where each generation likely overprints the preceding one. The generations of folds are as follows: small asymmetrical reclined tectonic folds adjacent to the major thrust faults; the large scale sub horizontally plunging Wartook Syncline; warp folding related to the Grampians allochthon and drag folds related to the bedrock faulting (Cayley & Taylor, 1997).

Wartook Syncline - From aerial photos the Wartook Syncline in the North of the ranges is the most readily recognised fold of the Grampians, with a gentle southerly plunge in the north flattening out in the south near Mackenzie River to create a natural topographic basin

(Cayley & Taylor, 1997; Spencer-Jones, 1965). The fold axis is sinuous curving from north-westerly to north-easterly heading south and has been refolded by the south plunging Asses Ears Anticline (Cayley & Taylor, 1997).

Décollement - It is thought that the Grampians Group has a truncated relationship with the underlying Proterozoic basement of the Delamerian Orogen via a regional décollement provided by the Marathon Fault. Against this feature the Grampians Group has an allochthonous relationship to the basement and hence the proposed style of thin skinned deformation of the sequence. The décollement is the primary evidence for post protected extension.

Jointing - Jointing In the Grampians area post-dates the lithification, folding, faulting and igneous intrusion of the Grampians Group (Spencer-Jones, 1965). The jointing likely occurred in the lower to mid-Carboniferous in an orogenic episode, the result is four definite joint sets north-north-west (parallel/sub parallel to eastern margin fault); east-north-east (associated with set 1); west-north-west (master joints); north-north-west (variably associated with set 3).

Spencer-Jones (1965) suggested that it wasn't until the late Mesozoic to early Tertiary that the Grampians Group exposure was a definite topographic feature. Meanwhile sea levels had surrounded the margins of the Grampians and the evident retreat allowed significant erosion in the Pleistocene and continued erosion since has only made the Grampians a more prominent feature. During this time significant uplift of the surrounding Central Highland and tablelands only increased the topography. The uplift brought with it significant volcanic activity as is evident in the Newer Volcanics Province which lasted into the Holocene.

For erosion to have carved such a prominent feature in the landscape 700 meters above the surrounding tablelands it has been accepted that differential weathering is the process responsible (Cayley & Taylor, 1997; Joyce *et al.*, 2003; Spencer-Jones, 1965). The quartzose units prove to be incredibly stable the only weaknesses are slight variations in lithologies and structural features (Spencer-Jones, 1965). For instance the Wannon River and Fyans Creek have eroded material where a less competent unit (Silverband formation) and significant faults have provided a surface on which to do so (Cayley & Taylor, 1997; Joyce *et al.*, 2003; Spencer-Jones, 1965).

The recognisable scree slopes in the foreground of the equally characteristic east facing scarps are simply an erosional product as scree and colluvium moves downwards as a result of the weathering of the in-place Grampians rocks (Cayley & Taylor, 1997). The scree slopes often have evidence of historic rock falls and debris flows in the obviously unsorted sediment with a wide variety of clast sizes.

3.5 Rock Fall and Debris Flow

There is field evidence of rock falls occurring, to support anecdotal evidence. There are enormous boulders found a distance from any cliff and to look at the eastern facing scarps fresh rock surfaces are readily visible. The incidence of rock falls is obvious, and the processes by which these occur are likely associated with the structural features such as that extensive jointing present in the ridges. This occurs in conjunction with day to day weathering processes such as: the action of water (both meteoric and groundwater), frost action, chemical weathering and vegetation.

Debris flows/landslides are direct evidence that these erosive processes occur, however past flows are often difficult to recognise as the transported material may itself be removed and vegetation readily colonises the freshly exposed material. The scree slopes that form aprons around the in-place-rock are composed of a variety of sized fragments (large boulders to clay) that generally fine at distance from the source. Adjacent to the scarps the scree is comprised of varied angular-rounded fragments of silt to boulder sized debris which is evidence of one form or another of debris flows/landslides (figure 3.3).

Figure 3.3 A freshly exposed profile of semi-consolidated debris on scree slopes (Debris Flow Site 5).

4.0 METHODOLOGY

The widespread landslides that occurred in January 2011 have variabilities depending on the conditions of the area proximal to each landslide. To address the large scale of the Grampians Ranges various techniques were required to undertake an incidence assessment of the landslides. To achieve accurate spatial data management GIS, in particular ArcGIS, was used. Using this program the failures were not only mapped but analysed with regard to their spatial relationship to each other and any contributing factors. Reconnaissance and walk-over field investigations re-affirmed relationships and constructed further connections to the underlying landscape and processes at play.

4.1 Data collection

Data collection in the context of this project was relatively straight forward. The number of stakeholders concerned with the event meant that all of the raw digital data had, out of necessity, already been collated often multiple forms of similar data from separate entities. Among the stakeholders who have directly supplied data, the Department of Environment and Primary Industries (DEPI) and Vic Roads have been the most gainful, with government resources at their disposal.

Following the mid-January event, Vic Roads and Parks Victoria conducted the initial risk assessment of local infrastructure and private property, using both field and aerial assessments. Vic Roads flew aerial photography of the areas that concerned roads under their jurisdiction as well as Parks Victoria’s forestry roads. The result was a reasonably extensive coverage of all the affected areas at a very fine scale (38cm pixels). The DEPI meanwhile used the readiness and means of the (Bushfire) Rapid Risk Assessment Team (RRAT) to compile a general inventory and report on the immediate risk to people and property, part of which was five metre pixel RapidEye[3] satellite images; the latter having complete coverage of the Grampians area before and after the landslide event.

Data regarding predetermined base layers such as land use, DEM, roads and water courses were provided courtesy of Stuart Brown of the University of Ballarat. Additional remote data such as 2010 seamless Geology and 2005 EVC layers are publically available on the Department of Primary Industries (DEPI) website.

4.2 Spatial and Temporal Distribution with Verification

To determine the distribution of the debris flows that occurred within a known period of time over a large area such as the Grampians it was necessary to use a scale of image that could cover the area yet still provide pixel detail that was sufficient to delineate the debris flows. The use of five meter pixel resolution RapidEye satellite images that were compiled by the DEPI, which included images of the area before and after the event, allowed the creation of polygons using GIS. By using the RapidEye images the location of the landslides could be defined at a scale that was representative of the size of the study area. Fortunately late in the data collection process Vic Roads was able to supply very fine scale ortho photo mosaics covering most of the affected areas. The advent of fine scaled imagery allowed a remote verification and refinement of the mass movements previously mapped using RapidEye images. This process restricted the count of landslides to those which were discernible at a coarse scale of imagery; this was an important aspect of the initial incidence assessment to avoid too much data in an otherwise groundwork report. Using the ortho photo mosaics also allowed example flows to be selected for the field investigations at a later date, simply by examining landslide occurrences that appeared to be characteristic

[3]Formerly RapidEye, currently BlackBridge, is an enterprise dedicated to providing 5 metre pixel (orthorectified) images from 5 spacecraft that orbit the earth at 630 km; capable of capturing 5 million km²/day of 5 spectral bands (www.blackbridge.com/).

of the majority of slides in the area. Yet despite the usefulness of these aerial images they did not cover all of the area affected by the debris flows particularly to the north of Halls Gap.

4.3 Field Investigation

With any scientific assessment it is important that a field investigation be undertaken to confirm various attributes of the project and visually affirm and build on the hypotheses developed. Keeping in mind the aims of the study, which relate to the relationships of the contributing factors and the processes that acted during the event, as well as best practice field investigation processes as outline in the AGS (2007d), a framework for the field was developed.

Following the AGS (2007c, 2007d) as a guide a reconnaissance and basic walk-over field assessment framework was created, Appendix B. The framework included locating specific changes in the debris flow that were related to slope angle. At each point, which was marked by GPS, variables were noted such as: up-slope and down-slope gradients, slope aspect, slide trend, rough slide width, vegetation type, debris comments (fragment size and deposition, lithology and character), location comments (natural drainage, character of slope, description of in-situ soil material or bedrock).

An initial reconnaissance of potential landslide sites allowed a basic evaluation of the areas to direct the following sections of the investigation. Between the reconnaissance and walk-over field trips an interim of remote research and refinement of parameters was used to guide the walk-over. This acted like a positive feedback loop where gaps in remote data or field data could be reassessed.

When undertaking field work it was highly important that due processes were adhered to because of the conditions in the Grampians and in the vicinity of the landslides. Before work was conducted a Hazard Identification Risk Assessment and Control (HIRAC) review was completed to minimise the possibility for injury or death while working in an otherwise potentially dangerous environment. While in the field participants were exposed to remote locations where the potential for injury or death was very high. Such hazards are outlined in Appendix C, where the risk assessment and controls are also provided.

4.4 ArcGIS Analysis

With the advent of field data, remote analyses became more purposeful with the collection of some definite parameters governed how the digital data was manipulated in the GIS program. Important data provided by Stuart Brown (University of Ballarat) is 20m pixel resolution DEM. From this single data set all of the elevation and relief of the Grampians area could be determined including: slope gradient and aspect. Using the points collected during the field trips certain gradations of slope angle could be delineated, this advancement in study allowed an in depth review of the relationship between the slope gradient and landslide processes to be determined. Coupled with slope aspect, which was also derived from the DEM, it became evident that there was also a strong correlation between the landslide occurrence and slope aspect.

The DEM derivatives acted as a platform from which to conduct more focussed analyses using data from the DEPI and University of Ballarat such as: the Seamless Geology 2010 and EVC 2005.

5.0 RESULTS

The results presented in this report strictly relate to the spatial and temporal distribution of the most recent mass wasting occurrences in the Grampians ranges (Gariwerd). Given the lack of any significant data regarding substantial historic landslide occurrences, only the landslides that occurred in the time surrounding the January 2011 event could be analysed within the timeframe of this research.

5.1 Landslide Spatial Distribution

As may be observed upon any trip to Grampians Ranges since the beginning of 2011 it is clear that the distribution of the landslides is widespread, initial estimates from the NGS (2011) suggest that over 190 landslides were recorded in the week after the January floods. The source of this estimate was likely a compilation of work done by the Rapid Risk Assessment Team (RRAT), Parks Victoria and volunteers as well as reports from local residents. However after completing the remote spatial distribution analysis in the ArcGIS program using the RapidEye imagery only 176 landslides were recorded at this resolution, Figure 5.1. Using GIS techniques to manipulate the remote data proved highly versatile and accurate at determining the characteristic of the landslides as whole.

Two methods were used: one using the polygons constructed to delineate the landslides; the other required a separate approach using points of failure.

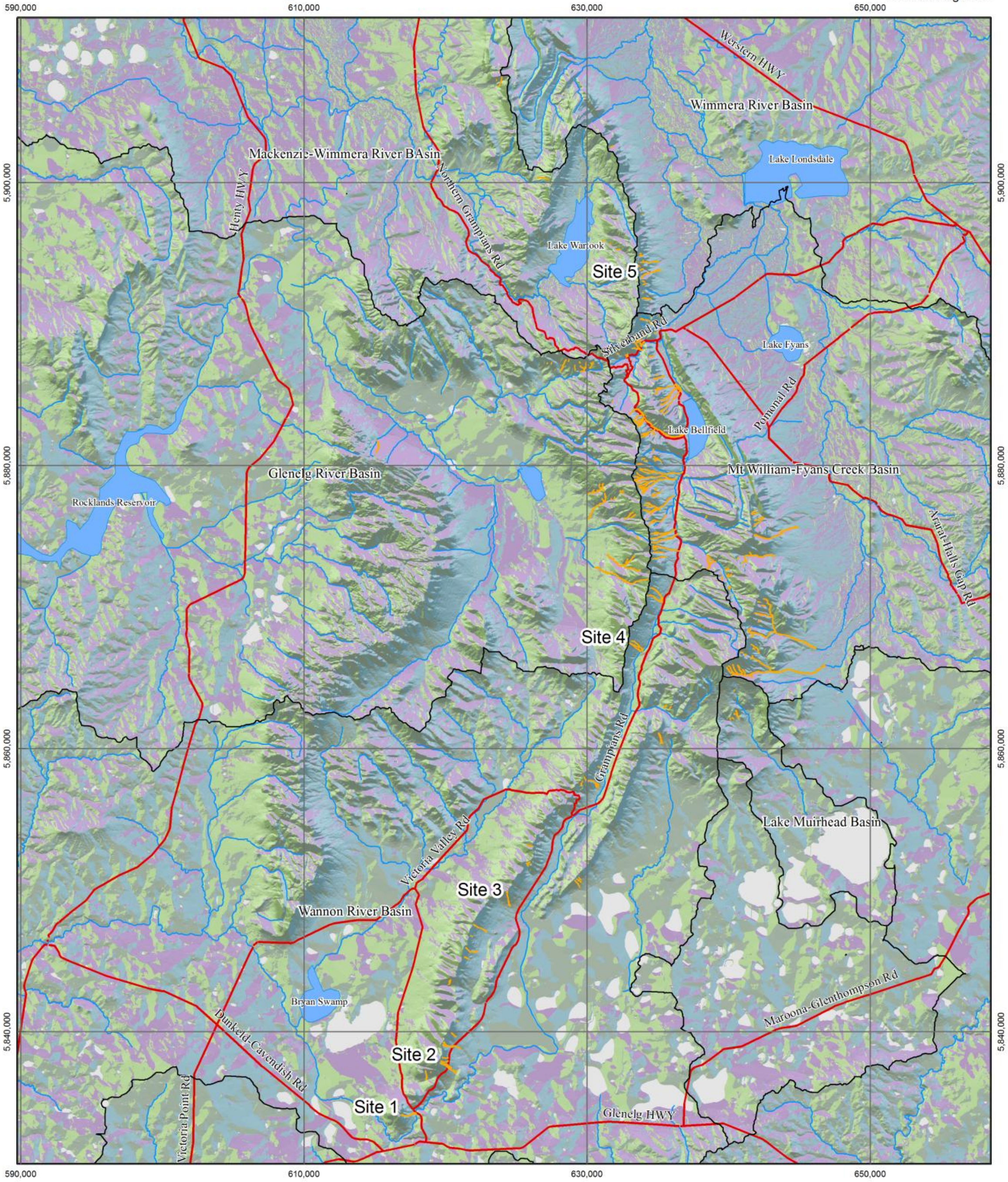
Many of the landslides had more than one failure point or zone which made the analysis process using polygons inaccurate; to overcome this a point layer was manually created representing the uppermost areas for each failure zone(s) of the landslides. With this new information, which numbered 274 points, analysis of the debris flow failure was possible.

LANDSLIDE DATABASE AND PROCESSES IN THE GRAMPIANS, VICTORIA

Figure 5.11

Debris Flow Incidence Map

Created by James Cameron
Date: 26 Aug 2013



Legend

- Debris Flow
- River Catchment
- Major sealed road
- Water body
- Stream

Slope Aspect

- Flat
- North
- East
- South
- West
- North

Debris flows mapped according to 5m Rapid-Eye images supplied by Wayne Buckman, co-ordinator of the Bushfire RRAT of the DEPI. Debris flows overlie the slope aspect to show the instrinsic relationship to the steep east-facing scarps that are a prevalent physiographic feature of the Grampians Ranges.
Additionally basins delineate river catchments; allowing the debris flows to be displayed and assessed at smaller scales.

0 2.5 5 10 15 20
Kilometers

N

1:250,000

Map Projection: Transverse Mercator
Horizontal Datum: GDA 94
Grid: GDA 94 MGA 54

Aspect - Despite an obvious correlation between slope aspect and debris flows (Figure 5.11), there was a range of slope aspects on which the flows occurred (007°-350° Azimuths) with a mean failure point direction of 113.2°. From this ambiguous information there were no clear connections so the data was better displayed as a frequency rose diagram (Figure 5.12), where frequency is measured as distance from centre and azimuth as a bearing. If the four major directions are north (315-045˚), east (45-135˚), south (135-225˚) and west (225-315˚) the eastern direction accounts for a large proportion of the failures whereas the south and north are secondary while west is almost negligible.

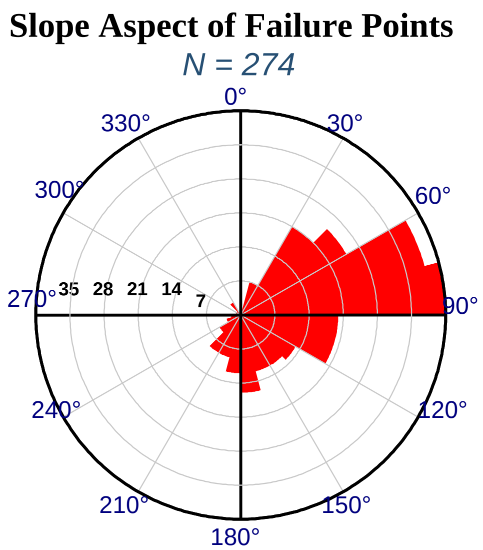


Figure 5.12 A rose diagram of the slope aspect of failure points.

Slope - Perhaps a more relevant control on landslide occurrence was in fact slope angle, which is loosely connected to slope aspect as slopes of greater gradient up to 90° exist as the east facing scarps. The slope data was widely distributed, considering the maximum range is 0°-90°, between 53.3° and 5.2° and was normally distributed with a mean failure angle of 34.3° and a median of 34.7° see Figure 5.13.

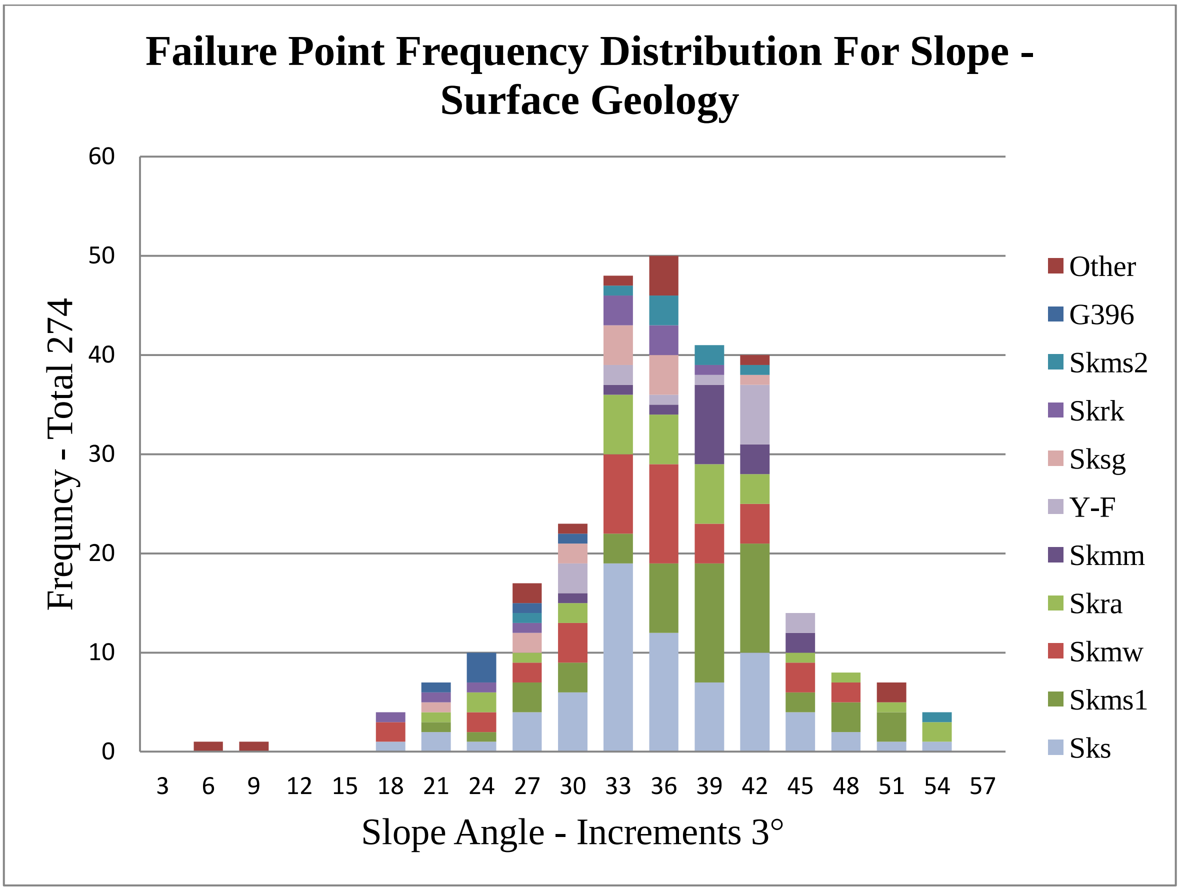


Figure 5.13 Normal frequency distribution of failure points related to slope; frequency of failures related to slope of geological units.

From Table 5.1 it becomes apparent that four rock units are responsible for a majority (70%) of the failure occurrences, in particular the Silverband Formation stands out with a quarter of the total failures. If Figure 5.13 is carefully examined the individual frequencies for each formations are normally distribute. The difference comes as each formation is transposed either in the increased or decreased slope angle direction. A large jump in overall frequency between the slope angles 30° and 33° is a significant fact that may be suggestive of a critical angle.

Frequency of Failure Within Each Geological Unit				
Geological Units	**Unit (Abbrev Name)**	**Name**	**Count**	**% of total**
	Sks	Silverband Formation	70	25.55
	Skms1	Serra Sandstone – sandstone	49	17.88
	Skmw	Wartook Sandstone	41	14.96
	Skra	Major Mitchell Sandstone	31	11.31
	Skmm	Moora Moora Sandstone	16	5.84
	Y-F	Felsic Dyke	15	5.47
	Sksg	Glen Hills Sandstone Member	14	5.11
	Skrk	Kalymna Falls Sandstone	11	4.01
	Skms2	Serra Sandstone - siltstone & sandstone	9	3.28
	G396	Mafeking Granodiorite	5	1.82
	Skmst	Teddy Bear Conglomerate Member	4	1.46
	Sksw	Wannon Sandstone Member	3	1.09
	Skrm	Murray Hill Sandstone	2	0.73
	G397	Epacris Hills Granite	1	0.36
	Mxn	Nekeeya Gravel	1	0.36
	Qc1	colluvium	1	0.36
	Skrw	Watgania Gap Sandstone	1	0.36
		Total	274	100

Table 5.1 Total frequency of failure relate to geological units, including percentage of total.

Rainfall – Rainfall can be difficult to measure due to the highly variable distribution from local and regional influences, such as topography. For this reason rainfall can only be analysed subjectively in this case. The average rainfall of the whole area including the surrounding lowlands is approximately 35mm for the month of January. However the rainfall experienced in 2011 averaged 177mm most of which fell during the 12th,13th and 14th of the month of January (BoM, 2013). Parts of the ranges experienced far greater falls of 297mm and 290mm at the Halls Gap and Mount William weather stations respectively (Figure 5.14).

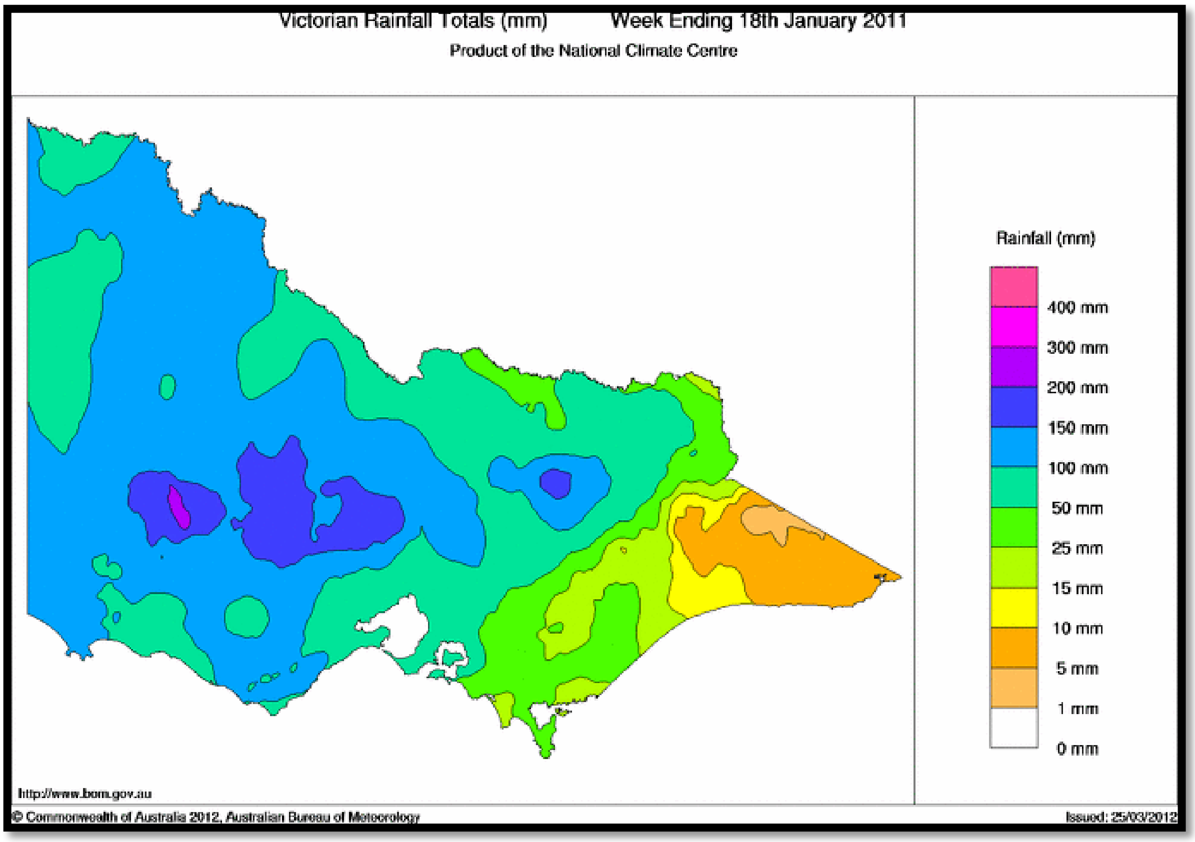


Figure 5.14 Rainfall for the week ending 18th January 2011 (BoM, 2013). Note the oblate 200mm to 300mm purple colour over Halls Gap and Mount William weather stations.

An important note to make, regarding Figure 5.15, which is the six month period to the 31st of January 2011 that experienced far above average rainfall for that time, 600-1200mm when a reference to Figure 1.2 will show the <u>annual</u> rainfall range is equal to or less than this amount (500-800mm). All of the months in this six month period experienced greater than average rainfall often double or treble the average, such as August and December 2010 and perhaps up to six times the average during January 2011.

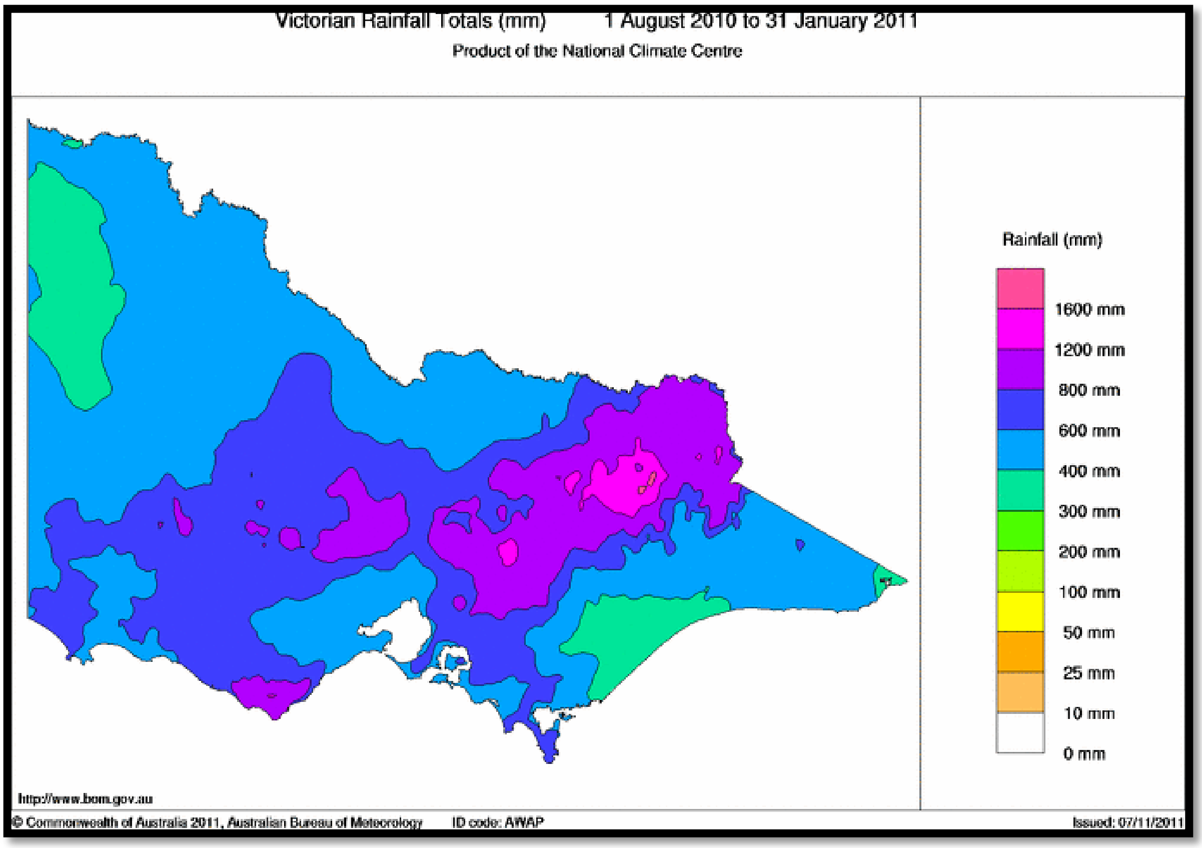


Figure 5.15 Rainfall totals for the state of Victoria to the 31st of January 2011 (BoM, 2013). The Grampians area includes the western most 800-1200mm rainfalls and surrounding dark blue areas.

The rainfall was analysed in a similar fashion where the failure points were measured against a rainfall map producing statistics that give an approximation of actual rainfall for the local areas. The range of rainfall (156.5mm-250mm) for the failure points can be, in part, attributed to the variable topography of the area, however if the statistics are calculated for the points they average of 227.6mm, a median 240mm.

Figure 5.16 at first may appear irrelevant with no real distribution shape. The graph shows a bimodal frequency with two maximums of the lowest and highest rainfalls in the range. Nevertheless the frequency in relation to geology does show some correlation, for instance the siltstone and sandstone dominated Serra Sandtone (Skms2) more readily fails at lower rainfalls and the Glen Hills Sandstone Member (Sksg). One very clear fact is if rainfall is greater than 210mm the frequency of landslides increases exponentially.

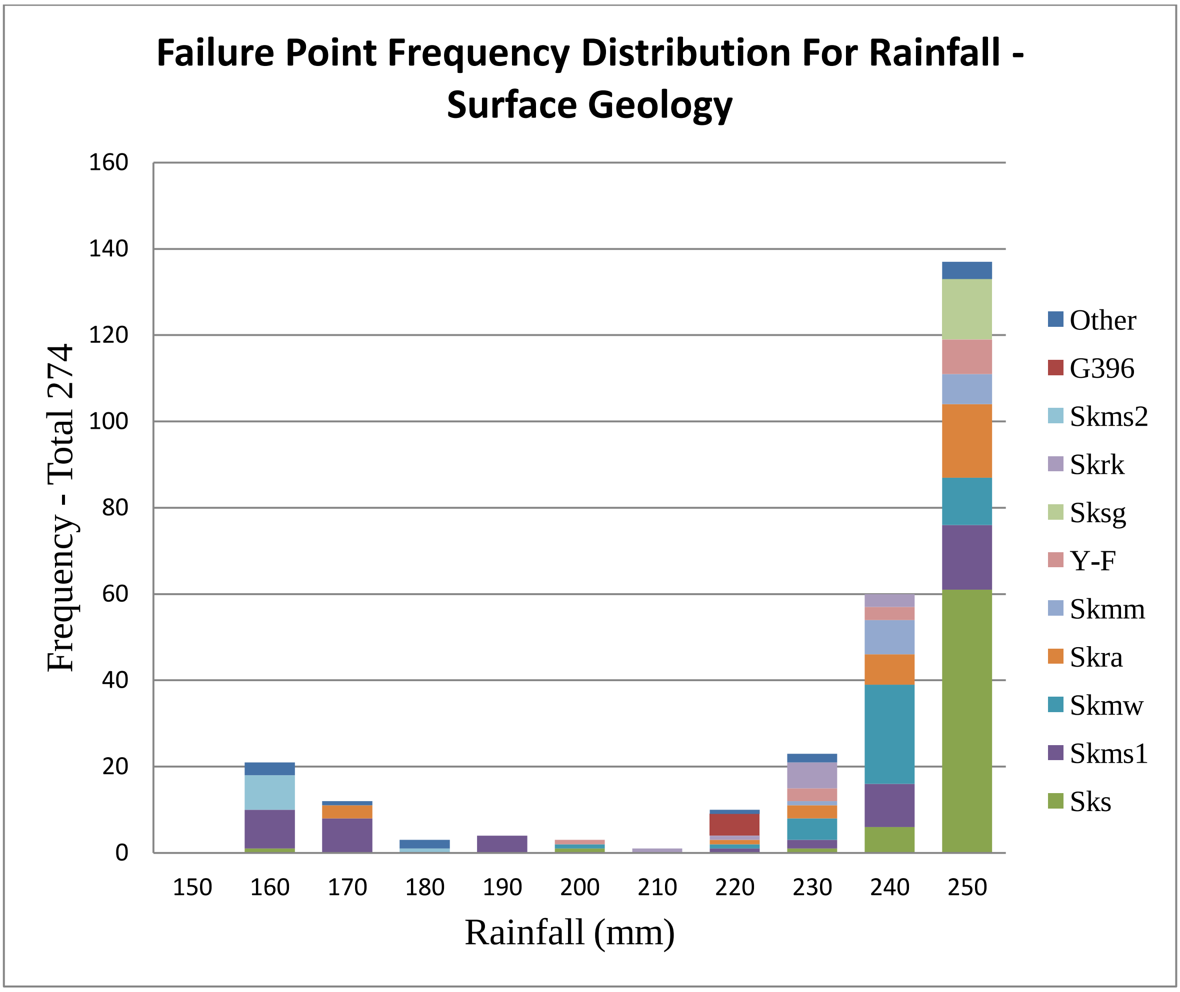


Figure 5.16 Frequency of failure points related to rainfall and geological units.

5.2 Debris Flow Analyses

For positions of debris flow sites, refer to Figure 5.11; the information for the field assessments was collected using Appendix C as a framework to generally answer/meet the questions/criteria for field investigation requirements in an AGS LRM (2007d). This section will be separated into three parts: one to explain the location of the slide, one to outline the specific zones and their characteristics and one to analyse the hydrological aspects (calculated as the total flow accumulated in the potential catchment during the three days of rainfall). Individual maps of each site are also included (Figures 5.201, 5.204, 5.206, 5.207, 5.209).

5.2.1 Debris Flow Site 1

5.2.1.1 Site description

This site was the southernmost landslide that occurred in the Grampians on the eastern flank of Mt Sturgeon just north of the Dunkeld township. This slide originated in the National Park but its run out impacted private property surrounding a residence and finally meeting the Wannon River, which is crossed by the Victoria Valley Rd nearby. From aerial photos it would appear to have originated in a gully high up on the escarpment of the mount where the sandstone dominated Serra Sandstone (Skms1) outcrops. This flow appeared to be confined to an existing drainage line. The slide is approximately 1,130m long with a maximum depth of 3m and in zone D where most of the deposition occurs it widens from 25m to > 80m (Figure 5.201).

5.2.1.2 Site zones

Zone A – This area was inaccessible due to the very steep rugged terrain, ≥22° increasing to near vertical, however remotely it is observed that there were two points of failure the primary point in the Serra Sandstone (Skms1) and the other in Silverband Formation (Sks). The flow was confined in a pre-existing gully.

Zone B – The transition between ≥15° and 11-12°, with the uncommon deposition of boulders ranging in size from 40cm to 2-3m this appears to be an area of wasting rather than deposition. The underlying soil and semi-consolidated pre-2011 debris has been excavated to some extent. See Figure 5.202. The vegetation in the area is size restricted heathy woodlands with no greater than 5-10m tall Stringybark's.

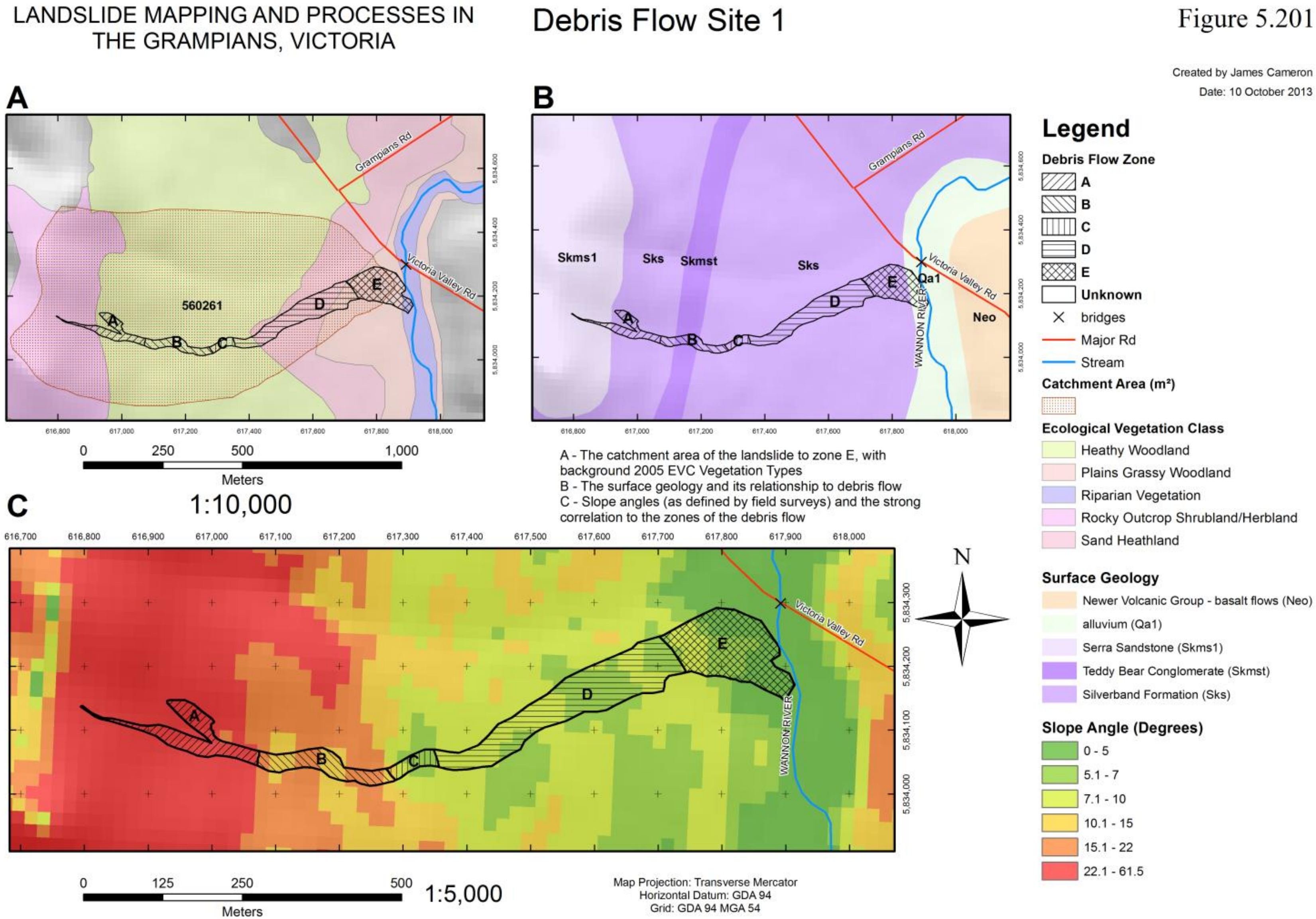

LANDSLIDE MAPPING AND PROCESSES IN THE GRAMPIANS, VICTORIA
Debris Flow Site 1
Figure 5.201
Created by James Cameron
Date: 10 October 2013
A
B
C
560261
Grampians Rd
Victoria Valley Rd
Skms1
Sks
Skmst
Qa1
Neo
WANNON RIVER
1:10,000
0
250
500
1,000
Meters
1:5,000
0
125
250
500
Meters
A - The catchment area of the landslide to zone E, with background 2005 EVC Vegetation Types
B - The surface geology and its relationship to debris flow
C - Slope angles (as defined by field surveys) and the strong correlation to the zones of the debris flow
Map Projection: Transverse Mercator
Horizontal Datum: GDA 94
Grid: GDA 94 MGA 54
N
Legend
Debris Flow Zone
A
B
C
D
E
Unknown
bridges
Major Rd
Stream
Catchment Area (m²)
Ecological Vegetation Class
Heathy Woodland
Plains Grassy Woodland
Riparian Vegetation
Rocky Outcrop Shrubland/Herbland
Sand Heathland
Surface Geology
Newer Volcanic Group - basalt flows (Neo)
alluvium (Qa1)
Serra Sandstone (Skms1)
Teddy Bear Conglomerate (Skmst)
Silverband Formation (Sks)
Slope Angle (Degrees)
0 - 5
5.1 - 7
7.1 - 10
10.1 - 15
15.1 - 22
22.1 - 61.5

Figure 5.202 Zone B with very large boulders ≥2m some trees strewn to the peripheries.

Zone C – is otherwise similar to zone B, but with deposition of the very large fragments (≥40cm boulders) and there is far less excavation of underlying regolith. Here the heathy woodland trees, stringy bark pines and black wattles, increase in size compared with those further up the slope. The composition of the boulders is primarily sandstone with vein quartz and sandstone pebbly lags. It is debateable, but some of the very pebbly fragments may have originated from the Teddy Bear Conglomerate (Skmst) further up the slope due to clasts more rounded nature.

Zone D – The primary zone of deposition where a large range of sizes of debris have dropped out: boulders (1.5-2m), gravel, sand, silt and trees. In this section, trees have been strewn to the edges of the flow (Figure 5.203). Figure 5.201 also shows this area to be the longest area over Silverband Formation and Sand Heathland vegetation. No downward erosion has occurred in this section; by contrast it shows characteristics of an alluvial fan, spreading out.

Figure 5.203 The area of transition from Zone C to Zone D Facing eastward.

Zone E – Here only fragments below cobble sized chunks of rock have been deposited, primarily sand and silt. This zone progressively levels out from between 7-8° to the river. The area grades from bushland to cleared land and merges into private property surrounding the residence.

5.2.1.3 Hydrology analysis

Figure 5.201 (Section A) shows the potential catchment of the debris flow. The area experienced the least amount of rainfall for the Grampians but in this particular case the large catchment of 560,261m² accumulated a huge volume of water over the three days, 87.96 Giga litres or 88 million cubic meters of water.

5.2.2 Debris Flow Site 2

5.2.2.1 Site description

This debris flow is one of the most recognisable due to its prominent appearance that intersects the Southern Grampians Rd 4.5km northeast of Site 1 (Figure 5.11). This significant flow can be seen from the Glenelg Hwy near Glenthompson. The slide is basically perpendicular to the strike of the range (015°) with a flow trend of 103° on the eastern flank of Mount Abrupt. The slide began as a single shallow slump (1-2m deep), possibly a translational slide against a plane of bedrock and at its widest, has a width greater than 50m across. After crossing the main road it separated into three flows, the southernmost and biggest of which followed the drainage line, while the other two followed its original path straight down the slope see (Figure 5.204). The longest dimension of the flow is 1,350m down the gully. Despite the massive size of the failure the maximum depth is no more than 4m and this could, in part, be due to subsequent erosion since 2011.

5.2.2.2 Site zones

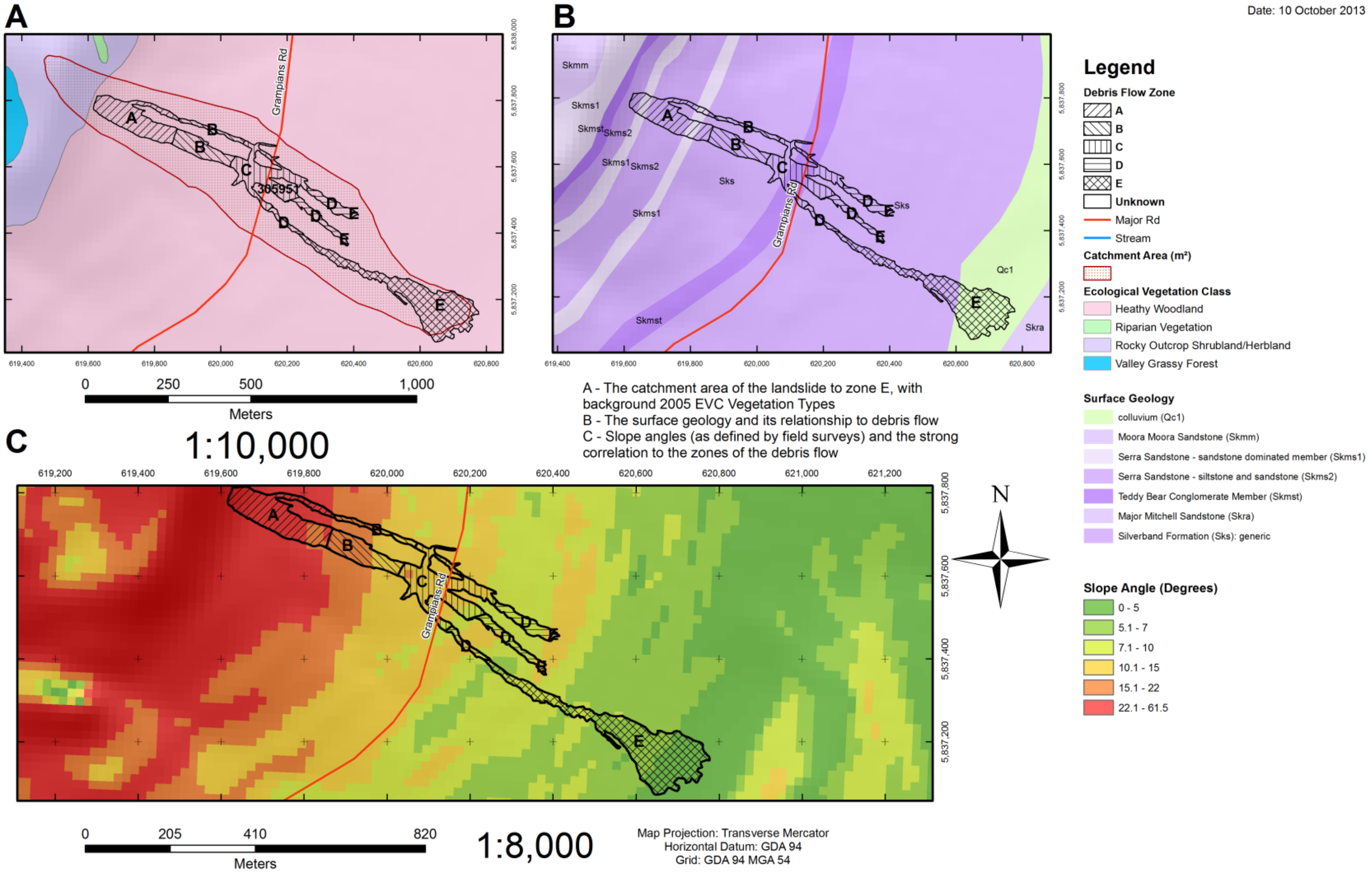
Zone A – The division of slope angle at this point is between 24° and 15°. Above this point there is no deposition except for some instances at the edges. It originates at the base of the cliff where the head scarp looks like a typical slump failure yet there are parts where all soil and debris is completely removed to reveal the bedrock. The head scarp looks to be primarily in the siltstone and sandstone member of the Serra Sandstone (Skms2) and does not seem to begin or follow any obvious drainage line. This zone is only an area of erosion no significant deposition.

LANDSLIDE MAPPING AND PROCESSES IN THE GRAMPIANS, VICTORIA

Debris Flow Site 2

Figure 5.204

Created by James Cameron
Date: 10 October 2013



A - The catchment area of the landslide to zone E, with background 2005 EVC Vegetation Types
B - The surface geology and its relationship to debris flow
C - Slope angles (as defined by field surveys) and the strong correlation to the zones of the debris flow

Map Projection: Transverse Mercator
Horizontal Datum: GDA 94
Grid: GDA 94 MGA 54

Zone B – This zone is only differentiated from the previous zone by a change in slope angle to 15° and the presence of more vegetation debris to the margins of the slide as well as some initial boulder (≥200mm) deposition, Figure 5.205.

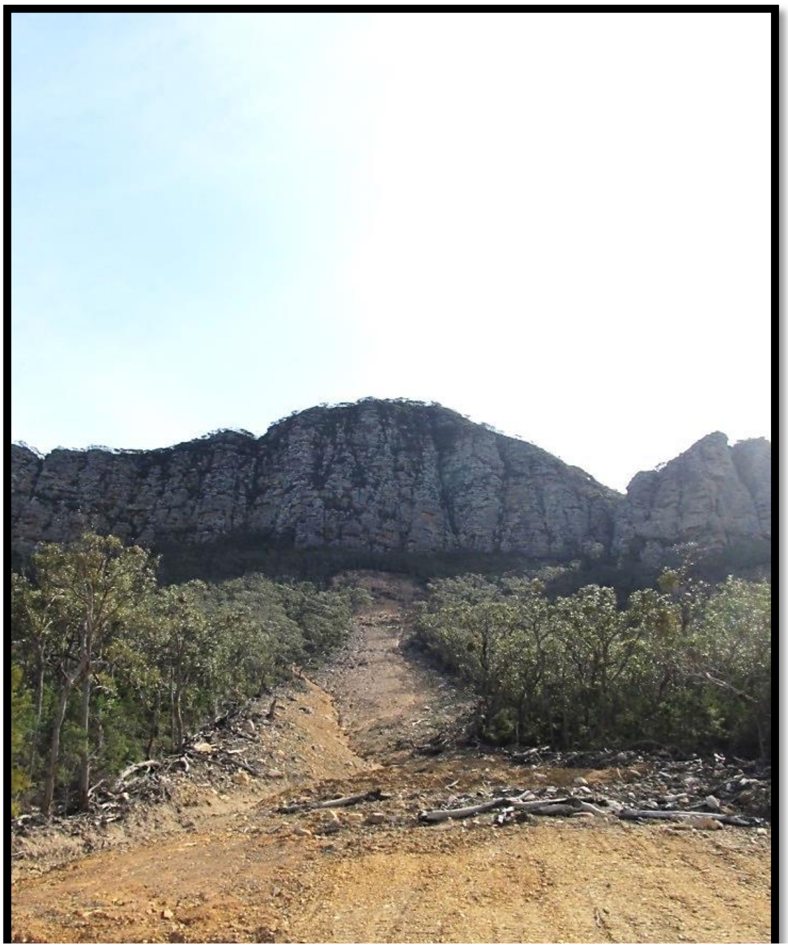


Figure 5.205 Looking upslope from the South Grampians Road (Zones A,B and the uppermost C) variable deposition of debris and vegetation.

Zone C – This zone marks the major area of deposition of large trees and boulders (up to and rarely above 1m diameter) the slope angle is 10°. At this point vegetation is still readily removed yet erosion of underlying soil and talus is at a minimum.

Zone D – This zone was the slope at which all of the remaining debris dropped out of the movement at slope angles of 7°. The removal of vegetation was minimal and the presence of large fragments greater than cobble size is non-existent.

Zone E –The run out of sand and silt comprised Zone E with only odd occurrences of gravel and cobbles. The vegetation remains completely undisturbed with rill-like features that negotiate between the large stringy barks and grass trees.

5.2.2.3 Hydrology analysis

The local catchment of this landslide was confined by slight undulations in the scree slope; however the total catchment area of 305,951m² provided plenty of surface area for 48 GL of water to flow to the nearest creek. The power of the slide was enough to move a 5m wide boulder from its original position down the slope.

5.2.3 Debris Flow Site 3

5.2.3.1 Site description

This slide may have been inconspicuous if not for the high resolution aerial photos, residing just north of the Griffin Fire Line, which comes off the Southern Grampians Road. This slide differs as it is oriented north-south but still originates at the escarpment in a gully as three separate failures. The slide is confined to a 20m width for the 1.06 kilometre length until it terminates where the sediment spreads out to 80 meters and divides into tongues of fine sediment (Figure 5.206).

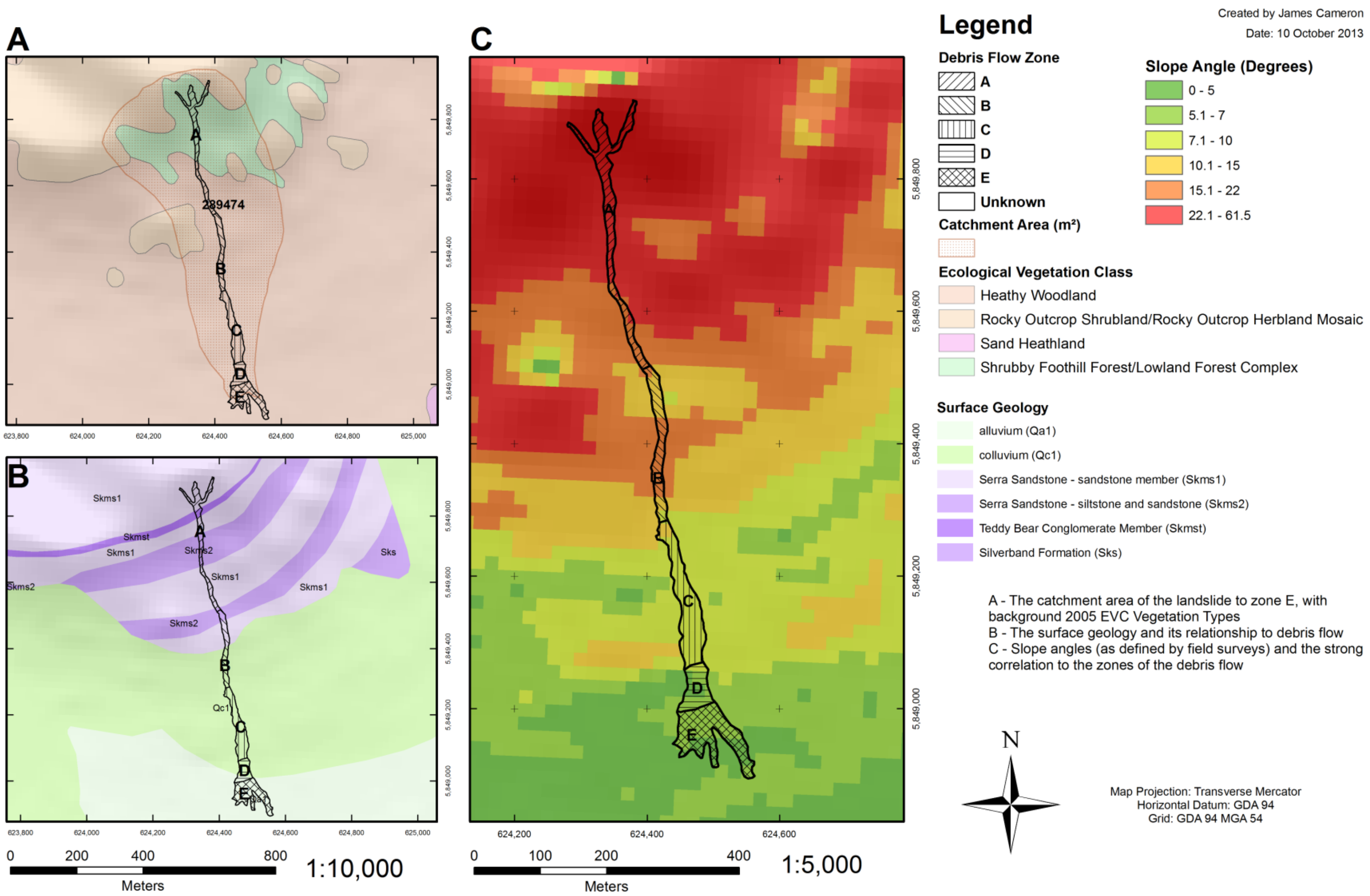
5.2.3.2 Site zones

Zone A – Zone A was completely inaccessible due to the numerous safety hazards however the boundary of zone A was marked at the point where the slope changed from ≥22° to 14°. Up the slope pre-existing soil and semi-consolidated debris had been excavated to a depth of ≤3 meters, with only random occurrences of large boulders (≥1 m) resting in the centre of the flow.

LANDSLIDE MAPPING AND PROCESSES IN THE GRAMPIANS, VICTORIA

Debris Flow Site 3

Figure 5.206



Zone B – This area between 15˚ and 10˚ of slope marked a major change in deposition which included boulders up to and exceeding 2m diameters but mostly 40cm coarse-sandstone fragments. Erosion was still evident almost as deep as the underlying bedrock at this point but transitioning from a v-shaped gully to a less confined gully.

Zone C – Was typically the first area to account for a large percentage of debris deposition here the flow had begun to spread out to widths greater than 20-25m on a slope angle of 8˚. All fragment sizes were less than a meter in diameter. The large trees in this area have provided a barrier where debris has accumulated but otherwise vegetation remains largely undisturbed

Zone D – The remaining sediment was deposited here where vegetation of all sizes has not been affected and slowed the sediment movement. The slope had by this point reduced to 5° and marked a point where no continuing erosion was evident. The largest fragments of cobble sized sandstone progressively graded to gravel and sand. The vegetation changed from heathy woodlands to a more open understorey of grasses and grass trees.

Zone E – Only sand and silt continued into this zone as rill-like 40cm streams meandered between vegetation at slopes less than 5˚.

5.2.3.3 Hydrology analysis

The debris flow had a large catchment for its relatively confined dimensions, of 289,474m^2; this provided a potential flow of 47 GL.

5.2.4 Debris Flow Site 4

5.2.4.1 Site description

This landslide was fairly inaccessible via Teddy Bear Track off the main Southern Grampians Road, but was worth noting the behaviour of sediment when slope angle changes are compressed. Due to the incredibly rugged nature of this slide all of Zone A, B and most of C have not been recorded other than remotely, the dimensions were measured as 1,020m long with various changes in width related to changes in slope (Figure 5.207).

5.2.4.2 Site zones

Zone A – Not described due to inaccessibility.

Zone B – Not described due to inaccessibility.

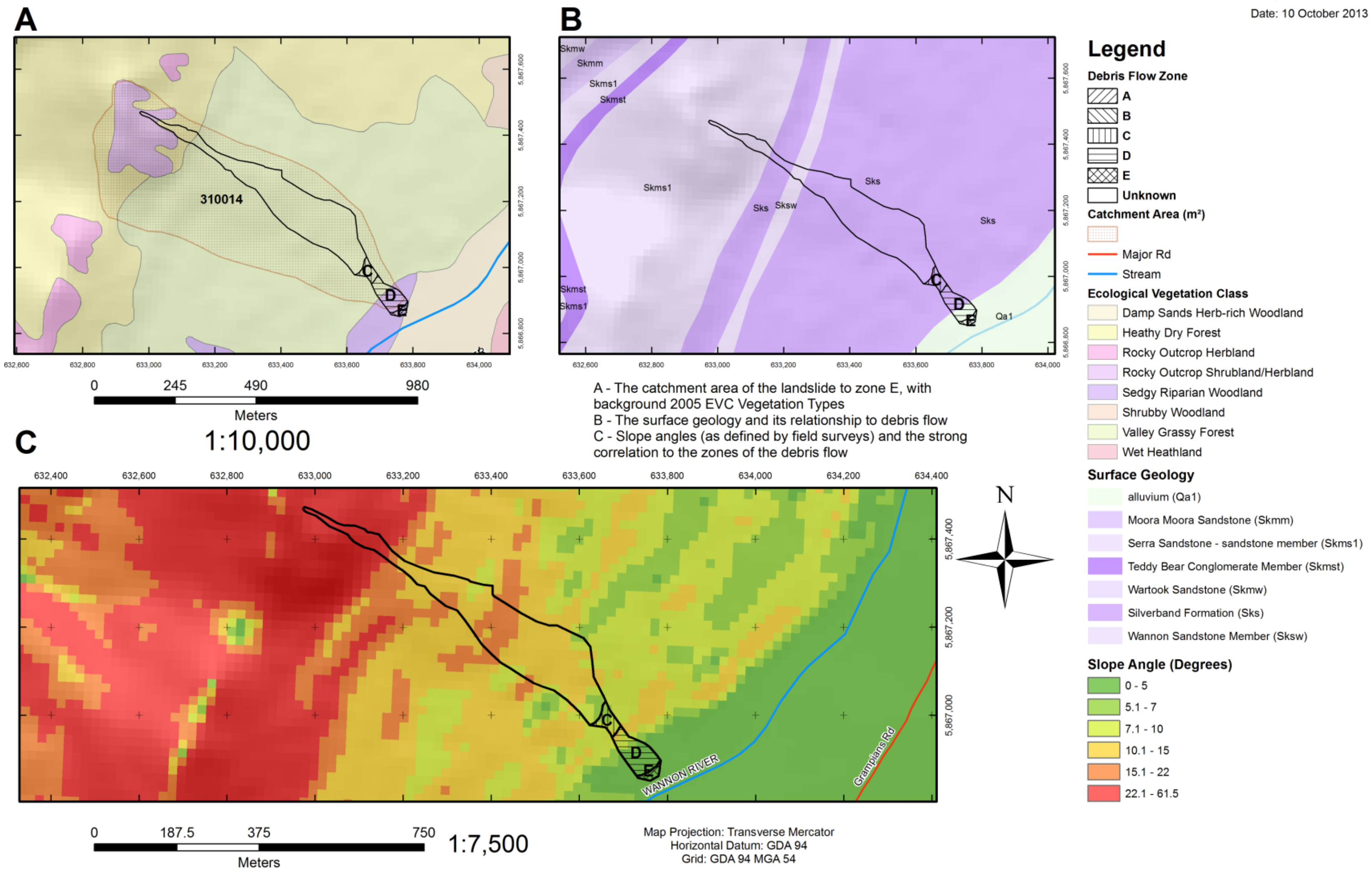
- Both these areas appear to have a slightly varied topography compared with others that have been observed by remote analysis. The area of failure is confined to a gully, and then the slope shallows rapidly almost skipping the 15˚-22˚ gradient interval; at this point there is a boundary in both the geology (from Serra Sandstone [Skms1] to Silverband formation [Sks]) and the vegetation (from heathy dry forest to valley grassy forest). The interval between 10˚ and 15˚ is very extended over which it is mainly Silverband formation and then rapidly drops off again.
- *Zone C* – The area marked as zone C may in fact continue further upslope based on the distance at which the 10˚-15˚ slope range persists. The area recorded was characterised by tall forest with a heath understorey which grew in a sheltered part of the valley. A gully that heavily confined the debris was significantly eroded into a V-shape. In this area only the largest boulders that had a maximum size of 1m were deposited on pre-2011 semi consolidated debris.

LANDSLIDE MAPPING AND PROCESSES IN THE GRAMPIANS, VICTORIA

Debris Flow Site 4

Figure 5.207

Created by James Cameron
Date: 10 October 2013



A - The catchment area of the landslide to zone E, with background 2005 EVC Vegetation Types
B - The surface geology and its relationship to debris flow
C - Slope angles (as defined by field surveys) and the strong correlation to the zones of the debris flow

Zone D – A major difference is marked by this zone as the slope all but terminates in this area where it meets an alluvial flood plain of Fyans Creek (Figure 5.208). The edge of the slope has a far greater loamy texture than sandy debris as is further up the slope. The slope angle rapidly changes from 8˚ to less than 5˚ where most of the sediment appears to drop out. The large fragments greater the 10 cm gradually peter out on the alluvial flats where there are dead trees in the photo.

Figure 5.208 Photo of the transition from Zone C to Zone D. Note the sandy loam soil at the termination of slope.

Zone E – Eventually all the energy is dissipated from the previous area and only fine material (sand and silt) is carried any further out on to the flat area where the sediment comes to a definite abrupt stop on slope less than 3 degrees. The width of the flow greatly increases as the slope decreases in this area. Despite the rapidly decreasing energy all small vegetation is removed and the tall trees have died, this could have been an area of ponding.

5.2.4.3 Hydrology analysis

The run out of sediment on to the flat area of the alluvial terrace is suggestive that the movement was highly fluidised with a rapid velocity; this could be attributed to the potentially large volume of water (69.13 GL) that could have flowed down the slope. The final gully just before the flat area is very confined (see Figure 5.208 in the foreground) this may have restricted and slowed the flow allowing the sediment to drop out.

5.2.5 Debris flow Site 5

5.2.5.1 Site description

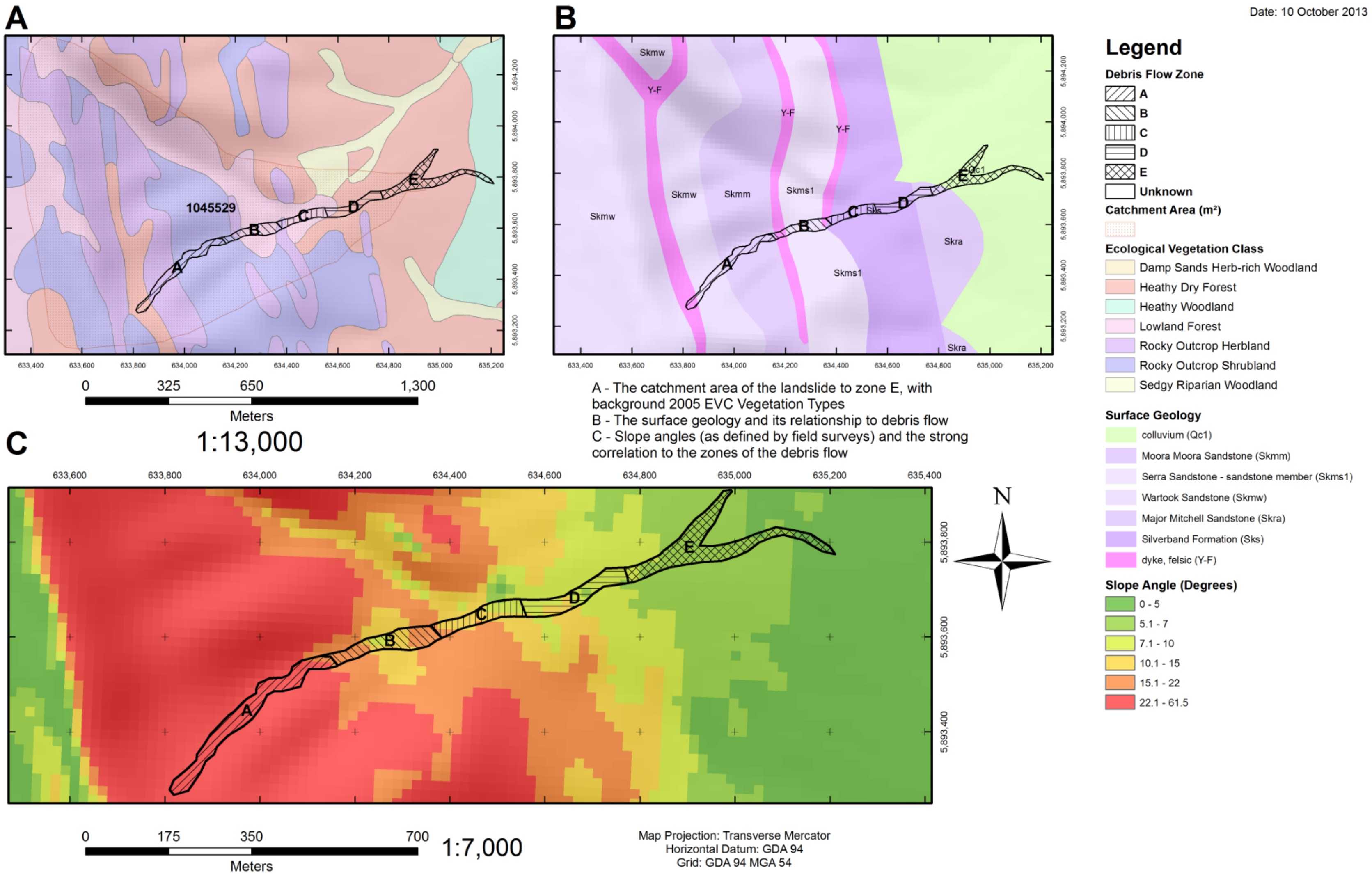
The final landslide to be analysed in the field is easily accessed via a bush track west of the Halls Gap Mt Zero Road about 5km north of the Halls Gap Township. This slide has typical characteristics of many others: occurring on the eastern flanks of the north striking mountain range with a 1,550m long travel distance confined to a constant width of 35m. The slides path crosses a number of vegetation classes and geologies. One lithology in particular is notable, the felsic dykes and sills associated with the Devonian granites, as it had not been observed in relation to prior slide field investigations during this research. This material at the surface is highly weathered and finger friable, which may account for why this slides failure, was associated with this unit. During its travel the slide crossed two more outcrops of the felsic igneous material which provided a larger quantity of debris disproportional to the area of outcrop. The felsic dyke material was useful to see how far the sediment, in various sizes, travelled. This was because it occurred in outcrop on a small scale and downstream the presence of the rock in the sediment aggrades. The flow was confined to a pre-existing drainage line that appeared to be the main trunk of a stream due to the presence of water trickling down it and the local topography providing a definite catchment and drainage line (Figure 5.209).

LANDSLIDE MAPPING AND PROCESSES IN THE GRAMPIANS, VICTORIA

Debris Flow Site 5

Figure 5.209

Created by James Cameron
Date: 10 October 2013



A - The catchment area of the landslide to zone E, with background 2005 EVC Vegetation Types
B - The surface geology and its relationship to debris flow
C - Slope angles (as defined by field surveys) and the strong correlation to the zones of the debris flow

Map Projection: Transverse Mercator
Horizontal Datum: GDA 94
Grid: GDA 94 MGA 54

5.2.5.2 Site zones

Zone A – The exact location of the steepest section of this slide of angles greater than 22˚ were reasonably difficult to locate due to the local topography. At about the point that would have typically displayed a gradient change a particularly resistant outcrop, the sandstone dominated Serra Sandstone (Skms1) occurs in outcrop at a waterfall (Figure 5.209. Areas immediately above and below the waterfall were level, as the felsic dyke and Silverband formation that outcrop are easily eroded.

Upstream of the base of Zone A, more resistant units formed a cliff that restricted vegetation growth. Slopes of a lesser gradient had a developed soil where coarse fragments were absent providing a substrate in which tall trees (20m) and a tall understorey (2-3m) could grow. Where the stream/debris flow occurred it had removed all overlying material to a depth of 2-3m and exposed the relatively unweathered bed rock of sandstone.

Zone B – Random gravel to cobble sized sediment has been deposited here probably due to the presence of the waterfall and therefore a momentary decrease in velocity by topographical variations. The vegetation, medium sized wattles and Stringybarks with an intermediate stratum of pines and heath, is more representative of the underlying soil which is more typical of the slopes, scree deposits. At times the rock debris is dominated by small boulders/cobbles of sandstone and/or cobbles/pebbles of the felsic igneous material; boulders are less than 2 meters in diameter. Included amongst the debris is a lot of sub round gravel and trees.

Zone C – A mix of all clast sizes greater than gravel sized fragments are present in this area of slope (about 10˚) dominated by large sandstone boulders ≤ 2.5 meters and tree debris strewn to the edges. The channel has been cut down to the bedrock at a number of points to a depth of 5m especially where the flow has been heavily controlled by topography that confines it. The downstream end of this section is marked by a large 2-3m high wall of boulders between 20 and 50cm, figure 5.210, which has altered the course of flow at the time of deposition due to washout on the bend to the right hand side of the photo. The course of the stream has since remained changed.

Zone D –A small change in gradient, to 8˚, has greatly changed the deposition of sediment with an evenly distributed mix of sediment where gravel and cobbles are a more significant component. Figure 5.211 shows a levee of tree and rock debris that has accumulated in a restricted area of the flow between large trees. This could be responsible for slowing the rate of movement. The vegetation is a more open heathy- dry grassy forest with medium to large trees.

Zone E – From slopes with angles less than 5˚ the vegetation does not readily change and the sediment grades to finer material of sand and silt from small cobbles and gravel.

5.2.5.3 Hydrology analysis

This debris flow unsurprisingly had a potentially large volume of water from the catchment of 1.05 km^2 238.4 GL, which is likely responsible for erosion of the existing scree slopes to depths of 5m.

Figure 5.210 An example of rock fragments banking up and creating an obstacle, changing the course of the flow.

Figure 5.211 An example of rock and tree debris damming the flow path.

6.0 DISCUSSION

The initial debris flow distribution and verification yielded explicit results where digitised polygons marked landslides within a map. The debris flows were typically long, narrow, and shallow: often kilometres in length; tens of meters wide and a couple of meters deep. This type of debris flow draws parallels with a sediment laden stream and Sturzstrom debris flows, both of which involve abundant water (dry Sturzstrom flows are the exception).

One undeniable theme with the landslides was the link to the greater than average rainfall that preceded the month of January and the anomalous January rainfall during the 12th, 13th and 14th. The idea of a threshold rainfall amount may be difficult to delineate with these debris flows as there is no obvious correlation. If Figure 5.16 is analysed, two modal rainfalls at opposite ends of the spectrum obscure the results. However closer inspection of the geology-frequency-rainfall graph shows some apparent trends. At greater than 210mm rainfalls the frequency of landslides increases significantly even in apparently very stable formations such as the Glen Hills Sandstone and the Moora Moora Sandstone that only occurred in areas where rainfall was at least 250mm and 230mm respectively. As mentioned in the results the siltstone/sandstone dominated member of the Serra Sandstone (Skms2) more readily failed at lower rainfalls, but this could also be related to the spatial distribution of the geological unit, which only occurs in the southern portion of the Serra Range where rainfalls were lower. If the unit outcropped anywhere else it may have had equally numerous incidences. Despite the obvious complexity of the relationship between the geology, rainfall and debris flow occurrence this data could be used as a maximum threshold for each of the listed geological units. Given the regular association of debris flows with depressions or pre-existing drainage lines the effect of the rainfall was likely amplified by the large areas of catchment for each failure, which could be tens of times larger than the area of the flow itself.

The obvious correlation to the fault bounded east facing scarps is probably less complex but equally diverse. Where debris flows began as a rock fall rather than along debris or soil plane failures there is likely a very strong connection with the parallel to sub-parallel major joint sets that trend north-north-west and west-north-west. The joints are least supported along the high cliffs of the ranges and can easily become unstable and dislodge with the aid of water. The east facing slopes also have the predisposition for failure due to the relatively steeper gradients.

Gradients are observed to a maximum of 61˚ but the debris flows were concentrated between 5˚ and 53˚. In Figure 5.13 there is a relatively normal distribution in terms of failure point to slope angle. The individual geological units are also normally distributed which suggests that there is an optimum and threshold slope gradient for each unit. The frequency histogram is a good representation of geological competency. Where the unit is more or less competent, dictates whether the curves are moved either right or left. For instance using this logic, the Major Mitchel Sandstone, coarser grained sandstone, is more competent than the Silverband formation that is a micaceous siltstone. This is assuming that the landslides all started in consolidated rock, when in fact they often began in the unconsolidated scree slopes.

The mean failure angle of 34.3° and a median of 34.7° are approximately the angle of repose which shows that most of the scree slopes where failure occurred were currently at their maximum angle of stability. The added weight of water and the decreased cohesive strength caused by the positive porewater pressure was obviously enough to initiate failure. If the measures of centre are approximately the angle of repose it could be assumed that all flows that were initiated at angles greater than this were potentially started by rockfall (consolidated material) and flows initiated at angles below this were started as planar failures and debris flows (less consolidated material).

Slope gradient also plays a significant role in how the flows behave, on inspection of any debris flow it becomes apparent that there are areas where there is: nil, minimal, major and fine deposition. The Hjulstrøm Diagram (Figure 6.1), despite referring to fluid streams, could be applied to the entrainment and deposition of sediment for most of the landslides. The diagram shows the critical velocities at which particles of various sizes begin to erode (above the curve), remain mobile (between the curves) and begin to drop out (below the curve), called the fall/settling velocity (Hugget, 2007). The diagram is applicable to ideal, well sorted, sediment conditions; but changes in grain density and shape and water viscosity and density can vary the energy required to move grains. Hjulstrøm's theory becomes more relevant to these landslides if it is considered that water density and viscosity changes with the proportion of sediment the stream carries (Hugget, 2007). From the field investigations five zones were observed where typical deposition occurred and these were related to the slope gradient, which ultimately is the main control on velocity. As the gradient decreases down-slope the velocity of the flow decreases. With reference to the Hjulstrøm Diagram the largest particles have the highest fall velocity and the smallest particles have the lowest fall velocity, this accounts for the areas of varying deposition. The zones outlined in in Section 5.2 can be generalise to:

Zone A includes all slopes above 22˚ and this usually accounted for the point of failure for undescribed flows and was always typified by a distinct lack of deposition and high levels of wasting (greatest velocity).

Zone B may have sometimes shown random deposition of boulders that ranged from 40cm to greater the 2-3m, but otherwise was still an area of erosion sometimes down to bed rock (constant to decreasing velocity). The erosion was emphasised where the debris flows had been confined to gullies or current drainage lines.

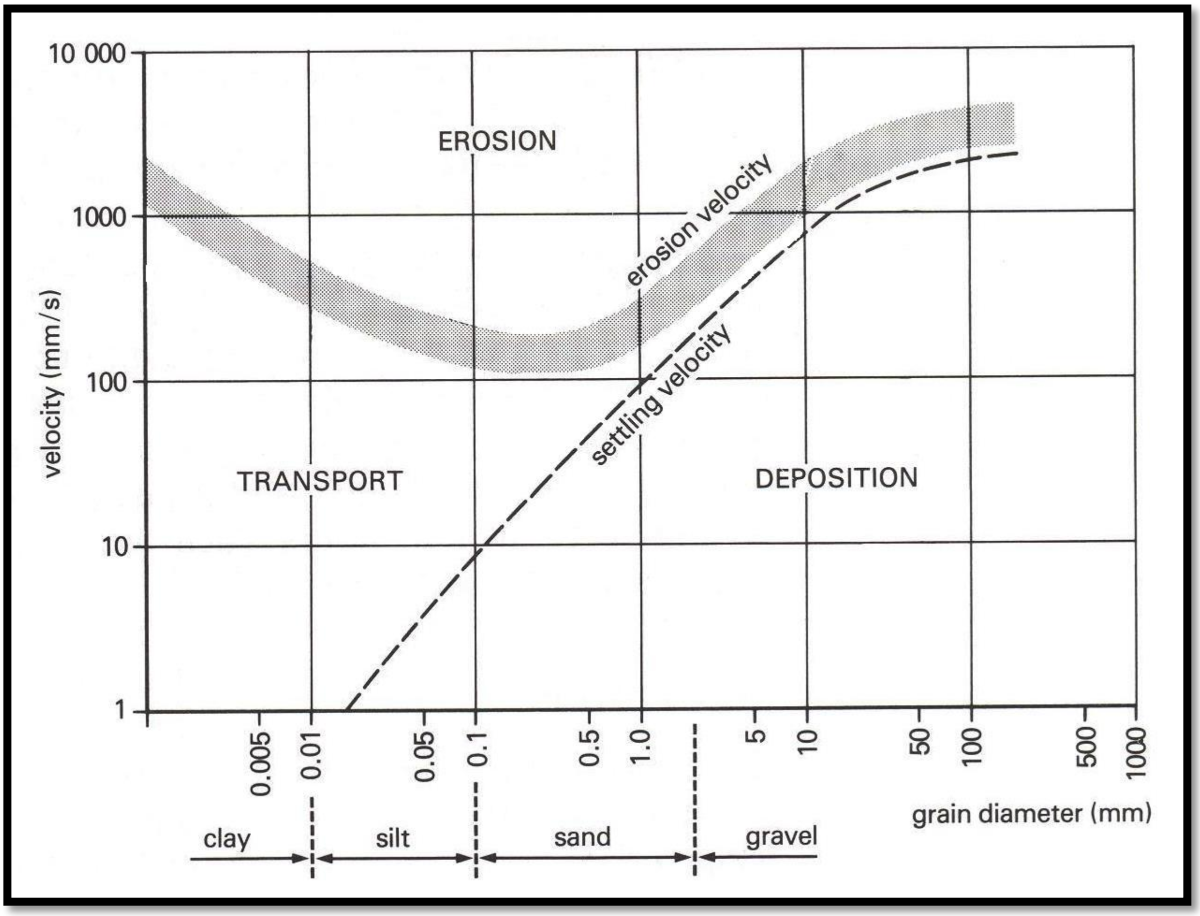


Figure 6.1 The Hjulstrøm Diagram (Geography-is-easy, 2013).

Zone C should be recognised as the area where the momentum decreases to a point where deposition becomes less random and erosion was minimal (critical decrease in velocity at which erosion stops and deposition starts). This area was allocated the slope gradient of between 10˚ and 15˚.

Zone D was perhaps the more significant area in terms of deposition, in this area all fragments sizes from silt to large boulders were deposited and was characterised by no wasting at all (velocity has decreased to at least the fall velocity of the smallest grains). The gradient of between 7˚ and 10˚ therefore must be the critical angle at which sediment drops out of entrainment. Conditions of high water content and sediment load of this type no longer have sufficient momentum to continue downwards and outwards.

Zone E was examined as everything of sand size and finer for the remainder of the run out (velocities below that of the smallest grains). These particles are small enough that they can still move via saltation and suspension for some distance over gradients less than 7˚. Often zones D and E were intermixed as vegetation provided obstacles that slowed movement and blurred the boundary.

The geology seems a major control on occurrence as shown in table 5.1, with 4 units responsible for 70% of failures in the ranges. However if it is considered that for angles with gradients less than the angle of repose, there is potential that initiation was in debris rather than bedrock, these statistics are not representative of the proposed relationship. For instance the Silverband Formation (Sks) is accountable for a quarter of all failures yet if the frequency histogram (Figure 5.13) is consulted, at least half of the Sks is in fact at or below the angle of repose. This point supports the hypothesis that there were three types of failure, rock falls that consequently triggered a debris flow and planar failures and debris flows that transformed into debris flows.

Vegetation does not seem a significant influence on the occurrence of failure but is a good representative of the underlying soil conditions and therefore slope angle as well as the processes of historic wasting. At the Debris Flow Site 1 (Figure 5.204) there is a good example of the progression from rocky outcrop vegetation to sand heathland with appropriate intermediate vegetation classes. The transition between classes is generally reflected in the slope angle and geology as outline in Figure 5.204. The change in vegetation shows a general fining of particle size in the scree slope the further from the source at the base of the cliffs.

From 176 debris flows/landslides that occurred, 274 points of failure were recognised, as explained in the results this was to account for more than one failure per flow. Likewise flows did in some instances divide into more than one flow partway along its total length. The first of these poly-dimensional aspects can probably be accounted for by the natural merging of streams; streams almost always combine to form larger streams this process is known as Horton’s Law of Stream Numbers (Anderson & Anderson, 2010). Where the debris flows divide into more than one flow this is known as bifurcation (creating distributaries), and likely occurs when the momentum of the moving body abandons or overcomes the natural drainage path. This process is not directly comparable to bifurcation in a meandering stream where the lack of topography forces the stream to find an alternate path, but an obstacle such as a boulder or tree impedes the path. This highly fluidal (stream like) behaviour only attests to the volume of water present during this landslide event. Where the debris flow was more definitely confined such as Site 5 (Figure 5.209), the flow was observed to behave more as a stream and remained on a single flow path. Site2 (Figure 5.206) shows how the debris flows could bifurcate. In this case the presence of the main road could be assumed to have been enough of an obstacle to the natural flow path to force the landslide to find alternate routes.

The underlying parallel between all of the mapped flows from 2011 is their intrinsic connection with the large rainfalls during mid-January. The amount of rainfall was obviously enough to over-saturate the soil and rock to decrease the cohesive strength to the point of failure. The soils of the Grampians are skeletal, as they are often shallow, stony and sandy overlying the bedrock. In places the soils are silica sand rich with even grain size distribution (Calder, 1987) often noticeable by the vegetation classes growing in distinct areas.

Most of the flows occurred in drainage lines: in between ridges of the scree slopes, gullies or depressions. Erosion caused by flowing water is a function of the kinetic energy (Ahnert, 1998), erosion may have removed the finer fragments by saltation and suspension to a point where large fragments became unstable, but would not have been sufficient enough to move them. Once large fragments had begun moving it could have been a self-propagating system. This action of movement has potential but does not account for the varied sized or volume of sediment that has been entrained, so is unlikely to have been the sole type of activation. The long run out distances and high percentage of rock and rock fragments could be explained by a form of debris flow known as Sturzstroms.

Sturzstroms are often generated by rock falls that trigger fast moving debris flows that can move across long distances of relatively flat ground (Kenneth, 1975). The movement is often identified by cohesionless grains in a fluid medium, not necessarily water, where the buoyancy of the substance reduces the effective normal pressure of the moving grains (Kenneth, 1975). The reduction of normal pressure by fluid and or self-propagating pulverisation of rock and particles decreases the friction therefore allowing further transport on otherwise low angled topography (Pollet & Schneider, 2004). Many aspects of the Grampians landslides are comparable to the movement type of the Sturzstrom debris flows but the run out of Sturzstroms are often tens of times that of the change in elevation. The action of pulverised rock does not apply the Grampians where minimal rock break up has occurred, visible from the lack of freshly broken surfaces.

The action of both streams and Sturzstroms are relatively rapid and fluidal, and could be the primary style of movement in many cases in the Grampians.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The 176 landslides mapped using GIS techniques have provided a platform from which an in-depth study of landslide processes and contributing factors was undertaken. As the first study of the Grampians landslides, this project has delineated some general conclusions from which future studies can expand.

7.1 Conclusions

- The landslides that occurred in January 2011 in the Grampians undoubtedly were triggered by the anomalous rainfall during the 12th, 13th and 14th of January. The preceding six months, where rainfall was at least but more commonly well above average monthly totals, preconditioned the slopes for potential failure due to saturation. The rainfall data shows that greater than 210mm in a short period such as this signifacntly increases the occurrence of landslide in the Grampians.
- Preparatory factors that allowed failure to occur such as: surface geology vegetation and topography played a less significant role as historically landslides are reasonably uncommon and rarely cause as much significant damage. However these aspects do impact the occurrence of failure to some degree as less competent geology such as the silty Silverband Formation account for a very large percentage of the failures. The vegetation has little impact on the occurrence of landslides but does dictate the extent of run-out to some degree. Where energy levels are lower, vegetation dissipates the remaining energy by providing obstacles that inhibit flow. Slope angle can also be gauged by the different ecological vegetation classes. Topography was most likely the dominant preparatory factor as there was a strong correlation between topography and debris flow occurrence both as slope angle and aspect. Slopes greater than 22˚-24˚ were responsible for 89% of all 2011 slides. The

landslides were wide-spread particularly on the east facing scarp of the Serra-Wonderland-Mount Difficult Range and the Mount William Range with only minor incidences on west facing slopes.

- The landslides began as either a rock fall high on the escarpment or as a slide in the scree slope debris. Rock falls were often narrow and followed the natural gullies, self-propagating during movement. Whereas slides began as either a slump or translational slide against the bedrock surface.
- The landslide movements can be classified as a flow according to the thickness-length ratio classification (Table 2.3), with ratios not uncommonly below 0.5%. Occasional occurrences may be classified as slides due the short travel distances to thickness, but are relatively infrequent. Using Varnes' classification the landslides are classified as:
    - currently inactive, however in some instances slope equilibrium may not be completely achieved so they may be dormant;
    - most flows were confined to pre-existing drainage lines;
    - consisted of more than one movement type, often a rockfall or slide transforming into a debris flow that often behaved as a stream or Sturzstrom debris flow due to the potentially large volumes of water;
    - the flow would have occurred very rapidly (3m/min) to extremely rapidly (5m/sec);
    - comprised of debris ('contains a significant proportion of coarse material; 20%-80% of the particles are larger than 2mm and the remainder is less than 2mm.'(Varnes, 1978))
- Once entrained the debris flows relationship to the underlying landscape had particular characteristics regarding slope that affected how the rock and soil

fragments were first removed and secondly, emplaced. For the purpose of this project the flows were divided into 5 zones that each displayed a certain erosional and depositional environment.

7.2 Recommendations

These recommendations refer to certain aspects of the landslides that occurred in the Grampians where further research could be conducted.

7.2.1 Hydrological Research

- Determine exact small scale hydrological parameters of the scree slopes, including: cohesive strength, maximum water content, thresholds etc.
- Examine the hydrological relationship between rock and debris/soil facies

7.2.2 Landslide Processes Research

- Examine the landslides and definitively determine the debris flow behaviour in relation to the slope and drainage.
- Examine debris flows to largely determine the cause of bifurcation in some instances.
- Specifically determine parameters for these types of flows. Where does the debris flow end being a mass wasting process and simply become a stream?
- Where rock fall has occurred as a trigger to debris flows, determine the processes the controlled to rock instability.

7.2.3 Geomorphological Research – Slope Stability (denudation, fire, vegetation)

- Conduct research creating associations between denudation, fire, vegetation and land use to generally determine the geomorphological processes that shape the Grampians.
- Specifically describe the scree slopes that skirt the ranges and construct a hypothesis that accounts for their formation and current physiography

7.2.4 Risk Management

- Create a susceptibility map that will contribute to Landslide Risk Management, taking into consideration seasonal variations in rainfall.

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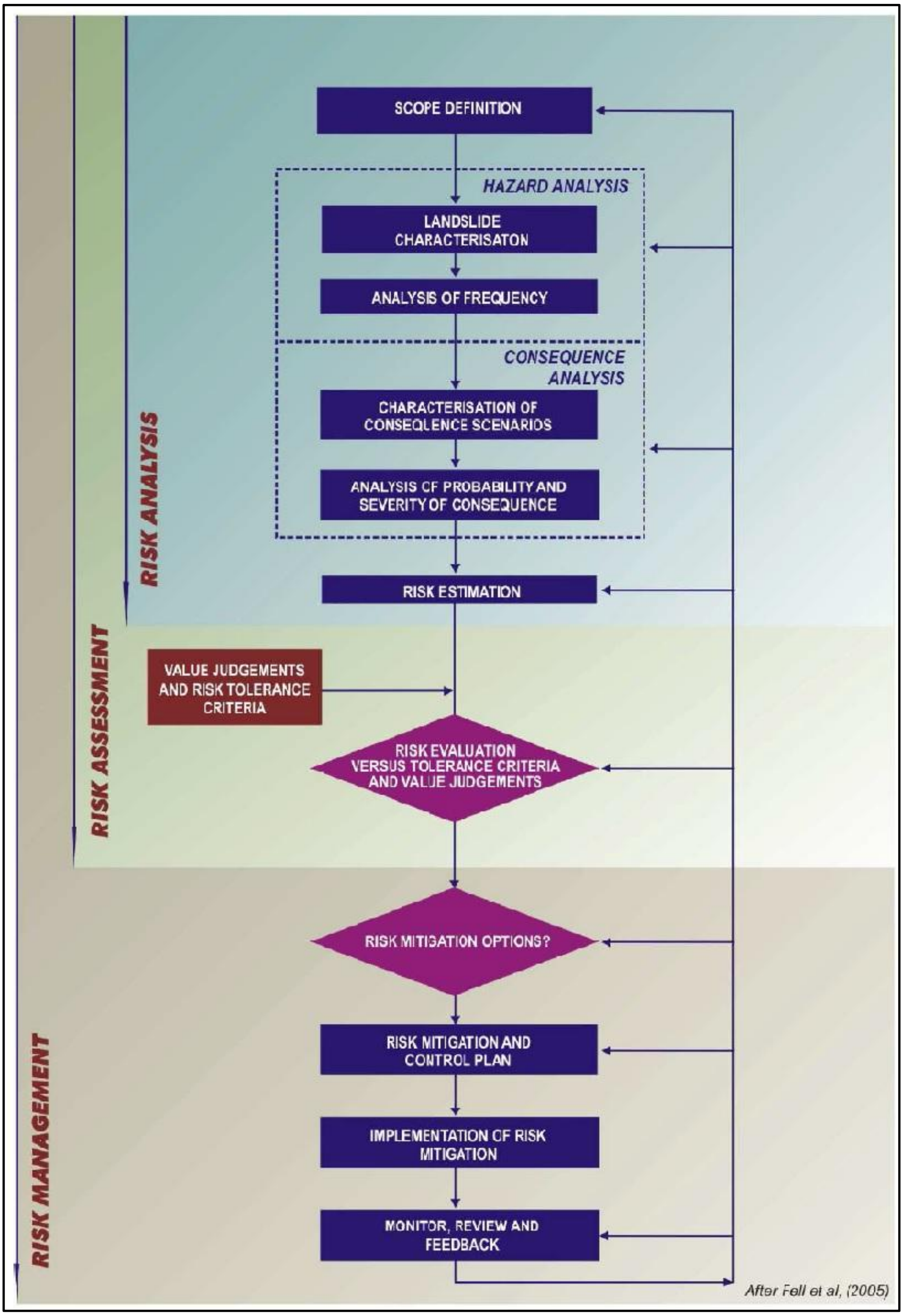
APPENDIX A

Landslide Risk Management

Landslide Nomenclature

Landslide Risk Management Ref: AGS (2007a, 2007c) An abbreviated LRM flowchart.



Landslide Nomenclature

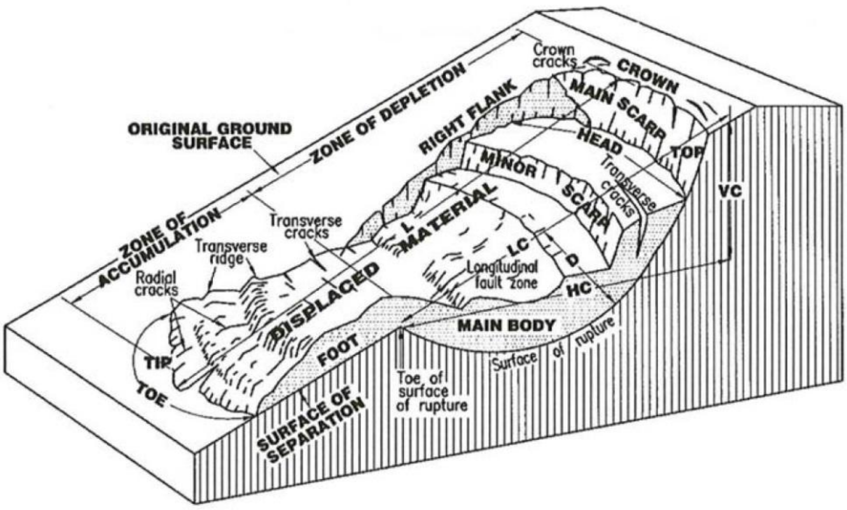


Figure A: Varnes (1978) diagram displaying typical landslide forms.

Nomenclature
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 between the lower part of the surface of rupture and the original ground surface. TOE – the margin of displaced material most distant from the top of the slide. TIP – The point on the toe most distant from the top of the slide. FOOT – That 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 the toe of the surface of rupture. FLANK – the side of the landslide. CROWN – The material that is still in place, practically in displaced and adjacent to the highest parts of the main scarp. ORIGNAL 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 & 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 on 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 undeformed state. ZONE OF DEPLETION – The area within which the displaced material lies below the original ground surface. ZONE OD ACCUMULATION – The area within which the displaced material lies above the original ground surface.
Table A: Glossary of landslide nomenclature relating to Figure A (AusIMM, 2011) based on description from (Varnes, 1978).

APPENDIX B

Field assessment record sheets

- Divisions (1,2,3,4) used to generally record significant Changes in slope and or sediment/debris deposition to generally determine the character of debris flows to define transitions in determined zones (A,B,C,D,E). Division parameters used as a guide rather than exact measurements.
- Subsidiary notes used to record debris flow character and environment to generally answer the guideline questions/criteria of AGS (2007d) p.121; Particularly relating to:
    - Topography
    - Geological Setting
    - Hydrology
    - History of movement
    - Geotechnical characterisation of the slide
    - Mechanisms and dimension of the slide
    - Mechanisms of shearing and strength of rupture surface
    - Assessment of stability
    - Assessment of deformations and travel distance

NAME: DATE:

INSTITUTION:

ASSISTANT:

LOCATION:

LANDSLIDE ID: GPS POSITION: Lat - Lon

Accuracy:

DIVISION 1: (?coarse fragments approx, +50cm diameter; slope angle change [22-15°]?)
GPS LOCATION: Lat - Lon
SLOPE ASPECT: SLIDE TREND: UPSLOPE ANGLE:
DOWNSLOPE ANGLE: WIDTH: LENGTH:
VEGETATION:
FRAGMENT SIZE('s):
FRAGMENT LITHOLOGY (possible formation):
-weathering? -roundness?
NATURAL DRAINAGE:
Does the slide follow drainage?
UNDERLYING BASE/SLIDE SURFACE MATERIAL:
WAS IT A REACTIVATED FAILURE:
OTHER COMMENTS:

DIVISION 2: (?medium fragments approx, 20-50cm diameter; slope angle change [15-10°]?)
GPS LOCATION: Lat - Lon
SLOPE ASPECT: SLIDE TREND: UPSLOPE ANGLE:
DOWNSLOPE ANGLE: WIDTH: LENGTH:
VEGETATION:
FRAGMENT SIZE('s):
FRAGMENT LITHOLOGY (possible formation):
-weathering? -roundness?
NATURAL DRAINAGE:
Does the slide follow drainage?
UNDERLYING BASE/SLIDE SURFACE MATERIAL:
WAS IT A REACTIVATED FAILURE:
OTHER COMMENTS:

DIVISION 3: (?coarse fragments approx, 10-20cm diameter; slope angle change [10-7°]?)
GPS LOCATION: Lat - Lon
SLOPE ASPECT: SLIDE TREND: UPSLOPE ANGLE:
DOWNSLOPE ANGLE: WIDTH: LENGTH:
VEGETATION:

FRAGMENT SIZE('s):
FRAGMENT LITHOLOGY (possible formation):
-weathering? -roundness?
NATURAL DRAINAGE:
Does the slide follow drainage?
UNDERLYING BASE/SLIDE SURFACE MATERIAL:
WAS IT A REACTIVATED FAILURE:
OTHER COMMENTS:

DIVISION 4 (Zone D): (?coarse fragments approx, <10cm diameter; slope angle change [7-5°]?)
GPS LOCATION: Lat - Lon
SLOPE ASPECT: SLIDE TREND: UPSLOPE ANGLE:
DOWNSLOPE ANGLE: WIDTH: LENGTH:
VEGETATION:
FRAGMENT SIZE('s):
FRAGMENT LITHOLOGY (possible formation):
-weathering? -roundness?
NATURAL DRAINAGE:
Does the slide follow drainage?
UNDERLYING BASE/SLIDE SURFACE MATERIAL:
WAS IT A REACTIVATED FAILURE:
OTHER COMMENTS:

Zone E (downstream of Division 4) Comments: Only fines component <2mm

OTHER COMMENTS:

DIAGRAM:

APPENDIX C

HIRAC Report

HIRAC Report

Risk, Health and Safety

University of Ballarat
Learn to succeed

This form relates to OHS Procedure – *Hazard Identification, Risk Assessment and Control (HIRAC)*

Date: 07/11/3013

Plant, Building, Task, Activity, Item Description: Honours Field Work – Grampians National Park

Campus: Mt Helen School / Section: S.I.T.E

HIRAC conducted by James Cameron and Sarah Dyer

HAZARD DESCRIPTION	RISK ASSESSED	CONTROL MEASURE(S)	WHO/ WHEN	DATE COMPLETED
Remote Location (The Grampians National Park)	Need for assistance will require emergency services (SES, Police, Parks Vic)	- Take mobile phone everywhere in case of emergencies (Police-000, SES- **(03) 5339 1122, Parks Vic** +61 3 5361 4000**)** - GPS	JC/SD	07/11/3013
Adverse weather conditions	Hypo/Hyperthermia, Sun burn	- Check weather conditions prior - Appropriate clothing for forecast weather - Sunscreen, hat, sunglasses	JC/SD	07/11/3013
Rockfall Hazards	Rock fall occurring when in the proximity of cliffs/elevated areas	- Avoid areas where rock fall could occur - Wear appropriate PPE – hard hat	JC/SD	07/11/3013
Personal injuries (sprains, breaks, abrasions, lacerations)	Rugged terrain highly increases risk of personal injury	- Wear PPE- hard Hat, Tough footwear, long pants and shirt - At least one participant has First aid training - Carry a first aid kit	JC/SD	07/11/3013
Dangerous Animals	Snakes in particular (Copperheads, Tiger Snakes, Red-Bellied	- Careful work practices (watch where you step) - Emergency Services Above - First aid training and kit	JC/SD	07/11/3013

	Black and Eastern Brown) Large Marsupials	- Avoid large animals		
Road Hazards – when working in the vicinity of major and minor road ways	Landslides are often near roads – risk of collision, persons hit.	- Safe driving practices - When parked park well of road - Wear PPE – high vis vest - Be aware of surrounds	JC/SD	07/11/3013