Geomorphology and geomorphological responses to climate change in the interior of sub-Antarctic Marion Island

By

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"I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I -
I took the road less travelled by,
And that has made all the difference"

Robert Frost
(The Road Less Travelled)

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sub-Antarctic Marion Island**

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Abstract

The influence of climate change on the geomorphology of the interior of Marion Island (above 750m a.s.l.) is investigated as climatic amelioration is thought to be responsible for the observed rapid melt out of the summit regions. Records have shown that the climate on Marion Island is warming and, as it represents a maritime periglacial environment characterised by small seasonal temperature ranges and steep temperature profiles, it is particularly sensitive to climate change. Marion Island is, therefore, an ideal location to address the poor understanding of periglacial environments in the Southern Circumpolar Region in the context of environmental conditions governing permafrost, seasonally frozen ground, and frost processes.

To ascertain the influence of climatic amelioration on the geomorphology of Marion Island's interior, thermokarst, periglacial, and rudimentary aeolian features were identified and mapped. Geomorphological features were documented to determine the extent of landscape response to climate change in the island's interior. In addition, identification and mapping of geomorphological features were, in some cases, used to provide evidence for the previous existence of permafrost. Ground temperatures were also monitored to determine the present state and possible existence of permafrost above 750m a.s.l.

Landscape development in the certain areas of the interior of Marion Island where glacial ice persists beneath sediment (scoria) and where permafrost previously existed has resulted in the manifestation of thermokarst features and the creation of a unique undulating topography. In parts of the study area, thermal erosion and subsidence of the thermokarst are identified as processes that are important agents of landscape evolution. Thermokarst processes, indicative of climate change are, however, limited to areas where buried glacial ice persists and permafrost existed. Thermokarst features studied were also noted to be ephemeral and easily destroyed through erosion by wind and water. Aeolian erosion, in particular, has a significant influence on thermokarst as the interior of the island represents a polar desert where almost no vegetation survives. Persistence of thermokarst features is further limited due to the nature of local sediment, namely scoria, being cohesionless,

thereby limiting the retention of water that can be frozen. The disappearance of the former permanent snowline sub-aerially exposing much of the interior suggests interaction between frost and aeolian processes will provide potentially relevant avenues for future geomorphological research. Furthermore, interactions between frost and aeolian processes are extremely important for plant colonisation in an area that is almost entirely devoid of vegetation.

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Finally, I have to thank the Lord for keeping me safe during this complete adventure, for all the opportunities and all I have gained from this experience.

May Marion Island forever stay wild and free…

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Chapter 1: Introduction

Permafrost Research in the Southern Circumpolar Region

Permafrost, glaciers and seasonally frozen ground are well documented indicators of climate change due to their delicate thermal balance (*e.g.* Haeberli, 1990; Zhang *et al*., 1997; Haeberli & Beniston, 1998; Boelhouwers, 2003). Substantial effort has, therefore, been devoted to monitoring permafrost, glaciers and seasonally frozen ground conditions and their responses to climate change, particularly in the Northern Circumpolar Region (*e.g.* Lachenbruch & Marshall, 1986; Haeberli *et al*., 1993; Demek, 1994; Pavlov, 1994; Haeberli & Beniston, 1998; Osterkamp & Romanovsky, 1999; Jin *et al*., 2000; Shaoling *et al*., 2000; and Harris *et al*., 2003). The Southern Circumpolar Region has, however, received significantly less attention from the scientific community with only a small number of studies having been completed focusing mainly on the distribution of permafrost (*e.g.* Bockheim, 1995), the response of glaciers to climate change (*e.g.* Allison & Kreage, 1986 and Kirkbride & Warren, 1999) and the responses of seasonally frozen ground and permafrost to climate change (Boelhouwers, 2003 and Guglielmin, 2004).

The Southern Circumpolar Region includes the continent of Antarctica, the Antarctic and sub-Antarctic islands as well as the southern tip of South America (Bliss, 1979). Permafrost occurs throughout the ice-free areas on the Antarctic continent ($\sim$280,000 km^2) and is also found on the Antarctic islands ($\pm$80,000 km^2) and the Sub-Antarctic Islands ($\pm$10,000 km^2) situated to the south of the Antarctic Polar Convergence (Bockheim, 1995). In addition, permafrost conditions, although sporadic, exist at sufficiently high altitudes on islands to the north of the Antarctic Convergence Zone; for example Marion Island (Van Zinderen Bakker, 1978; Bockheim, 1995 and Boelhouwers, 2003). However, there is a lack of awareness of the presence of permafrost in the Southern Circumpolar Region exists and, therefore, its distribution together with that of seasonally frozen ground for the Southern Circumpolar Region is not known (Bockheim, 1995). The perceived absence of ice-free land masses in the Southern Circumpolar Region, suitable for the existence of permafrost and seasonally frozen ground has led to permafrost research in the Antarctic and peri-Antarctic islands seldom being advanced through dedicated programmes (Boelhouwers & Hall, 2002).

Given that few data are published on permafrost in the Southern Circumpolar Region, a need exists to establish and map contemporary and former distributions as well as seasonally frozen ground. The sub-Antarctic islands, due to their relative position in relation to the zone of Antarctic Convergence, provide an ideal location to determine whether the extent of permafrost in the region is dictated by the position of the Antarctic Polar Convergence (Bliss 1979). Furthermore, establishing the contemporary and former distributions of permafrost as well as seasonally frozen ground may be of particular scientific value since environmental conditions affecting them in the Southern Circumpolar

Region could be different to frost processes encountered in the Northern Hemisphere (Boelhouwers & Hall, 2002). For example, Marion Island experiences a distinct hyper-maritime periglacial setting (Boelhouwers *et al*., 2003), which is in stark contrast to the continental setting of many northern hemisphere studies on permafrost. In addition, the fact that human disturbance is extremely limited on the island to other regions allows for landscape-process responses to easily be attributed to natural causes.

The upper interior of the Marion Island, above 750m above sea level (a.s.l.), is thought to comprise seasonally frozen ground and glacial ice buried under scoria and sporadic patches of permafrost (above 1000m a.s.l.) (Boelhouwers *et al*., 2001; Holness, 2001a). In addition, the area is largely devoid of vegetation allowing a more direct linkage between climate (air temperature) and ground temperatures. Thus, research in the interior of Marion Island represents an ideal location for establishing baseline data on the distribution of permafrost and seasonally frozen ground for a (hyper-maritime) sub-Antarctic island in the Southern Circumpolar Region. More importantly, the identification of geomorphological features indicative of climate change in a periglacial environment will provide the opportunity to monitor geomorphological responses to climate change in the region.

Marion Island's sensitivity to recent climate change has been highlighted (Boelhouwers *et al*., 2003 and Boelhouwers, 2003) through the analysis of soil temperature regimes on the island. In addition, contemporary responses to identified climatic amelioration (Smith, 2002) have recently been recognised (Sumner *et al*., 2004), but not yet fully documented. Photographic evidence clearly shows the rapid melt out of a 'fossil' ice cap, which now only exists as glacier ice buried under scoria in an area known as the 'Ice Plateau'. It is thus, possible to document the transition of the 'Ice Plateau' from a 'fossil' ice body recognised in the mid-1960s (Van Zinderen Bakker, 1971; 1973) to an area where, at present, sporadic patches of permafrost, buried glacial ice and seasonally frozen ground underlie a surface (Fig, 1.1). This transition is currently manifested in the development of thermokarst topography (*e.g.* kettle holes) on level surfaces and mass movements (*e.g.* debris flows and thaw slumps) on slopes. Existence of glacier ice in the 'Ice Plateau' may explain the observed lack of periglacial landforms, such as patterned ground since this area has only recently been sub-aerially exposed. In addition, the island has experienced recent volcanic activity (Verwoerd *et al*., 1981; Meiklejohn & Hedding, 2005) indicating that geothermal warming within the island, associated these volcanic events, may have accelerated the melt out of the various forms of ground ice found in the interior of the island and therefore also requires investigation; ground ice and permafrost exist not only in a delicate thermal balance with climate alone but also with the geothermal gradient (French, 1996; Bourgeois *et al*., 2000).
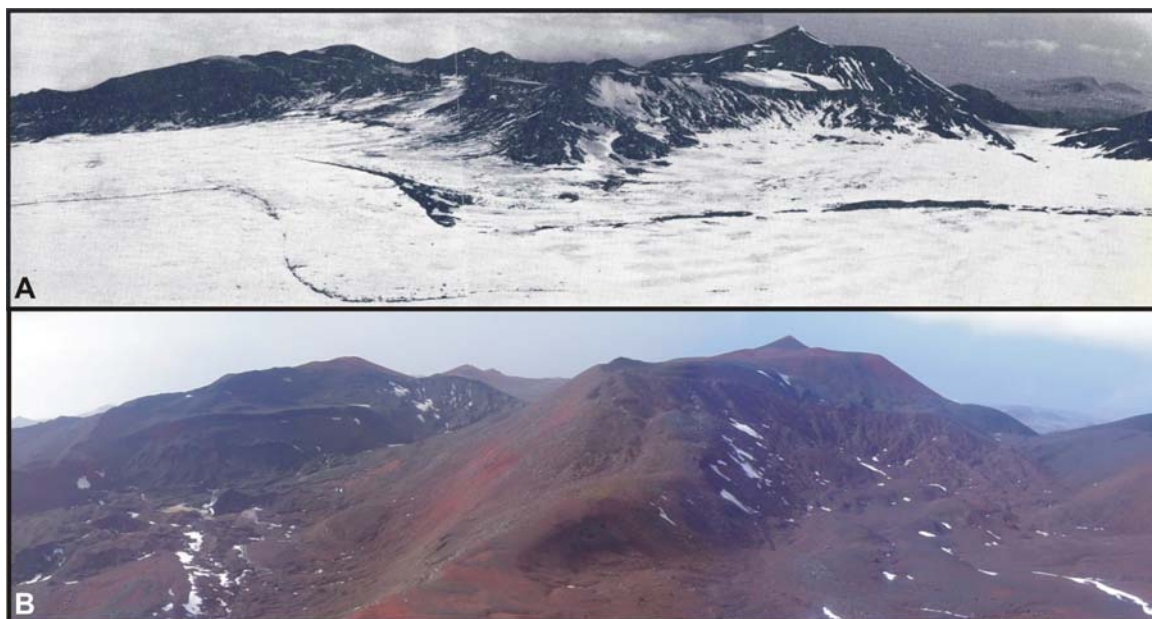
Figure 1.1: Photographic evidence of degradation of the fossil ice cap, formerly known as the 'Ice Plateau'. Photo A taken by W.J. Verwoerd in March 1966 (Verwoerd, 1971). Photo B taken from the same site in April 2005.

Previous Geomorphological Research on Marion Island

Until the early 1980s much of the geomorphological research on Marion Island concentrated on the reconstruction of palaeoclimatic conditions on the island from glacial evidence (*e.g.* Hall 1978; 1979; 1983a). Findings from this research were later scrutinised (Kent & Gribnitz, 1983; Gribnitz *et al*., 1986). Despite the objections from Kent & Gribnitz (1983) and Gribnitz *et al*. (1986) the palaeoclimatic reconstruction made by Hall (1980a) has now largely been accepted as correct (McDougall *et al*., 2001), with temperatures between 3°C and 6.4°C lower during the Last Glacial Maximum (LGM). Hall (1978; 1979; 1983a) used the altitude of lateral moraines to infer the palaeo-snowline which in turn could be used to determine the palaeo-temperatures on the island during the LGM. More recently, Holness (2003) used larger relict periglacial features, including stone-banked lobes and terraces, vegetation-banked features and blockstreams, to record Holocene environmental change; as many relict periglacial features were found in areas previously suggested to have been glaciated during the Last Glacial Maximum by Hall (1978; 1979; 1983a) and must, therefore, postdate this period. These identified periglacial features also imply that some deep freezing may have occurred in the unglaciated areas during the LGM (Holness, 2003). Reconstruction of the temperatures inferred by the processes required to generate the periglacial features suggest that temperatures were depressed between 4°C and 5.5°C below present during the period 15 – 17 kBP to 12 kBP. Both palaeo-temperature reconstructions by Hall (1980a) and Holness (2003) during the Holocene are compatible with palynological work for Marion Island (Van Zinderen Bakker, 1973) and an ocean core study from the southern Indian Ocean (Hays *et al*., 1976) for the same period indicate decreases in the mean annual temperature of 3 to 4 °C and 2.5 to 3.5°C respectively.

More recently, substantial research has been undertaken on periglacial landforms and climate change on Marion Island under the broad aim of the project – Cryogenic Landforms and Processes on Marion Island – where a quantitative understanding of the link between landforms, processes responsible for these landforms and their environmental controls was established (Boelhouwers *et al*., 2001). This project determined that some larger periglacial features (*e.g.* patterned ground and stone-banked lobes) are relict and are the product of a cooler period during the early Holocene (before 7kyr BP).

At present, Marion Island has been described as representing a distinct hyper-maritime periglacial environment (Boelhouwers *et al*., 2003), with four frost zones, (1) a coastal diurnal frost zone dominated by needle ice, (2) an upper diurnal frost zone with needle ice and ice lens formation, (3) a high altitude zone of seasonal freezing, (4) and summit pockets of permafrost (Boelhouwers *et al*., 2001). Representing the lower-most frost zone the diurnal frost zone is found between sea level and 300m a.s.l. and soil frost is the dominant geomorphological agent (Nel, 2001). The upper diurnal frost zone is situated between 300m and 750m a.s.l. and the general absence of vegetation allows for extremely high transport rates (Nel, 2001). Seasonal frost is found above 750m a.s.l. and sporadic permafrost bodies are found above 1000m a.s.l. on insolation-protected south facing slopes (Boelhouwers, 2003). In addition, the last remnants of glacial ice can also be found above 1000m a.s.l. in valley floors that underlay the former ice body now known as the 'Ice Plateau'. The present distribution and possible extent of permafrost (permanently frozen ground) and buried glacial ice on Marion Island is, however, still not known, as is the case with most sub-Antarctic islands (Bockheim, 1995).

The main focus of this study is to document the geomorphology and identify geomorphological responses to climate change in various forms of frozen ground, namely buried glacial ice, permafrost or seasonally frozen ground, found in the interior of Marion Island. Initial observations indicate a distinct paucity of periglacial features in the interior of Marion Island. However, geomorphological responses resulting predominantly from climatic amelioration are typically manifested in the development of thermokarst and mass movement features. Thermokarst features are particularly conspicuous in this distinct maritime periglacial environment underlain by permafrost or buried glacial ice.

Thermokarst features are karst-like topographic landforms produced by the melting of ground ice or ice-rich permafrost and the subsequent settling or caving of the ground (Higgins *et al*., 1990), and are peculiar to periglacial regions. Thermokarst processes are probably the most rapid erosional agents operating in periglacial environments (French, 1996) and are also a record of present or former permafrost. If they occur in a non-permafrost environment and buried glacier ice can be excluded, they

are proof of a former permafrost regime and of a climatic change (Washburn, 1979). Moreover, thermokarst features are in many areas an expression of fairly recent thaw and collapse processes prompted by climate change or the destruction of the vegetation cover (Higgins *et al*., 1990). Since the interior, above 750m a.s.l., is devoid of vegetation these geomorphological responses are considered to be the result of climate change. The effects of geothermal heating, however, cannot be excluded from playing an ancillary role in the development of thermokarst on Marion Island. The supplementary role of geothermal heating becomes evident when considering that the amount or extent of morphological change associated with the thermokarst process depends upon (a) the magnitude of the increase in depth of the active layer, (b) the ice content in the soil, and (c) the tectonic regime of the region (French, 1996). Therefore, in tectonically active regions, small local geothermal anomalies, associated with volcanoes, exceeding the mean heat flux by several orders of magnitude (Björnsson, 1988; Blakenship *et al*., 1993; Jonsson *et al*., 1998) can be considered as one of the external conditions affecting ice dynamics (Paterson, 1994). Geothermal induced melting of ice from the area known as the 'Ice Plateau' coincides with geothermal activity associated with volcanic eruptions (*circa* 1980). Further evidence of geothermal activity was witnessed on the island in 2004 (Meiklejohn & Hedding, 2005) and thus geothermal activity seems to be more active than previously assumed and therefore cannot be discounted as a cause for exacerbating the melt out of permafrost and buried glacial ice on Marion Island. The localised nature of the observed geothermal activity on Marion Island can only influence local changes in the ice and, therefore, the recognised widespread climatic amelioration across the sub-Antarctic is deemed predominantly responsible for the geomorphological responses documented in this study.

Research Aims and Objectives

Marion Island has experienced a dramatic shift in climate since meteorological observations began in the 1950s (Smith, 2002). Therefore, the aim of this study is to ascertain the influence of this change in climate on the development of the landscape in the upper interior of Marion Island (above 750m a.s.l.). Investigation of the relationships between permafrost and seasonally frozen ground conditions with associated landforms (*e.g.* thermokarst features) is of particular importance since the potential responses of seasonally frozen ground and permafrost to climate change are poorly understood in the Southern Circumpolar Region (Bockheim, 1995). Furthermore, understanding the dynamics of frozen ground conditions is necessary, given their potential impact on erosion rates and ecosystem functioning.

To ascertain the influence of recent climatic change (Smith, 2002) on the development of the landscape in the upper interior of Marion Island (above 750m a.s.l.) the following objectives of research were undertaken:

- Monitoring ground temperatures to establish the thermal characteristics of the ground above 750m a.s.l. in the interior of Marion Island.

- Documenting and mapping geomorphological features as well as identification of geomorphological processes currently active in the island's interior.

- Identifying geomorphological features indicative of climate change to determine the geomorphological responses to the observed climatic amelioration on Marion Island.

Project Outline

The need for geomorphological research into the distribution and extent of permafrost, glacial ice, seasonally frozen ground and the geomorphological processes active in the upper interior (above 750m a.s.l.) of sub-Antarctic Marion Island is highlighted above. Chapter 2 presents the general historical, environmental, climatic, geological and glacial setting for Marion Island. The methods adopted to document the geomorphology of the interior of Marion Island and determine the extent, state and distribution of permafrost, buried glacial ice and seasonally frozen ground as well as the geomorphological responses to climate change on Marion Island are described in Chapter 3. Chapter 4 will present a thematic geomorphological map of the interior of Marion Island and will describe measurements and observations regarding these mapped features. Ground thermal data of a pre-determined altitudinal range for Marion Island illustrating the influence of aspect and altitude on the existence and maintenance of seasonally frozen ground and permafrost is also presented. In addition, Chapter 4 will describe the extent and state of buried glacial ice on the island. Chapter 5 describes geomorphological responses to climate change on Marion Island and its significance in the context of the sub-Antarctic. A summary of this study and recommendations for future research to provide a better understanding of geomorphological responses to climate change on not only Marion Island, but across the entire sub-Antarctic region, are presented in Chapter 6.

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Chapter 2: Historical and Environmental Setting

Location and Discovery of Marion Island

      Marion Island (46°54'S, 37°45'E), the larger of two islands that constitute the Prince Edward Islands group, is one of the very few islands in the vast Southern Ocean (Fig. 2.1). Hall (1978) has described the island as a bleak and inhospitable volcanic complex that is a vital environment for land-breeding birds and mammals of the Southern Ocean. It also provides an ideal location for geomorphological and other research on climate change in the Southern Circumpolar Region. Marion Island, as recognized by Holdgate (1970, cited in Bockheim, 1995), is situated on the northern periphery of the sub-Antarctic Islands, which allows for determination of the northern most extent of permafrost and/or glacial ice in the Southern Circumpolar Region. The significance of geomorphological research on climate change is further emphasised considering that Marion Island is presently situated approximately 250km north of the Antarctic Polar Convergence and any pronounced shift, particularly a southward shift, in the position of the Antarctic Polar Convergence may have significant effects on the climate and geomorphological activity on the island due to climate-process responses.
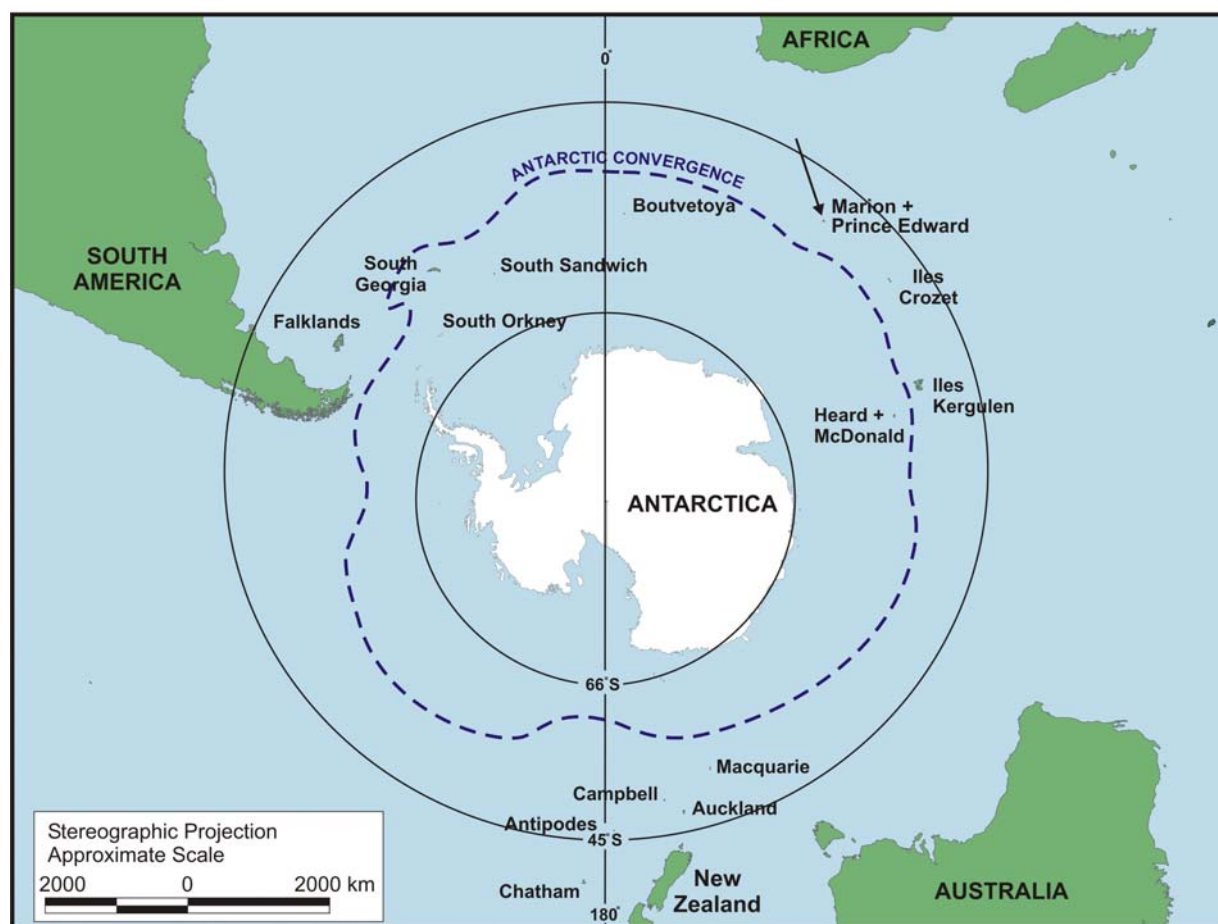
Figure 2.1: Location of Marion Island in relation to other islands in the maritime sub-Antarctic, the Antarctic Polar Convergence and Antarctica.

Barent Barentszoon Ham, captain of the Dutch East India Company's 210-ton galleon '*Maerseveen*', is thought to have been the first to sight Marion and Prince Edward Islands on 4 March 1663. According to Leupe (1868, cited in Gremmen, 1981) he named the larger 'Dina' (on some maps called 'Denia') and the smaller '*Maerseveen*' but owing to the inexactitude of his navigational instruments the positions given by first mate Michiel Gerritsz Boos in the logbook are at 41°S. Marion and Prince Edward Islands then eluded rediscovery for over a century until on 13 January 1772 when the French sailor Marc Joseph Marion Dufresne sited and fixed the correct positions but was unable to land. Thinking that he had found the outposts of the not yet discovered southern continent, he called the larger one '*Terre de l'Esperance*' (Gremmen, 1981) meaning Ilse of Hope and the other island to the north-east '*Ile de la Caverne*', after a large cave he sighted near the coast of this island. For five days the French made unsuccessful attempts to find safe anchorage and to set foot on this new territory; the weather was constantly against them and Dufresne eventually gave up and squared away his ships towards the east (Marsh, 1948). Dufresne had learnt that these islands were not part of the southern continent and so, in disgust, changed their name to '*Iles des Froides*' (The Frigid Islands). The next discoverer to see these islands was Captain James Cook with the *Resolution* and *Adventure*, who also 'rediscovered' the islands on 12 December 1776 not realising Marc Joseph Marion DeFresne precedent named them the Prince Edward Islands after the fourth son of Britain's King George the Third. However, upon learning his mistake Cook renamed the larger island after the French discoverer (Hall, 1978). After the discovery of Marion Island and other isolated islands in the Southern Ocean they became the haven for whalers, sealers, buccaneers and merchants who visited these bleak and foggy regions in search of wealth (Nel, 2001). Signs of their occupation, in the form of rusted utensils and trypots, can still be found in many bays and caves on Marion Island.

The first scientific endeavour ashore was undertaken by Richard Harris of the sealers *Betsy* and *Sophia*, when he observed and collected sea birds during a visit in 1830-31. Scientific exploration of Marion and Prince Edward Islands only began in earnest in 1873, one century after their discovery, when the British Challenger-expedition landed a party on Marion Island (Gremmen, 1981) to make biological and geological observations ashore and to allow for samples to be taken. Later in 1939, members of the little known French Bougainville-expedition also made a short visit to Marion Island on its way to the French sub-Antarctic Islands where a small number of specimens were collected and some photographs taken (Hänel & Chown, 1999).

In 1948 the South African Government on the initiative of Field-Marshal Jan Smuts annexed the Prince Edward Island Group from Great Britain, who had possessed the islands since 1908, for strategic reasons (Van Zinderen Bakker, 1971). Initially only a meteorological station was maintained on Marion Island, but later in 1963 Van Zinderen Bakker initiated the first intensive biological and geological research programmes (Van Zinderen Bakker, 1971). The islands have subsequently (3

November 1995) been declared a special nature reserve in terms of Section 18 of South Africa's Environmental Conservation Act (Act 73 of 1989) and all fauna and flora on the islands are now protected by law. In addition authorities have also, for a number of years, been trying to avoid the further introductions of any alien organisms.

Topography

Marion Island presents a dome-shaped profile, climbing from a raised coastal bench, with many small volcanic cones interspersed over the whole area (Hall, 1978). It is roughly oval in shape with a subaerial extent of 293km^2, a coastal perimeter of 72km, and rises to its highest peak of 1240m a.s.l., now known as Mascarin Peak, near its centre (Fig. 2.2). Verwoerd (1971) recognises five distinct physiographic units on Marion Island: (1) Central Highland, (2) Island Slope, (3) Western Escarpment, (4) Coastal Plain and (5) Volcanic Cones. The Central Highland has the form of an arcuate plateau at an approximate altitude of 1000m a.s.l. with a number of higher volcanic cones rising above it. Within this plateau region a small area of former permanent snow and ice, known as the 'Ice Plateau', has previously been recognised (*e.g.* King, 1954; Verwoerd, 1971; Van Zinderen Bakker, 1973; Hall, 1978); this area no longer even exhibits permanent snow cover and the last remnants of glacial ice are rapidly disappearing (Sumner *et al.*, 2004).

From the elevated interior, the Island Slope extends down to the Coastal Plain on the north, east and southeast and to an escarpment in the west (Nel, 2001) and forms the greater portion of the island (Gremmen, 1981). The gradient of the slope from the coast to the interior varies from 2° above East Cape to 19° above the Santa Rosa Valley. This area is characterised by valleys and plains separated by ridges and plateaus, with the recent black lavas present in the valleys and the ridges and plateaus almost always consisting of grey lava (Gremmen, 1981). These plateaus or ridges and valleys, according to Hall (1978), represent horst and graben structures respectively, which are usually demarcated along the radial faults and are typically aligned by scoria cones.

The Western Escarpment stretches from 200m to 400m a.s.l. in altitude and is situated between 1 and 2 km inland from the coastal cliffs where it runs essentially parallel to the coast on the western shore of Marion Island. Verwoerd (1971) suggests that this major faulted area represents a previous position of the coastline. The Coastal Plain at the foot of Western Escarpment is formed from a bench of recent black lava flows at an altitude of 50m a.s.l. Around the rest of the island the Coastal Plain is from 5 to 60m a.s.l. and is composed of a mixture of glacial deposits, old grey lavas and young black lavas (Nel, 2001).

Some 130 volcanic cones can be found scattered across the entire island; as many are over 200m in height and are red or reddish black in colour, they form prominent landscape features (Fig.

2.2). Many of the scoria cones are well preserved; often showing circular crates and sometimes containing a crater-lake (Gremmen, 1981). The significance of the volcanology and faulting of Marion Island, first described in detail by Verwoerd (1971) and subsequently by Chevallier *et al*. (1992) were initially put into a glaciological context by Hall (1978; 1982) and later by McDougall *et al*. (2001) and will be described below.
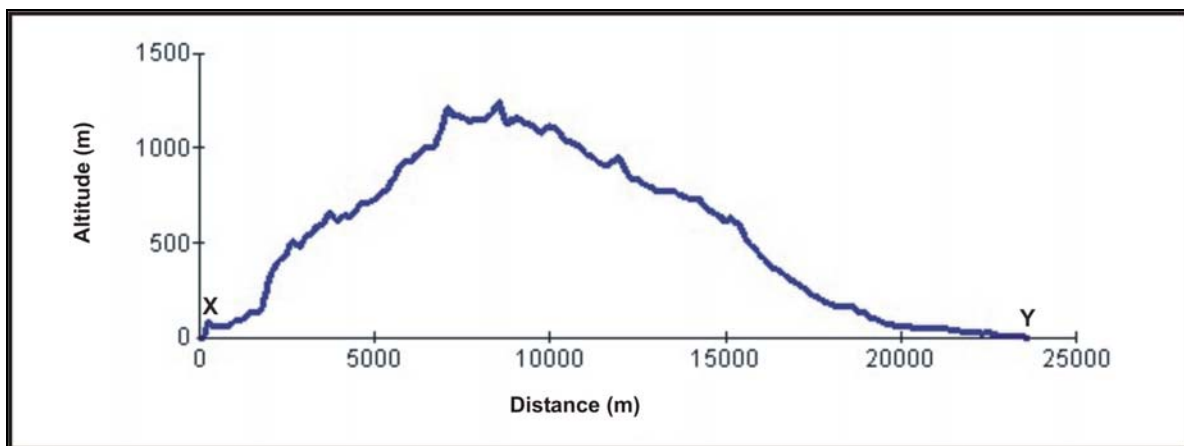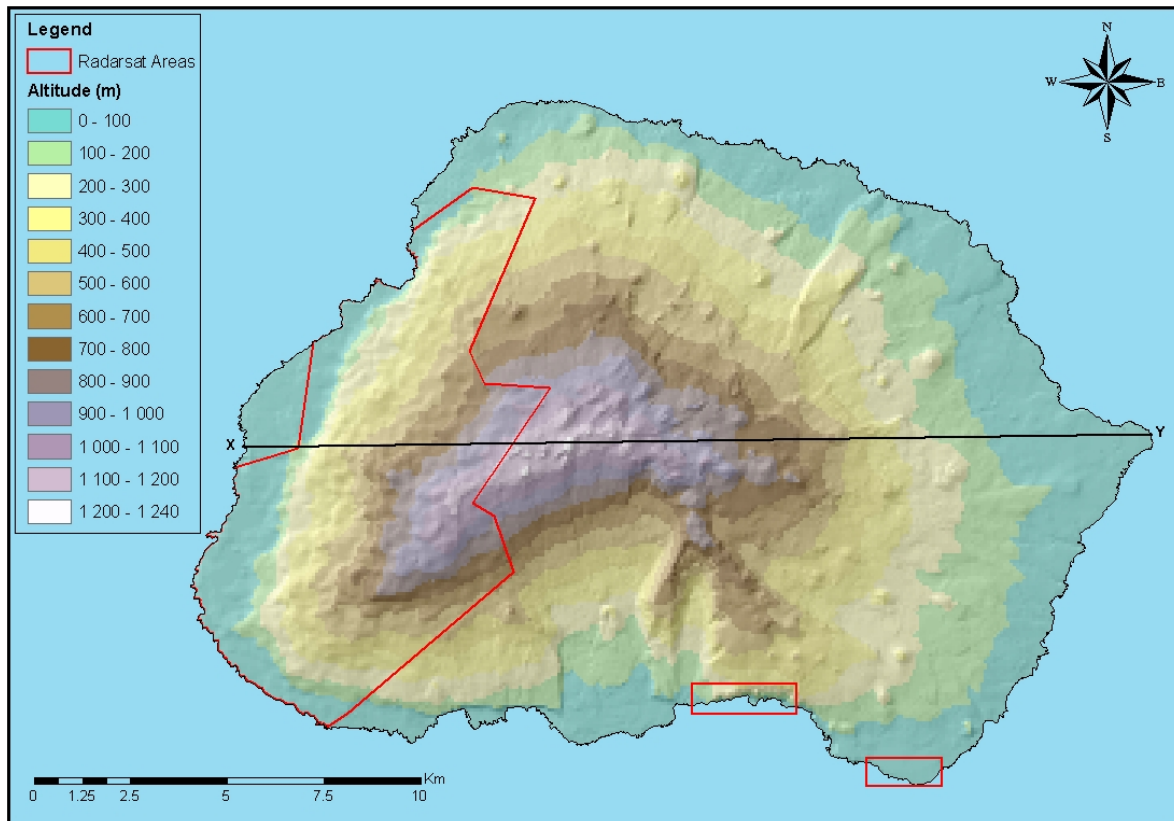
Figure 2.2: Topography and profile of Marion Island. The profile of Marion Island has a 9x vertical
   exaggeration.

Volcanics, Geology, Geochronolgy and Glacial History

Marion Island was previously considered to represent the peak of an extinct shield volcano comparable to, but not entirely of the Hawaiian type (Verwoerd, 1971). Volcanic eruptions in 1980, documented by Verwoerd *et al*. (1981), and observations during 2004 of volcanic activity (Meiklejohn & Hedding, 2005) on Marion Island have, however, forced the abandonment of the idea that volcanic activity on Marion Island no longer occurs (see Verwoerd, 1971). Further, volcanic activity was observed on Prince Edward Island, a mere 19km's north north-east of Marion Island, in early January 1948 from the H.M.S.A.S. Transvaal during the annexation of the islands (Marsh, 1948). Marion Island has recently been described by McDougall *et al.* (2001) as the tip of an active oceanic intraplate volcano. It is situated 300km south of the South West Indian Ridge and adjacent to the N20°E Eric Simpson Fracture Zone and, together with the neighbouring Prince Edward Island and the nearby Funk Seamont, is also considered to mark the present position of a long-lived hotspot: the surface expression of a mantle plume (McDougall *et al*., 2001). Thus, it is not surprising that Marion Island has experienced numerous volcanic eruptions. Petrologically all the lavas on Marion Island belong to an alkaline oceanic island basalt (OIB) suite with SiO_2 ranging between 45% and 55% (McDougall *et al*., 2001). McDougall *et al*. (2001) indicate that volcanic activity on Marion Island has not been continuous during the last half million years on a local scale due to the presence of unconformities and time gaps in the sequences that have been dated. However, volcanological features from the Holocene indicate that Marion Island has had a very low eruptive rate over the Holocene; with 150 eruptions during the last 10 000 years, *i.e.* an average of one or two eruptions per century (Chevallier *et al*., 1992).

Previous geological investigations (*e.g.* Verwoerd & Lagenegger, 1967; Verwoerd, 1971; Hall, 1978) and K-Ar dating (*e.g.* McDougall, 1971 and McDougall *et al*., 2001) identified two main periods of volcanic activity which have only recently been mapped (Fig. 2.3). The first main volcanic period, during the Pleistocene, produced grey-coloured lavas that have been glaciated whilst the second period, during the Holocene, is represented by black-coloured lava and scoria cones that show no sign of glaciation. The approximately 130 scoria cones scattered around the island, result from the most recent phase of volcanic activity (Verwoerd, 1971). Thus the island surface is characterised by extensive areas of black lava and scoria cones, grey lava moraines and tills from earlier glaciations (Sumner, 2004).

Hall (1978) provided a glacial reconstruction for Marion Island based on detailed examination of the stratigraphy of coastal exposures of till, which included preferred clast orientations, variations in clast shape consistent with till and the existence of striated clasts in some strata. Hall (1978) placed the glacial reconstruction of Marion Island in a timeframe provided by the limited geochronological data available at that time, which indicated that the oldest grey lava dated on Marion Island was 276 000 BP ± 30 000 (McDougall, 1971), and evidence, suggested that there were three glaciations named

'Oldest' (276 000 – 215 000 BP), 'Penultimate' (200 000 – 111 000 BP) and 'Wűrm' (73 000 – 12 000 BP) corresponding to cycles B, C, D of Kukla (1977) (equivalent to marine isotope stages 2-4, 6 and 8). However, since an older age of 454 000 BP ± 21 000 has been obtained for the grey lavas on Marion (McDougall *et al.*, 2001) the 'Oldest' glaciation may in fact be associated to cycles D, E or F of Kukla (1977) (marine isotope stages 8, 10 or 12). In addition, the evidence presented by Hall (1978) for the two glacial periods pre-dating the last glacial has been questioned by Kent & Gribnitz (1983) who consider that the sequences are volcanic in origin. Hall (1990), however, points out that as all the material available for reworking by glaciers on the island is volcanic in origin, thus the fact that volcanic materials are present within the deposits is inevitable, and does not preclude glacial deposition (Holness, 2001a).

Two major sets of faults have been documented: a dominant radial system and a secondary peripheral group (Hall, 1982) upon which many of the eruptive centres are presently aligned. Hall (1982) also indicates that radial faults are located roughly parallel to the former glacier margins in the reconstruction of former ice cover (Hall, 1978; 1979; 1982). This led Hall (1982) to propose the hypothesis that periods of volcanic activity on Marion Island were initiated by rapid deglaciation, whereby removal of the weight of ice caused faulting (isostatic readjustment) and subsequent volcanism due to the island's close proximity to the volcanically active Mid-oceanic Ridge. Justification that periods of volcanism were active during interglacial phases was based upon the occurrence of palaeosols and fossil peats (Hall, 1982). McDougall *et al.* (2001), using K-Ar dating of rock samples from Marion Island, have noted that of the eight volcanic episodes only the latest three, (VI, VII, VIII) coincide with interglacial stages, whereas the oldest three (I, II, III) are accompanied by major glaciations (Fig. 2.4). Close inspection of this observation does not reveal the same interpretation in that all stages of volcanic activity on Marion Island appear to lag behind the glacial stages derived from marine oxygen isotope stages. Nonetheless, the observation made by McDougall *et al.* (2001), contradicts the hypothesis of periodic volcanism triggered by rapid deglaciation suggested by Hall (1982) for Marion Island. If Hall's (1978, 1979, 1982) glacial reconstruction, based on the limited geochronological data available at the time, is accepted as essentially correct, the last of three glacial maximums terminated approximately 12 000 BP towards the end of the Pleistocene. This would correlate well with the deglaciation of South Georgia and the Antarctic Peninsula, which was largely complete by 9500 BP (Sugden & Clapperton, 1986), when considering that Marion Island has a more northern latitude. Using data from striation observations, till fabric analysis, moraine recognition, surface megaclast fabrics and till stratigraphy Hall (1978) showed that the island was glaciated extensively but not fully during the (LGM) with six, possibly seven, glaciers covering most of the eastern part of the island. More recently, the margins of these glaciers have been reinterpreted as some of the areas previously thought to have been glaciated (Hall, 1978; 1978; 1983a), namely Feldmark Plateau and Long Ridge, are devoid of any glacial evidence but do, however, display very
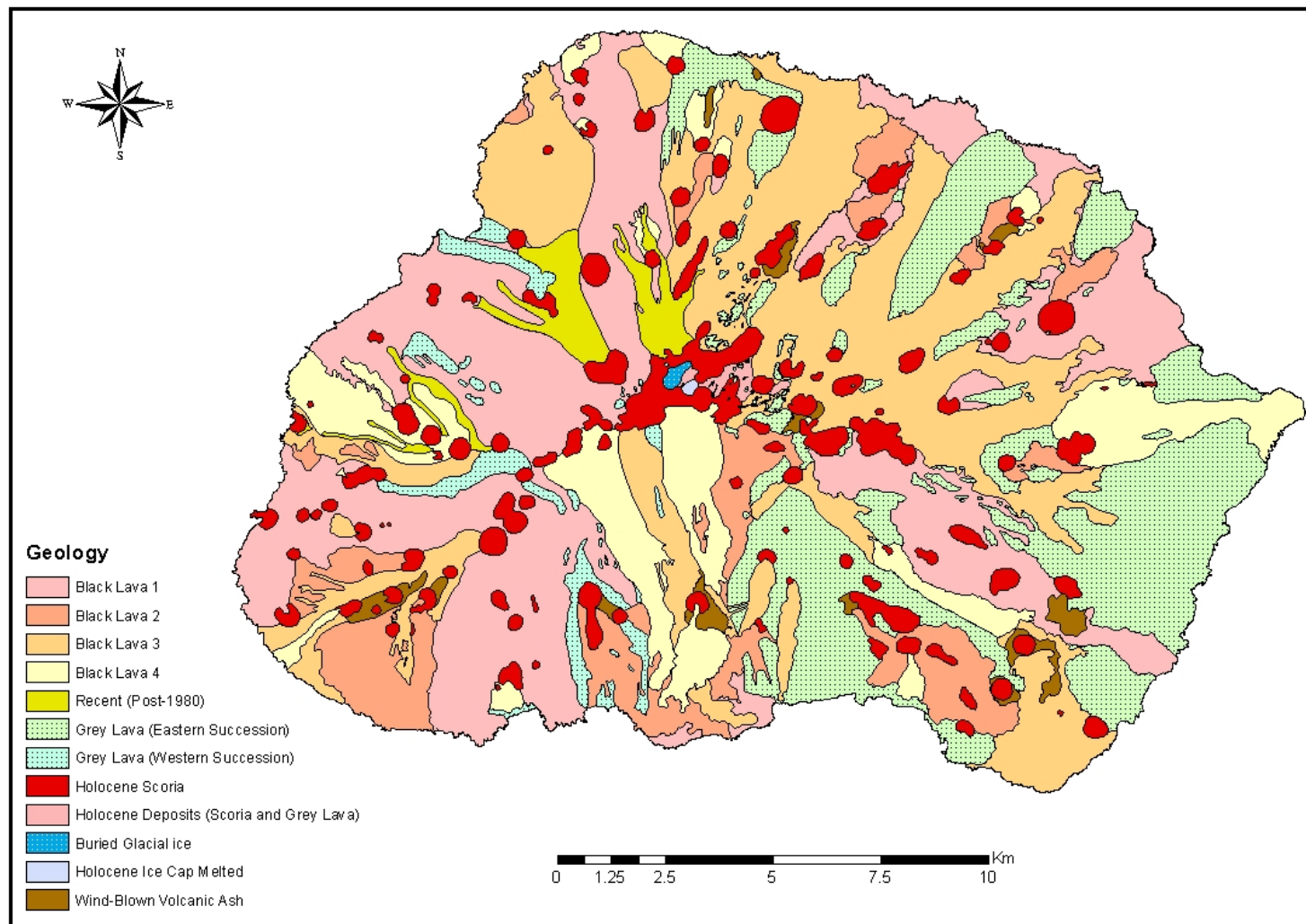
Figure 2.3: Geology of Marion Island adapted from Verwoerd (1971) and Chevallier (1992). The Black Lava 1 and Black Lava 4 groups represent the oldest and youngest flows in the black lava group respectively. Recent black lava flows were found in the south-western region of the island but because they were not mapped they are not included in this map
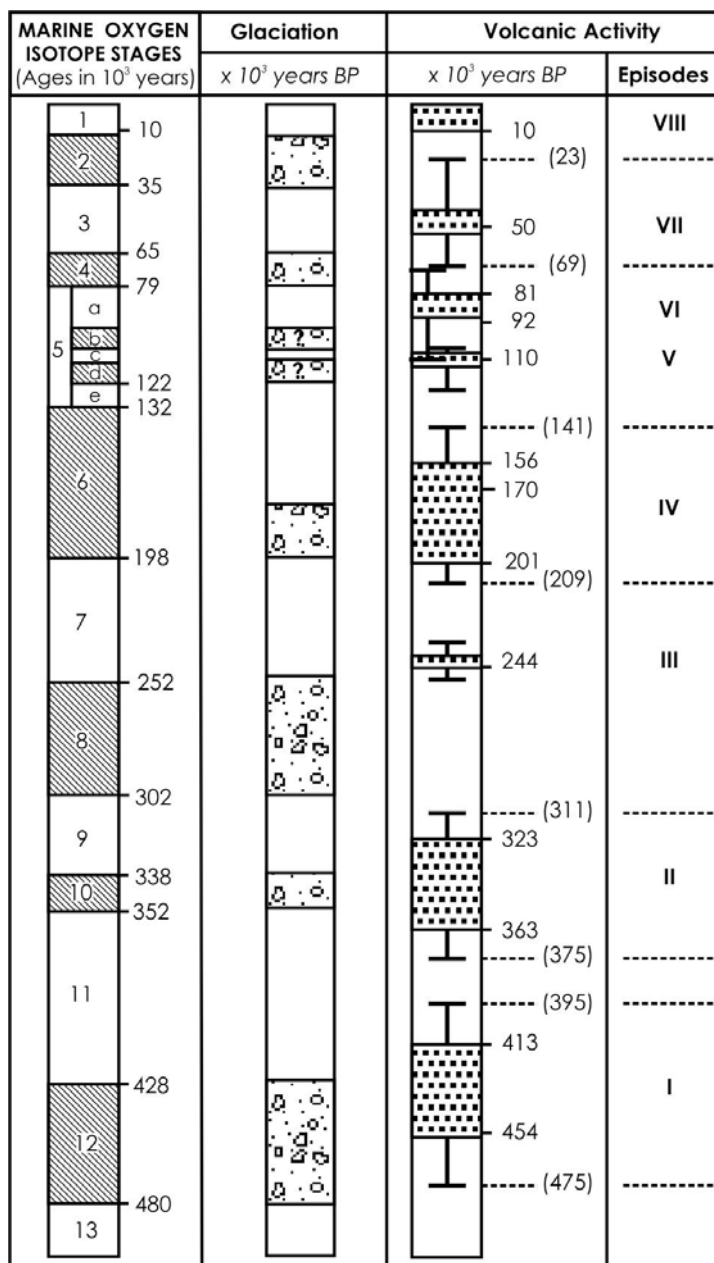
Figure 2.4: Relationship of volcanic activity, field evidence of glaciation on Marion Island and Marine Isotopes indicating Glacial Stadials (Adapted from McDougall *et al.*, 2001).

large periglacial features (Nel, 2001) (Fig. 2.5). Hall (1983a) notes that some of the margins of the reconstructed glaciers, namely the margins around Long Ridge, were hypothesised to a large extent, indicating that these areas may not have been glaciated during the Last Glacial maximum or at the very least that these areas became deglaciated before other parts on Marion Island.
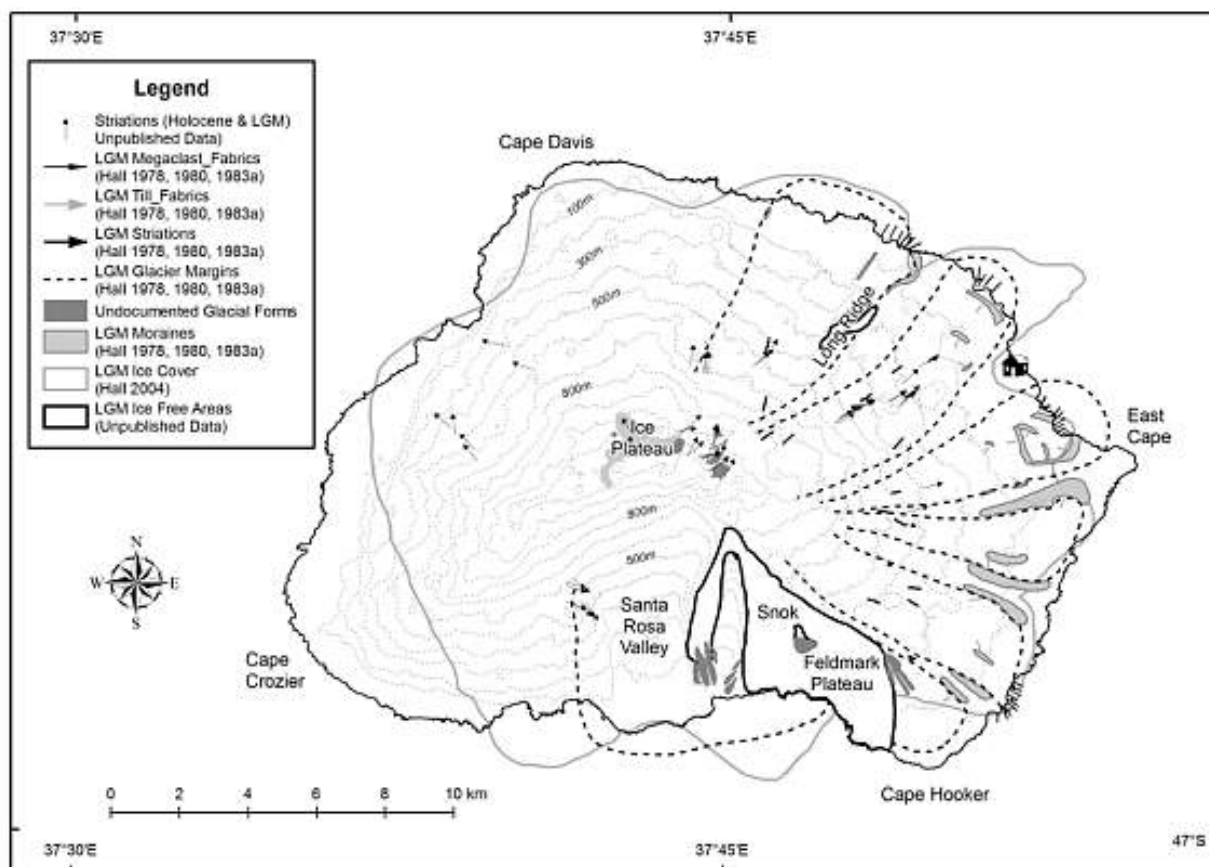
Figure 2.5: Reinterpretation of the glacier margins from the glacial reconstruction for the Late Pleistocene proposed by Hall (1978: 1979; 1983a) (Boelhouwers *et al*., in prep).

Climate

Marion Island experiences one of the most oceanic climates on Earth (Smith, 1987) as a result of it being such a small island surrounded by the vast thermally-stable Southern Ocean (Holness, 2001a). This hyperoceanic position, just north of the Antarctic Polar Convergence, results in the island having a distinct climate (Holness, 2001a). The island is thus subjected to the general meteorological characteristics of this oceanic region and well illustrates the hyper-maritime setting of the sub-Antarctic islands (Boelhouwers *et al*., 2003) in a zone of prevailing westerlies. The South African Weather Service (formerly the South African Weather Bureau) Meteorological Station established in 1948 is located at 22m a.s.l. on the northeast coast of Marion Island (Fig. 3.1) and provides essential meteorological data for this region in the vast Southern Ocean. Unless otherwise stated, all climate data presented in this and other sections regarding the general climate of Marion Island is provided the South African Weather Service. It is pertinent to note that some climatic elements are modified by the topography of the island as the island itself provides a natural obstacle to the numerous depressions that travel from the north-west to the south-east through the area (Gremmen, 1981). Thus some of the climatic elements measured, most notably wind direction, are not necessarily representative of the region.

Temperatures are relatively low, with a mean annual air temperature (MAAT) of 5.6°C but sub-zero temperatures can be experienced throughout the year and are predictably more frequent in winter at higher altitudes. Mean monthly maximum and minimum temperatures at sea level are 8.6 and 3.1°C, whilst the mean monthly temperature range is 5.4°C (Fig. 2.6). Marion Island receives a low incidence of incoming radiation due to a high mean monthly cloud level, averaging 6.2 oktas. At present, the average total annual precipitation at sea level is 2326 mm (Table 2.1) with current snowfall records indicating an approximate average of 50 days per year at sea level Holness (2001a). Snowfall appears to be more frequent at higher altitudes but snow does no longer persists on the ground throughout the year.

The yearly average wind speed is 8.4 m/s or 30.2 km/hr (Holness, 2001a) whilst full gales of at least 66 km/hr (and stronger) often run for as long as 10 hours (Hall, 1978). During these gales (of which at least one a month is encountered) wind gusts of over 200 km/h have been recorded. Mean wind direction is almost due west (269°) and winds blow most frequently from west-northwest (Holness, 2001a) at the meteorological station but as is mentioned above this may be unrepresentative for the entire region due to wind deflection by the island. The island is also subject to a high relative humidity (the mean being above 80%) and fog often occurs. It has also been shown, from upper-air soundings by radio-sonde balloons, that the environmental lapse rate is about 4.5°C per 1000m in winter and 4.0°C in summer (Hall, 1978).

Table 2.1: Summary of climatic variables recorded on Marion Island between 1949 and 2004.

Air Temperature	Mean annual: 5.6°C
Precipitation	Average: 2326mm *per annum*
Humidity	Annual average: 83%
Wind Speed	Monthly average: 30.2 km/h
Cloud Cover	Monthly mean: 6/8

In summary, Marion Island experiences a small temperature range, relatively low but not sub-zero temperatures, low sunshine radiation, high relative humidity, high precipitation at sea level and because it is located in the midst of the 'Roaring Forties' it is also consistently subjected to strong westerly winds, often of gale force (Beaufort force 8). These climatic conditions result in an extremely harsh environment, which has a profound effect on the biota of the island (Hall, 1978). In addition, the number of gale force winds and days with fog has a marked effect on the number of days available for fieldwork (Hall, 1978). Days available for fieldwork at higher altitudes are further limited due to the persistence of snow on the ground, which typically falls during the winter months (May-October) down to 600m a.s.l. and occasionally covers the entire island down to sea level. It is pertinent to highlight that meteorological records indicate that Marion Island has experienced a dramatic shift in

climate over the past 50 years (see Chapter 4 for discussion) and, therefore, the climatic setting is not as stable as some of the current averages suggest.
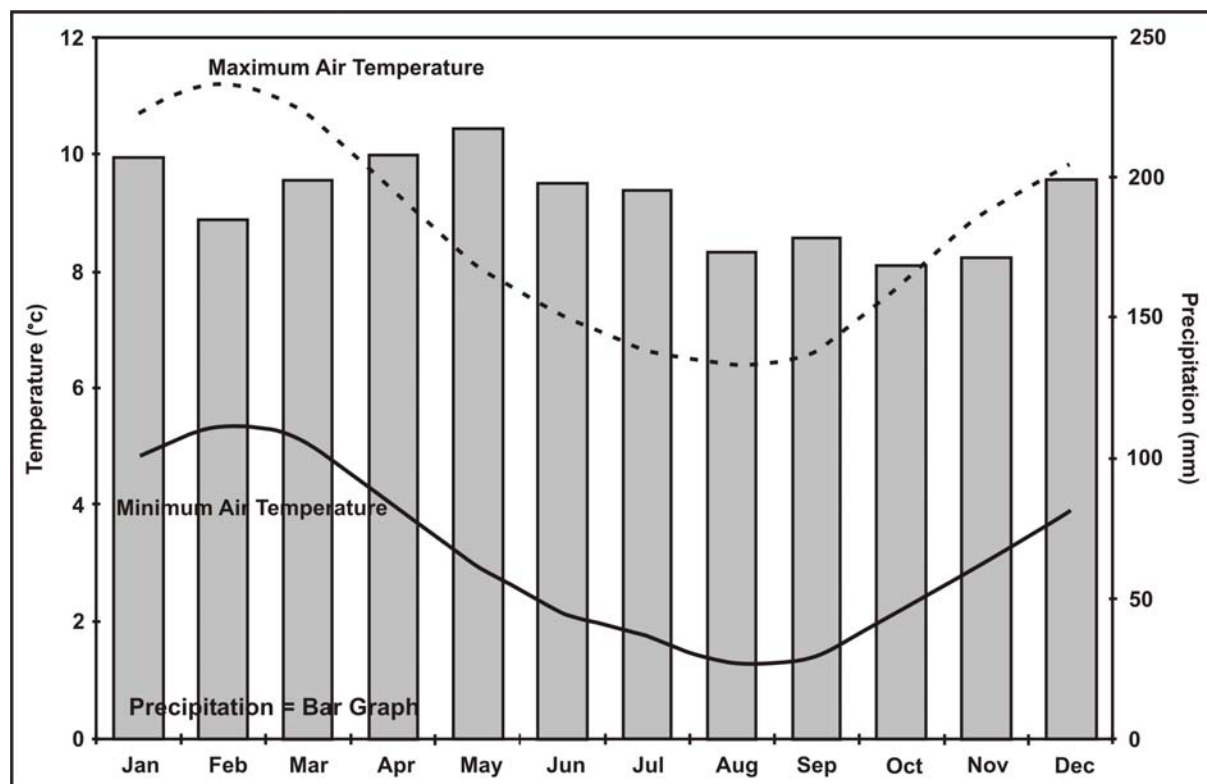
Figure 2.6: Monthly precipitation totals and monthly maximum and minimum average air temperatures. Derived from South African Weather Services data (1949-1999).

Fauna and Flora

Marion Island initially presents a very barren appearance as no trees or tall shrubs grow on the island (Holness, 2001a). The island is, however, densely vegetated at lower altitudes but due to its isolation, recent geological origin and harsh climate, still exhibits a limited diversity of plant species. Only 38 vascular species inhabit the island (Gremmen, 1981), but a wider variety of lower plants species, which includes 72 species of mosses, 35 species of liverworts and approximately 100 species of lichen, can be found (Smith, 1987). The rugged coast comprises a salt-spray community of *Cotula plumose and Crassulo moschata*, while well-drained areas mainly comprise *Poa cookii* tussock grassland. Lowland areas are characterised by poorly drained bogs and mires which are covered with carpets of Bryophytes in which *Agrostris magallanica* and *Acaena-Pringlea* communities often occur (Hall, 1978), while the exposed grey lava ridges support an open *Azorella selago* fjaeldmark with a low cover percentage (Holness, 2001a). Between 200 - 300m a.s.l. fjaeldmark communities dominate, while above 300m vascular are rare, and cryptogamic communities predominate (Huntley, 1971). At present the uppermost known limit of vascular plants, namely *Azorella selago*, is approximately 840m a.s.l., whereas during the visit of naturalists in 1873 aboard the H.M.S. Challenger the upper vegetation limit was recorded at 2000ft (approximately 600m a.s.l.) on the mountain slopes (Marsh, 1948) and 765m a.s.l. for *Azorella selago* in the mid-1960s (Huntley, 1970).

Despite the paucity of plant species, the isolated position and poor weather conditions there is a rich faunal assemblage as a result of proximity to the rich food source of the Antarctic Polar Convergence (Hall, 1978). Thus, Marion Island provides an extremely important site for breeding and moulting seabirds and ocean-going mammals (Hall, 1981a). In total, twenty-six species of seabirds breed at Marion Island, which Hall & Williams (1981) classified into three groups: (1) surface breeding species that can fly, (2) burrowing species that can fly, and (3) flightless surface breeding penguins. Each of these different groups of birds have their own particular erosive effect but the flightless penguins cause the most erosion and even affect bedrock by polishing and deep grooving the basalts, creating an almost 'glacial' appearance within penguin colonies.

Four penguin species, with a combined population of about 3.4 million individuals come to Marion Island to breed and moult: these are the king (*Aptenodytes patagonicus*), macaroni (*Eudyptes chrysolophus*), rockhopper (*Eudyptes chrysocome*) and gentoo (*Pygoscelis papua*). It is the movement of these birds, to and fro between their nests and the sea, which is the effective agent of erosion and as such erosion is particularly concentrated along the main route-ways between penguin breeding colonies and the sea (Hall & Williams, 1981). The island also supports approximately 10 000 southern elephant seals (*Mirounga leonine*) and an ever increasing population of Antarctic fur seals (*Arctocephalus gazella*) as well as sub-Antarctic fur seals (*Arctocephalus tropicalis*). Of the three seal species breeding on the island, only the southern elephant seal (*Mirounga leonine*) can be regarded as a significant erosive agent due to its tremendous weight compressing and eroding peat. The erosive impact of the southern elephant seal (*Mirounga leonine*) is, however, very small when compared to penguins, who can be regarded as the most effective erosive zoological agent on Marion.

Documented Environmental Change on Marion Island

Boelhouwers (2003) has highlighted that the maritime mid-latitudes may be particularly sensitive to cryospheric warming and can provide early clues to the changes in landscape dynamics resulting from climate warming. The highlighted sensitivity to cryospheric warming of Marion Island may be particularly important since environmental conditions in the southern hemisphere in which frost processes occur could be very different from those encountered in the northern high-latitude environments (Boelhouwers & Hall, 2002). Thus, a hyper-maritime (sub-Antarctic) perspective may provide the potential to help understand the basic driving mechanisms and boundary in permafrost and periglacial processes (Boelhouwers & Hall, 2002).

Sumner *et al.* (2004) illustrate that the observed shift in climatic conditions is now manifested in the recent and rapid melt out of the last remnants of glacial ice in the upper interior of Marion Island. Verwoerd (1971) described this residual glacier on Marion Island as having crevasses up to half a metre wide showing that the ice was slowly moving as recently as the mid-1960s in what is

presently known as the 'Ice Plateau'. Van Zinderen Bakker (1973) even suggests that ice tongues may have flowed from this ice mass in northern and south-western directions. The former permanent snowline has now also disappeared, considered to be associated with the recorded climatic change. In the 1950s, the former permanent snowline on Marion Island was situated at an approximate altitude of 2000ft (approximately 600m a.s.l.) (King, 1954). Some ten years later, Verwoerd (1971) indicated that the island had an average summer snowline between 650m and 850m a.s.l. Verwoerd (1971) also indicated that some of the summit peaks were snow free on the windward sides in late summer. Almost a decade later in the late 1970's Hall (1979) notes the existence of permanent snow and ice above 950m a.s.l. However, since the start of direct observations in 1996 no permanent snowline could be discerned on the island (Boelhouwers, 2003). This disappearance of the former snowline on Marion Island is further emphasised when it is highlighted that the first observation of snow on Marion Island was noted at 800 feet (approximately 270m a.s.l.) during a day visit on 26 December 1873, mid-summer, by naturalists aboard the H.M.S. Challenger but this observed snowline may not necessarily have been "permanent".

In addition, to the observed changes in climate (Smith, 2002; Rouault *et al*., 2005), disappearance of a former permanent snowline at an approximate altitude of 600m a.s.l. (King, 1954) and residual glacier (Fig. 1.1), in an area known as the 'Ice Plateau', there has also been a recognisable increase in thermokarst and mass movement features in areas underlain with glacial ice as well as surrounding areas not underlain with buried glacial ice (Sumner *et al*., 2004). These responses to climate change illustrate that significant environmental changes are presently under way not only in the areas underlain by glacial ice. The recent development of thermokarst features and recorded climatic change (Smith, 2002) indicate a strong climate-process relationship. Thus mapping and documenting these features as well as the present distribution of buried glacial ice, permafrost and seasonally frozen ground will provide a better understanding of the link between landforms, processes and climate.

Chapter 3: Methodology

Extent of the Project

The main aim of this study is to document the geomorphology and identify geomorphological responses to climate change in the interior of Marion Island above 750m a.s.l. (Fig. 3.1). Therefore, this research first requires the development of a comprehensive understanding of the geomorphological processes and landforms present on Marion Island as well as the periglacial environment in which these geomorphological processes and landforms occur. Second, the study entails the identification and mapping of existing geomorphological features, particularly in areas that are prone to shifts in geomorphological processes and subsequent landform development and maintenance. Third, the present state and form of geomorphological features within the interior of Marion Island are described to determine any geomorphological responses driven predominantly by climate. However, as is noted in Chapter 2, geothermal activity may have also had, and may still be having, an accentuating effect on geomorphological responses. Finally, monitoring any shifts in the state of the ground, the geomorphological processes and subsequent manifestation in the development of new or alteration of old landforms is required. This study will, therefore, include geomorphological mapping, describing and measuring mapped geomorphological features and associated environmental variables in the interior of Marion Island to finally provide the means with which to analyse the relationship between certain geomorphological processes and subsequent landform development and their related environmental factors, past and present.
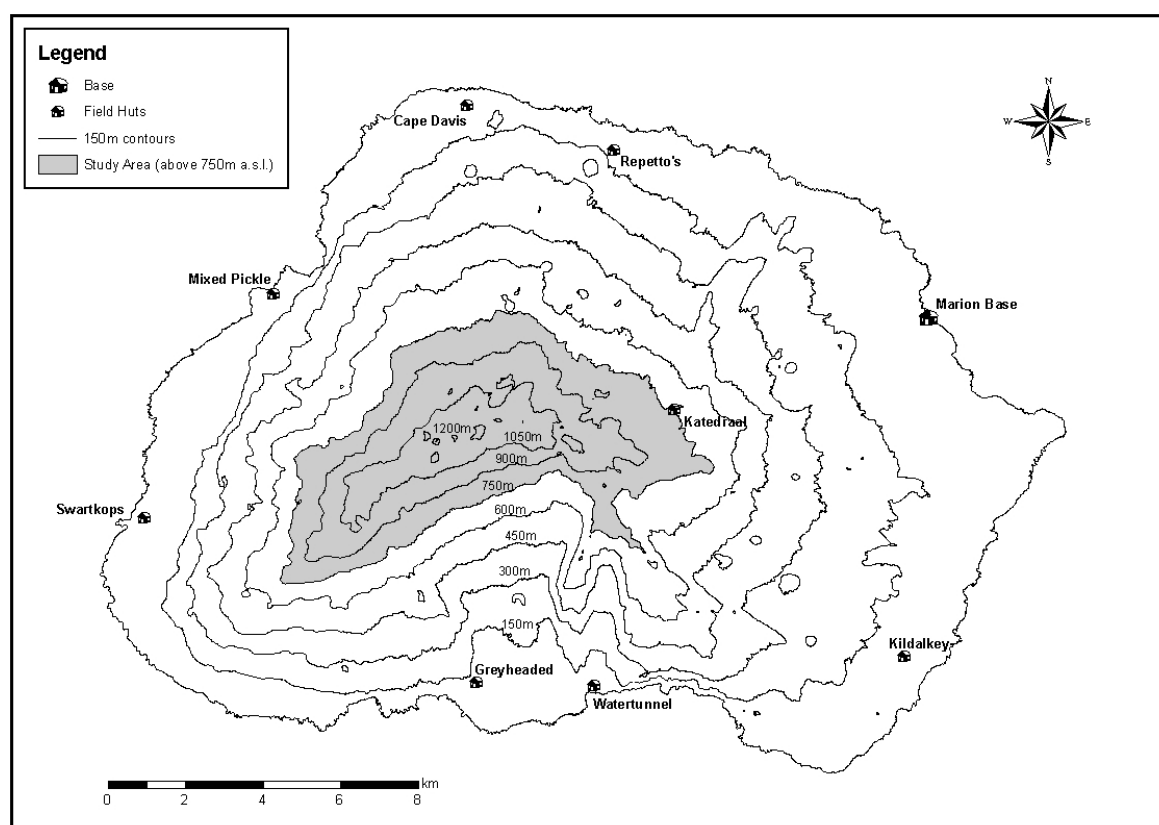
Figure 3.1: Study area in the upper interior of Marion Island (above 750m a.s.l.).

Theoretical Background

To identify and describe the geomorphology and geomorphological responses in the interior of the island, which is thought to be the result of the recognised climate amelioration on Marion Island (Smith, 2002), an extensive body of literature was perused from general texts on geomorphology (*e.g.* Summerfield, 1991) and periglacial geomorphology (*e.g.* French, 1996; Thorn, 1992) to specific papers on geomorphological mapping (*e.g.* Klimaszewski, 1982), thermokarst features and processes (*e.g.* Czudek & Demek, 1970; Higgins *et al.*, 1990) and geomorphological responses to climate change (*e.g.* Meadows, 1988; Eybergen & Imeson, 1989). The necessary theoretical and practical foundation was thereby provided to instigate the 12-month period of fieldwork on Marion Island between April 2004 and April 2005 and geomorphological interpretation thereafter. A broad and detailed theoretical foundation is necessary when cognisance is made that any study, qualitative or quantitative, of landforms and land-forming processes in the context of environmental change is an enormously complex task (Meadows, 1988). The complexity of studying landforms and land-forming processes is due to the many variables (*e.g.* climate, lithology, structure and vegetation), past and present, that play a role in geomorphological processes, landform development and even maintenance, which can all be mutually exclusive. The largely qualitative approach, namely the identification and description of landforms, adopted by this study is done in recognition of the argument made by Thorn (1992; p. 5) that "… although form alone has no explanatory power, explained form provides us with our only opportunity to link past, present and future. Consequently, we must treat process and form symbiotically, while recognising that process is pervasive. However, the form we identify and treat discretely is only a portion of a much larger related continuum". Therefore, geomorphology is more than simply the description of contemporary landscapes, it is the elucidation and explanation of their histories (Meadows, 1988) and possible futures.

Regardless of the scientific methodology adopted, there has been considerable contemporary interest in the natural sciences as it is hoped that they may offer new perspectives on global climatic and environmental change (Dixon & Abrahams, 1992). Periglacial environments, in particular, have received much attention in the context of global climatic and accompanying environmental change as it is in these environments where such changes will have their greatest impacts (Dixon & Abrahams, 1992). According to French (2000) the term "periglacial" was introduced by Lozinski (1909) to describe the landforms and processes occurring on the periphery of the Pleistocene ice sheets. Modern use of the term 'periglacial', however, covers a wide range of cold, non-glacial conditions, regardless of proximity to a glacier, either in time or space, and it is characterised by intense frost action and at least seasonally snow free ground (Summerfield, 1991). However, French (1996) recently described periglacial environments as those in which frost action and permafrost-related processes dominate. Despite these contrasting definitions, periglacial geomorphology is that part of geomorphology which has as its primary object physically based explanations of the past, present, and future impacts of

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diurnal, seasonal, and perennial ground ice on landform and landscape initiation and development (Thorn, 1992). However, it is also worth remembering that "any landform labelled periglacial may be periglacial only in origin, growth, or maintenance, or may be periglacial throughout its development" (Thorn, 1992; p. 10).

Marion Island embodies a periglacial environment that Boelhouwers *et al*. (2003) suggest to represent a distinct hyper-maritime periglacial environment; the hyper-maritime setting with low mean annual temperatures results in very high frost cycle frequencies, and associated effectiveness in surface sediment transport and patterned ground development. The small seasonal temperature ranges and steep temperature profiles of Marion Island thus facilitate its high sensitivity to climate change in the sub-Antarctic (Boelhouwers *et al*., 2003), illustrated by the recent recognition of the geomorphological responses in the summit regions to the highlighted climate change by Smith (2002) on Marion Island (Sumner *et al*., 2004). These observations endorse the broad concept of climatic geomorphology postulating that different climates, through their effects on processes, produce unique assemblages of landforms (Meadows, 1988). Even though this concept is overly simplistic by sacrificing precision for generalisation (Fig. 3.2) this is not an error, providing it is done consciously (Thorn, 1992). Thus, notwithstanding its flaws, described in detail below, climatic geomorphology has become entrenched in geomorphology and dominated a good deal of geomorphological research in the past (*e.g.* Derbyshire, 1973; Derbyshire *et al*., 1979); primarily, as climate has an influence on the rate or frequency of many geomorphological processes (Nyberg & Lindh, 1990).

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┌──────────────┐        ┌──────────────┐        ┌──────────────┐
│   Climate    │ ─────▶ │   Process    │ ─────▶ │   Landform   │
└──────────────┘        └──────────────┘        └──────────────┘
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Figure 3.2: The concept of climatic geomorphology.

Much of current periglacial and geomorphological research has turned to process-based studies since climatic geomorphology has many shortcomings (Thorn, 1992). Among the more obvious flaws cited are: the disparate and inappropriate criteria used to establish climatic zones; failure to establish climate-process links; inadequate corroboration of process-form links: and uncertainty of temporal relationships between meteorological and/or climatic inputs and geomorphological responses (Thorn, 1992). In addition, the same geomorphological processes can occur under different climatic regimes and different processes within the same climatic regime can produce the same landforms or products (convergence of form). Sumner *et al*. (2004) present evidence that the similarity of weathering products across different environments can be attributed to the recognition that thermal changes, the actual driving force behind thermally induced rock weathering, tend to be azonal and thus question the concept of process zonality. Moreover, if one uses a climatic geomorphological approach it is particularly pertinent to highlight that climate in itself is a complex phenomenon and as Stoddart

(1969; p. 210, cited in Meadows, 1988) has noted: "… while climatic factors are important, they are not necessarily dominant: landform geometry results from a complex interplay of climate, lithology and structure and vegetation… To isolate a single group of factors is unrealistic and distorting…" In addition geomorphological features are usually more sensitive to changes in precipitation than temperature but, as is noted above, the precise nature of a climate-landform relationship is rarely, if ever, clear (Meadows, 1988). It is pertinent to highlight that the time it takes processes to adapt to a different climate regime can take longer than the actual climate change itself (Brunsden, 1996). Therefore, it is also imperative, when studying landforms as indicators of processes and ultimately climate, to examine these factors and take them into consideration (Nel, 2001). Brunsden (1996) illustrates this point through the theory of persistence of form where the lifetime of a landform can be defined as the sum of the successive time intervals between the formation and the erosion on the landform created, and that all landforms have a specific life expectancy (Nel, 2001). Nevertheless, climatic geomorphology founded the concept of the development of characteristic forms (Brunsden & Thornes, 1979), which Priesnitz (1988; p. 64, cited in Thorn, 1992) expressed succinctly as "constant climates cause characteristic forms". Such a view requires one-to-one correspondence between climate and geomorphological process as well as between process and form under ideal circumstances (Thorn, 1992) but as is stated above this is almost never the case. Therefore, it follows that only in specific instances when certain climatic thresholds are maintained, or exceeded in certain environments, do specific landforms develop.

Thermokarst features and processes predominantly represent a climate process response distinct, or peculiar to, regions underlain by permafrost. Although it should be recognised that in addition to climatic amelioration, the destruction or removal of vegetation, fires and geothermal activity can also initiate thermokarst processes and the development of thermokarst topography. The removal of vegetation and/or fires can be excluded as environmental initiators of thermokarst processes and resultant features since the area under investigation on Marion Island (above 750m a.s.l.) is almost entirely devoid of vegetation. Only climatic amelioration and geothermal activity remain to provide plausible environmental variables responsible for the presence of thermokarst processes and features on Marion Island. Furthermore, even though Marion Island is a volcanic island with volcanic activity and it's inherent geothermal activity having been observed in 1981 (Verwoerd, 1981) and as recent as 2004 by the author (Meiklejohn & Hedding, 2005), the hypothesis that geothermal activity on Marion Island has initiated and/or is maintaining the melt out of the interior of Marion Island is only considered to provide a secondary or contributory role due to both the localised nature and small scale of the observed geothermal activity on the island. Climatic amelioration, documented by Smith (2002) for Marion Island, suggests that climatic warming is the primary environmental factor driving geomorphological responses, predominantly in the form of thermokarst processes and features. Therefore, despite the obvious objections of solely linking climate to landform

development as well as taking into account the complex relationship that exists between climate and landform development in itself, the concept of climatic geomorphology does in specific instances, as is present in this study with the use of thermokarst features, warrant application to indicate geomorphological responses to climate change.

Ground and Atmospheric Monitoring

The lack of climatic, namely air temperature and precipitation, data for the interior of Marion Island necessitated the need to obtain such records to provide a basic climatic setting for this area. This is especially so when considering that atmospheric environmental lapse rates of approximately 4.5°C in winter and 4.0°C in summer per 1000m (Hall, 1978) occur resulting in the air temperatures in the interior of Marion Island to be much lower but are as yet largely unknown apart from the data provided by Blake (1996). An air temperature sensor was thus installed at approximately 975m a.s.l. to the south west of No Name Peak (Fig. 3.3) to record daily minimum and maximum air temperatures. Two automatic rainfall gauges, one at approximately 800m a.s.l. near the Ned's South ground temperature logger site and the other at approximately 975m a.s.l. near the air temperature logger were installed (Fig. 3.3). Precipitation data for the interior of Marion Island is of great importance since it would allow for a general altitudinal trends to be determined. However, as Harris & Corte (1992) highlight determining the actual amount of precipitation (water equivalent) at a given site in mountain permafrost areas can be problematic because snow can be redistributed by wind.

Air temperatures are not necessarily a good indicator of ground temperatures (French, 1996) and therefore direct ground temperature monitoring was conducted to provide an accurate ground temperature record, which in turn could be used to determine the thermal characteristics of the ground, above 750m a.s.l. Ground temperature data covered an 11-month period from mid-May 2004 to late-April 2005. The limited time period of ground temperature monitoring was pre-determined, as sensors could only be maintained in the field during the 12-month period of fieldwork on the island. Six sites above 750m a.s.l. were chosen to describe the ground thermal characteristics of the study area as well as to investigate impacts of altitude and aspect on ground temperature regimes. These six ground temperature sites were split between north and south-facing slopes at corresponding altitudes (800, 900, 1000m a.s.l.), in a homogenous substrate (Fig. 3.3). The chosen altitudes were mainly decided upon due to accessibility but also, owing to budgetary constraints, there were not enough ground temperature sensors to be placed at the uppermost altitudes on the island (above 1000m a.s.l.).

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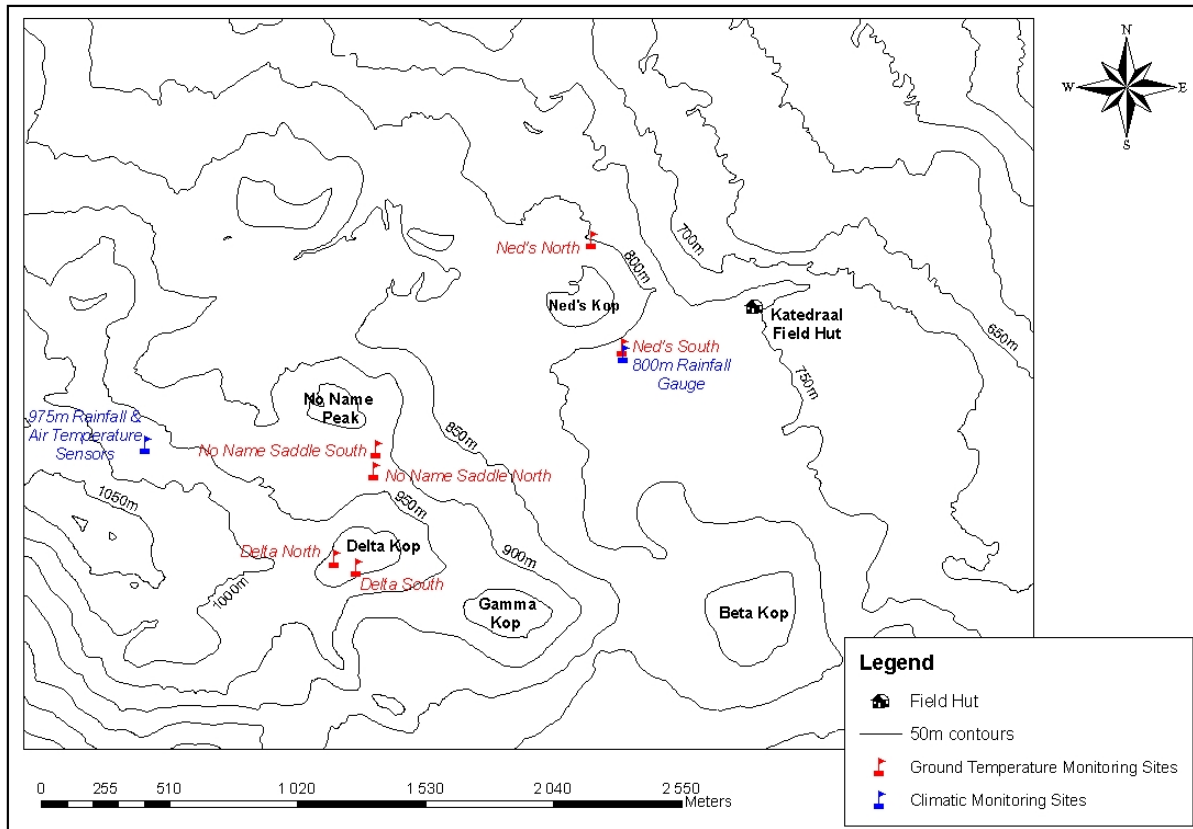
Figure 3.3: Location of ground temperature and climatic monitoring sites (above 750m a.s.l.).

Monitoring ground temperatures in the upper interior of Marion Island will assist in determining the present distribution of permafrost versus seasonally frozen ground. Surface as well as subsurface ground temperature values were recorded by monitoring daily minimum and maximum at equal depths apart in the ground (*i.e.* -0.01m, -0.25m, -0.5cm, -0.75m) to investigate the affects of surface insulation and depth of active layer on ground thermal dynamics. Each ground temperature logger constituted a Mike Cotton 4-channel logger, comprising of thermistor sensors which have a thermal measuring range of -20ºC to +70ºC, accuracy of ±0,2ºC at 25ºC and resolution of ±0,1ºC.

In order to assess the effects of aspect and altitude on ground thermal dynamics, sensors were placed at selected altitudes (800m, 900m and 1000m a.s.l.) on both north and south aspects at each different altitude (Fig. 3.3). In addition, field excavations across wind swept and lee-side areas in the interior, conducive to the development of permafrost and existence of buried glacier ice, were conducted to determine the presence or absence of permafrost and buried glacial ice. Therefore, ground temperature monitoring at set depths on different aspects at various altitudes described above will provide a more comprehensive picture of the possible extent of permafrost versus seasonally frozen ground. Investigation of the upper-most altitude at which ground conditions remain suitable for vegetation to survive will also be of interest.

Geomorphological Mapping

Cooke & Doornkamp (1990) note that geomorphological mapping is both subjective and dependent upon the skill of the mapper; whereby the subjectivity is highlighted in the choices made over what to include, and skill (allied to experience) shown not only in the accuracy of plotting but also in the ability to recognise land features and their relationships (Cooke & Doornkamp, 1990). Geomorphological mapping, nevertheless, represents the best approach to analyse the spatial distribution of surface form, materials (soil and rock), surface processes and (in some cases) the age of landforms and therefore will be used as a component in this study. A detailed map of the spatial distribution of features such as landforms, soils and rock materials, or features created by surface processes (Cooke & Doornkamp, 1990), provides an unrivalled way for a researcher to become familiar with landforms of an area, and it provides a basis for additional analytic studies (*e.g.* Nel, 2001). Furthermore, geomorphological maps act as a great stimulus to thought concerning both the relationship between forms, materials, and processes, and the manner of landform development (Cooke & Doornkamp, 1990).

Mapping Procedure

The most successful approach to geomorphological mapping is to combine field inspection with air-photo interpretation (Cooke & Doornkamp, 1990) but as no true geomorphological mapping system has previously been developed for Marion Island and for reasons of comparison and standardisation, there is no need to introduce a new legend within this dissertation, but rather apply a widely accepted procedure (Nel, 2001). These mapping schemes proposed by the International Geographic Union (IGU) are laid out in the *Manual of Detailed Geomorphological Mapping* (Demek, 1972) and in the *Guide to Medium-scale Geomorphological Mapping* (Demek & Embleton, 1978). The IGU system is widely known for its concepts and principles but a major complaint, highlighted by Leser (1974, cited in Boelhouwers, 1988), is that although a very elaborate legend has been compiled (500 units), little flexibility actually exists inhibiting the provision of detailed information. According to Meijerink *et al*., (1983 cited in Boelhouwers, 1988), the International Institute for Aerial Survey and Earth Sciences constructed the International Training Centre (ITC) system based on the IGU principles but rather than creating an extensive list of legend units, the ITC system is kept flexible for adjustment to local differences in landforms as well as including some degree of synthesis, which is contrary to the purely analytic approach in the French and IGU legends (Boelhouwers, 1988). Verstappen (1970, cited in Boelhouwers, 1988) indicates that this is realised by allocating coloured areas to major landform units (*e.g.* moraines), which in practice tend to coincide with landsystems. An advantage of this approach is that major legend units can be detected from aerial photos prior to field survey (Nel, 2001). Minor genetic landforms are indicated by black line symbols, while overcrowding can be avoided to improve readability by the construction of complimentary maps (Nel, 2001). It is evident that for reconnaissance mapping, the ITC system is to be preferred because it follows

internationally agreed upon concepts, has a high degree of flexibility, good readability and is widely used (Boelhouwers, 1988). Thus Nel (2001) utilized only the ITC working procedure and not the ITC system, outlined by Boelhouwers (1988), adapted from Verstappen (1970) and Verstappen and van Zuidam (1975), to map periglacial, glacial and mass movement features on the grey lava areas of the eastern side of Marion Island.

In creating the maps of the study area, the approach previously utilised by Nel (2001) will be adopted in which the ITC working procedure, outlined by Boelhouwers (1988), adapted from Verstappen (1970) and Verstappen & van Zuidam (1975) as it also suits this study (Fig. 3.4). The mapping component of this study, as with Nel (2001), will follow the adaptation made by Boelhouwers (1988) in that preliminary maps will only be created after the field surveying stage as many of the landforms cannot be identified from aerial photographs; first, because many of the features are too small to be detected in the aerial photographs and second, because aerial photographs of much of the interior of Marion Island is covered in snow hampering the identification of geomorphological features.
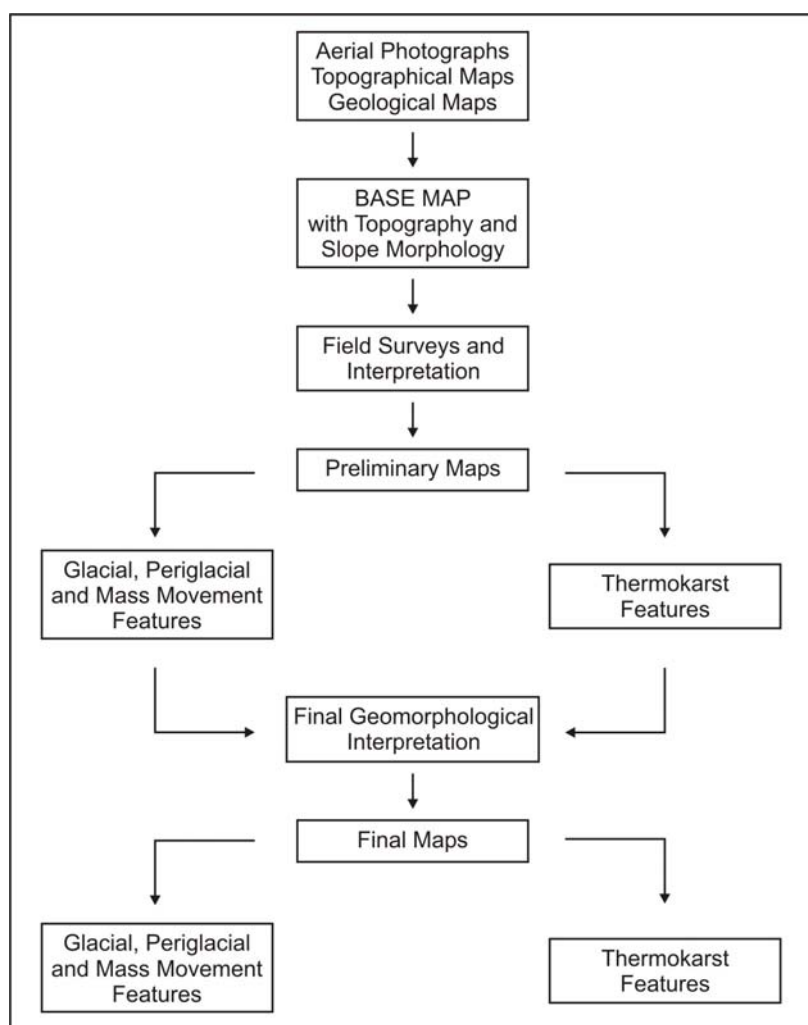
Figure 3.4: Flow diagram of the adapted working International Training Centre (ITC) procedure to map the geomorphological features in the interior of Marion Island (Adapted from Boelhouwers, 1988).

The strategy adopted to map the geomorphological features on Marion Island was to compile existing background information, where available, in the form of literature, maps and aerial photographs. In particular, the Volcanological Map of Marion Island, produced by Verwoerd & Lagenegger (1968), depicting the geology and the extent of the former snowline and ice, which existed at the time the map was produced, provided a considerable amount of baseline information and in essence presented the starting the point for this study. The geology of the island controls the presence or absence of many of the geomorphological features and, therefore, determines the spatial interaction between geology and landforms. Furthermore, as the broad geochronology of Marion Island is known (McDougall, 2001) it provided insight into the temporal interaction with regards to landform development, maintenance and possible alteration.

Although the Volcanological Map (Verwoerd & Lagenegger, 1968) provided an essential platform from which to start this study the map itself is not complete due to the presence of a permanent snowline obscuring much of the geology above approximately 650m a.s.l. In addition the mapped geology is not entirely correct due to the difficulty of surveying on the island highlighted above. This became principally evident when comparing the Topographic Map, also produced by Verwoerd and Lagenegger (1968), to the current, but still not completely accurate, topographic map of Marion Island (Provisional Map March 2005). Herein lay the starting point of mapping component of the study to digitise and rectify the geology of the island, which had been previously mapped by Verwoerd and Lagenegger (1968) as well as map the geology of the interior of Marion Island which has now been sub-aerially exposed after the disappearance of the former permanent snowline on to the more accurate topographic data. A task accomplished through examination of digital aerial photographs, where available, and subsequent ground proofing of areas in question through field surveys. Whilst this is not a geological study, an accurate geological map, particularly of the interior, is essential in the spatial analysis of geomorphological features and geology when determining the potential areas prone to contemporary geomorphological responses, mostly in the form of thermokarst and mass movement and features, to climate change as opposed to areas that are largely geomorphologically inert to climate change such as black lava flows.

Once a base map comprising of a topographic and geological information appropriate for the mapping component of this study had been constructed (*i.e.* mapping of previously unmapped areas and rectification of the mapped geology on to a more accurate topographic map), the field surveys and subsequent mapping of geomorphological features could then be concentrated in areas deemed prone to potential geomorphological responses and formation of features indicative of environmental change. As such, black lava flows are excluded from the mapping since they are non frost-susceptible and contain insufficient moisture for needle ice growth (Boelhouwers *et al.*, 2001). Even the development of mass movements is limited due to the nature of black lava deposits on low slope angles (Nel, 2001).

In addition, whilst mapping previously undocumented periglacial, glacial, mass movement and aeolian features, the verification of previously identified landforms, mainly striations and their directions, was also incorporated where possible.

The interior of the Marion Island, above 750m a.s.l. (Fig. 3.1), has been demarcated as the area of investigation because, first, it represents the lower limit of seasonally frozen ground (Boelhouwers *et al.*, 2001) and thus constitutes the only remaining area on the island which can support permafrost and buried glacial ice (above 1000m a.s.l.). Therefore, certain geomorphological features, indicative of environmental change, can only develop in this fragile periglacial environment. Second, the size of the island itself coupled with the difficulty of the terrain and adverse weather conditions limited the possibility to map the entire island in the time available. It must also be noted that full geomorphological mapping, even of the interior, is beyond the scope of this study; full geomorphological mapping includes information on morphography, morphometry, morphogenesis and morphochronology (Boelhouwers, 1988) and the ITC system classifies only broad landscape units. In addition, for the mapping component of this study the ITC system is not applied but only the procedure. Therefore, the mapping component of this study will not culminate in a full geomorphological or even a comprehensive map of all features but rather a thematic map of glacial, periglacial and mass movement features with a particular focus on geomorphological features indicative of environmental change.

Geographical Information System (GIS)

The spatial differentiation of several factors of the physical environment (*i.e.* geology, climate, vegetation and soil) have been presented on maps since the middle of the Nineteenth Century (Klimaszewski, 1982 cited in Boelhouwers, 1988). With the advancements in technology (*i.e.* technical, magnetic, electronic, *etc.*), which cartographers have usually been quick to borrow and adopt (Robinson *et al.*, 1995), maps no longer only need to represent a two-dimensional analogue image and they have become a digital record of spatial information that can now be represented in the form of a three-dimensional image. Thus, spatial information has become managed by specifically-designed Geographic Information Systems (GIS) to serve, not only environmental needs, but also cartography in general (GIS has also been used as the abbreviation of Geographic Information Science but in this study GIS will refer to Geographic Information Systems unless otherwise stated). For example mapping surface form, which is an important component of many geomorphological studies, has in the past been based on a system of morphological mapping that depends on the recognition of the junction between slopes of differing steepness, cliff forms, and both the amount and direction of slope (Cooke & Doornkamp, 1990). The map is constructed by recording the nature and position of slope junctions, and by placing a V-symbol on the steeper side of the line (and pointing downhill; Cooke & Doornkamp, 1990). Generally slope direction arrows are included and steepness of slope

may be shown as a numerical value or as a shading (or colour) to identify a steepness class (Cooke & Doornkamp, 1990). But, to the untrained eye, these morphometric maps are generally difficult to read and/or obtain useful information. Many GIS's, now utilise algorithms to interpret a surface, or a three-dimensional model known as a Digital Elevation Model (DEM), using contour data. Notwithstanding the fact that contour data are only an imperfect reflection of surface form (Cooke & Doornkamp, 1990) these DEM's, depending on the resolution of the contour data, can produce a realistic representation of surface form, which is easily understandable and readily provides useful information on slope steepness and aspect. In addition, the flexibility of a GIS allows the prompt classification of slopes into any number of classes (*e.g.* Demek, 1972) as slope gradient is the most important morphometric variable for many processes and applications (Goudie *et al*., 1998), particularly in the formation of mass movement and solifluction features. Therefore a GIS can be utilised to measure and classify slope steepness to identify oversteepened slopes and investigate their spatial relationships on Marion Island. Previously identified oversteepened slopes (Boelhouwers, 2003) are thought to be the result of ice cementing due to the extremely porous nature of the scoria. In summation, GIS's concentrate on doing, by machine, many operations that were formerly painstakingly done by hand (Robinson *et al*., 1995) that provide prompt integration of spatial information to analyse spatial relationships between mapped features and the flexibility to display these features and relationships in a variety of different ways. Thus, a GIS provides a fast and efficient way to map features but more importantly provides an effective means to analyse spatial relationships.

The availability of relatively cheap hand-held Global Position System (GPS) receivers from the 1990s has opened new opportunities for detailed and rapid mapping of features, including those biological (Underhill *et al*., 2003). These opportunities were further enhanced by the removal, on 2 May 2000, of "selective availability" by the United States Department of Defence, whereby position fixes had been substantially degraded (Underhill *et al*., 2003). The boundaries of all features for the mapping component of this study were mapped using a stand-alone handheld Garmin Summit GPS, which were then recorded within a GIS to enable relatively accurate plotting and increase the accuracy of the spatial analysis of geomorphological features with environmental variables. Coordinates were recorded to a tenth of a second and these represent approximately 1.8m of latitude and 1.3m of longitude at the latitude of Marion Island. Even with the removal of selective availability, the resolution of the coordinates using a stand-alone handheld GPS units are not as fine as this and errors in coordinates can be expected to be approximately an order of magnitude larger (Merry, 2000). This level of accuracy is, however, deemed sufficient, as the symbols used on the maps generally do not indicate each individual feature but rather the area where these features are located.

As stated above, an initial requirement to the mapping component of this study was the construction of a complete and accurate digital geological map for Marion Island. This required that

the analogue Volcanological Map produced by Verwoerd & Lagenegger (1968) be imported into a GIS, in this case the ESRI software package ArcGIS 9, geo-referenced and then digitised. The 10m contour map of Marion Island obtained from the Chief Directorate: Survey and Mapping was interpreted from a DEM generated using data from RADARSAT[TM] (Radarsat International, Canada) and SPOT[TM] (Spot Image, France) satellite imagery. Subsequently, contour data was made available as shapefiles within ArcGIS 9, however, the contour data provided required editing in the form of interpolating missing contour lines and joining broken contour lines. Correcting attribute data was also required which involved checking the data linked to the spatial data and correcting any missing and/or incorrect data associated with the spatial data. The need for a better topographic map of Marion Island arose as all previous contour maps of the island were either not complete (*e.g.* Provisional 2005 Map, 2005) or were produced at a scale insufficient for the mapping of geomorphological landforms (*e.g.* Verwoerd & Lagenegger, 1968). In addition, mapping of geomorphological features in relation to aspect, slope gradient and altitude are extremely important in terms of spatial relationships and thus necessitated the creation of a topographic map with a better spatial resolution onto which these features could be mapped analysed. Thus, once an accurate and complete topographic map had been constructed within a GIS, mapping of the geomorphological features could simply be done by plotting mapped coordinates, using a stand-alone handheld GPS into the GIS to be mapped and analysed assisting in providing a geomorphological interpretation of the upper interior of Marion Island.

Description of Geomorphological Features

Glacial, periglacial, mass movement and aeolian features that were mapped, and which are present in the map legends, are described in literature as follows:

Glacial Features

Glacial features, namely moraines, striations and *roches moutonnées*, found on Marion Island generally date from the last major glaciation which affected the island between 18 000BP and 13 000BP (Hall, 1978). Most of these features have previously been mapped, apart from the upper interior and western half of the island (*e.g.* Hall, 1978; Nel, 2001) where the previous presence of persistent snow cover and difficulty of the terrain prevented geomorphological mapping of the interior of the island and western half of the island. With climatic amelioration the snow cover in the interior of the island, which used to persist throughout the year down to an altitude of 2000ft (approximately 600m a.s.l.; King, 1954), has now disappeared during the some summer months exposing many previously unseen relict glacial features, such as moraines and striations, in the interior of the island. Many *roches moutonnée* type features have also now been observed in the interior of Marion Island, indicative of unconfined ice flow. Moraines are landforms composed and produced by till, a highly variable deposit laid down by ice and can occur parallel, transverse or may even in some cases lack orientation with ice flow. Thus lateral moraines, formed parallel to the direction of ice flow

(Summerfield, 1991), and end moraines, formed perpendicular to the direction of the ice movement along the front of a glacier (Sumnnerfield, 1991), can be used to depict the lateral and maximum extent of palaeo-ice flow respectively (*e.g.* Hall 1980a; 1980b and 1983a). Striations, produced by the scouring action of rocks frozen into the base of a glacier (Whittow, 2000), typically demonstrate the direction of former ice movement. Therefore, in mapping the direction of glacial striations and delineating glacial margins through the identification and mapping lateral moraines it will be possible to provide a more comprehensive interpretation of the palaeo-ice flow particularly for the interior of the island, at least, during the Holocene.

Thermokarst Features

The term "thermokarst" was first proposed by the Russian M.M. Ermolaev (spelt M.M. Yermolayev in Czudek & Demek, 1970) in 1932 to describe irregular hummocky terrain due to the melting of ground ice (French, 1996). Subsequently the term has been applied specifically to the process of ground ice melt accompanied by local collapse or subsidence of the ground surface (French, 1996). Although Dylik (1968) argued initially to reserve the term for the melting of underground ice as opposed to buried glacial or surface ice, but it is now accepted that the word 'thermokarst' applies to the melting process of all ground ice bodies, irrespective of origin. Importantly thermokarst depressions by definition are a record of present or former permafrost, and if they occur in a non-permafrost environment and buried glacial ice can be excluded, they are evidence of a former permafrost regime of a climatic change (Washburn, 1980).

Thermokarst processes encompass a whole range of geomorphological effects from subsurface water on landforms in permafrost regions (Higgins *et al*., 1990). Of the various processes included within the term 'thermokarst', Czudek & Demek (1970) have proposed the basic distinction between thermokarst subsidence and thermal erosion but it is pertinent to remember that these processes are not mutually exclusive and in mature stages of thermokarst development can thus operate simultaneously. Thermal erosion is a dynamic process involving the 'wearing away' by thermal means, *i.e.* the melting of ice (French, 1996). The easily identifiable characteristics of thermal erosion are flowing water, a slope and ice which can be melted. By contrast, thermokarst subsidence is 'thermal solution' or more precisely 'thermal melting' whereby the loss of water then results in subsidence (French, 1996).

From a geomorphological point of view, thermal erosion generally results in lateral permafrost degradation or backwearing while thermokarst subsidence results in permafrost degradation from above or downwearing (French, 1996). Ground ice slumps, thermo-erosional niches and thermokarst (thaw) lakes are some of the more distinctive features developed through permafrost degradation which takes place as a result of cliff retreat, lateral river erosion, and marine or lacustrine abrasion (French, 1996). Permafrost degradation from above mainly occurs on flat terrain and is a process of

subsidence and collapse of the ground surface (French, 1996). Where it operates over extensive areas, the end result is the destruction of the original surface relief and the creation of a new thermokarst relief, incorporating closed depressions, collapse features and hummocky terrain, at a lower elevation (French, 1996).

In the area known as the 'Ice Plateau', the presence of buried glacial ice beneath insolation protecting scoria has initiated the development of additional features in form of ice caves and dolines into which the meltwater streams disappear. The melt water streams exhibit a deranged or beaded drainage pattern indicating that there has been insufficient time for the drainage to become adjusted to the underlying topography. This area also displays a somewhat inverted topography, attributed to insolation protecting scoria overlying buried glacial ice whereby the ice limited scoria cover largely prevents the melt out of the buried glacial ice from above.

Mass Movement Features

Only specific mass movement features, namely screes, debris flows and thaw slumps, were observed and mapped in the upper interior of Marion Island. At lower altitude, however, both translational and rotational slides, together with debris flows, constitute the predominant contemporary rapid mass movement features in peat areas that overly grey and black basaltic lava on sub-Antarctic Marion Island (Nel *et al*., 2003). Screes, as described by Nel *et al*. (2003), are open block deposits from rockfall origin that are superimposed on slope material. Debris flows are triggered by sediment mobilisation upon saturation of the frost-heaved surface gravel and overland flow over the low-permeability and frost susceptible slope materials (Boelhouwers *et al*., 2000). These features are, however, short-lived because it was observed that they were obliterated by subsequent frost heave activity (Hall, 2002), and erosion from melt out water specifically where debris flows were found overlying snow (pers. obs). Thaw slumps, arcuate embayments facing downslope, formed by the exposure and thawing of ground ice (Summerfield, 1991) are extremely conspicuous on the slopes of scoria cones in the interior of Marion Island.

In addition, mass movement landforms previously identified on Marion Island include stone and Azorella-banked lobes and terraces (Hall, 1981b; Hall, 1983b; Holness & Boelhouwers, 1998) and solifluction or gelifluction (at higher elevations) terraces (Holness & Boelhouwers, 1998). Only stone-banked lobes and solifluction or gelifluction lobes/terraces/sheets comprising of grey lava material and scoria material respectively exist above 750m a.s.l. Stone-banked lobes are described by Benedict (1970) as "lobate masses of rocky debris underlain by relatively stone-free, fine-textured, moving soil (p. 176)" and Embleton & King (1975) describe these landforms as "gelifluction and other deposits confined by crescent shaped stony embankments (p.112)". A 'typical' stone-banked lobe on Marion Island has an unvegetated tread, which shows signs of sorting and may even exhibit sorted stripes or

polygons on its surface (Hall, 1981b). Holness & Boelhouwers (1998) divided stone-banked lobes into two groups based on material composition. Lobes with blocky risers are associated with material supply from bedrock outcrops, while those with platy fronts appear to be the result of transport processes in till (Nel, 2001). Lobate forms, which have a larger horizontal extent than tread length are mapped as terraces.

Periglacial Features

Sorted stripes (Hall, 1979; Holness, 2001b), circles (Holness, 2003), polygons and nets (Hall, 1983b; Holness & Boelhouwers, 1998, Nel, 2001) have been previously documented on Marion Island. Collectively described as patterned ground, they represent some of the most common features in periglacial environments (Summerfield, 1991). The term 'patterned ground' is given for more or less symmetrical forms that are characteristic of, but not necessarily due to, frost action (Washburn, 1956). Washburn (1956; p. 827) describes sorted circles as features "whose mesh is dominantly circular and which have a sorted appearance commonly due to a border of stones surrounding fine material". Derbyshire *et al*. (1979) follow on to indicate that when the margins of sorted circles merge they are then known as sorted polygons. It is clear that descriptions of sorted patterned ground, circular forms (mounds of fines bordered by coarser material) in particular, can be both arbitrary and subjective in nature and, therefore, requires that these features be mapped as sorted polygons to keep maps objective and constant in this study.

A pronival (protalus) rampart (Hedding, 2003), defined as a ridge or ramp of debris formed at the downslope margin of a snowbed or firn field (Shakesby, 1997), in the interior of Marion Island has been included in this study. Hedding (2003) proposes a retrogressive mode of genesis representing a geomorphological response to climate change on the island whereby a decreasing snowbed size maintains a retrogressive mode of development, alternate to the conventional downslope (outward) development of pronival ramparts proposed by Ballantyne & Kirkbride (1986) for the orthodox supranival mechanism of debris transport. Blockfields and blockstreams documented for the area known as the "Feldmark Plateau" on Marion Island (Holness & Boelhouwers, 1998; Sumner & Meiklejohn, 2004) illustrate a previously more intense periglacial period in this area but none have been identified in the upper interior of the island.

Aeolian Features

As vegetation cover is extremely scarce in scoria areas in the interior, aeolian processes and subsequent features prevail owing to the consistent high wind speeds (32km/h) recorded at the meteorological station on the island. Even at lower elevations where vegetation is more dense some areas exist where aeolian features dominate the landscape contrary to the apparent lack of these features observed by Gribnitz *et al*. (1986). The main limiting factors for the effectiveness of aeolian

processes are vegetation cover, low wind velocities, particle size of sediment in this case scoria and the cementing of water in peat areas and ice in permafrost areas. Therefore, the upper interior of Marion Island is susceptible to aeolian processes due to consistent high wind velocities, a lack of vegetation cover and increased availability of sediment (scoria), provided through the transition of permanently to seasonally frozen ground. In addition, new fines may also be created through the continued breakdown of clasts into smaller pieces by weathering processes. For instance Sumner (2004) indicates that extrapolated values from mass loss data from Marion Island over a time period of 3 years that black lava clasts can weather completely within 200 years and grey lava clasts within approximately 1000 years at high altitudes.

Aeolian processes also contribute to the rapid destruction of thermokarst features (*e.g.* thaw slumps and kettle topography) and modification of periglacial features (*e.g.* sorted stripes and solifluction features). Sorted stripes have already been investigated by Hall (1979) but other wind-modified periglacial features, namely solifluction features have not been described. In addition, aeolian features themselves have only recently been described on the island by Callaghan (2005). Whilst Callaghan (2005) provides the first insights into the characteristics and proposed mechanisms of development of aeolian features on Marion Island these findings still have to be compared with studies of aeolian features on other sub-Antarctic islands (*e.g.* Löffler, 1983; 1984). Some findings of Callaghan (2005) will be discussed in more detail in the next chapter, which highlights the future potential of aeolian features to sculpt the interior landscape of Marion Island in light of climate change.

Geomorphological Evidence for Environmental Change

Geomorphology is more than simply the description of contemporary landscapes, but rather the elucidation and explanation of their histories (Meadows, 1988). Thus in documenting and describing geomorphological features all previous geomorphological (*e.g.* Hall, 1978; 1980a; 1980b; Holness & Boelhouwers, 1998; Boelhouwers *et al*., 2001; Holness, 2001a; Nel, 2001) and other appropriately related research (*e.g.* Verwoerd, 1971; Smith, 2002) from Marion Island was collected to furnish the quintessential environmental background from which to provide a geomorphological interpretation, for the interior of the island. A solid theoretical background is necessary in recognition that the concept of change through time is one of the most important factors in Geomorphology, and analysis of landforms can take place only with an appreciation of their historical development against the backdrop of environmental variability (Meadows, 1988). Furthermore, whilst remaining aware of the objections regarding convergence of form, the most geomorphologically productive measurements of Earth surface form are those which relate form to process in some way (Goudie *et al*., 1998). For example, in certain instances, when an equilibrium between form and process can be assumed, this relationship can be exploited in both directions. Therefore, the correlation between landform

characteristics and process variables can be used to interpret the physical adjustment of the landscape to prevailing process regimes, while at the same time process variables can be predicted from landform characteristics (Goudie *et al*., 1998). This provides the context within which to document geomorphological features and environmental variables in the island's interior.

A focus will, therefore, be placed on documenting geomorphological evidence illustrating responses of buried glacier ice, permafrost and seasonally frozen ground to changes in environmental variables, namely climate, manifested in the development or alteration of geomorphological features. This aspect of research will therefore encompass the identification and description of recognised responses, in the form of geomorphological processes and subsequent landform development or alteration, of changing seasonally frozen ground and permafrost conditions as well as the degradation of buried glacier ice on landscape development. Geomorphological evidence may then be used to determine if the existence of the fossil ice cap prevented the development of periglacial features (*e.g.* patterned ground) in the vicinity of, but not limited to, the area known as the 'Ice Plateau'. Geomorphological evidence, in the form of relict glacial features (*e.g.* moraine deposits and striations), will also be used to determine the previous glacial extent to reconstruct the palaeoenvironment of the interior (above 750m a.s.l.) on Marion Island. Reconstruction of previous permanent snowlines in the area known as the 'Ice Plateau' will also be investigated to further highlight evidence for recent climate change on Marion Island.

In addition, certain 'diagnostic landforms', namely thermokarst features, will be used to aid in the mapping the limits of the present extent of buried glacial ice, permafrost and seasonally frozen ground. The recognition of certain ground ice pseudomorphs or casts within regions beyond the present permafrost limits will provide evidence of the former existence of permafrost (French, 1996). Therefore, thermokarst features will be used in this regard as these features by definition are a record of present or former permafrost (Washburn, 1979). However, it is pertinent to highlight that the extent to which permafrost mapping based exclusively on geomorphological features can provide a reliable picture must be questioned (Jeckel, 1988). As even though the existence of certain 'diagnostic landforms' prove that permafrost is present at these locations, or at least was, the converse cannot be concluded: the lack of diagnostic landforms does not *per se* prove that there is no permafrost (Jeckel, 1988). As a result, ground temperature monitoring of the upper interior of Marion Island, described above, will also be recorded to provide a more comprehensive picture of the possible extent of buried glacial ice, permafrost and seasonally frozen ground. Another aspect worthy of investigation is the possible effects any changes in the conditions of permafrost and seasonally frozen ground may have on future landscape dynamics in response to climate change of the sub-Antarctic islands (*i.e.* plant colonisation and occurrence of aeolian features).

A large emphasis will placed on surveying the area known as the 'Ice Plateau' to determine the precise nature of the geomorphological features, mainly thermokarst features, found adjacent to and within this area, since correct identification of these features is imperative to provide an accurate interpretation of geomorphological responses to climate change. An emphasis will also be placed on the identification of geomorphological processes, namely thermokarst subsidence *vs*. thermal erosion, in and around the area known as the 'Ice Plateau' to determine which processes are active and how they interact to produce the peculiar features found in the upper interior of Marion Island. In addition, even though site specific, excavations at various altitudes in the interior of Marion Island and at various times of the year will be required to investigate varying depths of the active layer and to determine where permafrost persists.

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Chapter 4: Results and Observations

Climate Change on Marion Island

As alluded to in Chapter 2 Marion Island has experienced a dramatic shift in climate, predominantly with regard to precipitation, solar radiation receipts and air temperature, since meteorological observations began in 1948. These climatic changes are extremely significant in terms of landscape dynamics since all the meteorological variables highlighted above play a large role in determining the type and rate of geomorphological processes present. Marion Island's interior (above 750m a.s.l) is particularly sensitive to climate change as it represents a marginal and climatically fragile area of frozen ground (sporadic permafrost and seasonally frozen ground) and buried glacial ice where even a small increase in ground temperature (linked to air temperature) may lead to significant thaw and subsequent alteration of the landscape.

The first indication of recorded climatic warming at Marion Island came from an analysis of daily (maximum + minimum)/2 surface air temperature by Smith & Steenkamp (1990) between 1952 and 1988 and showed that mean annual temperatures had started increasing after 1968. Subsequently, Smith (2002) has shown that Marion Island has experienced a significant increase of 1.2°C in mean annual surface air temperature between 1969 and 1999, with MAAT of around 6.5°C since 1990 to present. This warming trend corresponds to a 1.4°C increase in sea-surface temperature recorded over the same 50-year period (Mélise *et al.*, 2003). The greatest rate of warming has been from late austral winter to midsummer (September-January), and the least in late summer, autumn and winter (February-August), with the notable exception of April which has shown the greatest warming of all the months (Smith, 2002).

When reliable meteorological observations began in 1948 precipitation initially displayed a general increasing trend up until it peaked in 1967 at 2993mm *per annum* but has decreased considerably since then to its lowest ever recorded value of 1799mm in 2004. These variations have led to an ever-fluctuating average that has been as high as 2576mm *per annum* (Schulze, 1971) but is presently 2326mm *per annum* (Smith, 2004). The 1990s was the driest of the five decades that precipitation has been measured on the island: the average annual total for the 1990s was nearly 700mm (25%) lower than that for the 1960s (Smith, 2002).

In addition, Smith (2002) found that between the period 1951 and 1999 the annual total sunshine hours increased for all the months but the strongest increase was for April, May, August, and the weakest was for July. Smith and Steenkamp (1990) have shown that total annual radiation (measured as hours of sunshine) have increased in two stages between 1950 and 1988; on average by

17 hours each year between 1959 and 1968, and by 31.5 hours each year between 1982 and 1988; in the interval between the two periods, hours of sunshine declined by 11 hours each year.

The total annual precipitation on Marion Island increased up to the mid-1960s, and has since steadily declined. An absolute maximum of 2993mm and minimum of 1799mm were recorded in 1966 and 2004 respectively (Fig. 4.1). Snowfall on the island seems to have followed a similar trend over the same 50-year period; whereby an average of 71 days per year was recorded in the early 1950s (King, 1954), it then increased to an average of 89 days per year between 1951-1965 (Schulze, 1971), and decreased to approximately 50 days per year at sea level based on observations by Holness (2001a).
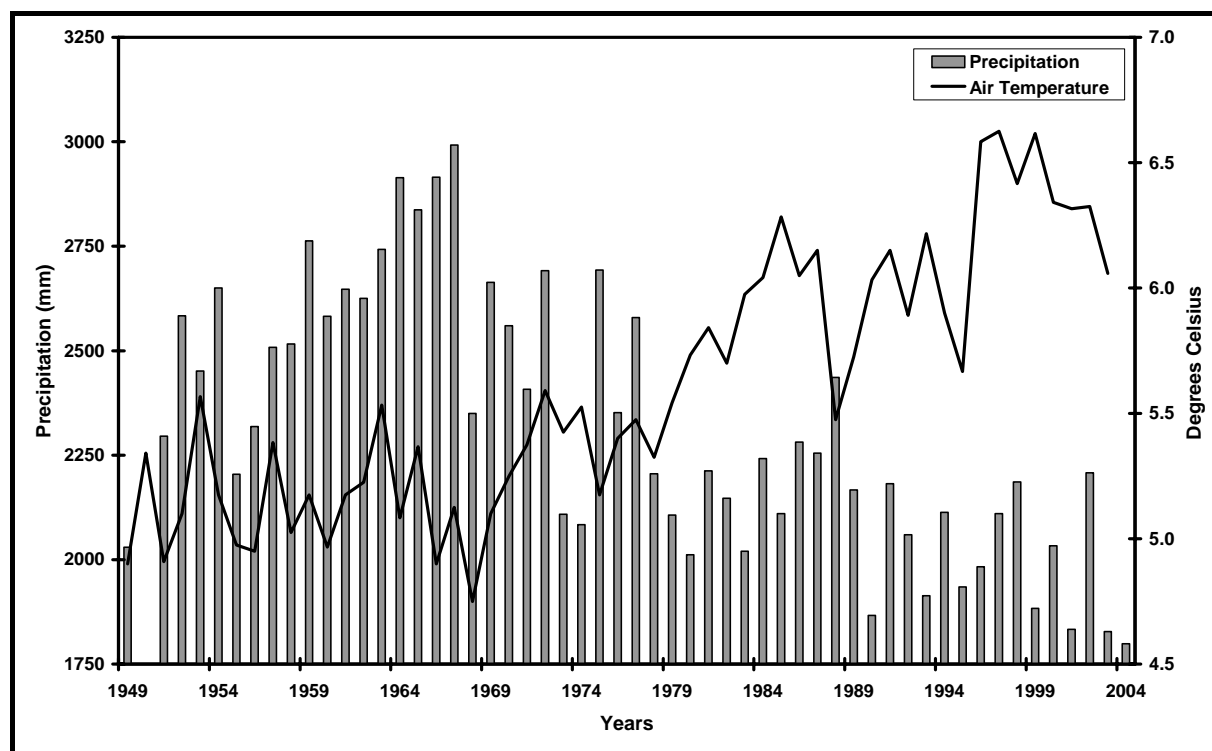
Figure 4.1: Recorded air temperature and precipitation on Marion Island between 1949 and 2004. Note precipitation data for 1950 and air temperature data for 2004 are missing.

Environmental Setting of the Upper Interior of Marion Island

Marion Island, above 750m a.s.l., is characterised by different climatic conditions than those already described for the lower coastal regions. Climatic data for the interior is, however, very scarce with Blake (1996) and Holness (2001a) providing the only climatic data to describe this region. Thus an attempt was made to monitor general climatic conditions, namely air temperature and precipitation, over the ground monitoring period in order to provide a general environmental setting for this region. Previously collected data (Blake, 1996 and Holness, 2001a) and data collected for this study are presented below:

Air Temperature

An air temperature logger was installed at 975m a.s.l. (46° 54' 12.3"S; 37° 44' 35.2"E) (Fig. 3.3) but unfortunately it failed due to condensation within the logger. Consequently, previously collected air temperature data (Blake, 1996 and Holness, 2001a) will be used to describe this climatic variable for the interior. Both Blake (1996) and Holness (2001a) collected air temperature data across an altitudinal range but only sites within the study area (above 750m a.s.l.) are described below.

Blake (1996) obtained an average annual air temperature of 2.6° C (1.2m above the ground) at a site near the Katedraal Field Hut, at approximately 750m a.s.l., whereas Holness (2001a) obtained average annual air temperatures of 2.0, 1.5 and 0.8° C (all 0.1m above the ground) for the Katedraalkrans (approximately 750m a.s.l.), Katedraalkrans Nek (approximately 750m a.s.l.) and Delta Extension (approximately 1000m a.s.l.) sites respectively. The air temperature data collected by Blake (1996) between May 1992 and April 1993 supports Schulze (1971) proposed environmental lapse rate in the free atmosphere of 0.45° C/100m during summer and 0.40° C/100m during winter. Air temperature data collected near the ground surface (0.1m above the ground) by Holness (2001a) between May 1997 and April 2000 at various sites named above suggests a marginally higher environmental lapse rate of 0.50° C/100m. Therefore, the summit regions (above 1000m a.s.l.) of Marion Island can be expected to experience a mean annual air temperature of less than 0.9° C.

Precipitation

Precipitation data for the interior of Marion Island are also scarce. Only Blake (1996) has previously collected data in this regard. Thus, two automatic tipping rainfall gauges were installed but one installed at approximately 800m a.s.l. (46° 54' 00"S; 37° 46' 04.8"E) failed soon after being placed in the field. The second automatic tipping rainfall bucket set up at approximately 975m a.s.l. (46° 54' 12.3"S; 37° 44' 35.2"E) collected data for almost eight months before it failed on 22 December 2004 (Table. 4.1). All precipitation data are presented in Table 4.1. Data should be regarded as site specific and cannot be extrapolated for a longer time period. It is pertinent to point out that the automatic tipping rainfall bucket installed at approximately 975m a.s.l. may have been covered by snow at some stage during the monitoring period. As such some of the precipitation totals may include water released from snow melt and are probably not fully representative of the actual precipitation (water equivalent). In addition, snow generally sublimates into the atmosphere rather than melts also limiting the accuracy of the precipitation values recorded in this study.

Table 4.1: Monthly total precipitation recorded at the 'high altitude' site (Blake, 1996) and the 975m a.s.l. climatic monitoring site in the current study. The annual and monthly totals are estimates of the annual and monthly rainfall as missing records were ignored.

Site	High (±750m a.s.l.) (Blake, 1996)	Current Study (±975m a.s.l.)
May	463.8	166.4*
June	***	390.2
July	0.4	100.0
August	***	24.4
September	39.4	0.0
October	1.6	359.8
November	8.0	315.6
December	32.8	331.2**
January	17.6	-
February	35.3	-
March	32.5	-
April	303.6	-
Total	935.0	1687.6

*   Total recorded precipitation from 8 May – 31 May 2004.

**   Total recorded precipitation from 1 December – 21 December 2004.

***   Data from Blake (1996) not indicated if missing or if zero totals were recorded for June and August.

Ground Temperature Data

As discussed in Chapter 3, air temperatures cannot be used as a surrogate for ground temperatures and therefore direct ground temperature monitoring was conducted above 750m a.s.l. to supplement geomorphological mapping. All the ground temperature monitoring sites are completely unvegetated, with vegetation being restricted to occasional moss balls, as well as some moss and lichen growth on the leeward side of boulders. All ground temperature data were recorded within a homogenous substrate (*i.e.* scoria) on both north and south-facing slopes. Loggers ran unattended for almost a year, and hence due to memory limitations, only daily maximum and minimum temperatures were recorded. A settling period of approximately a week after installation of the ground temperature sensors at the various sites was observed before analysis of data was conducted. As such all ground temperature data discussed in this section represents records collected between 17 May 2004 and 29 April 2005. The general physical structure of the monitoring stations is displayed in Figure 4.2. Temperature sensors were located below the ground surface at -0.01m, -0.25, -0.50 and -0.75m. Every sensor at all the stations recorded daily maximum and minimum temperatures. The data from each ground temperature monitoring site are described below.
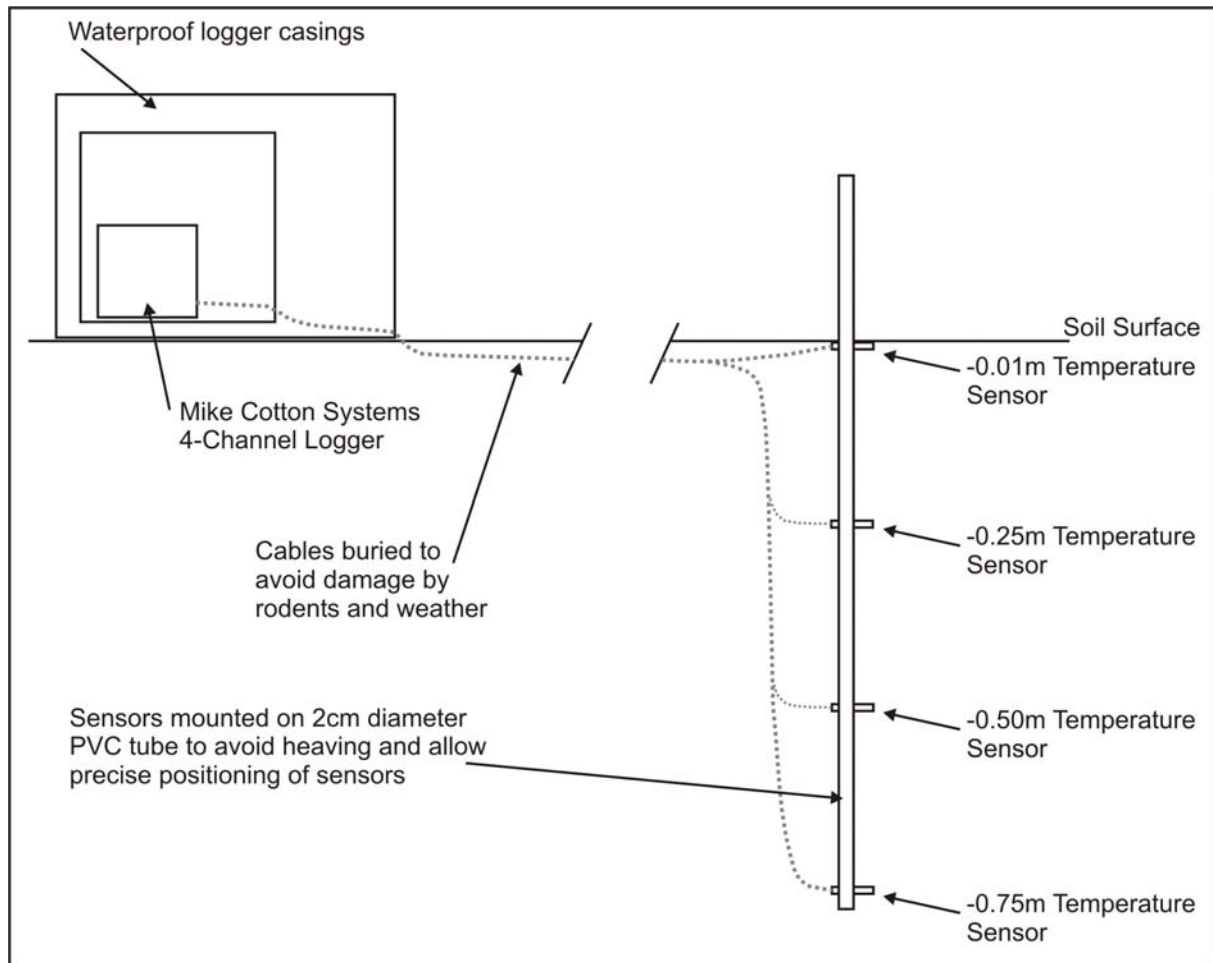
Figure 4.2: Diagram showing general ground temperature logger setup.

Delta North

Ground temperature data at the Delta North site (46° 54' 26.8"S; 37° 45' 11"E) (approximately 1000m a.s.l.) was recorded on a slope with a 20° gradient and aspect of 290° (Fig. 3.3). Maximum and minimum ground temperatures recorded at this site were 39.2° C and -11.1° C respectively; both were recorded just below the ground surface (-0.01m). A ground thermal profile (see for example French, 1996, p. 53) is constructed for the Delta North site from probe absolute and average maximum and minimum values over the recording period (Fig. 4.3). Records from just below the ground surface (-0.01m) did not indicate a period of 'seasonal' freeze with only a maximum of 4 consecutive days being recorded below 0°C. Diurnal oscillations around 0° C just below the ground surface (-0.01m) occurred on a total of 236 days. At 0.25m depth, minimum and maximum ground temperatures of -5.7° C and 14.5° C were recorded. Ground temperatures below 0° C were recorded for a continuous period of 71 days, between 3 August and 13 October at 0.25m below the surface representing a period of 'seasonal' freeze. Diurnal fluctuations around 0° C at 0.25m occurred on a total of 143 days.

Both minimum and maximum daily temperatures remained below 0° C at a depth of 0.5m for an unbroken period of 112 days from the 26 June to 16 October 2004; the largest number recorded at

this depth. The minimum and maximum temperatures recorded at 0.5m below the surface were -3.7° C and 13.2° C respectively. Diurnal oscillations around 0° C at the ground surface occurred on a total of 113 days. At a depth of 0.75m the minimum and maximum temperatures recorded were -2.1 and 11.6° C respectively. Complete freeze-up occurred for a total of 110 days between 28 June and 16 October 2004 at 0.75m depth; the largest number recorded at this depth. An average daily range of 8.7° C was recorded just below the ground surface (0.01m) but decreased significantly to 2.7, 1.7 and 1.1° C at depths 0.25, 0.5 and 0.75m respectively.

Figure 4.3: Thermal profiles derived from maximum and minimum temperatures recorded on sensors at the Delta North site between 17 May 2004 and 29 April 2005 (approximately 1000m a.s.l).

Delta South

The Delta South ground temperature monitoring site (46° 54' 28"S; 37° 45' 15"E) (approximately 1000m a.s.l.) was installed on the southern slopes of Delta Kop (Aspect: 183°) on a slope with a gradient of 28° (Fig. 3.3). Unfortunately, the Delta South ground temperature logger failed soon after installation and all data were lost from this logger.

No Name Saddle North

The No Name Saddle North ground monitoring site (46° 54' 15.5"S; 37° 45' 18.3"E) (approximately 900m a.s.l.) was located on the north-facing slope of the scoria cone named Delta Kop (Fig. 3.3). The slope had a 15° gradient and the site had an aspect of 331°. Maximum and minimum ground temperatures recorded at this site were 28.2° C and -8.3° C respectively (Fig. 4.4). Only at a depth of 0.25m below the ground surface was period of 'seasonal' freeze, comprising 76 consecutive days between 1 August and 16 October 2004, recorded. Just below the ground surface there were

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numerous, in total a 197, diurnal oscillations around 0° C. This number decreased to 46, 37 and 21 diurnal oscillations around 0° C at depths of 0.25, 0.5 and 0.75m below the ground surface respectively. Average daily ground temperature ranges of 4.6, 0.8, 0.5 and 0.3° C were recorded at depths 0.01, 0.25, 0.5 and 0.75m respectively.

Figure 4.4: Thermal profile derived from maximum and minimum temperatures recorded on sensors at the No Name Saddle North site between 17 May 2004 and 29 April 2005 (approximately 900m a.s.l.).

No Name Saddle South

The No Name Saddle South ground temperature monitoring site (46° 54' 12.6"S; 37° 45' 18.6"E) (approximately 900m a.s.l.) was installed on the southern slopes of No Name Peak (Fig. 3.3). The slope on which this ground temperature logger was located had a slope gradient of 14° and aspect of 158°. The maximum and minimum ground temperatures recorded at this site were 28.6° C and -9.1° C respectively (Fig. 4.5). At 0.25m depth, this site experienced the longest recorded period of 'seasonal' freeze, below 0° C, with a total of 143 consecutive days, from 16 July to 6 December 2004. At a depth of 0.5m the period of 'seasonal' freeze started 3 days after the upper sensor on 19 July and remained frozen for a total of 94 days until 21 October 2004. The deepest sensor, placed at 0.75m, also experienced a period of 'seasonal' freeze for 66 days, starting on 16 August and ending on 21 October 2004. The sensor at the ground surface experienced an extremely high number (249) of diurnal oscillations. Sensors placed deeper experienced much lower diurnal oscillations around 0° C with only 34, 37 and 26 being recorded at depths 0.25, 0.5 and 0.75m respectively. Average daily ground temperature ranges of 4.6, 0.8, 0.5 and 0.3° C were recorded at depths 0.01, 0.25, 0.5 and 0.75m respectively.

Figure 4.5: Thermal profile derived from maximum and minimum temperatures recorded on sensors at the No
Name Saddle South site between 17 May 2004 and 29 April 2005 (approximately 900m a.s.l.).

Ned's North

The Ned's North ground temperature monitoring site is located on the northern side of the scoria cone known as Ned's (46° 53' 45.3"S; 37° 45' 58.8"E) (approximately 800m a.s.l.). This ground temperature monitoring site was installed on a slope with a 19° gradient and an aspect of 353°. Maximum and minimum ground temperatures recorded at this ground temperature monitoring site were 22.6° C and -8.1° C respectively (Fig. 4.6). The recorded near-surface ground temperatures indicated no period of 'seasonal' freeze (below° C) but did, however, show a high number (192) of diurnal oscillations around 0° C. At 0.25m depth a total of 30 consecutive days, between 2 September and 2 October, were recorded below 0° C whereas a continuous period of 45 below 0° C were recorded at a depths of 0.5m from 31 August to 15 October 2004. Duration of freeze-up increased with depth to the point where a period of 'seasonal' freeze was experienced between 1 August and 20 October at a depth of 0.75m. The number of diurnal oscillations around 0° C, however, decreased with depth. At 0.25m depth 72 diurnal oscillations around 0° C were recorded whereas only 36 and 23 diurnal oscillations around 0° C were recorded at depths of 0.5 and 0.75m in that order. Average daily temperature ranges of 4.6, 1.4, 0.8 and 0.6° C were recorded at depths of 0.01, 0.25m, 0.5 and 0.75 respectively.
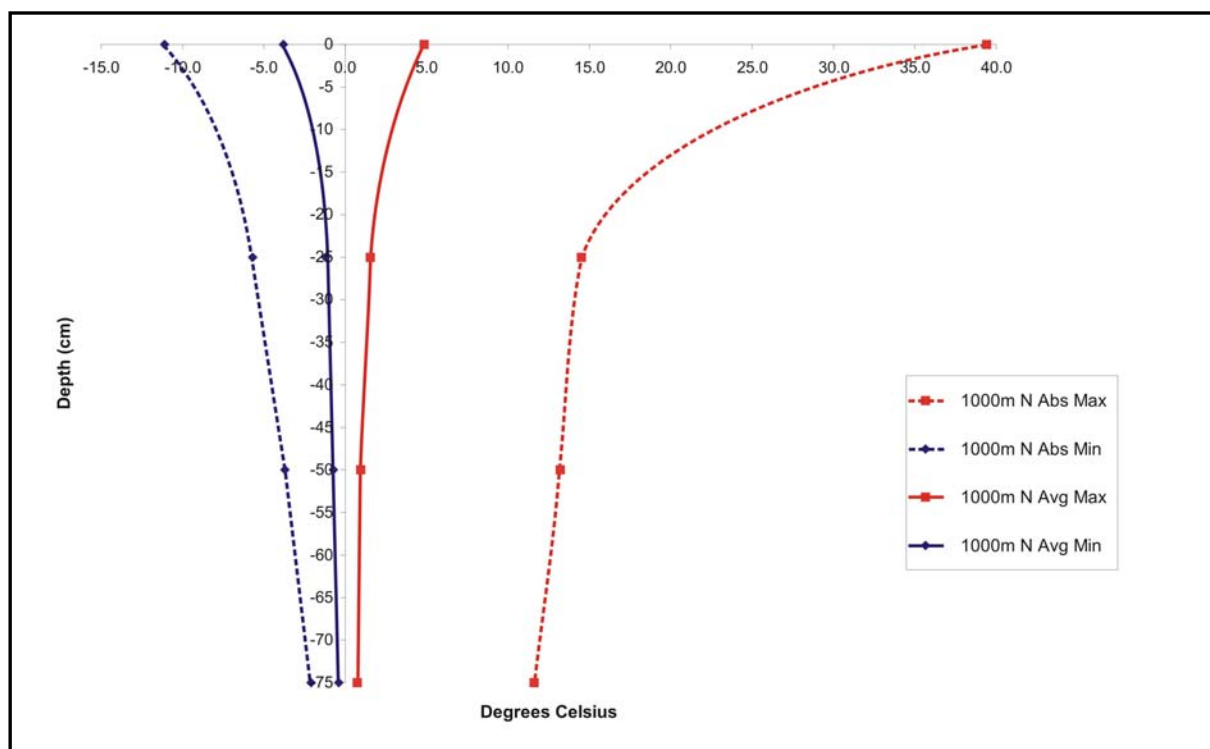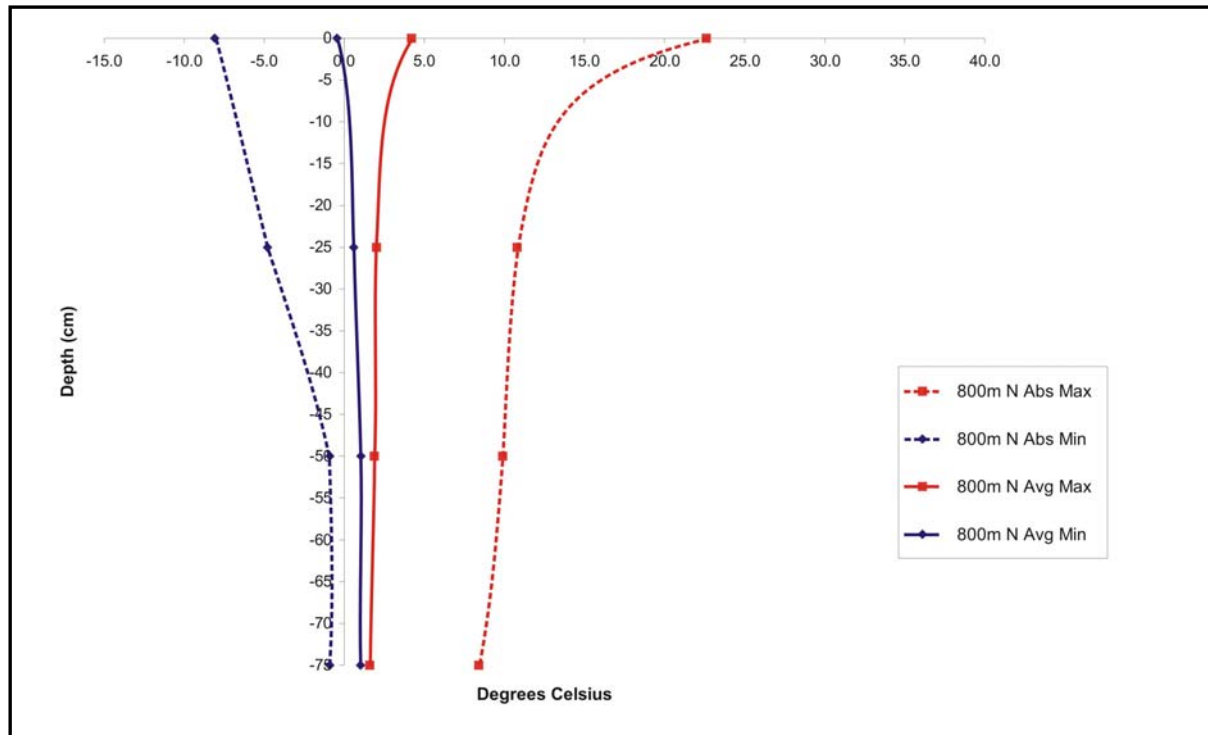
Figure 4.6: Thermal profile derived from maximum and minimum temperatures recorded on sensors at the Ned's
North site between 17 May 2004 and 29 April 2005 (approximately 800m a.s.l.).

Ned's South

The Ned's South ground monitoring site was located near the 800m a.s.l. rainfall monitoring site on the southern slopes of the Ned's scoria cone (46° 53' 59.1"S; 37° 46' 04.6"E) (approximately 800m a.s.l.). It was situated on a slope angle of 18° and aspect of 153°. Maximum and minimum ground temperatures at this site, recorded 0.01m below the ground surface, were 25.7 and -7.9° C respectively (Fig. 4.7). No period of 'seasonal' freeze (below 0° C) was experienced at 0.01m below the ground surface, however, a high number (225) of diurnal oscillations around 0° C were recorded. At depth 0.75m below the surface, 71 consecutive days were recorded where the maximum temperature was below 0° C, representing a period of 'seasonal' freeze. At depths 0.5 and 0.25m below the surface this value decreased to 26 and 12 days respectively. Indicating a similar trend to that identified at the Ned's North ground temperature monitoring site whereby the duration of freeze-up increased with depth whereas the number diurnal oscillations around 0° C decreased with depth. Minimum and maximum ground temperatures recorded at 0.25m were -0.7 and 8.6° C respectively. Whilst at 0.5m below the ground surface minimum and maximum ground temperatures of -0.8 and 5° C were recorded.
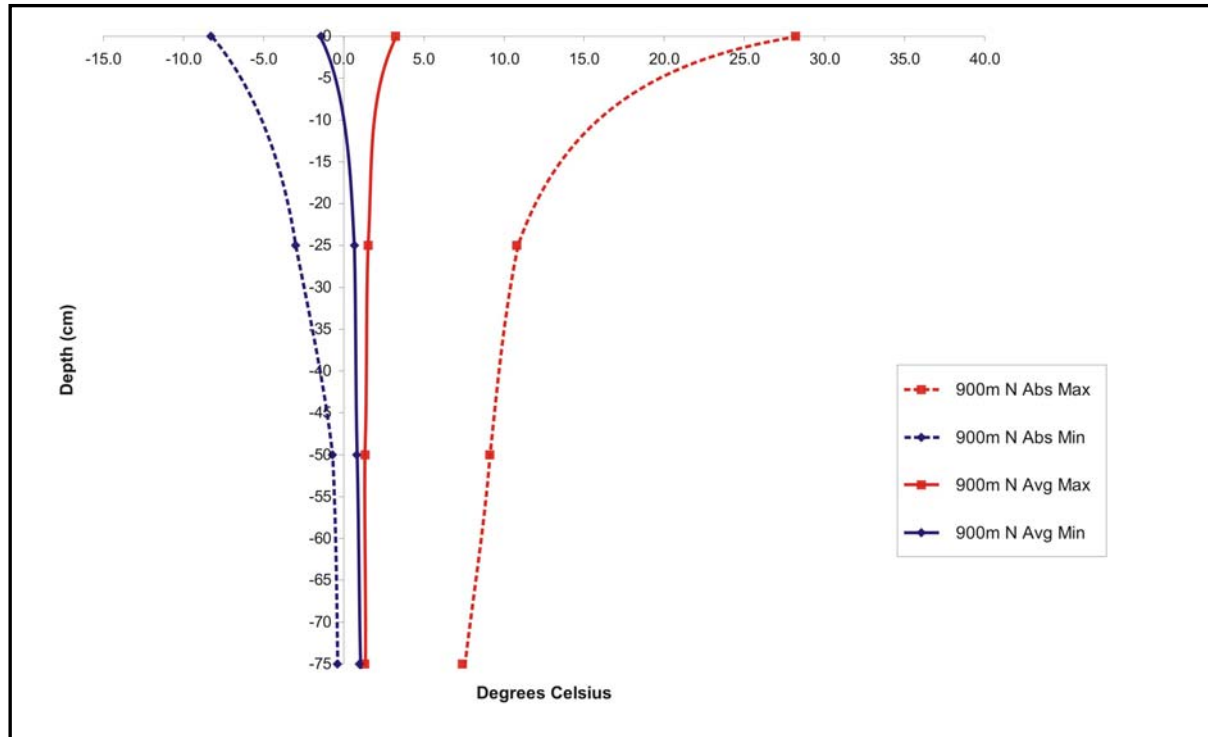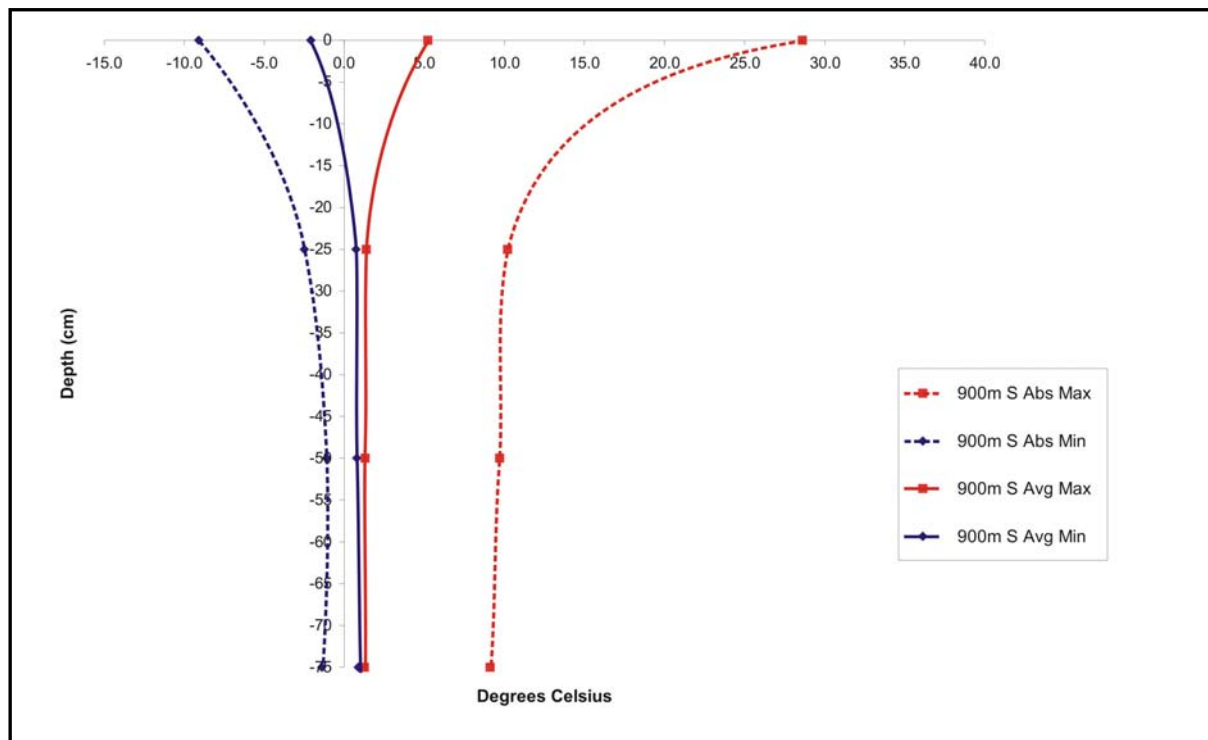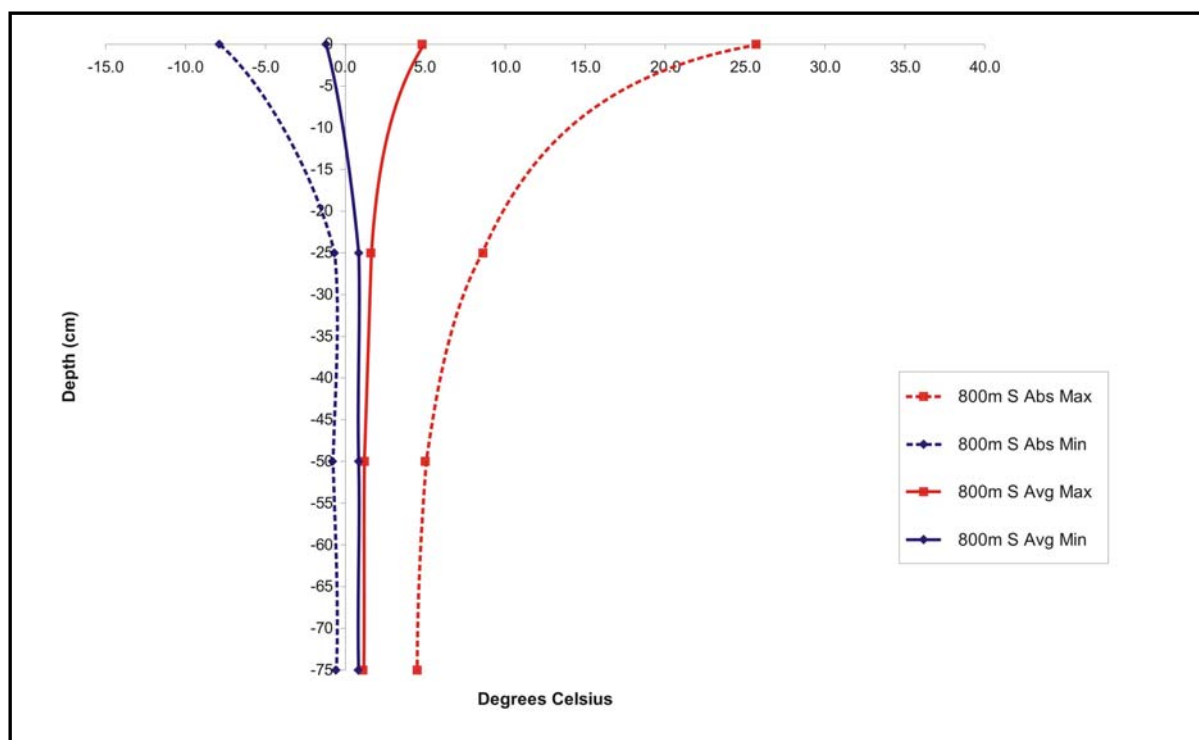
Figure 4.7: Thermal profile derived from maximum and minimum temperatures recorded on sensors at the Ned's South site between 17 May 2004 and 29 April 2005 (approximately 800m a.s.l.).

Summary

Daily maximum and minimum ground temperatures for all the sites during the recording period are summarized in Table 4.2. All the collected data for the ground temperature sensors at each of the ground temperature monitoring sites over the recording period are displayed on separate graphs (see Appendix A). Most importantly, the recorded ground temperature data indicates that following the typically accepted definition of permafrost (*cf*. Muller, 1947, p.3, *cf*. p.219), which only adheres to a thermal criterion (see Van Everdingen, 1976 for discussion), permafrost does not exist at any of the sites where ground temperature monitoring was undertaken. This conclusion is, however, site specific and therefore does not preclude the existence of permafrost at other sites, namely valley floors and on insolation protected south-facing slopes, above 1000m a.s.l. as has previously been suggested by Boelhouwers (2003) and Sumner *et al*. (2004). The recorded ground temperature data do indicate that seasonal freezing is experienced across the altitudinal range of collected data (approximately 800m - 1000m a.s.l.). As would be expected the ground temperature monitoring site at approximately 1000m a.s.l. experiences the most intense depth and duration of freeze whereas the north-facing site at approximately 800m a.s.l. only experiences surficial freezing. When analysing the intensity of minimum recorded ground temperatures versus depth at the various sites, sites on north-facing slopes experience more intense frost penetration. At first this may seem unusual because one would expect north-facing slopes to receive more direct solar radiation in the southern hemisphere. However, considering that snow cover usually persists on south-facing slopes on Marion Island, it insulates the underlying ground from intense minimum and maximum temperatures.

Table 4.2: Summary of ground temperature data recorded from the interior of Marion Island (above 750m a.s.l.) between 17 May 2004 and 29 April 2005.

Delta North (Slope: 20°; Aspect: 290°; Altitude: ±1000m)					Delta South (Slope: 28°; Aspect: 183°; Altitude: ±1000m)			
Depth	0.75m	0.50m	0.25m	0.01m	Depth	0.75m	0.50m	0.25m	0.01m
Avg Max	0.7	1.0	1.5	4.9	Avg Max	-	-	-	-
Avg Min	-0.4	-0.7	-1.2	-3.8	Avg Min	-	-	-	-
Absolute Max	11.6	13.2	14.5	39.4	Absolute Max	-	-	-	-
Absolute Min	-2.1	-3.7	-5.7	-11.1	Absolute Min	-	-	-	-
Median	0.2	0.1	0.2	0.5	Median	-	-	-	-
Freeze/Thaw	101	113	145	236	Freeze/Thaw	-	-	-	-
Days < 0	211	203	180	77	Days < 0	-	-	-	-
Avg Daily Range	1.1	1.7	2.7	8.7	Avg Daily Range	-	-	-	-
Max Daily Range	10.0	10.9	12.8	41.3	Max Daily Range	-	-	-	-

No Name Saddle North (Slope: 15°; Aspect: 331°; Altitude: ±900m)					No Name Saddle South (Slope: 14°; Aspect: 158°; Altitude: ±900m)			
Depth	0.75m	0.50m	0.25m	0.01m	Depth	0.75m	0.50m	0.25m	0.01m
Avg Max	1.3	1.3	1.5	3.2	Avg Max	1.3	1.3	1.4	5.2
Avg Min	1.0	0.8	0.7	-1.4	Avg Min	0.9	0.8	0.7	-2.1
Absolute Max	7.4	9.1	10.8	28.2	Absolute Max	9.1	9.7	10.2	28.6
Absolute Min	-0.4	-0.7	-3.0	-8.3	Absolute Min	-1.4	-1.1	-2.5	-9.1
Median	1.1	1.1	1.1	0.9	Median	1.1	1.0	1.1	1.6
Freeze/Thaw	21	37	46	197	Freeze/Thaw	26	37	34	249
Days < 0	6	50	82	111	Days < 0	132	136	152	60
Avg Daily Range	0.3	0.5	0.8	4.6	Avg Daily Range	0.4	0.5	0.6	7.3
Max Daily Range	3.8	3.9	5.4	28.5	Max Daily Range	2.9	4.2	4.7	29.2

Ned's North (Slope: 19°; Aspect: 353°; Altitude: ±800m)					Ned's South (Slope: 18°; Aspect: 153°; Altitude: 800m)			
Depth	0.75m	0.50m	0.25m	0.01m	Depth	0.75m	0.50m	0.25m	0.01m
Avg Max	1.6	1.9	2.0	4.2	Avg Max	1.1	1.2	1.6	4.8
Avg Min	1.0	1.0	0.6	-0.4	Avg Min	0.8	0.8	0.8	-1.2
Absolute Max	8.4	9.9	10.8	22.6	Absolute Max	4.5	5.0	8.6	25.7
Absolute Min	-0.9	-0.9	-4.8	-8.1	Absolute Min	-0.6	-0.8	-0.7	-7.9
Median	1.3	1.5	1.3	1.9	Median	0.9	1.0	1.2	1.8
Freeze/Thaw	23	36	72	192	Freeze/Thaw	22	42	56	225
Days < 0	80	75	80	41	Days < 0	109	87	75	47
Avg Daily Range	0.6	0.8	1.4	4.6	Avg Daily Range	0.3	0.4	0.8	6.0
Max Daily Range	5.2	6.9	9.3	21.1	Max Daily Range	1.0	1.5	3.9	24.3

All maximum and minimum ground temperatures were recorded near the surface (-0.01m). Therefore, as expected, due to radiational heat exchange, the greatest diurnal temperature fluctuations were also recorded near the surface. It is, however, pertinent to point out at this stage that data recorded near the ground surface cannot be regarded as being totally representative due to possible sensor exposure to direct solar radiation through superficial mass movement around the temperature sensor.

Despite the possibility of sensor exposure to direct solar radiation absolute maximum and minimum ground temperatures were recorded near the ground surface. Minimum temperatures increase with depth, similar to findings by Sumner (2003) for the Lesotho Highlands in southern

Africa. However, both average and maximum daily ground temperature range decreases with depth. Onset and duration of freeze-up does vary between sites but thaw generally took place in mid-October 2005. Massive ground freezing generally commences first at the highest ground temperature monitoring site, Delta North (approximately 1000m a.s.l.), followed by the No Name Saddle South and then the No Name Saddle North, illustrating the effect of altitude and aspect on ground temperatures. Most sites thaw by mid-October (late austral spring) with the exception of the ground temperature sensor at a depth of 0.25m at the No Name Saddle South monitoring site.

Notwithstanding the above mentioned possibility of unrepresentative ground temperature data near the ground surface as well as the limited time period of ground temperature monitoring, the data nonetheless provides some interesting differences when compared to previously collected ground temperature data (*e.g.* Boelhouwers *et al*., 2001; Boelhouwers *et al*., 2003). It is, however, pertinent to highlight that the Delta Extension site (1000m a.s.l.) referred to in Boelhouwers *et al*. (2001) and Boelhouwers *et al*., (2003) was placed on a horizontal slope whereas the Delta North logger (approximately 1000m a.s.l.) was placed on slope with a gradient of 20°. The most notable difference in data from the Delta North logger site and the Delta Extension site (Boelhouwers *et al*., 2001) can be found in the depth of soil frost penetration between the study. Boelhouwers *et al*. (2001) indicate that the maximum depth of soil frost penetration at the Delta Extension (1000m a.s.l.) ground temperature monitoring site is 0.30m whereas the data collected in this study indicates that the maximum depth of soil frost penetration exceeds the maximum depth of ground temperature measurement set at 0.75m. In addition, whilst the number of freeze-thaw days is comparable at the ground surface with 212 days being recorded just below the surface (-0.01m) in the study done by Boelhouwers *et al*. (2001), and 236 days being recorded in this study. The number of freeze-thaw days at deeper but comparable depths varies greatly between the data presented above and the data presented by Boelhouwers *et al*. (2003). At a depth of 0.20m in the Boelhouwers *et al*. (2001) study, 27 freeze-thaw days were recorded whereas 145 days were recorded at a depth of 0.25m in this study. Even deeper, at a depth of 0.8m no freeze-thaw days were recorded in the Boelhouwers *et al*. (2001) whilst 101 freeze-thaw days were recorded at 0.75m in this study. The above findings illustrate the site specific nature of ground temperature monitoring, and possibly more importantly, that soil frost penetration is deeper than previously measured at some locations.

Excavations throughout the period of fieldwork at various sites provided little information in the interior of the island apart from the area formerly known as the 'Ice Plateau' where the depth of the buried glacial ice could be estimated through exploring ice caves. The maximum estimated thickness of buried glacial ice within the 'Ice Plateau' is approximately 5m (Fig. 4.8), representing a significant volume of remaining buried glacial ice which upon melting could alter this landscape

drastically. Other excavations made, in summer, outside the 'Ice Plateau' highlighted the sporadic nature of the frozen ground even in a very close proximity (Fig. 4.9).

Figure 4.8: A section of buried glacial ice within the 'Ice Plateau' (April 2005).

Figure 4.9: Excavations of ground in the interior of Marion Island at approximately 1000m a.s.l. in late austral summer (March 2005) indicate that within a very small area the ground can remain ice-cemented (left of centre) or provide no evidence of frozen ground (right of centre). Rod is 1.2m in length (March 2005).

Geomorphological Mapping

Mapped Geomorphological Features

Figure 4.10 displays the extent of the mapped geomorphological features. Harsh weather and difficult terrain prevented mapping of the western section of the interior of the island (above 750m a.s.l.) in the time available. Mapped geomorphological features are displayed in Figure 4.11 and Figure 4.12. Figure 4.11 displays Section A depicted in Figure 4.11, which includes the area known as the 'Ice Plateau' and summit regions whereas Figure 4.12 represents Section B in Figure 4.10 covering the eastern interior (above 750m a.s.l.) of Marion Island. The conspicuous lack of periglacial features in the summit regions (Holness, 2001a), specifically patterned ground, may indicate that this area has only recently become sub-aerially exposed by the disappearance of the former permanent snowline. It may, however, also indicate that the main substrate (*i.e.* scoria), due to a lack of fines, is not susceptible to frost processes and the development of patterned ground and other periglacial features as has been suggested to be the case for volcanic lava flows (*i.e.* black lava flows) (Boelhouwers *et al*., 2001). Therefore, whilst these black lava flows were explored virtually no development of geomorphological features, apart from some aeolian features, was found.
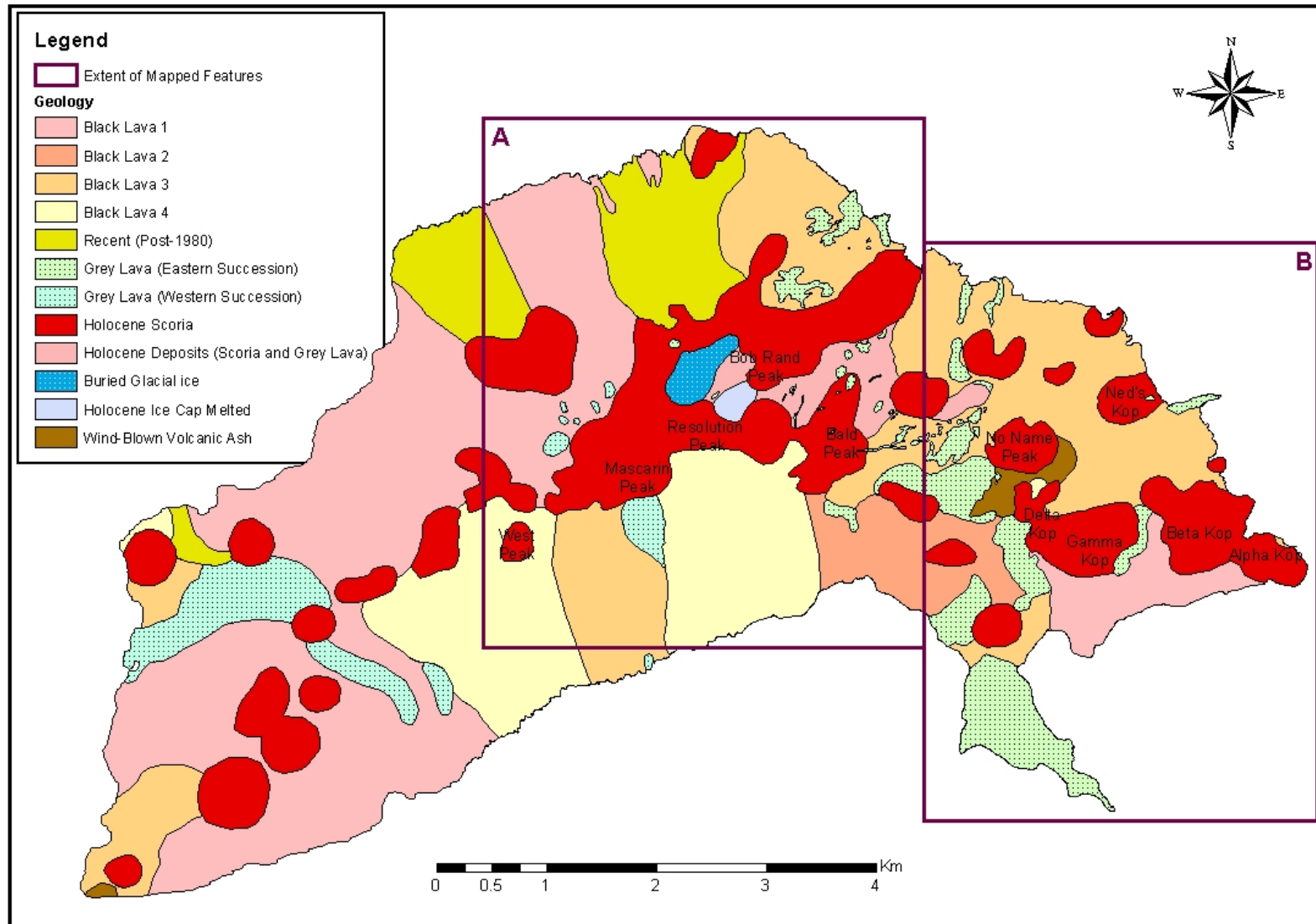
Figure 4.10: Extent of mapped geomorphological features above 750m a.s.l. Section A refers to figure 4.12 and section B refers to figure 4.13. The Black Lava 1 and Black Lava 4 groups represent the oldest and youngest within the black lava group respectively.
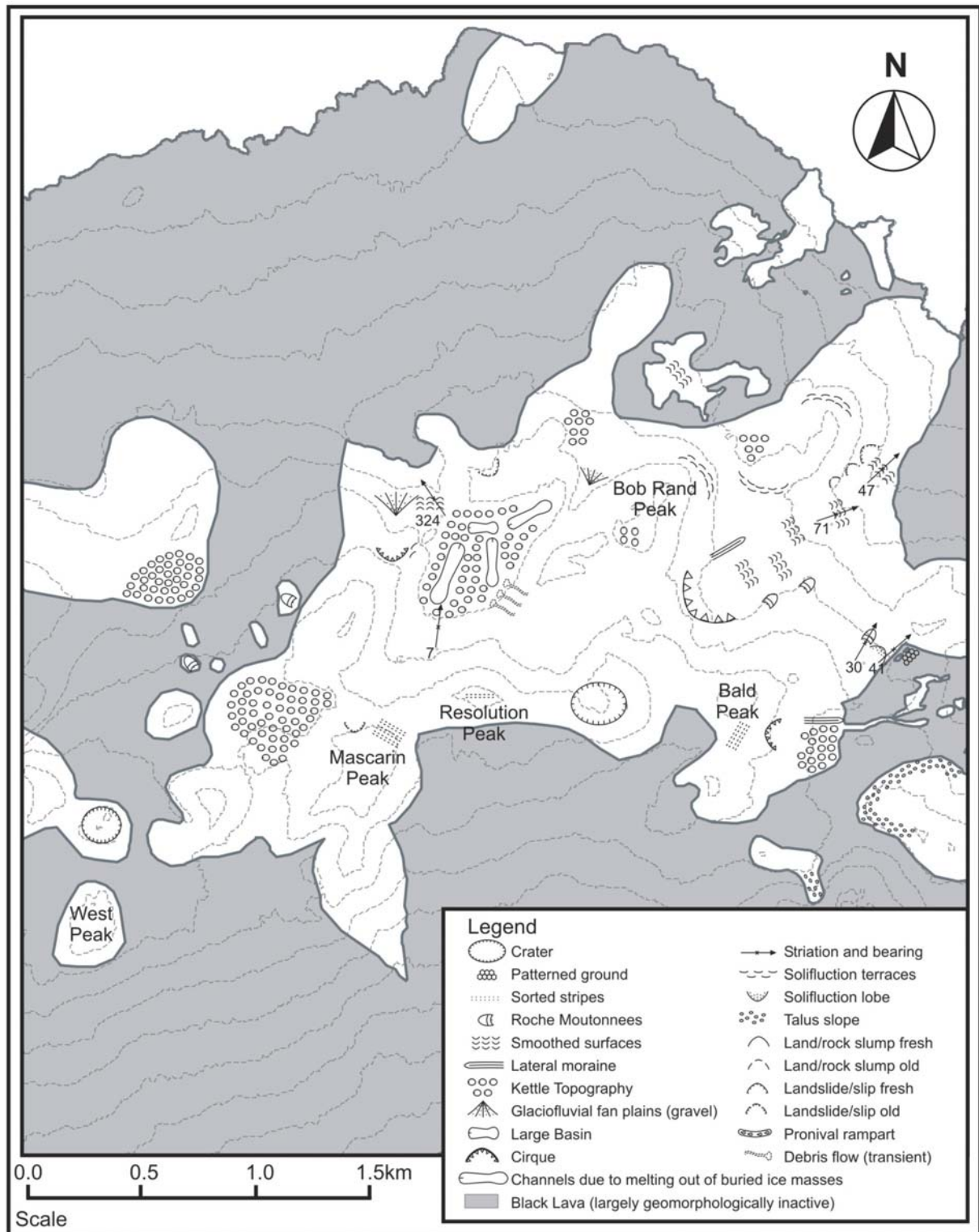
Figure 4.11: Geomorphological-type map of the interior of Marion Island (Section A). Note that the grey areas demarcate black lava flows which show no almost evidence of the development of geomorphological features. Map symbols adapted from Klimaszewski (1963, cited in St-Onge, 1968).
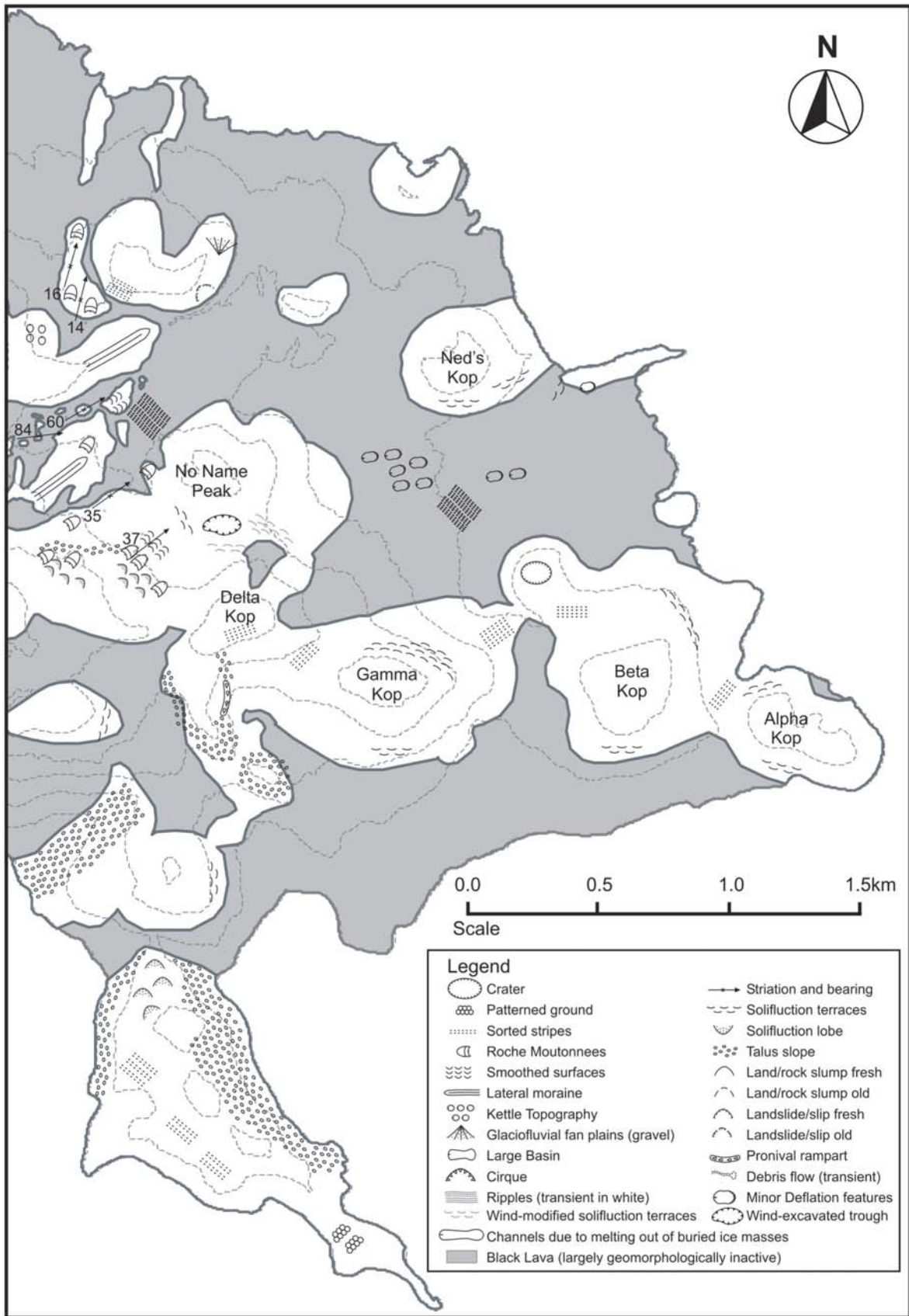
Figure 4.12: Geomorphological-type map of the interior of Marion Island (Section B). Note that the grey areas demarcate black lava flows which show almost no evidence of the development of geomorphological features. Map symbols adapted from Klimaszewski (1963, cited in St-Onge, 1968).

Thermokarst features mainly in the form of kettle topography are pervasive but not limited to areas underlain by buried glacial ice. They represent a crucial piece of evidence for this study as they are by definition indicative of climate change. In addition, subterranean flow manifested in the form of pipes, similar to the observations of Sepällä (1997), were also noted. Other previously undocumented features such as striations, polished bedrock and *roches moutonnées*, created during prior glacial periods that were extensive but did not completely cover the island during The Last Glacial Maximum (Hall, 2002), were also recorded. A cirque glacier (Fig. 4.13) as well as relict cirques were identified and subsequently mapped. Patterned ground, whilst being sparse, was the main periglacial feature mapped (Fig. 4.14). Scree slopes were mapped due to the considerable relative size (Fig. 4.15). Small unvegetated solifluction sheets/terraces/ lobes were recognised on almost all scoria cones (Fig. 4.16). Larger solifluction lobes, approximately 0.5m in height, were observed on older grey lava areas (Fig. 4.17). A number of thaw slumps were identified and mapped (Fig. 4.18). These thaw slumps have only recently been identified but examination of aerial photographs reveal that they can be recognisable as far back as 1988 (Fig. 4.19). By comparing their position on the 1988 aerial photographs to their current position they seem to have stabilized. Debris flows were observed to develop over snow and thus they were extremely transient and did not survive for long before being eroded away during summer by slope wash and melt of the underlying upon which they developed (Fig. 4.20). Lastly, an identified pronival rampart is also included due to the suggested retrogressive manner of development as a result of a disappearing snowpatch representing a climate-process response to climatic amelioration (Fig. 4.21) (see Hedding, 2003 for further discussion).

Figure 4.13: Cirque glacier. The cirque is found on a north-facing slope north west of the Ice Plateau at an approximate altitude of 1100m a.s.l. Person for scale (Meiklejohn, April 2005).

Figure 4.14: Sorted stripes found on Delta Kop (Meiklejohn, April, 2005).
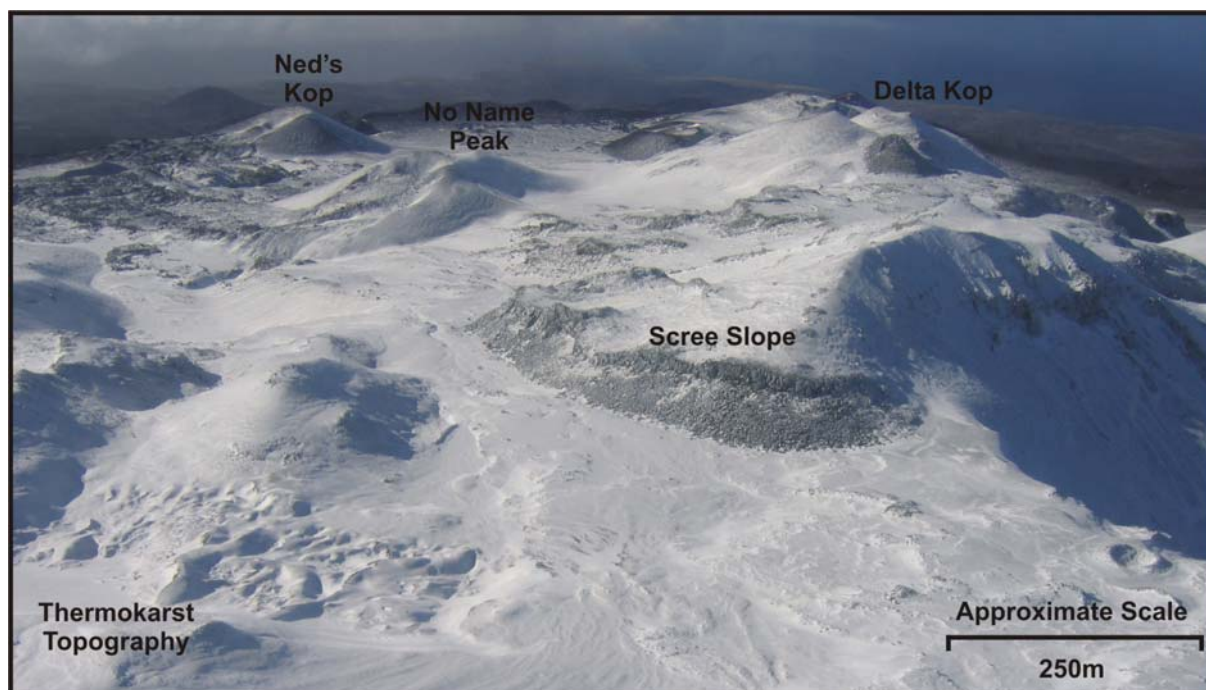
Figure 4.15: A long scree slope in the upper interior of Marion Island. Note the kettle (thermokarst) topography
in the bottom left hand corner.

Figure 4.16: Solifluction terraces/sheets found between the glacial cirque and the 'Ice Plateau' on a scoria cone that has not yet been named (April, 2005).

Figure 4.17: Large solifluction lobes in a grey lava area south of No Name Peak (March, 2005). Rod is 1.2m in length.

Figure 4.18: Thaw slumps identified north-east of Bob Rand Peak (June, 2004).
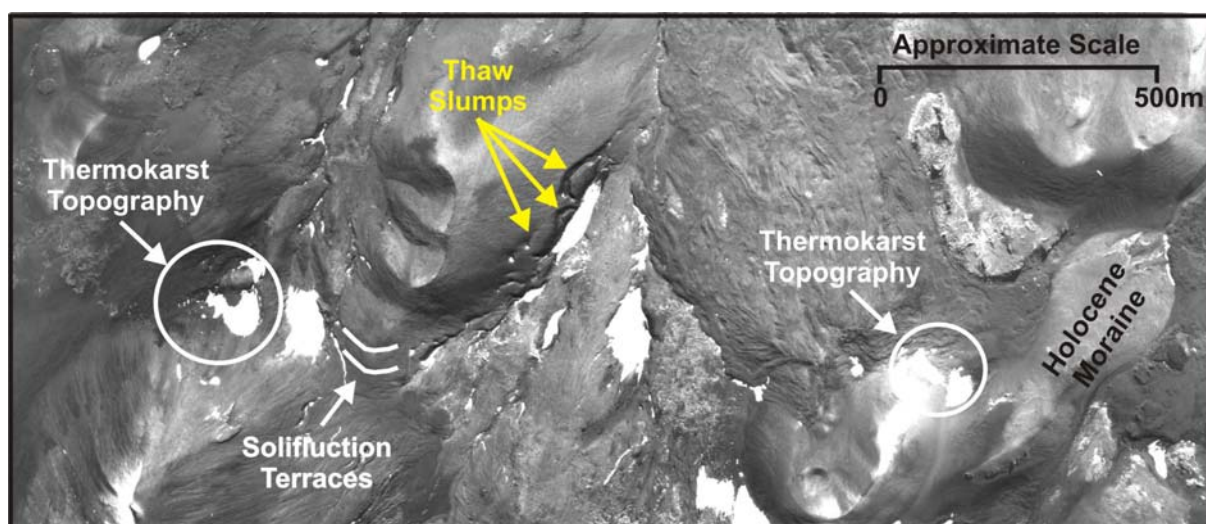
Figure 4.19: Thaw slumps and other geomorphological features of interest visible on an aerial photograph taken in 1988 (South Africa, April 1988).

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Figure 4.20: Ephemeral debris flows formed over snow beds within the 'Ice Plateau' (October, 2004).
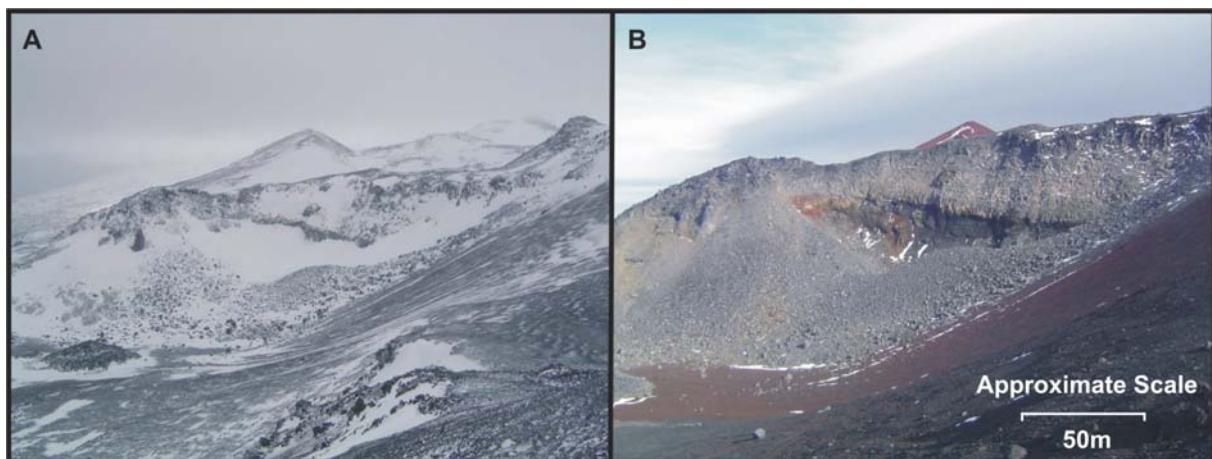
Figure 4.21: Photo A: pronival rampart south-east of Delta Kop in early austral spring (September, 2004). Photo
        B: pronival rampart in late austral summer (April, 2005). Note the absence of the snowbed in Photo B
        (late summer).

Morphometrics

Figure 4.22 is a Digital Elevation Model (DEM) of Marion Island created in ArcGIS 9. It was created from a Triangular Irregular Network (TIN) based on 10m contour data. This artificial surface provides a good visualisation of the surface of the interior and the island in general. Figure 4.22 is composed of a DEM, with a transparency of 45%, draped over a Hillshade model, also created from the DEM, giving a more realistic impression of the surface of Marion Island. A limiting factor evident in Figure 4.22 is the lower spatial resolution of the DEM in areas where RADARSAT[TM] data was used to create the DEM. The cell size of this DEM is 20m.
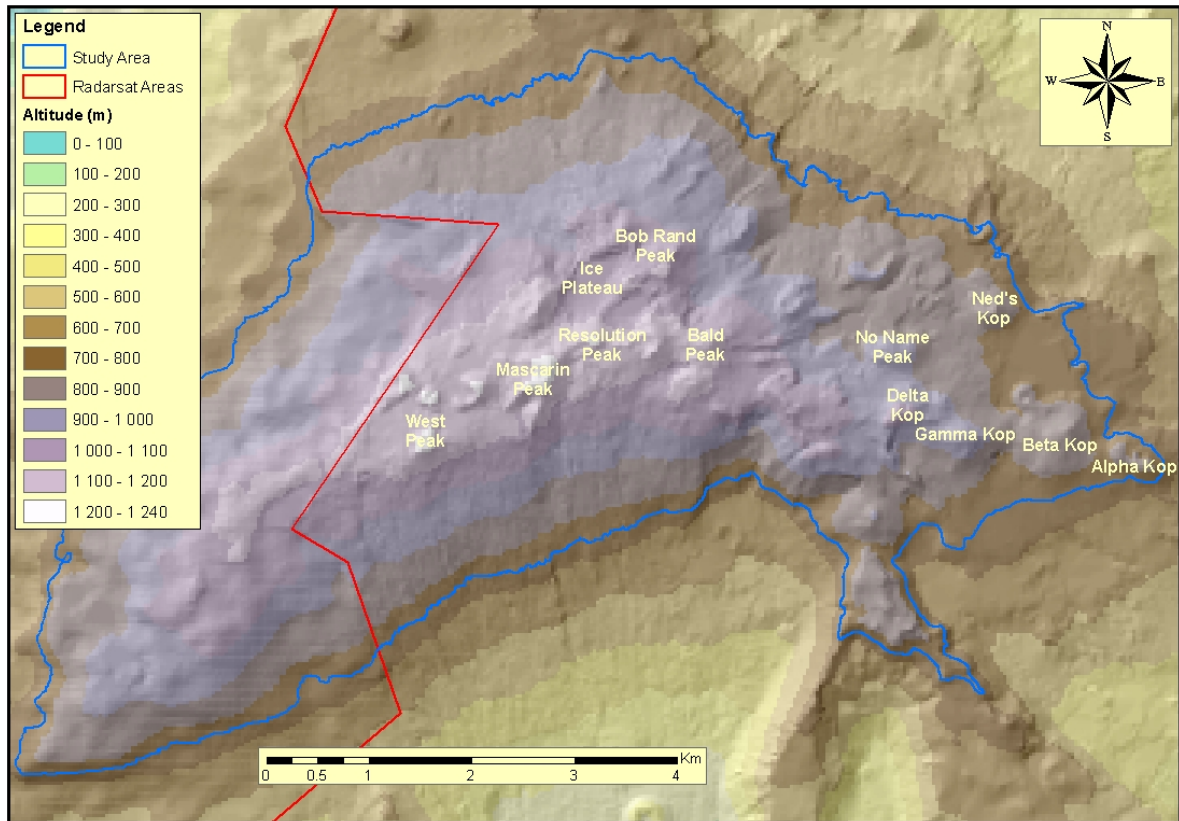
Figure 4.22: Digital Elevation Model (DEM) of the upper interior of Marion Island. Note that the area to the west of the red line is based on data derived from RADARSAT[TM] data and is, therefore, not as accurate as the elevation data derived from SPOT[TM] data.

To the author's knowledge, a complete slope analysis of Marion Island, let alone the upper interior, has never been conducted apart from the geomorphological mapping of grey lava areas on the eastern side of the island by Nel (2001) and some field observations by Boelhouwers (2003). Boelhouwers (2003) indicates that the slopes of scoria cones, particularly southern and eastern aspects above 1000m a.s.l., can exist at angles up to 46°, well beyond their angle of repose (38°). These observations of oversteepened slopes, attributed to the cementing effects of ice, were used to provide field evidence of permafrost conditions above 1000m a.s.l. A slope analysis of Marion Island, focussing specifically on the interior of the island, however, indicates that slope angles of scoria cones, even above 1000m a.s.l., do not typically exceed 35°, less than the angle of repose of 38° suggested by Boelhouwers (2003) (Fig. 4.23). This observed lower slope angle of scoria cones for the upper interior may be due to the fact that as the slope analysis is developed with a cell size is 20m, limiting its spatial resolution, whereas Boelhouwers (2003) based his observations on spot angles determined with an abney level. Thus, even though it is plausible that some sections of slopes of scoria cones may attain slope angles beyond 38° as is suggested by Boelhouwers (2003) slope analysis in this study indicates that slope angles of scoria cones generally do not exceed 35°. Therefore, oversteepened slopes are probably not as common in the interior as has previously been suggested.
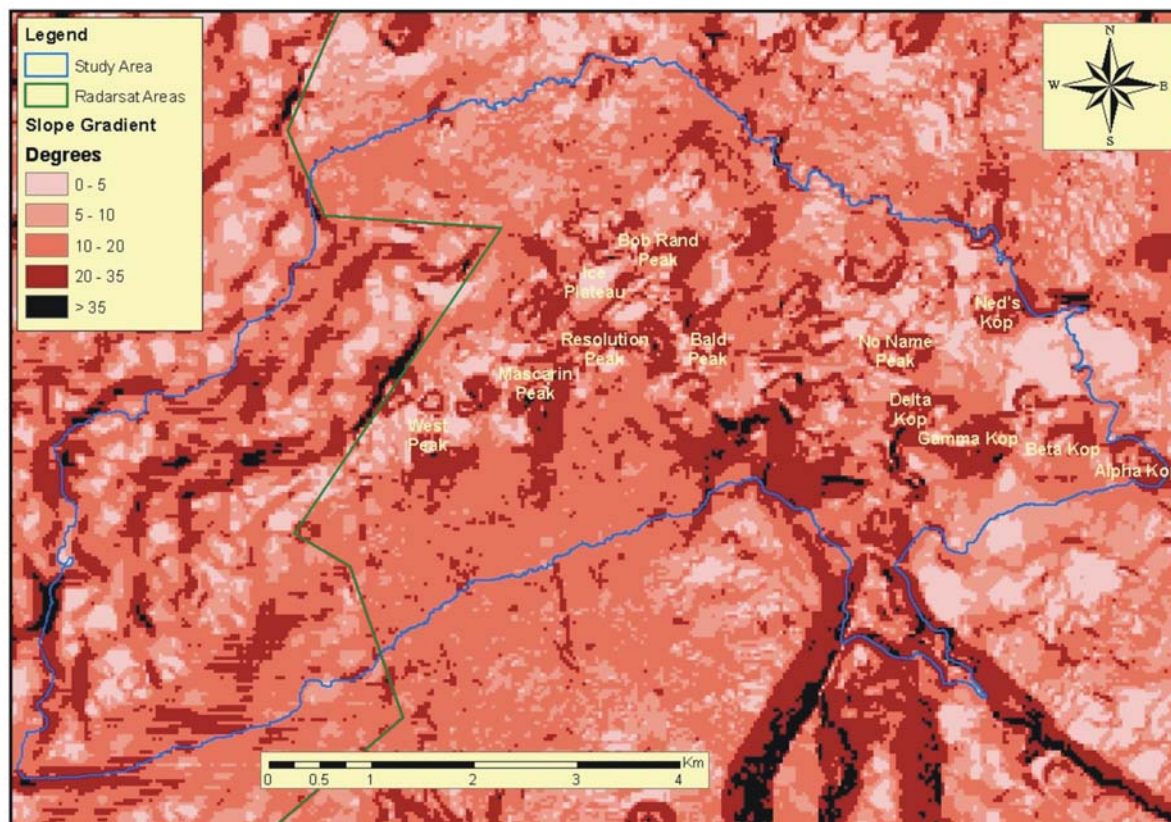
Figure 4.23: Slope analysis focussing of the upper interior of Marion Island. Note that the area to the west of the green line is based on data derived from RADARSAT[TM] data and is, therefore, not as accurate as the elevation data derived from SPOT[TM] data.

Contemporary Geomorphological Processes

In light of the comment made by Thorn (1992; p.10) that "any landform labelled periglacial may be periglacial only in origin, growth, or maintenance, or may be periglacial throughout its development" the question as to whether or not the interior landscape of Marion Island is still undergoing change as a result of climate amelioration or whether features presently found were formed under a previous environmental change becomes relevant. This can perhaps be answered through the description of contemporary geomorphological processes.

Periglacial Processes and Features

Ground temperature data from this study and Holness (2001a) indicate that the interior of the island represents a periglacial environment dominated by frost processes even though there is an observed paucity of common periglacial features (*e.g.* patterned ground). Evidence of active frost processes are nevertheless visible in the form of needle ice activity and ice lens formation in suitable material above 750m a.s.l. (Fig. 4.24). Frost processes, particularly in the interior of the island, may even intensify in future due to increased radiational heat exchange as a result of the observed decrease in snow cover associated with recorded climatic amelioration (Smith, 2002). However, this will only take place if material susceptible to sorting by frost processes is present (*i.e.* availability of fine

particles within the ground matrix). The creation of fine particles in sediment is possible through weathering and the release of cemented fines through the thawing of frozen ground. Patterned ground, mainly in the form of sorted stripes, was observed on the slopes of some scoria cones where sorting suitable sediment was present (Fig. 4.14).

Figure 4.24: Observation of needle ice on Ned's Kop (September, 2005).

Mass Movement Processes and Features

Various mass movement features (*e.g.* debris flows, solifluction features and scree slopes) were identified. However, rates of sediment movement were not determined as the one year time period of this study did not provide an adequate time period to investigate it sufficiently. Nevertheless, mass movement processes such as downslope creep, induced by needle ice, and solifluction are most certainly active. Experiment results and observations of soil frost processes show that frost creep associated with needle ice activity is the dominant slope process in the scoria areas of Marion Island (Holness, 2004). Other slope processes such as slopewash and debris flows appear to play a relatively minor and localized role in sediment transport (Holness, 2004). The transient debris flows documented in the 'Ice Plateau' (Fig. 4.20) provide such an example.

Thermokarst Processes and Features

Contemporary thermokarst processes are driven by climate change. Active thermokarst processes are, however, restricted to areas where buried glacial ice and permafrost persist and not because of unfavourable climatic conditions. For example, whilst thermokarst processes are

recognised to have resulted in the identified thaw slumps, which can be recognised as thermokarst landforms, they are now considered to be inactive due to the observed lack of movement since 1988. They are, therefore, relict and currently being eroded by slope wash.

The region known as the 'Ice Plateau' is currently undergoing drastic change due the relatively large amount of buried glacial ice, up to approximately 5m in places, that can still be found in this area (Fig. 4.9). Upon melting, this buried glacial ice has provided, and continues to provide, a considerable amount of water for surface as well as sub-surface erosion similar to the piping described by Sepällä (1997). Thermal erosion (Fig 4.25) plays a significant role in sculpting the 'Ice Plateau" whereas thermal subsidence (Fig. 4.26) is not limited to the 'Ice Plateau'.

Figure 4.25: Example of thermal erosion within the 'Ice Plateau' (December 2004). Note the sub-surface erosion in the form of an open-closed pipe system.

Figure 4.26: Example of thermal subsidence within the 'Ice Plateau' (April 2005). Note the coalescence of the
thermokarst ponds.

Aeolian Processes and Features

The recognition of wind-modified periglacial features on Marion Island is not new (Hall,
1979; Holness, 2001b), particularly since wind is one of the climatic parameters that control
periglacial processes (Washburn, 1979). Hall (1979) proposed that sorted stripes on Marion Island are
predominantly aligned parallel to the dominant wind direction, even in areas with a very low (less than
1°) slope angle (Callaghan, 2005). As such these wind-orientated sorted stripes typically lie in a
westerly or northwesterly direction (depending on local topography) (Hall, 1979). This study proposes
that wind-modified features are not limited to sorted stripes and "true" aeolian features are also
recognised. Other periglacial features, in this instance solifluction terraces, were also visually noted to
have been modified by wind (Fig. 4.27). Removal of finer sediments (scoria) from the tread sections
of solifluction terraces in the interior were observed, resulting in the creation of a crest-like feature
along the top of the riser, which typically consists of coarser material. In addition, many other small
ripple marks (Fig. 4.28) and deflation hollows (Fig. 4.29) directly attributed to aeolian processes were
also noted and mapped (Fig. 4.12). Their recent detection is probably due to the interior of the island
only recently being sub-aerially exposed through the disappearance of the former permanent snowline
(Sumner *et al*. 2004) and dominance of frost processes at higher elevations disrupting the generation

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of aeolian features. They are, however, not unexpected as wind speeds about the mountain peaks are accelerated (Huntley, 1970) and the 'protecting' effects snow on the ground wane, even in winter (Fig. 4.30).

Figure 4.27: Wind modified solifluction terraces found in the saddle between Delta Kop and No Name Peak. Note the pronounced ridges of coarser material at the tops of the riser (Meiklejohn, April 2005).

Figure 4.28: Aeolian ripple marks found near Katedraalkrans (780m a.s.l.) (Callaghan, April 2005). White lines indicate two different generations of ripples exhibiting different orientations.

Figure 29: Aeolian deflation features found near Katedraalkraans (Callaghan, April 2005).

Approximate Scale

2m

Figure 4.30: Aeolian ripple marks observed in winter in the glacial valley north-west of No Name Peak (June 2004).

Figure 4.31: Aeolian features found on a flat area at lower altitudes (200m a.s.l.) in the south eastern quadrant of Marion Island (April 2005). Note that these aeolian features are better defined than similar features at higher elevations.

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Chapter 5: Discussion

Climate Change Across the sub-Antarctic

To examine the geomorphic responses observed in the interior of Marion Island it is necessary to determine the intensity of climatic change on Marion Island, identified by Smith (2002) and described in Chapter 4, in a global and regional context. In a global context the Southern Circumpolar Region and the sub-Antarctic Islands in particular represent a region of severe climatic change. Comparing the global mean warming of 0.6 ± 0.2°C, confirmed by the Intergovernmental Panel on Climate Change (IPCC), during the 20th century (Vaughan *et al*., 2001) with the mean temperature trend of +1.2°C per century for all Antarctic stations for 1959-96 (Jacka & Budd, 1998) and +1.2°C per century for Marion Island (Smith, 2002), highlights the need to investigate this region more thoroughly. Investigation of the climate change on sub-Antarctic islands is particularly important considering the suggestion by Barsch (1993) that climate change represents an enormous geomorphic experiment, which, if utilised, will allow insights to be made into how periglacial systems work.

Vaughan *et al*. (2001) argue that regional climate changes will have more profound effects than the suggested mean global warning trend but it also implies that there is a need to be investigate regional climatic change, in the form of type or even intensity, since it may not correlate regionally (*i.e.* between islands across the sub-Antarctic). However, regional climatic change across the sub-Antarctic is extremely difficult to assess due mainly to the poor temporal consistency of climate records but also as only mean monthly air temperature data are generally available from weather stations across this region. Comparing the mean monthly air temperature data that is available from the South African Weather Services for Marion Island and the British Antarctic Survey for the other sub-Antarctic islands the data indicates that Marion Island has experienced some of the most intense changes in recorded climate throughout the sub-Antarctic region. This may be a result of Marion Island having the northern most latitude of all sub-Antarctic islands but this requires further investigation.

Differences climate change become evident when comparing Macquarie and Marion Islands. The differences, described below, illustrate regional differences in climate change and highlight the point made above by Vaughan *et al*. (2001). The choice of Macquarie Island for a comparison is made owing to the fact that, like Marion Island, the climate records for the island cover the same time period, the dataset is almost temporally complete and Macquarie Island is the only other island where monthly precipitation data was available to supplement mean monthly air temperature data (data obtained from British Antarctic Survey). The most notable difference in climate change over the same time period between Marion and Macquarie Island is that whilst there has been a decrease in precipitation on Marion Island this is not the case for Macquarie Island. Macquarie Island has,

contrary to the observed trend on Marion Island, experienced a slight increase in precipitation; it has also experienced an increase in air temperature but not as intense as has been recorded on Marion Island, indicating that climate change across the sub-Antarctic is not uniform (Fig. 5.1). In addition, the observed trend of increasing air
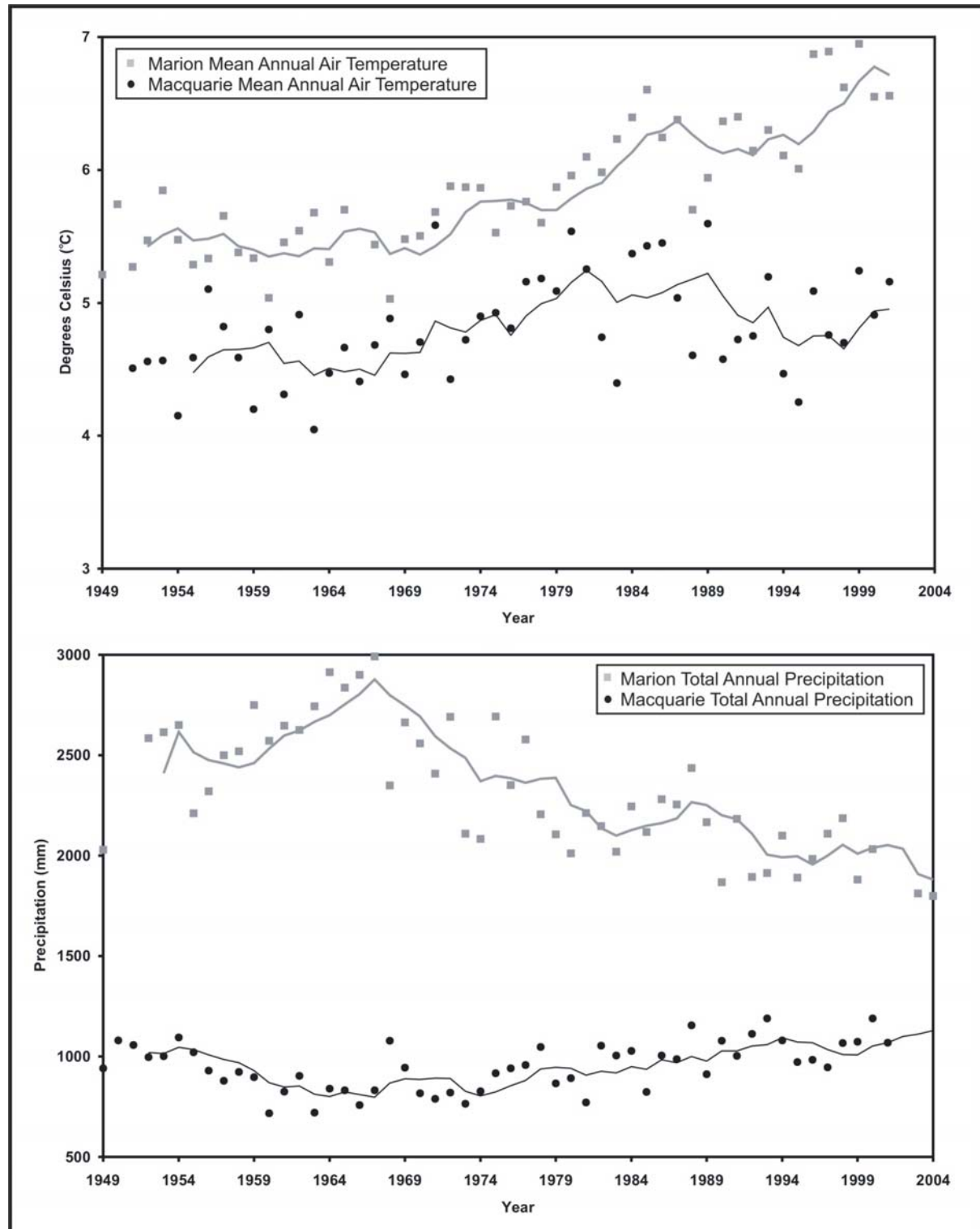

Figure 5.1: Comparison of weather data on Marion and Macquarie Islands. Data obtained from South African Weather Services (Marion Island) and British Antarctic Survey (Macquarie Island). The trend lines represent 5 per. Moving Averages.

temperatures coupled with decreasing precipitation illustrates the point made by French (1996) that in reality an increase in mean annual temperatures generally leads to the diminution of heat exchange in the soil and a lower summer soil temperatures, since it would most likely be associated with an increase in precipitation and cloud cover. Therefore, thermokarst development in relation with regional climatic changes, should be most intense when: (a) associated with a rise in mean annual temperature of the soil, *i.e.* an amelioration of climate, and (b) associated with an increase in amplitude of temperature, *i.e.* an increase in continentality (French, 1996).

Climatic changes, namely increasing mean annual air temperatures and decreasing annual precipitation described above, documented for sub-Antarctic Marion Island provide the ideal platform for thermokarst processes to operate. Macquarie Island, on the contrary, has experienced an increase in mean annual temperatures as well as an increase in annual precipitation providing substance to the statement made above by French (1996). Therefore, the need to systematically collect climatic data across this region, particularly now that automated weather stations can be set up on islands that are only inhabited or visited during short research expeditions during the austral summer months, should be considered to provide a more complete climatic picture for the entire sub-Antarctic region.

Finally, it should also be pointed out that the trends in climate change from Marion Island, highlighted above, may in fact only be describing what appears to be part of a cycle. The suggested cycle is most evident when looking at the precipitation data which peaked in the mid-1960s and has reached a possible low in recent years. Thus, the severe climatic change of a 1.2°C increase in annual air temperature and an approximate 25% decrease in annual precipitation totals highlighted for Marion Island (Smith, 2002) may not be as intense as has suggested since they may represent only part of a longer temporal cycle in climate. This hypothesis, however, can only investigated with continued climatic monitoring.

Distribution of Permafrost, Seasonally Frozen Ground and Buried Glacial Ice

Marion Island represents a periglacial environment where frost processes dominate. However, the distribution of permafrost, seasonally frozen ground and buried glacial ice is largely unknown. Only Holness (2001a) has previously proposed a possible distribution of permafrost, seasonally, short term and diurnally frozen ground for the eastern half of the island. Based on ground temperature data, the size of periglacial features across an altitudinal range and the observation of needle ice activity as apposed to ice lens formation Holness (2001a) proposes a possible frost zonation, illustrating a strong altitudinal trend in soil frost activity. However, although there is an increase in the intensity of soil frost activity with altitude, fundamental differences exist within the periglacial environment of Marion Island, and the frost environments do not represent a smooth continuum of increasing soil frost activity

with altitude (Holness, 2001a), evident in the conspicuous lack of patterned ground features in the upper interior of the island.

The ground temperature data presented in this study correlate relatively well with previously presented data (Boelhouwers *et al*., 2001; Holness, 2001a; Boelhouwers *et al*., 2003). However, none of the ground temperature data collected thus far indicate the thermal presence of permafrost, which requires that ground temperatures remain below zero for a minimum of two years (French, 1996). The spatial and altitudinal locations for ground temperature monitoring must, however, be questioned as ground temperature monitoring has not yet taken place at the highest altitudes (above 1000m a.s.l). Nonetheless, relict pockets of permafrost were identified through the presence of thermokarst features and buried glacial ice illustrating the limitation of using only a thermal criterion to define permafrost regions (see Van Everdingen, 1976 for discussion). The presence of permafrost is, however, regarded as relict since the current environmental conditions present appear unsuitable for the formation of new permafrost nor its long term maintenance.

Based on the assumption that ground temperatures will follow air temperature trends and analysis of the recorded ground temperature indicates that even a 1°C increase in ground temperature will drastically reduce the number of days, where minimum ground temperatures are below zero, which in turn will reduce the number of freeze thaw cycles (Table 5.1). Boelhouwers (2003), using previously collected data (Boelhouwers *et al*., 2001), indicates that there will be about a 25% reduction in days with frost in the summit regions of the island (1000m a.s.l.) with every one degree Celsius warming. Under such conditions, the hypothetical impact of cooling and warming may be speculated upon assuming no changes in snow cover conditions (Boelhouwers, 2003) as is done here. Ground Temperature data collected, at 1000m a.s.l., on a north western facing slope of a Delta Kop, from this study indicate that there will only be about a 10% reduction in days with frost with every one degree Celsius warming (Table 5.2). This figure, however, increases drastically with a decrease in altitude. At approximately 800m a.s.l. ground temperature data indicate a reduction of just over a 60% in frost with every one degree Celsius warming, highlighting the sensitivity of the upper interior of Marion Island, namely for frost processes to climatic warming. Not surprisingly, the ground temperature data (800m and 900m a.s.l.) indicate that northern slopes are affected more in terms of a reduction in frost days; with an average reduction of 55% in frost as apposed to only 28% for southern facing slopes. The reduction in days with frost decreases with an increase in altitude but it increases drastically with depth across the altitudinal range of ground temperature monitoring sites. Ground temperature data also indicates that frost penetration is very surficial as only the Delta North site at a 1000m a.s.l. would experience a small number of days where minimum temperatures would fall below zero beneath the ground surface.

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Table 5.1: Number of days with minimum temperatures below 0°C, and a +1°C and +2°C warming scenario for the various sites where ground temperature monitoring was conducted on Marion Island (Boelhouwers, 2003).

Depth	-0.8m	-0.4cm	-0.2m	-0.1m	-0.05m	-0.01m
Present	0	0	137	194	162	259
+ 1°C	0	0	0	35	77	191
+ 2°C	0	0	0	13	47	142

Table 5.2: Number of days with minimum temperatures below 0°C, and a +1°C and +2°C warming scenario for the various sites where ground temperature monitoring was conducted on Marion Island.

Delta North (Slope: 20°; Aspect: 290°; Altitude: ±1000m)			
Depth	0.75m	0.50m	0.25m	0.01m
Present	312	320	326	314
+ 1°C	13	69	145	282
+ 2°C	1	19	76	247

Delta South (Slope: 28°; Aspect: 183°; Altitude: ±1000m)			
Depth	0.75m	0.50m	0.25m	0.01m
Present	-	-	-	-
+ 1°C	-	-	-	-
+ 2°C	-	-	-	-

No Name Saddle North (Slope: 15°; Aspect: 331°; Altitude: ±900m)			
Depth	0.75m	0.50m	0.25m	0.01m
Present	32	94	130	312
+ 1°C	0	0	14	161
+ 2°C	0	0	6	96

No Name Saddle South (Slope: 14°; Aspect: 158°; Altitude: ±900m)			
Depth	0.75m	0.50m	0.25m	0.01m
Present	159	176	190	311
+ 1°C	1	1	6	241
+ 2°C	0	0	1	168

Ned's North (Slope: 19°; Aspect: 353°; Altitude: ±800m)			
Depth	0.75m	0.50m	0.25m	0.01m
Present	108	112	152	233
+ 1°C	0	0	10	89
+ 2°C	0	0	2	50

Ned's South (Slope: 18°; Aspect: 153°; Altitude: 800m)			
Depth	0.75m	0.50m	0.25m	0.01m
Present	138	142	145	276
+ 1°C	0	0	0	181
+ 2°C	0	0	0	115

Under a two degree Celsius warming, the reduction in the number of days where minimum ground temperatures are below zero is naturally higher, although the magnitude of the reduction of days with frost is severe. The Ned's North ground temperature monitoring site, which represents one of the lowest altitudinal (800m a.s.l.) monitoring sites, and is on a north-facing slope, indicates that there will be a decrease of about a 78% in the number of days under a two degree Celsius warming scenario. This suggested reduction in potential frost activity at 800m a.s.l. implies that the effectiveness of frost processes will become extremely limited at this altitude but more so at lower altitudes where, at present, only short term and diurnal freeze take place.

Figure 5.2, adapted from Holness (2001a), depicts the proposed distribution of permafrost, seasonally, short term and diurnally frozen ground as well as buried glacial ice. Possible pockets of relict permafrost are thought to potentially exist above 1200m a.s.l. due to the presence of relict pockets of permafrost at lower altitudes (approximately 1100m a.s.l.). The distribution of frost zonation proposed by Holness (2001a) is largely accepted in this study apart from the additional inclusion of buried glacial ice which is regarded as separate to permafrost areas. A brief description of

the synthesized distribution of sporadic pockets of relict permafrost, seasonally, short term and diurnally frozen ground as well as buried glacial ice is described below.

The zone of diurnally frozen ground extends from the coast to approximately 300m a.s.l. and Holness (2001a) indicates, through direct observation, that ice lens formation is rare or absent within this zone, while extensive needle ice activity occurs throughout the year except for the period from December to February. The zone of short term frozen ground is found between 300m - 750m a.s.l. and is characterised by a high number of freeze-thaw cycles (Holness, 2001a). Interestingly, the transition from a purely soil frost regime restricted to needle ice activity, to a soil frost regime with longer duration frost events and solifluction as well as needle ice activity, correlates with a noticeable change in the nature of the vegetation on Marion Island (Holness, 2001a). Below 300m a.s.l. vascular plants dominate whereas above this altitude cryotogamic communities consisting largely of lichen and moss species predominate (Huntley, 1971). This study, similar to Holness (2001a), indicates that the zone of seasonally frozen ground is found above 750m a.s.l. and characterised by mild seasonal freezing between June and October. Possible pockets of relict permafrost may occur above 1000m a.s.l. in a number of valley depressions and volcanic craters. Buried glacial ice is regarded as a separate entity as it represents the remnants of a fossil ice cap which through melting is drastically altering the area known as the 'Ice Plateau' through thermokarst processes.
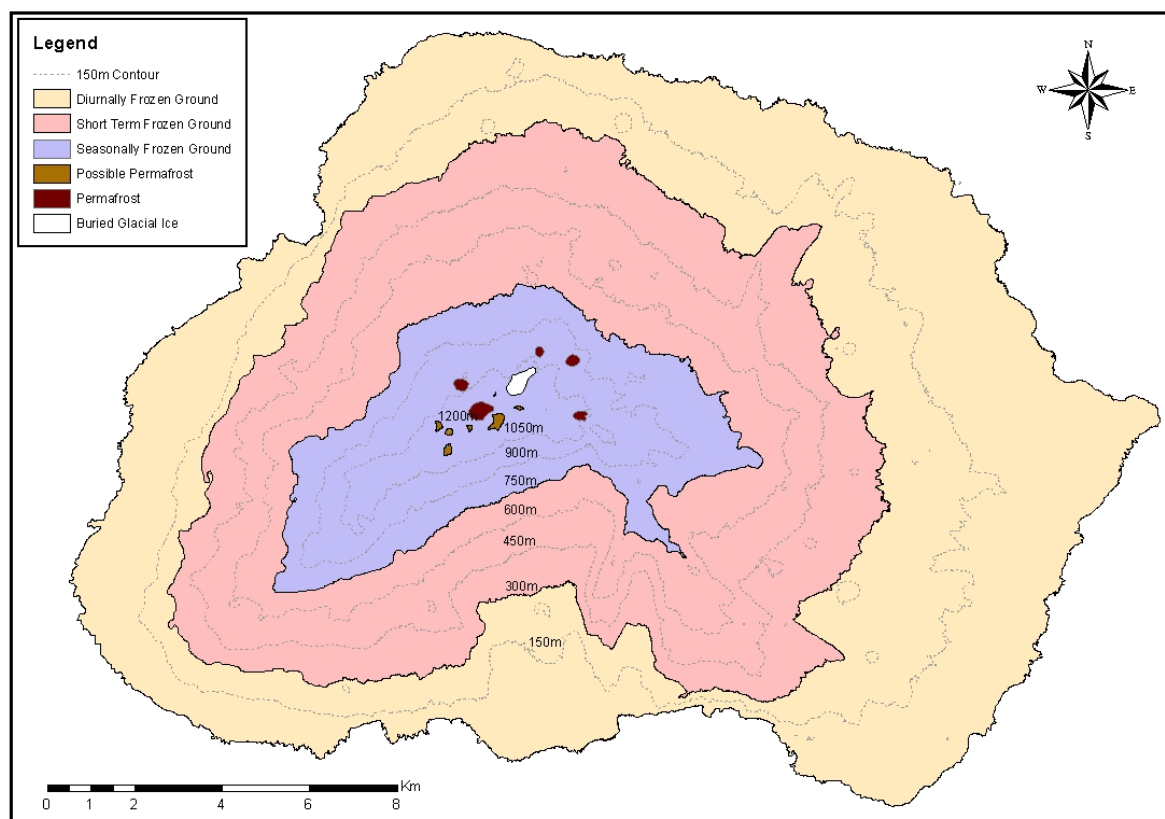

Figure 5.2: Distribution of permafrost, seasonally frozen ground and buried glacial ice. All permafrost is regarded as relict. Possible permafrost refers to areas above 1200m a.s.l. (Adapted from Holness, 2001a).

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Contemporary Landscape Dynamics

Ground temperature data presented in Chapter 4 show that at present Marion Island, above 750m a.s.l., is dominated by frost processes owing to the diurnal, short term and seasonal freezing and thawing of the ground. Sporadic permafrost, which is regarded as relict, can be found on insolation south-facing slopes and valley floors but this is rapidly disappearing owing to the dramatic climatic warming that has been experienced on the island since the mid-1960s. Therefore, thermokarst processes are active, particularly in the area known as the 'Ice Plateau', on Marion Island. The reason for this is that the 'Ice Plateau' represents the only area where buried glacial ice still persists, providing water for thermal subsidence and thermal erosion. Thermokarst identified in areas outside the 'Ice Plateau' represent areas of relict permafrost.

Thermokarst features are by definition an illustration of a landscape response to climate change. However, the question remains as to whether or not these features are forming under contemporary environmental conditions or are they the result of previous climatic amelioration when permafrost still existed. For instance, if the climate continues to warm but there is no suitable substrate (*i.e.* buried glacial ice or permafrost) for thermokarst features to form it will not and, therefore, would indicate that climatic warming is not occurring, illustrating a flaw in using climatic geomorphology.

The general absence of periglacial features such as patterned ground in the interior of Marion Island has been observed but this may be due to the relatively recent sub-aerial exposure of much of this region through the recent disappearance of a former permanent snowline or an unsusceptible substrate for frost processes. In areas that are largely unsusceptible to frost processes (*i.e.* black lava flows) aeolian processes indicate their presence whereby these black lava flows create areas with a higher surface roughness causing wind energy to decrease which in turn results in the deposition of wind transported material (Fig. 5.3).

Wind-modified periglacial features (*i.e.* sorted stripes) have been studied to some degree on Marion Island (Hall, 1979) but features attributed directly to aeolian processes have, however, received almost no attention with Gribnitz *et al.* (1986) even doubting the presence of aeolian processes in general, due to the perennially wet conditions found on the island. Verwoerd & Lagenegger (1968) mapped the extent of area dominated by wind-related features, bar much of the interior of the island which was permanently covered in snow at the time of mapping. This prompted the pilot study of Callaghan (2005) to document the characteristics of aeolian features on Marion Island. Textural analysis done by Callaghan (2005) indicates that the aeolian features are deflation features. The supply of fine sediment probably comes from the thaw of former permafrost and the creation of new fines through weathering.

Figure 5.3: Wind-deposited material over a black lava flow between Ned's Kop and No Name Peak (April, 2005). Note the deflation hollows around obstacles. Backpack for scale.

Aeolian features found at lower altitudes (*i.e.* the mapped areas in the south eastern quadrant of Marion Island; Fig. 2.3.) are better defined than similar features found at higher elevations (Fig. 4.31). Features found in the island's interior can nonetheless provide much information in terms of recent climate change. Aeolian features in the upper interior are poorly developed as these features may be disturbed through frost processes. The time period for wind to form aeolian features is also limited due to the ground surface being protected under a blanket of snow frequently throughout periods during the winter months and even during summer. However, if the observed trend of climatic amelioration (Smith, 2002) and associated declining snow cover continue the protection of snow cover of underlying ground will become less effective in the future. The massive ground freezing during winter may also limit aeolian processes through ice cementing the ground. However, due to the extremely porous nature of the ground (scoria) the cementing effects of the ground by ice coupled with the presence of an upper, active layer the efficiency of this limiting factor of aeolian processes. Aeolian processes may, therefore, become more prevalent in future due to more favourable conditions provided by climate change, having significant implications for plant colonisation at higher elevations. Aeolian processes may play even a more important role in moulding the interior landscape of Marion Island in the future.

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Interactions between frost and aeolian processes will require further investigation particularly if snow cover continues to disappear further as this will affect both these processes. Disappearance of snow cover will enhance frost processes (Matsuoka, 1996) whilst at the same time allowing aeolian processes to sculpt the surface; provided the surface is not cemented by ice. However, the extremely natural porous nature of scoria could limit the effects of ice cementing particularly since even if only the surface is thawed aeolian processes could operate. Areas above 750m a.s.l. could, therefore, become extremely susceptible to aeolian processes, with only particle size being a limiting factor. The suggested future prevalence of aeolian processes and incumbent features is also due to the almost entire absence of vegetation at altitudes above 750m a.s.l. and consistent high wind velocities indicating that wind velocities are more than capable of initiating the transport of sediment (*i.e.* scoria) even though sediment can be relatively large in size (e.g. >2cm).

Geomorphological Processes and Landforms within the 'Ice Plateau'

French (1996) states that with respect to regional climatic changes, thermokarst development should be most intense when: (a) associated with a rise in the mean annual temperature of the soil, *i.e.* an amelioration of climate, and (b) associated with an increase in amplitude of temperature *i.e.* an increase in continentality. French (1996) continues to suggest that a combination of these two conditions should lead to maximum increase in the depth of the seasonally thawed layer. In reality, however, an increase in mean annual temperature would probably lead to a diminution of heat exchange in the soil and a lower summer soil temperature, since it would most likely be associated with an increase in precipitation and cloud cover. As a result, there would be a decrease in the depth of thaw, which is the exact opposite to what is required for thermokarst development. Therefore, the simplest condition for the onset of thermokarst would be the progressive increase in continentality of climate resulting in a greater range of soil temperatures and summer thaw depths (French, 1996). This is, however, not the case for Marion Island. Cloud-cover has stayed relatively constant whilst an increase in annual temperature and a decrease in precipitation have been recorded at base (Smith, 2002). Thus, even though Marion Island may be unique in terms of climate change it, nonetheless, provides the ideal environment to monitor responses to climate change. The 'Ice Plateau' in particular represents an extremely sensitive environment to climate change since it is the only area where glacial ice persists. Thermokarst features described in this area are the result of thermal erosion and thermal subsidence. The mapped distribution of thermokarst features is, however, likely to change since these features are transient; being easily destroyed and reworked. In addition, the maintenance and further formation of thermokarst features is questioned since remaining permafrost and buried glacial ice found in the 'Ice Plateau' is rapidly disappearing.

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Volcanics

Even though Marion Island is a volcanic island where volcanic activity has been observed as recently as 2004 (Meiklejohn & Hedding, 2005) it can not be regarded as the initiator or the cause of continued melting of buried glacial ice and relict permafrost in the upper interior of Marion Island resulting in the manifestation of landscape responses. The possible ancillary role of volcanic activity initiating and maintaining is therefore questioned mainly due to the limited size, sporadic temporal nature and relative distance away from the upper interior of Marion Island.

Environmental Significance

The recent sub-aerial exposure of much of the interior of Marion Island above 750m a.s.l. provides "virgin" territory for many geomorphological processes to now operate. Frost processes may even have intensified through increased radiational heat exchange, following the disappearance of snow cover over a thawed upper layer of sediment; this, in turn, will also provide the potential for increased aeolian activity. The interaction of aeolian and frost processes may result in some interesting landscape dynamics which will require future investigation and monitoring. Sub-aerial exposure of the ground, coupled with thawing of previously frozen ground will also logically increase the rate of erosion by water, sourced from melting permafrost and glacial ice, and a higher proportion of precipitation that will fall as rain and not snow. Sub-aerial exposure of the ground in the island's interior will also provide the opportunity to investigate soil formation through pedogenic processes in a hyper-maritime periglacial environment (Boelhouwers *et al*., 2003). The types and magnitude of erosion in the island's interior will, therefore, also require further investigation.

Another important impact of climatic amelioration and associated landscape responses in the form of thawing of permanently and seasonally frozen ground on Marion Island is that of plant colonisation at higher elevations. Plant colonisation at higher altitudes is already evident with the recent discovery of *Azorella selago*, a cushion-type plant, growing at an altitude of 840m a.s.l. (*pers. obs.*), whereas it was only found at a maximum altitude of 765m a.s.l. in the mid 1960s (Huntley, 1970). The significance of *Azorella selago* growing at higher elevation becomes clear considering that it is the pioneer plant of loose scoria slopes, and is thus crucial to vegetative succession (Huntley, 1970). Interestingly, the observation represents the highest record of *Azorella selago* growth in the sub-Antarctic. Because the effect of soil frost and downslope sediment movement through solifluction on vegetation succession to higher elevations on Marion Island the potential for further study is clear.

Chapter 6: Conclusion

Geomorphology of the Interior of Marion Island

Many previously undocumented glacial, periglacial and rudimentary aeolian features were documented in the interior of Marion Island (above 750m a.s.l). Conspicuous in the research was that few periglacial landforms are found in the interior of Marion Island, even though frost processes currently predominate.

Thermokarst was found at altitudes above 1000m a.s.l. in areas where buried glacial ice and/or permafrost persist. The thermokarst provided an ideal opportunity to investigate the impact of climatic warming on periglacial processes and landforms. In this context, thermal erosion was only recorded in the 'Ice Plateau', while thermal subsidence was more ubiquitous to thermokarst and also found in areas with no buried glacial ice. Distribution and maintenance of thermokarst features in the island's interior is likely to change since they are considered to be transient. Therefore, formation of any new thermokarst features is regarded as unlikely. Identified thermokarst features, nevertheless, indicate that the interior on Marion Island (above 750m a.s.l.) is particularly sensitive to climate change and should thus be monitored closely.

Monitored ground temperatures indicate that permafrost does not occur at any of the ground temperature monitoring sites. However, permafrost may still be found on insloation-protected south facing slopes and valley floors at higher altitudes, as suggested by the existence of buried glacial ice and frozen ground at altitudes of approximately 1100m a.s.l. Ground temperature data indicates the potential for frost processes to geomorphologically dominate the upper interior even though periglacial features (*e.g.* patterned ground) typically associated with frost environments are sparse.

Consistently high winds speeds and the availability of "wind-transportable" material in the upper interior of Marion Island suggest a potentially major role for aeolian processes; this is especially so, considering that the decreasing snow-cover is exposing more and more ground. Interaction of aeolian and frost processes, could, thus, result in an interesting myriad of geomorphological features.

Geomorphological Responses to Environmental Change

Current responses to climate change in the upper interior of Marion Island are most evident where thermokarst is melting and this can be observed in the form of undulating topography where permafrost and buried glacial ice persist. Thermokarst processes of thermal erosion and thermal subsidence, were observed during the study. Both permafrost and buried glacial ice are regarded as relict as contemporary environmental conditions are not favourable for their maintenance. Current

ground temperature regimes indicate that frost processes potentially dominate the upper interior of Marion Island.

The recent disappearance of the former permanent snowline may enhance frost processes through an increase in radiational heat exchange. However, the recent disappearance of the former permanent snowline coupled with the provision of a thawed upper layer of sediment will also provide the platform for aeolian processes to operate. It is suggested that that frost processes will continue to dominate the upper interior of Marion Island and that aeolian processes will become more prevalent.

Future Geomorphological Research Possibilities

Permafrost temperatures are generally only a few degrees Celsius below freezing and therefore even a small ground temperature increases may lead to significant permafrost thaw (Harris *et al*., 2001). Within this context, Marion Island, due to its relatively low latitudinal position and only possible limited existence of (relict) permafrost on insolation protected south facing slopes and valley floors above 1000m a.s.l., is considered to be particularly vulnerable. Therefore, an attempt should be made to monitor ground temperatures in remnants of permafrost and buried glacial ice on Marion Island in accordance with the standards of other cryosphere monitoring programmes such as the Global Terrestrial Network for Permafrost (GTN-P).

The degradation of Marion Island's 'Ice Plateau' is an important indicator of current changes affecting the cryosphere at southern hemisphere mid-latitudes (Sumner *et al*., 2004). Therefore, identified thermokarst processes and resultant features, representing a landscape response(s) to climate change, should be monitored through repeat photography and documentation. Continued monitoring and documentation will provide insight into possible outcomes on other sub-Antarctic islands if the present identified trend of climatic amelioration continues. Monitoring the development of aeolian (wind) generated and modified features on Marion Island provides another avenue of potential research. Investigation into the development of features directly attributed to aeolian processes may provide some interesting results; comparison between features found in higher and lower elevations on Marion Island could provide a much needed basic understanding of aeolian processes on Marion Island as highlighted by Callaghan (2005). In addition, comparison of the identified aeolian features on Marion Island and aeolian features found on other sub-Antarctic islands (*e.g.* Löffler, 1983; 1984) could also be of value; particularly, as many researchers neglect to consider the occurrence of aeolian processes on the sub-Antarctic islands due to their perennially wet conditions (e.g. Gribnitz *et al*., 1986). The recent sub-aerial exposure of the island's interior will also provide the opportunity to investigate soil formation through pedogenic processes in a hyper-maritime periglacial context.

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       Investigation into the interactions between frost and aeolian processes and subsequent development of a landscape in the upper interior of Marion Island are also of considerable importance due to the possible influences this interaction may have on the colonisation of plants to this almost vegetation free landscape.

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Appendix

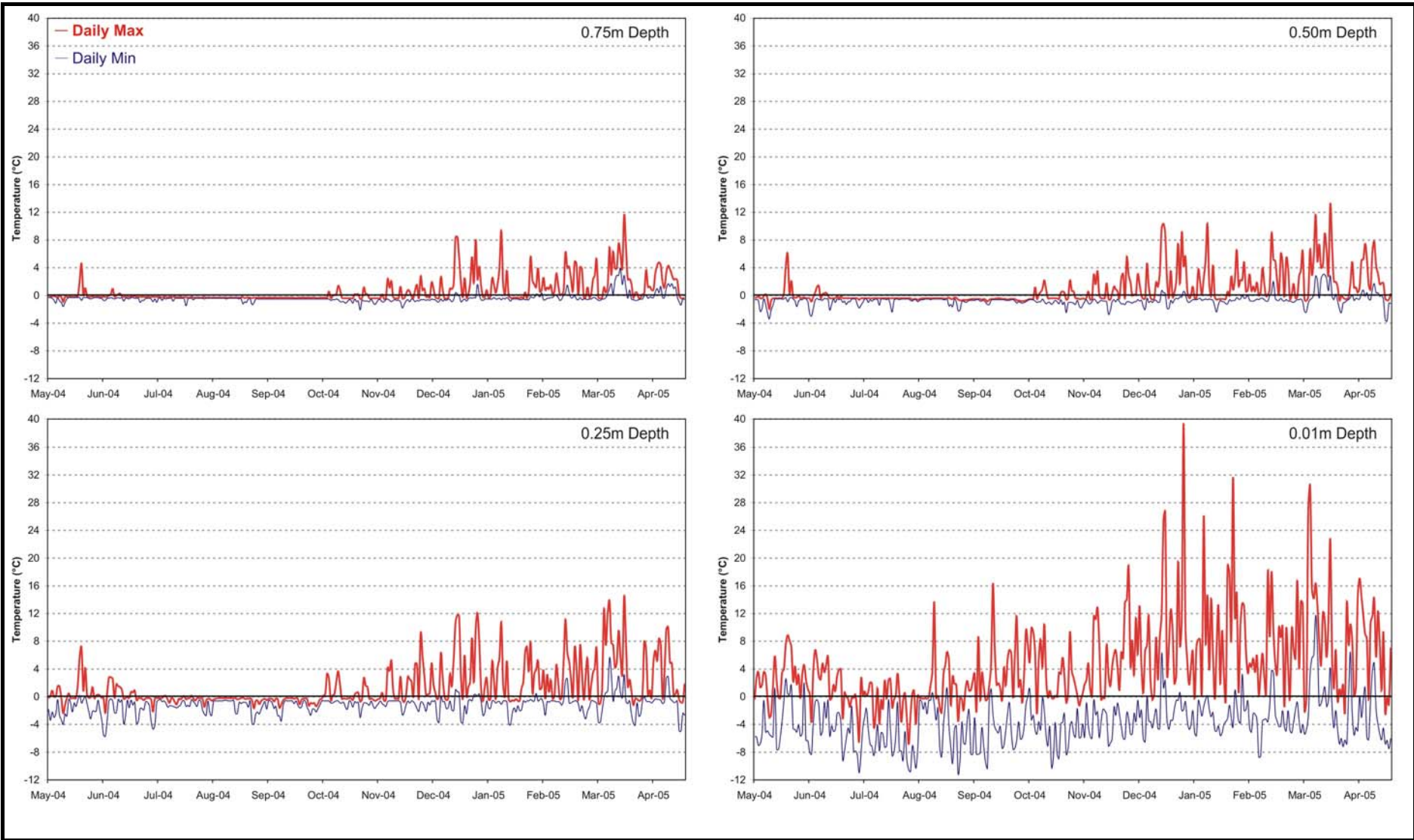**Appendix A: Ground Temperature Data (17 May 2004 – 29 April 2005)**

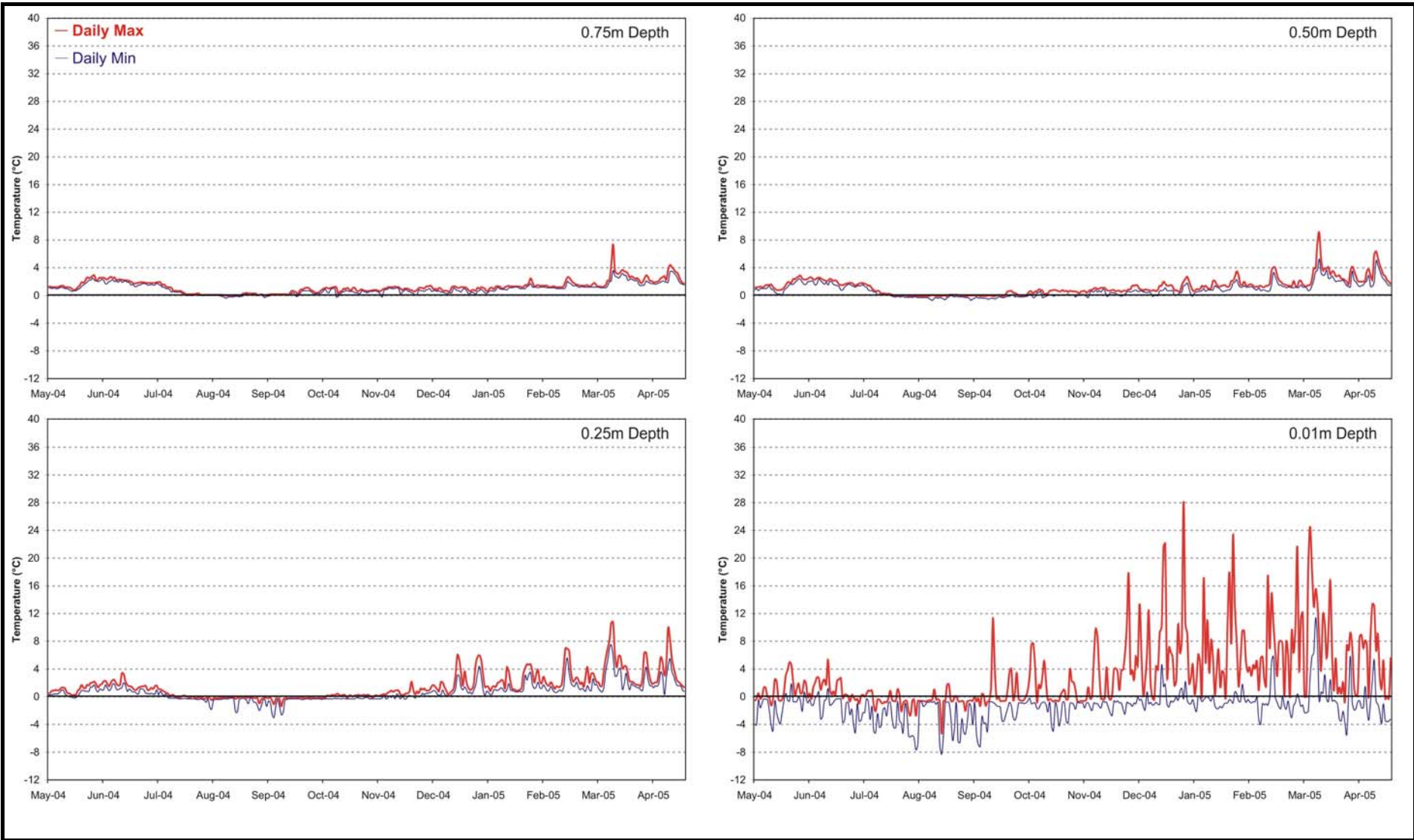Figure 1: Delta North (1000m a.s.l.).

Figure 2: No Name Saddle North (900m a.s.l.).

Figure 3: No Name Saddle South (900m a.s.l.).

Figure 4: Ned's North (800m a.s.l.).

Figure 5: Ned's South (800m a.s.l.).

Figure 1: Delta North (1000m a.s.l.).
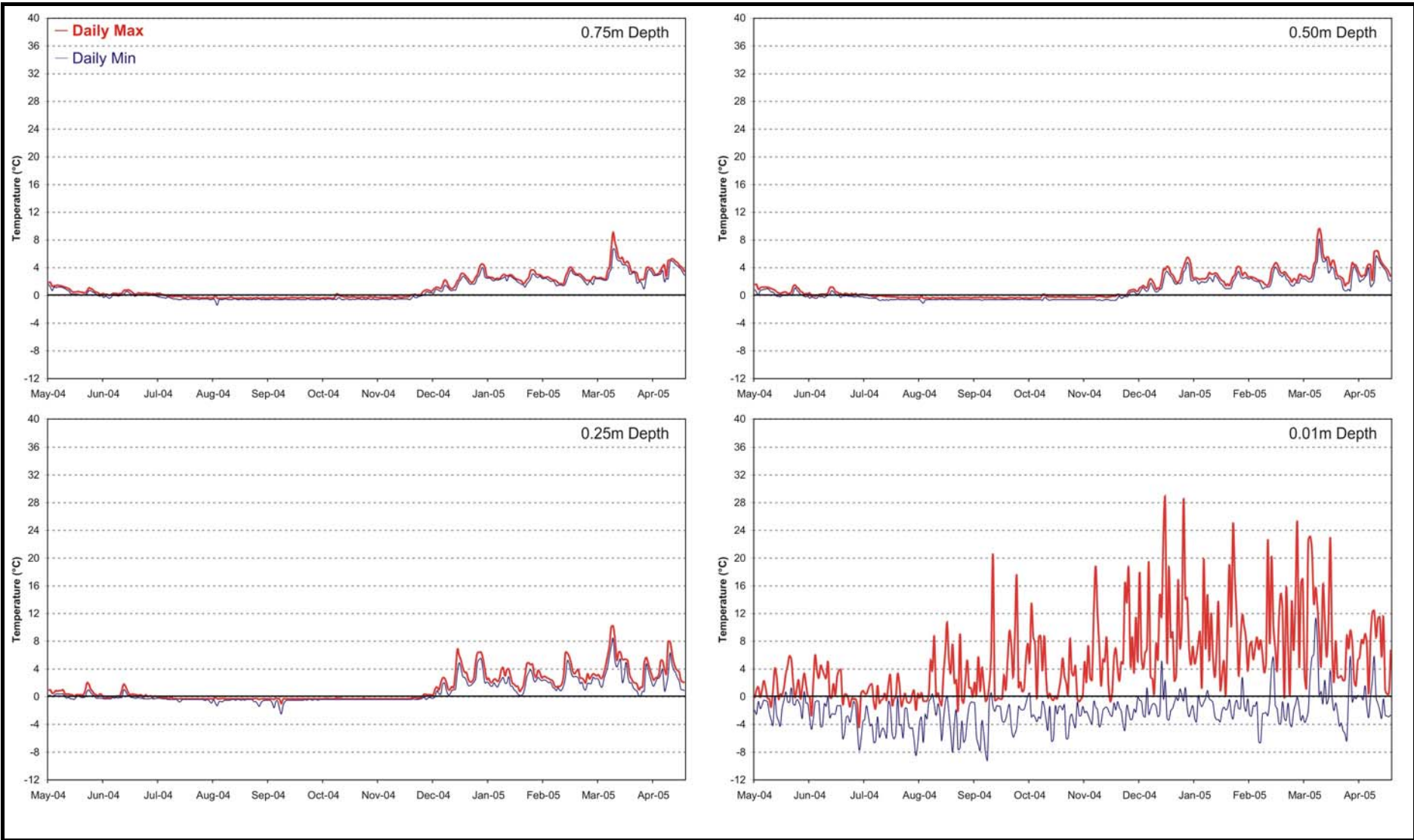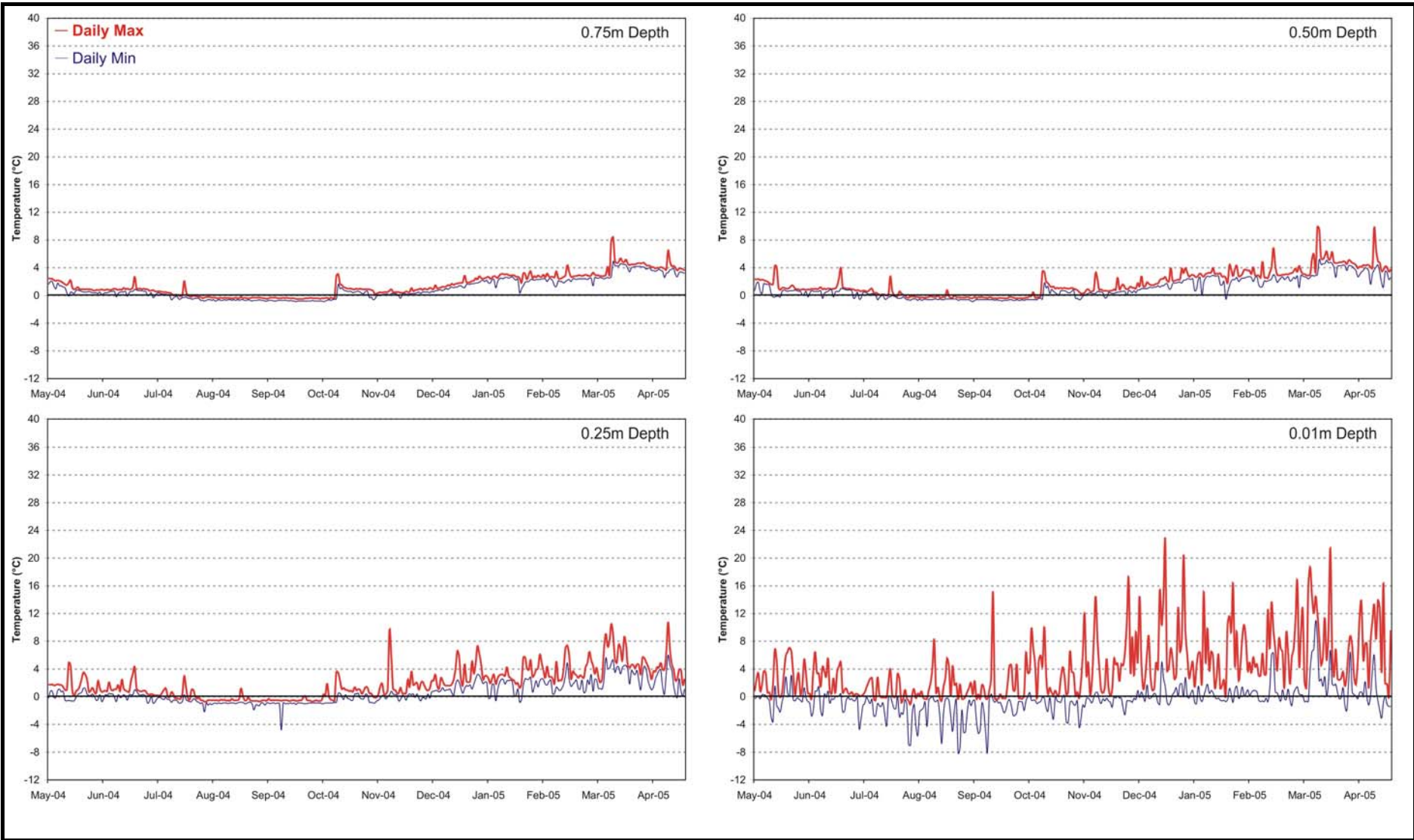
Figure 2: No Name Saddle North (900m a.s.l.).

Figure 3: No Name Saddle South (900m a.s.l.).
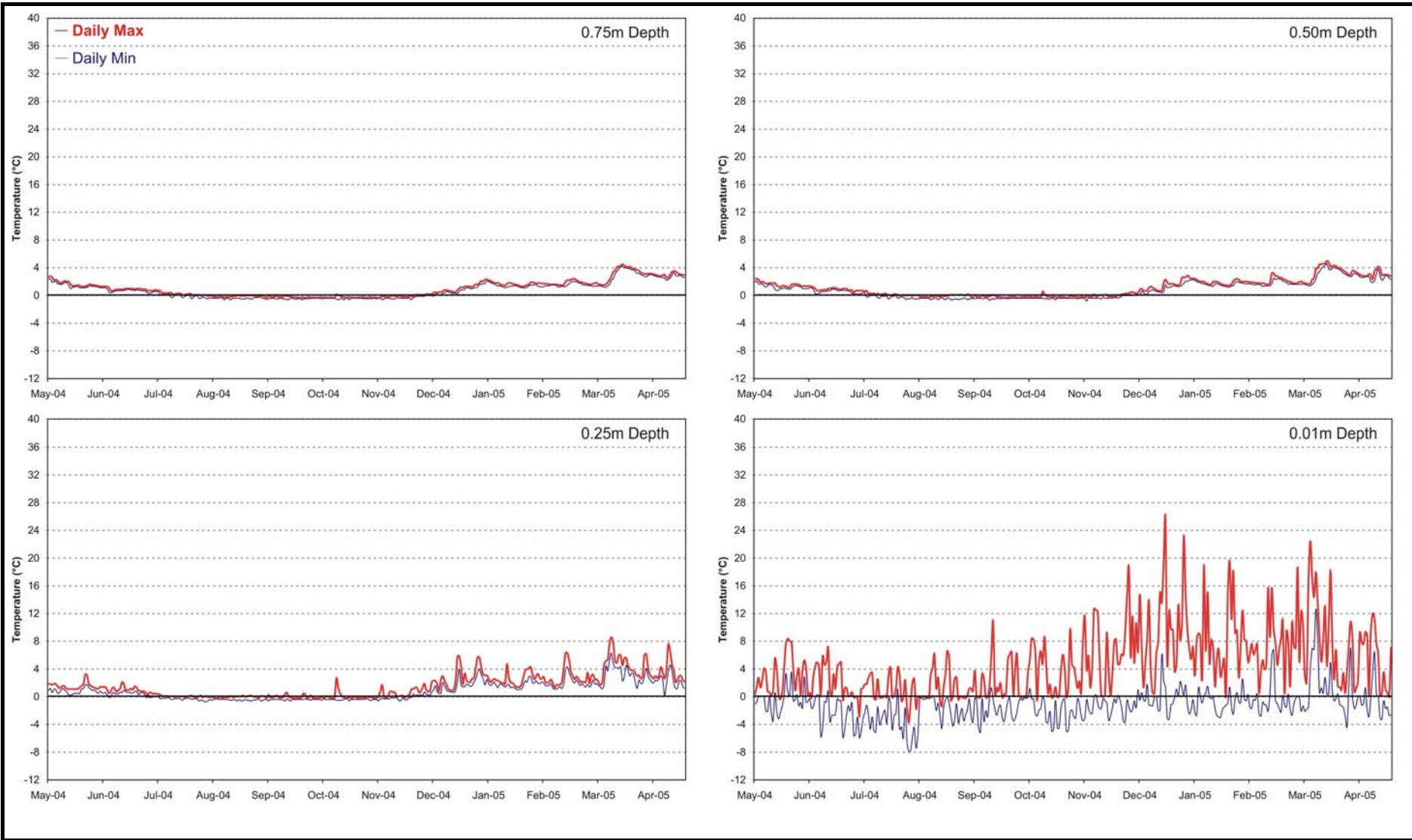
Figure 4: Ned's North (800m a.s.l.).

Figure 5: Ned's South (800m a.s.l.).

Appendix B: Additional Maps

Figure 1: Digital Elevation Model (DEM) of Marion Island.

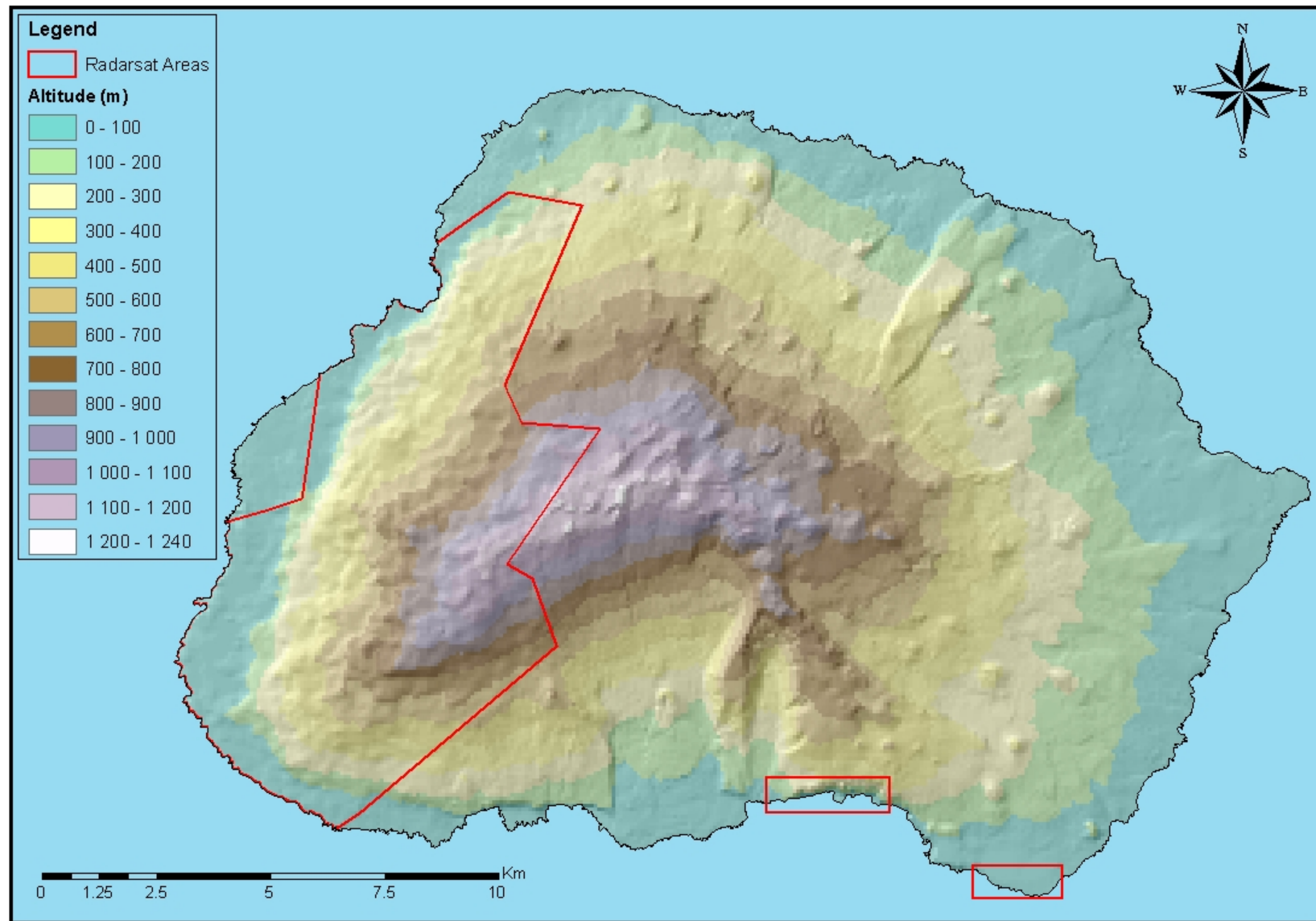Figure 2: Slope analysis of Marion Island.

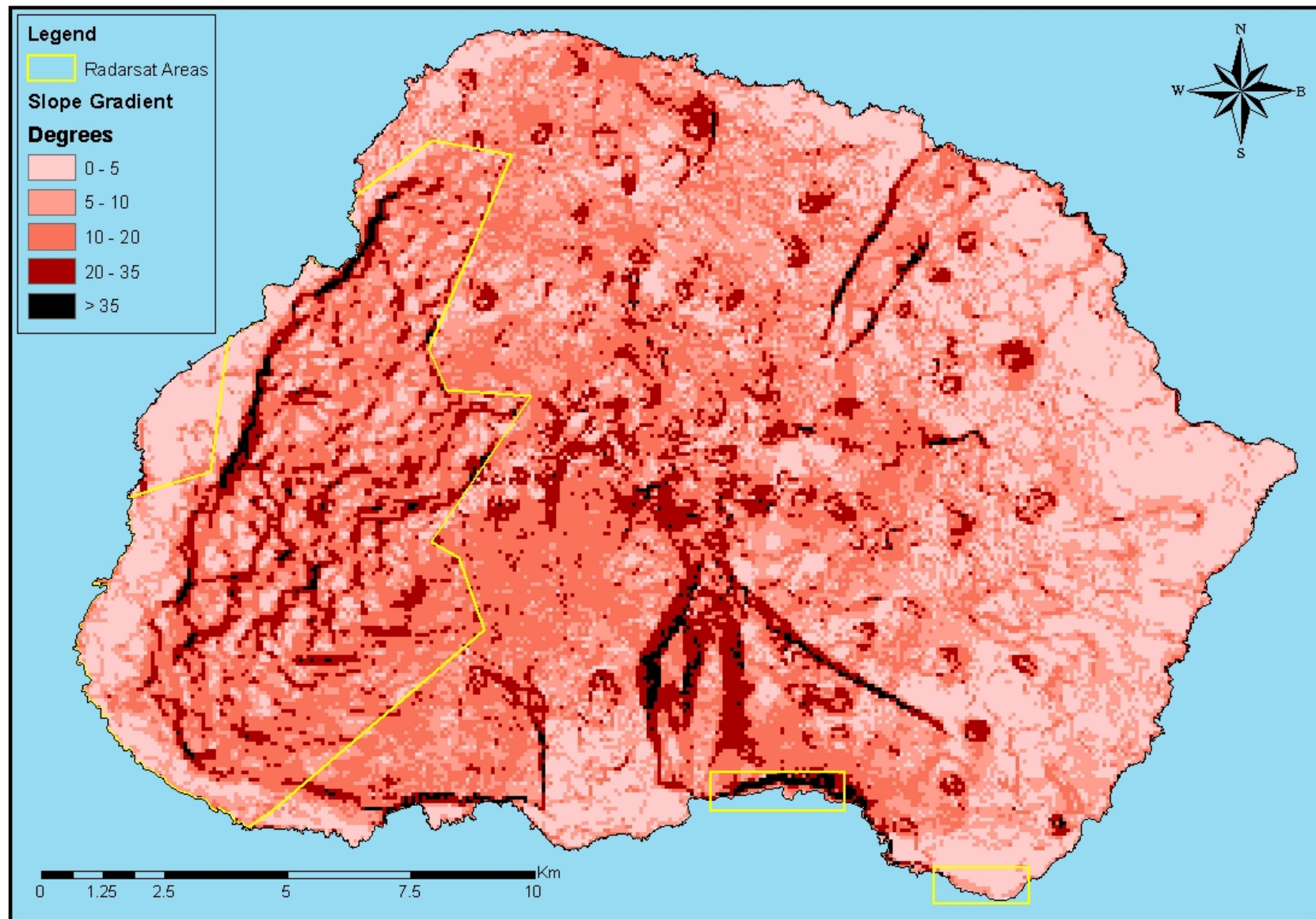Figure 1: Digital Elevation Model (DEM) of Marion Island.

Figure 2: Slope analysis of Marion Island.

"And I tell you, if you have the desire for knowledge and the power to give it physical expression, go out and explore. If you are a brave man you will do nothing: if you are fearful you may do much, for none but cowards have the need to prove their bravery. Some will tell you that you are mad, nearly all will say, "What is the use?" For we are a nation of shopkeepers, and no shopkeeper will look at research which does not promise him a financial return within a year. And so you will sledge nearly alone, but those with whom you sledge will not be shopkeepers: that is worth a good deal. If you march your Winter Journeys you will have your reward, so long as all you want is a penguin's egg."

Apsley Cherry-Garrard
(*The Worst Journey in the World*)