A SPATIAL INVENTORY OF GLACIAL, PERIGLACIAL AND RAPID MASS MOVEMENT FORMS ON PART OF MARION ISLAND: IMPLICATIONS FOR QUATERNARY ENVIRONMENTAL CHANGE

By

Werner Nel

Submitted in partial fulfilment of the requirements for the degree of
Master of Science (Geography and Geoinformatics)
Faculty of Natural and Agricultural Sciences
University of Pretoria
Pretoria

December 2001

A spatial inventory of glacial, periglacial and rapid mass movement forms on part of Marion Island: Implications for Quaternary environmental change

Werner Nel

Supervisor: Dr. K.I. Meiklejohn
Department of Geography and Geoinformatics
Master of Science

Abstract

While climate change is expected to have its greatest impacts in the earth's polar regions, most studies to date concentrate on Northern Hemisphere landscape changes. In contrast, Southern Hemisphere periglacial environments are poorly understood, both in terms of basic understanding of geomorphological dynamics as well as sensitivity to climate change. Marion Island constitutes such an environment and the purpose of this project was to assess the Late Pleistocene and Holocene glacial, periglacial and mass movement morphology on the island, and to use these data as indicators for climate change. A survey and thematic mapping, following an adaptation from the ITC working procedure, was used to compile an inventory of the glacial, periglacial and mass movement features for grey lavas on the eastern side of Marion Island.

Glacial moraines, glacially polished and striated bedrock surfaces identified from previous research verified and mapped, while undocumented sites were added to the inventory. Data support the findings of Hall (1978; 1980a; 1982) and that the suggested palaeoreconstruction and glacial succession on Marion Island from that research is correctly interpreted.

Periglacial landforms occur on all the grey lava areas that were surveyed on Marion Island. The features are found throughout the whole island altitudinal range, and definite trends can be discerned, where landform size increases with altitude. No significant differences, however, appear to exist between the warmer north-facing and colder south facing slopes with regards to the size distribution of periglacial features on

Marion Island. Increasing periglacial activity with altitude is indicative of an increase in frequency and/or intensity of frost induced processes.

Stone-banked lobes, stone-banked terraces, vegetation-banked lobes and blockstreams identified in this study and whose morphology cannot be explained by present day soil frost activity are considered relict. These features indicate and confirm conclusions from previous studies that Marion Island experienced a more severe frost environment than present.

Rapid mass movement features are present in most grey lava areas, except where there is an absence of cliffs or where low slope angles are found. Screes are mostly found where high free faces exist and the extent of the screes is related to the morphology of the cliffs above. Peat slides are common in middle and low altitudinal areas between 150m a.s.l. and 450m a.s.l. where thick soil and steeper slopes are present. However, peat slides are conspicuously absent form the feldmark environments due to a lack of peaty soil. Most peat slides on Marion Island occur on the north facing slopes of the major ridgelines. It is concluded from observations that major scree production occurred during a period of more intensive periglacial activity during the early Holocene lasting from 12kBP until 7kBP.

The area demarcated as Feldmark Plateau, is bounded by faults due to isostatic uplift on deglaciation, which indicates that the ice cover in this region must have been extensive. However, no irrefutable proxy evidence for glacial activity has been found in this area. Periglacial features on the Feldmark Plateau are relatively larger than the same landforms in other areas at similar altitudes and possible reasons for this could be that the Feldmark Plateau was not glaciated in the Pleistocene; the features would then have developed under a cold, but ice-free environment. It should be noted that all slopes of the Feldmark Plateau are south facing and thus receive less insolation than north facing slopes. In addition, the slopes occupy the southern sector of the island, which may further contribute towards a cooler and more intense frost environment. It is hypothesised that a period of intense scree production occurred during the early Holocene, and this is manifested in the scree on the slopes of the Feldmark. If glaciation did occur, over-steepend slopes following ice retreat, would also have been conducive to intense scree production. It can, therefore, be concluded that the Feldmark Plateau, if glaciated, became ice-free rapidly after glaciation, so that the intense periglacial activity, plus the oversteepend slopes left by the glacial activity, produced large amount of scree from the cliffs.

The inventory of periglacial, glacial and mass movements on grey lava areas of Marion Island provides a useful baseline for geomorphological studies on Marion Island. Through refinement this database has the potential for palaeoenvironmental research and is a useful resource for earth and biological scientific studies.

ACKNOWLEDGEMENTS

During the course of this project a thirteenth month research period was spent on Marion Island. The South African National Antarctic Program under the Department of Environmental Affairs and Tourism gave logistical and financial support for this project as well as my other research endeavours on Marion Island, they are gratefully acknowledged.

I would like to express my sincere thanks to the following:

- My supervisor, Dr. K.I.M. Meiklejohn, for his help with my writing of this dissertation, and the wonderful support he has always given me.
- Prof. J.C. Boelhouwers for initiating this study and the valuable time he has spent corresponding with me while on the island, as well as the ongoing interest in my research.
- My friend and mentor, Mr. Paul Sumner, for his enthusiasm for life and everything related to research, mountains, rock and ice, and for the best travelling experiences south of the Sahara.
- Dr. Steve Holness for his ongoing friendship and company during those long months on the island, and the valuable comments and advice given while in the field.
- The members of the Marion Island 56th Expedition Team for their companionship and mutual support under somewhat difficult conditions, especially my friends Alvan Gabriel, Bianca Harck, Azwianewi Makhado, Claire Potgieter and Elizma Kitchoff.
- My family, for their love and support, and putting up with my constant explorations into the wild. Thank you for the freedom that you have given me to find my own way, and I hope this piece of work will make you proud.

I want to express my deepest gratitude to my best friend and wife, Martelize Nel, who through those long months on the island has given me all her love and encouragement. Thank you for the privilege of sharing your life with me.

Finally, to my Lord Jesus Christ, who have saved me on numerous occasions from death and injury. I want to thank you God for taking me into your care and for keeping me safe.

The Lord is my Shepard... Psalm 23

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CHAPTER 1: INTRODUCTION

Geomorphology is the science concerned with the form of the landscape and the processes which create it (Summerfield, 1991). 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). 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). Geomorphology is more than simply the description of contemporary landscapes, but also a explanation of their histories and landforms are also a reflection of the cumulative effects of all scales of environmental change (Meadows, 1988), and therefore geomorphology to a great extent is a historical science (Summerfield, 1991).

The concept of climatic geomorphology assumes that different climates, through their effect on geomorphic processes; produce unique landforms (Fig. 1.1) but this association of climate to landform development is a simplistic outlook. Climate itself is a very complex phenomenon (Meadows, 1988) and while climatic factors are important in geomorphology they are not necessarily dominant (Stoddart 1969). Further, geomorphological features are usually more sensitive to changes in precipitation than temperature (Meadows, 1988). Stoddart (1969) noted that to isolate climate as a single factor is unrealistic and distorting and to observe that different sets of landforms are found under different climates are “methodologically trivial” for the same geomorphological processes could occur under different climatic regimes and that different processes produce the same landforms (convergence of form).

Figure 1.1: The association between climate and landform.

Brunsden (1996) summarizes 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. The time it takes for the processes to adapt to a different climate regime can take longer that the actual climate change itself.

Therefore, it is imperative, when studying landform as an indicator of process and ultimately climate, to examine these factors and to take it into consideration.

Notwithstanding the complex relationship between climate and landform development, it cannot be denied that climate influences geomorphic process and therefore landform. This fundamental attitude of climatic geomorphology has remained the foundation of a great deal of geomorphological research (Derbyshire, 1973). In specific instances certain climatic thresholds must be exceed for specific landforms to develop. When these thresholds are exceeded the resulting landforms must then be an indisputable indication of the climatic regime.

In the case of persistence and convergence of form, Marion Island is unique. Temperature conditions indicate that cryogenic weathering processes are unlikely under current conditions at sea level, while temperature cycles over the 0° isotherm have been recorded at 750 and 1000m a.s.l, none of the lavas on the island are susceptible to clast breakdown from freeze-thaw processes (Boelhouwers *et al.*, 2001). Rock weathering rates on Marion Island are very slow. Grey lava rates of weathering range from 1.6% to 8.5% mass loss per 100 years (Boelhouwers *et al.*, 2001) and this rate is in the same order of magnitude, and compares well with the mechanical weathering rates on Signy Island in the maritime Antarctic (Hall, 1990a). However, breakdown of landforms results not only from weathering, but also erosion. Unfortunately no quantitative data exist with regards to erosion rates. Experimental results and observations of soil frost processes suggest that frost creep associated with needle ice activity is the dominant slope process on Marion Island (Boelhouwers *et al.*, 2001).

Periglacial geomorphology is that part of geomorphology, that concerns the past, present, and future impacts of diurnal, seasonal, and perennial ground ice on landform and landscape initiation and development (Thorn, 1992). As discussed previously, global climatic and accompanying environmental change represents a contemporary focus of research, and the periglacial environment is where such changes will have their greatest impacts (Dixon & Abrahams, 1992). 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" cover a wide range of cold, non-glacial conditions, regardless of proximity to a glacier, either in time or space, and it is characterized by intense frost action and at least seasonally snow free ground (Summerfield, 1991). French (1996) describes the periglacial environments as those in which frost action and permafrost-related processes dominate. Using the definition of French (1996) Marion Island can be classified as a periglacial environment as frost creep associated with needle ice activity is the dominant slope process on Marion Island. Sporadic permafrost bodies are also found above 1000m a.s.l in association with permanent ice masses and in valleys depressions and volcanic craters (Boelhouwers *et al.*, 2001).

While climate change is expected to have its greatest impacts in the polar regions of the Earth (IPCC, 1996), most studies to date concentrate on Northern Hemisphere landscape changes (Boelhouwers *et al.*, 2001). In contrast, Southern Hemisphere periglacial environments are very poorly understood, both in terms of basic understanding of geomorphological dynamics as well as sensitivity to climate change (Boelhouwers *et al.*, 2001).

Marion Island is one of a few islands in the Southern Ocean and hence represents an important location for geomorphological research on climate change in this region. A feature of some importance in this oceanic region is the Antarctic Polar Convergence, which is the boundary between cold poorly saline Antarctic surface water and less dense warmer Sub-antarctic water (Taljaard, 1957). At this boundary the cold denser water sinks below the warmer water and the convergence is characterized by a sharp change of temperatures at the surface. The mean position of the convergence in the south Indian Ocean is about 50° S Latitude, but according to Macintosh (cited in Taljaard, 1957), a displacement of 120 km either way is not uncommon. Marion Island is situated just north of the Antarctic Polar Convergence (46° 54' S) (Fig. 1.2), and any shift in the position of the convergence has a tremendous effect on the climate of Marion Island. If this shift in the convergence and the effect on climate is prolonged enough and significant enough, it can be manifested in the relict landform development through process (Fig.1.1).

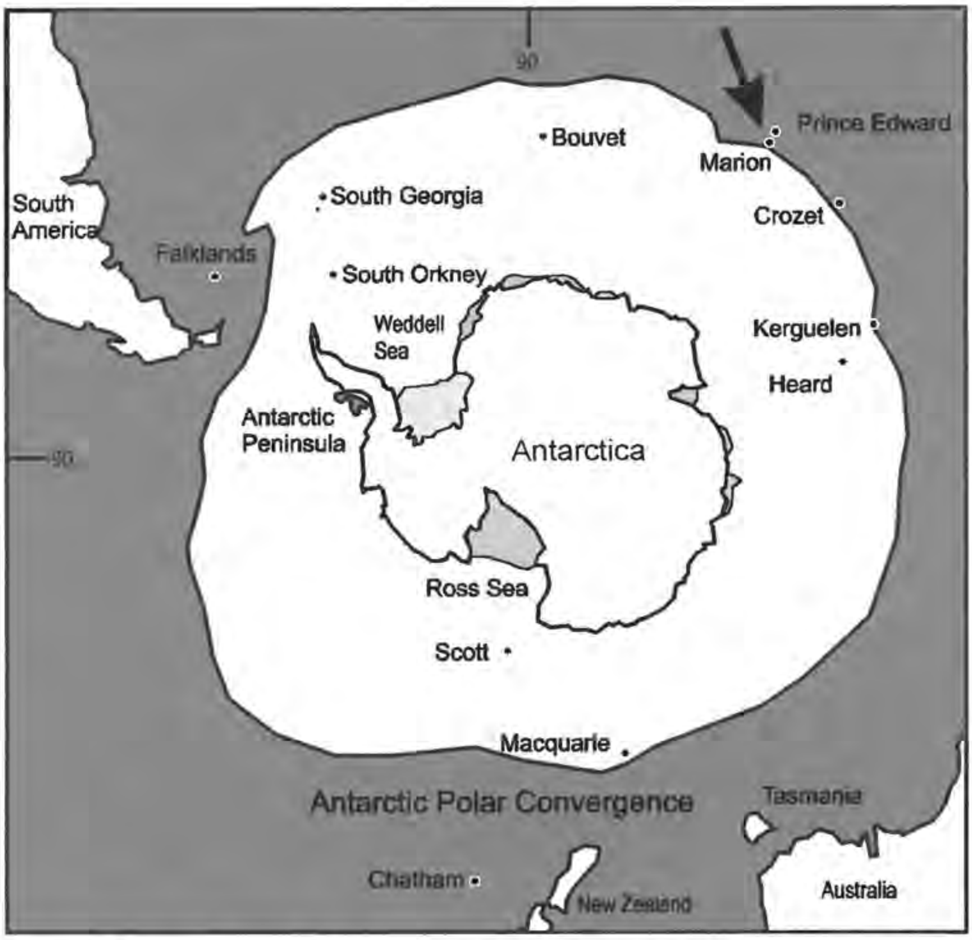

Figure 1.2: Geographic location of Marion Island with respect to Antarctica the Polar Convergence and some of the Southern Oceanic Islands.

1.1 The research problem, aims and objectives.

A broad aim of the project - Cryogenic Landforms and Processes on Marion Island –of which this research is a part, is to assess Late Pleistocene and Holocene glacial and periglacial development on Marion Island and to understand these processes and landforms and use it as indicators for climate change. Hall (1978; 1980a) undertook a substantial amount of research on Quaternary glaciation, which was later challenged, in part, by Kent and Gribnitz (1983) and Gribnitz *et al* (1986). Hall (1981; 1983a) further assessed periglacial landforms and their environmental implication. Recently, significant research has been concluded on cryogenic landforms and processes on Marion Island, evaluating periglacial landforms and climatic change (Holness & Boelhouwers, 1998). Extensive evidence of Holocene periglacial activity exists on Long Ridge, Marion Island, while considerably colder conditions earlier in the Holocene are suggested together with a steeper periglacial gradient than at present (Holness & Boelhouwers, 1998). However, Holness & Boelhouwers (1998) called for further research to be carried out to allow more quantitative estimation of the palaeoenvironmental conditions.

Holocene palaeoclimatic records on Marion Island can be constructed from the spatial variability of populations of active and relict cryogenic landforms (Boelhouwers *et al*., 2001) and an objective of this research is the compilation of inventories that indicate the spatial distribution of periglacial landforms on the island. Hall (1983a) in his observations of some periglacial features and their palaeoenvironmental implications compiled a map of the spatial distribution of some periglacial landforms on Marion Island. Hall's (1983a) map was compiled after field observations and gives no detail on morphology and density of the landforms.

Past expansion/contraction of the glacial ice sheets on Marion Island has resulted in identifiable geomorphological landforms and has influenced the spatial distribution of relict periglacial landforms (Boelhouwers *et al*., 2001). A thematic mapping and inventory will allow the documentation of the extent of the Marion Glacials and the consequent periglacial landforms associated with the glacial deposits. Therefore, a second objective is the compilation of inventories that show the spatial distribution of glacial landforms on the island largely based on the work of Hall (1978). Hall (1978) compiled maps of the coastal grey lava areas on the eastern side of the island that include glacial features like moraines, and striated bedrock.

Glacial activity on Marion Island has left oversteepend slopes and loose glacial debris (Nel, 2000), both of which are conducive to the development of screes (French, 1996). Mass movement features are, therefore, common on Marion Island and are predominantly found on regolith in grey lava areas. Rapid mass movements such as peat slides and screes are also common. However, little research has been undertaken on rapid mass movement features on Marion Island. Some research has been conducted on the characteristics of small debris flows (Boelhouwers *et al*., 1999) but no maps or inventories exist that describe the spatial distribution of rapid mass movement landforms.

Existing maps of the spatial distribution of periglacial, glacial and rapid mass movement landforms on Marion Island are inadequate and there exists a need in current geomorphological research for maps of high resolution that incorporate morphology and density of features. A 13-month period of fieldwork was undertaken on Marion Island to describe and map the spatial distribution of periglacial, glacial and mass wasting landforms and to develop an inventory that included morphology, density, and altitudinal trends of features. This inventory of features also provided a basis for relative-age dating of slope forms (Sumner *et al*, in press).

1.2 Background to the Study Area

Marion Island (46° 54' S, 37° 45' E) is the larger in a group of two islands that constitute the Prince Edward Islands and lies approximately 21 km from Prince Edward. Marion Island has an area of 290 km^2 and rises to 1230 m above sea level; the island has an oval shape with a circumference of about 72 km (Fig. 1.3). Situated in the "Roaring Forties", Marion is a wind swept and desolate place. The island is situated in the southern Indian Ocean, north of the Antarctic Polar Convergence, and is 2131 km from the southern tip of Africa, and 2567 km from Antarctica (Fig. 1.2). The closest land mass to Marion Island is the Crozet island group some 1050 km to the east, while Bouvet is 2530 km to the west (Fig. 1.2).

The Marion and Prince Edward Islands were probably first discovered in 1663 by Barent Barentz Ham of the galleon *Maerseveen,* but due to the inaccuracy of the contemporary navigational instruments the location was slightly in error. On January 10th 1772 the French explorer Marion-Dufresne sited and fixed the position of the island group, but was unable to land. The next discoverer to see the islands was Captain Cook. However not knowing that it was the same islands already found by the French, Cook "discovered" the Prince Edward Islands on 12 December 1776 and named it after the fourth son of Britain's king (Van Zinderen Bakker *et al*, 1971). Later on, when realising his error, he named the bigger island after the French explorer Marion. After the discovery of the several-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 for wealth, the signs of whose occupation can still be found in bays and caves in the form of rusted utensils and trypots.

In 1948 the South African Government on the initiative of Field-Marshall Smuts annexed the Prince Edward Island Group for strategic reasons (Van Zinderen Bakker *et al*, 1971), but the islands have since been declared a special nature reserve (Act 73 of 1989) and the fauna and flora is therefore protected under law. 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 *et al*, 1971). These investigations have been sponsored by the Department of Transport from the time of inception, but currently all research on Marion falls under the auspices of the South African National Antarctic Programme as part of the Department of Environmental Affairs and Tourism.

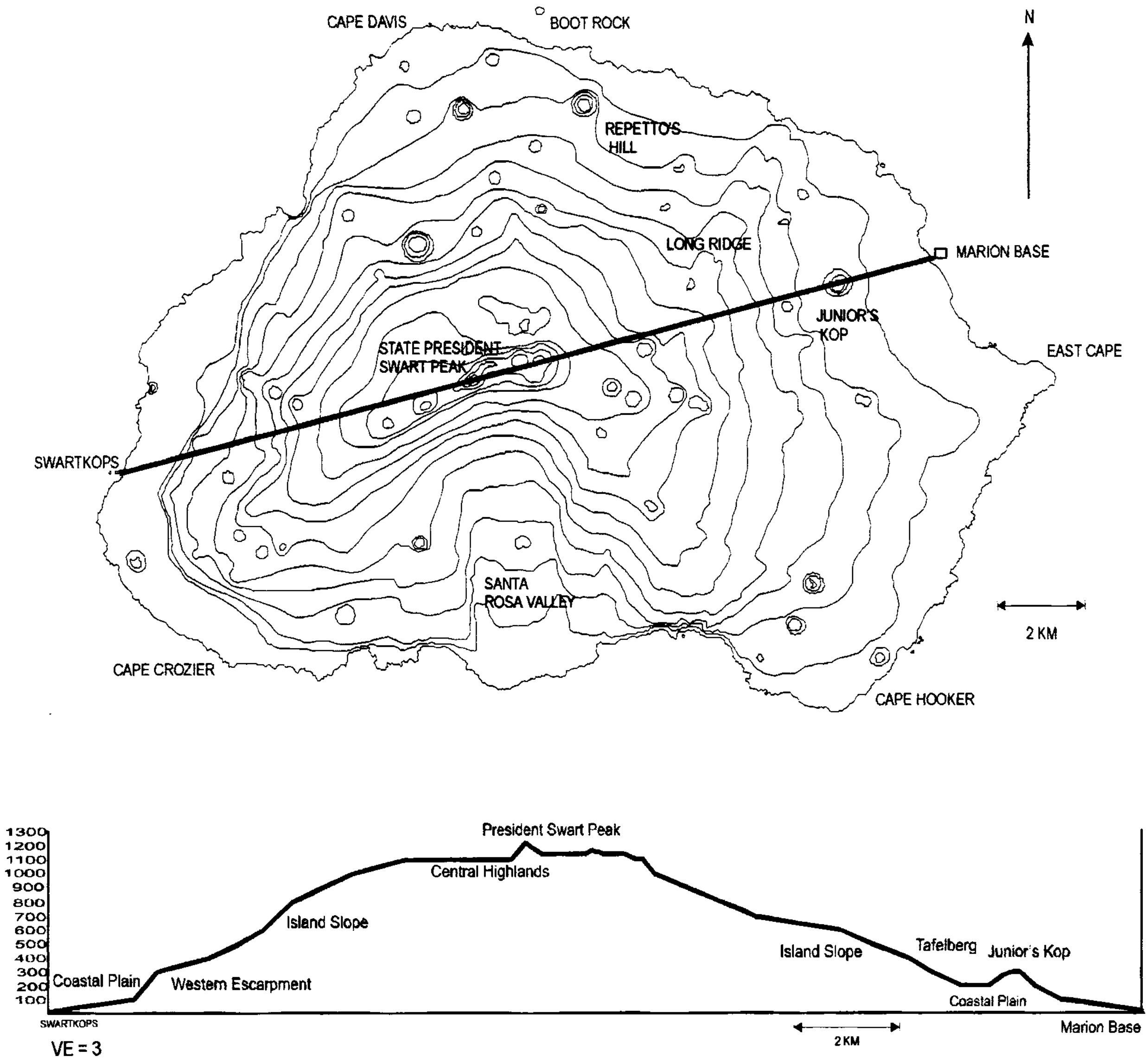

Figure 1.3: Topography and profile of Marion Island

CHAPTER 2: PHYSIOGRAPHY OF MARION ISLAND

2.1 Climate

Marion Island, situated within the Southern Ocean, is subjected to the general meteorological characteristics of this oceanic region and has pronounced maritime climate, with strong westerly winds, high relative humidity, small temperature range, relative low temperature, low sunshine radiation and high precipitation at sea level (Schulze, 1971). The average daily maximum temperature is 10,5°C during the summer and 6,0°C in winter, whilst the minima are 5.0°C and 1°C respectively (Schulze, 1971). Sub zero temperatures can be experience throughout the year. Winds are predominantly from the northwest (60% of occurrence) and often reaching gale force (Schulze, 1971). The average monthly wind speed is in the order of 32 km/h, (Table 2.1) while full gale force winds (Beaufort force 8) can last over 10 hours. During the gales (of which at least one a month is encountered) wind gusts of 198 km/h has been recorded, while gusts of 129 km/h are frequent (Hall, 1978).

TABLE 2.1: Summary of the climatic features of Marion Island (from Schulze, 1971)

Temperature	Annual average: 5°C
Precipitation	Average 2500 mm/year
Humidity	Annual average 83%
Wind speed	Monthly average 32 km/h
Cloud cover	Monthly mean 6/8

Associated with the low temperatures and high wind speeds, is a high annual precipitation with 311 days out of 365 receiving some form of precipitation that totals 2500mm annually (Hall, 1978). On average, every month of the year receives 25 days of precipitation. Occasionally, a month (especially winter) will have precipitation every day (Schulze, 1971). The island is also subjected to a high relative humidity (the mean being above 80%) (Schulze, 1971) (Table 2.1) and fog often occurs. In summer the fog is a result of advection of warm, moist northerly air flowing over a cold-water surface. The possibility of steam fog, caused by cold southerly air flowing over warmer water, cannot be ruled out and occurs mostly in winter (Schulze, 1971). Mean cloud cover is 6 oktas, and this results in the low incidence of incoming radiation. In summer Marion Island only receives 33% of the possible radiation and in winter the values are between 20-25 %.

Marion Island can be described as a wet, windy place with low average coastal temperatures. Incoming radiation is limited an owing to the high relative humidity, fog is common, and precipitation very high.

2.2 Fauna

Even though the climate and isolated location limits the diversity of plant species, Marion Island has an abundance of animal life. Mammals on the island include approximately 10 000 elephant seals (Rand, 1955), and an increasing number of Antarctic and Sub-Antarctic fur seals. Twenty-six species of seabirds breed at Marion Island (Williams *et al*, 1978). These birds can be classified into three groups: (1) surface breeding species that can fly, (2) burrowing species that can fly, and (3) flightless surface breeding penguins (Hall and Williams, 1981). Four penguin species with an estimate of over 5 million individuals breed on Marion and Prince Edward Islands (Van Zinderen Bakker Jnr., 1971) and the combined Marion Island penguin population is about 3.4 million individuals (Hall and Williams, 1981). The zoogeomorphological effect, which is predominantly erosional, is well documented, with the penguins as the most potent zoological erosive agent on Marion (Hall and Williams, 1981; Holness, 2000).

2.3 Topography

The profile and topography of Marion Island are typical of a shield volcano (Verwoerd, 1971). On the eastern side there is a uniform rise from the coast to the peaks. The western part of the island shows some modification however, with a narrow coastal plain. Beyond the western escarpment the rise to the peaks are gentler (Fig. 1.3). As expected of a young volcanic island, the morphology is strongly related to geological structures (Verwoerd, 1971). Large tracts are of primary constructional origin, while fluvial erosion is found to have played an almost insignificant part in the sculpturing of landforms despite the heavy rainfall (Verwoerd, 1971).

On Marion Island the physiography can be categorised into five major units (Verwoerd, 1971:43): (1) Central Highland, (2) Island Slope, (3) Western Escarpment, (4) Coastal Plain, and (5) Volcanic Cones (Fig, 1.3). The Central Highland is an arcuate plateau surmounted by a series of volcanic cones. Within this region a small area of permanent ice and snow is located. From this elevated area, the Island Slope extends down to the coastal plain on the north, east and southeast side and to the Escarpment in the west. The Island Slope comprises the greater part of the island and the angle varies from 2° above East Cape to 19° above Santa Rosa Valley and consist of horst and graben structures, with recent black lava flows present in the grabens (Hall, 1978). Along the radial faults, which demarcate the structures, a series of aligned scoria cones can be found (Fig. 2.1). The Western Escarpment is situated between 200 to 400m in height and is 1 to 2 km inland from the western shore. Verwoerd (1971) suggests that the Escarpment represents a previous position of the coastline. The Coastal Plain lies at the foot of the Escarpment approximately 50m a.s.l. and is formed from a bench of recent black lava flows. 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.

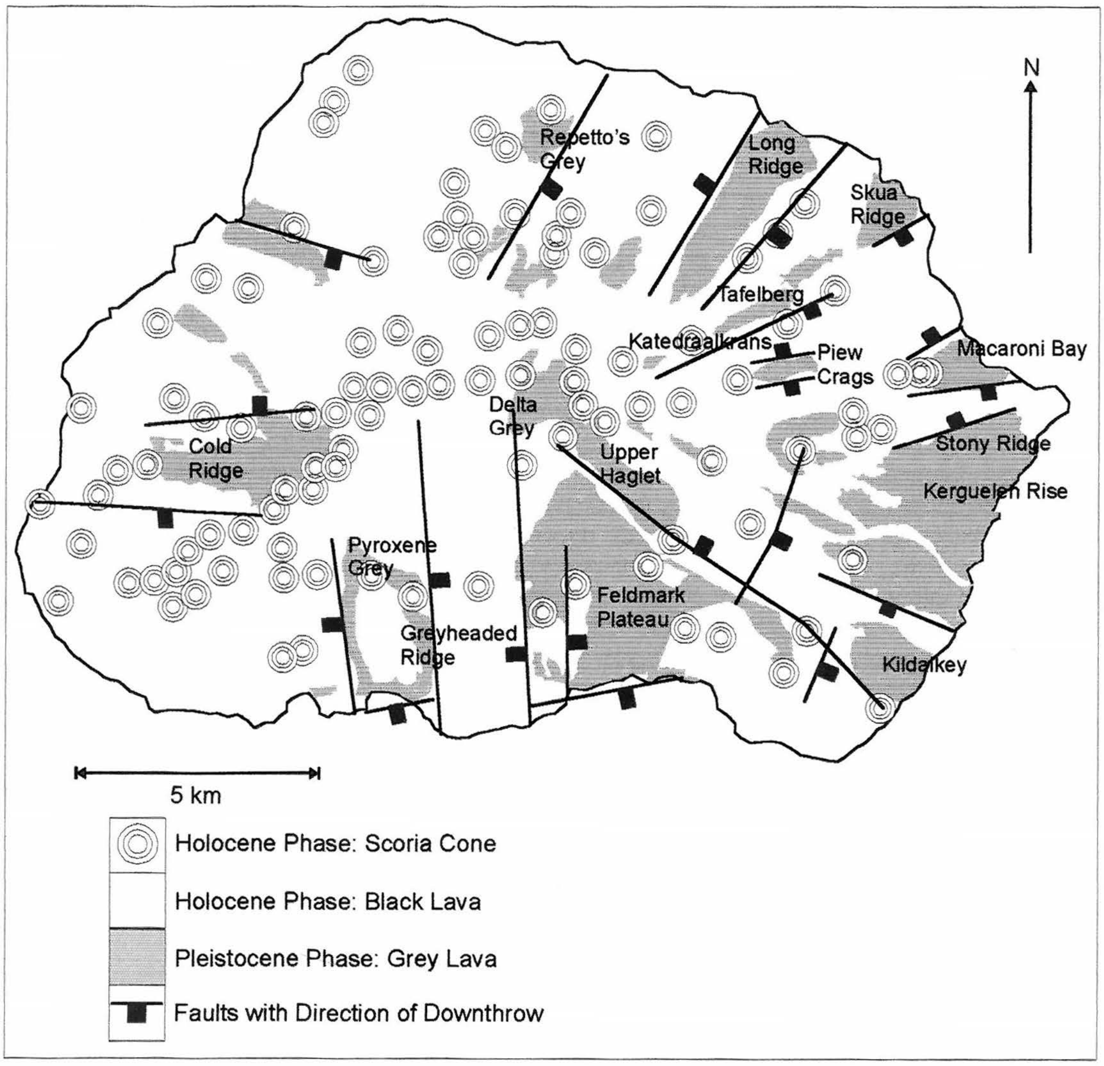

Figure 2.1: Geology of Marion Island adapted from a compilation by Holness (*unpublished data*) from Verwoerd (1971) and Chevallier *et al* (1992). Location of primary faults adapted by author from Verwoerd (1971) and Hall (1982). Place names refer to major grey lava areas.

Some 130 volcanic cones can be found over the whole island (Fig. 2.1). They are prominent landscape features with a colour mixture of red and black and many are over 200m in height. The significance of the volcanology and faulting, which were described in detail by Verwoerd (1971) was later put into glaciological context by Hall (1978; 1982) and are described below.

2.4 Geology, Geochronology and Glacial History

Marion Island is the peak of a shield volcano and Verwoerd (1971) identified two series of lavas, each with its own pyroclastics. There is older pre-glacial grey basaltic lava, which in most places, is covered by post-glacial black basaltic lava and scoria cones (Fig. 2.1). Hall (1978:22) summarises the geology of Marion Island as follows: "Two distinct lava types are found that can be distinguished by colour, form and age. The island is composed solely of volcanic material with the majority of that visible on the surface resulting from the younger, black lavas. The island is sectioned by radial faults along which are often found the recent eruptive centres in the form of scoria cones".

Studies have shown that Marion Island was subject to multiple glaciations during the last 300 000 years, which were named “Oldest”, “Penultimate” and “Würm-age” (Hall, 1978). To estimate the geochronology of Marion Island a number of grey and black lava samples were K-Ar dated by McDougall (1971) and overall the geochronology of Marion Island is described by Hall (1978) and can be described as a grey lava volcanic stage around 276 000 years BP. Subsequent to the above volcanic episode a glacial event occurred (Oldest), which was followed by an extensive eruption of lava and pyroclasts and it is suggested that this was a major event of some duration. After this interglacial volcanic stage the global temperature decreased, the Antarctic Polar Convergence moved northwards and a next glacial stage was initiated (Penultimate) (Hall, 1978). Termination of the Penultimate glacial stage is marked by extensive outpours of grey lavas and before the black lava stage a final Würm–age glacial episode occurred (Hall, 1978). Evidence for this is the striated grey lavas from this glacial episode, which were successfully dated by McDougall (1971) and it indicates a glaciation post-dating the grey lava stage and pre-dating the black lavas.

The volcanic activity on Marion Island is suggested to have occurred only during the interglacials and the present volcano distribution is associated with a radial and peripheral fault system and the location of the faults appear to be related to the former glacier distribution (Hall, 1982). Hall (1982) presents a hypothesis suggesting that the faulting is a result of rapid deglaciation and that the specific location of the faults is due to the differential stresses occurring between ice-covered and ice-free areas during isostatic uplift. The faulting then initiated volcanism due to the location of the island within a volcanic region at about 12 000 BP, with many of the eruptive centres being located along the faults. However, the first geological investigation of Marion Island (Verwoerd, 1971) revealed young volcanological features indicating that the island is still volcanically active. Verwoerd *et al*, (1981) presents new observations, from a fissural eruption near Kaalkoppie in 1980, arguing against Hall's (1982) hypothesis, for a continuous low-intensity volcanic activity through the Holocene.

2.5 Periglacial landforms

As mentioned before, Marion Island is a periglacial environment and can be divided into 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). The diurnal frost zone is between sea level and 300m a.s.l and soil frost is the dominant geomorphic agent. 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. The seasonal frost zone is found above 750m a.s.l. and sporadic permafrost bodies above 1000m a.s.l.

Previous studies have assessed periglacial landforms and their environmental implications (Hall, 1981; 1983a, Holness and Boelhouwers, 1998; Boelhouwers *et al.*, 2001). In these studies, which mainly relate to patterned ground, it was observed that some of the landforms were relict and being a product of cooler than present post-glacial conditions (Hall, 1983a). Observations on stone-banked lobes also support this theory (Hall, 1981). Present day periglacial morphology on the island is dominated by patterned ground on grey lava and scoria areas from close to sea level through to the highest altitude areas. Sorted circles/polygons are generally restricted to areas of low slope angles with an average slope of 5° or less (Boelhouwers *et al.*, 2001). Sorted stripes are associated with a variety of slope angles from near horizontal through to 24° (Boelhouwers *et al*, 2001). Observations indicate that sorted stripes are predominantly aligned parallel to the wind (Hall, 1979; Boelhouwers *et al.*, 2001; Holness, 2001).

Recently substantial research has been undertaken on periglacial landforms and climatic change under the Cryogenic Landforms and Processes on Marion Island project (Holness & Boelhouwers, 1998, Boelhouwers *et al.*, 2001). These studies present the first detailed quantitative description of relict periglacial slow mass wasting landforms (stone-banked lobes, stone-banked terraces, vegetation-banked terraces and blockstreams) dating from the Late Pleistocene and early Holocene. Extensive evidence of Holocene periglacial activity on Marion Island, as well as evidence for considerably colder conditions earlier in the Holocene were found. In addition evidence is advanced for a steeper periglacial gradient than at present as well as a confirmation of previously contested palaeoreconstruction based on palynological and glaciological information (see Hall, 1978; Hall, 1980a; Kent & Gribnitz, 1983; Gribnitz *et al*, 1986).

CHAPTER 3: METHODOLOGY

Since the middle of the Nineteenth Century the spatial differentiation of several factors of the physical environment i.e. geology, climate, vegetation and soil has been presented on maps (Klimaszewski, 1982 cited in Boelhouwers, 1988). In many landform studies the most useful contribution from a geomorphologist is an inventory, and the provision of a detailed map of the spatial distribution of geomorphic features. This is particularly true where information is required concerning the distribution of landforms, soils and rock materials, or features created by surface processes (Cooke and Doornkamp, 1990). Such a map provides an unrivalled way for a researcher to become familiar with landforms of an area, and it provides a basis for additional analytic studies. Further, it is a great stimulus to thought concerning both the relationship between forms, materials, and processes, and the manner of landform development (Cooke and Doornkamp, 1990). Setting up an inventory of periglacial, glacial and mass movement features on Marion Island, mapping these features, and the consequent maps provide the basis for analysing the spatial relationship of active and relict forms. It also provides insight into spatial and temporal interaction in regards to landform development, because the broad geochronology on Marion is already known. Therefore to analyse the spatial distribution of features on Marion Island the best method and approach is that of thematic mapping.

No mapping system for Marion Island has previously been developed. For reasons of comparison and standardisation, there is no need to introduce a new legend within this thesis, but rather apply a widely accepted procedure. The mapping schemes proposed by the IGU are set out in *Manual of Detailed Geomorphological mapping* (Demek, 1972) and in *Guide to Medium-scale Geomorphological Mapping* (Demek and Embleton, 1978). Although the IGU system is widely known for its concepts and principles a major complaint is that, although a very elaborate legend has been compiled (500 units), little flexibility actually exists, thereby inhibiting the provision of detailed information (Leser, 1974 cited in Boelhouwers, 1988). The ITC system was constructed by the International Institute for Aerial Survey and Earth Sciences based on the IGU principles (Meijerink *et al*, 1983 cited in Boelhouwers, 1988). Rather than creating an extensive list of legend units, the 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 legend (Boelhouwers, 1988). This is realised by allocating coloured areas to major landform units (for example, moraines), which in practice tend to coincide with landsystems (Verstappen, 1970 cited in Boelhouwers, 1988). An advantage of this approach is that the major legend units can be detected from aerial photos prior to field survey. Minor genetic landforms are indicated by black line symbols, while overcrowding can be avoided to improve readability by the construction of complimentary maps. Therefore, it is evident that for basic reconnaissance mapping, the ITC system is to be preferred because it follows internationally agreed concepts, has a high flexibility, good readability and is widely used (Boelhouwers, 1988).

It must be noted however, that full geomorphological mapping is beyond the scope of this project. Full geomorphological mapping includes info on morphography, morphometry, morphogenises and morphochronology (Boelhouwers, 1988) and the ITC system classifies broad landscape units. For this project the ITC system is not applied but only the procedure. Therefore, this project is not a full geomorphological mapping or a comprehensive mapping of all features, but rather a thematic inventory of glacial, periglacial and rapid mass movement features.

3.1 Extent of the Project

Probably the most fundamental of periglacial processes are those associated with frost heaving and ice segregation (French, 1996) and periglacial features, by default, are those features created or directly related to these processes. As indicated in Chapter 2, the grey lava on Marion Island pre-dates the glacial events and therefore all evidence of the Pleistocene glacials can only be in, or superimposed on, the grey lava lithology. Further, till deposits in grey lava are generally frost susceptible and have sufficient moisture for segregation ice development (Boelhouwers *et al.*, 2001). Even in grey lava areas with thin till, 43.8% of samples contained sufficient fines and moisture for needle ice growth (Boelhouwers *et al.*, 2001). Screes and other mass movement features are predominantly on regolith in grey lava areas, where recent glacial activity has left oversteepend slopes and loose glacial debris, both of which are conducive to the development of rapid mass movement features (Nel, 2000). Black lava areas are all non frost-susceptible and contain insufficient moisture for needle ice growth (Boelhouwers *et al*, 2001) and due to the nature of black lava deposits on low slope angles, this lithology does not lend itself to rapid mass movement. It is, therefore, obvious that glacial, periglacial and rapid mass movement landforms only occur in grey lava and, therefore, only these areas are mapped.

Approximately 75% of all grey lava areas occur on the eastern side of the island (Fig. 2.1) as well as most of the glacial evidence (Hall, 1978). Also due to the difficulty of the terrain and weather conditions, having the base and meteorological station situated on the eastern side (Fig. 1.3) assist research in this area. As a result previous glacial and periglacial research (Hall, 1978; 1979; 1980; 1981; 1983a); (Holness & Boelhouwers, 1998) concentrated on this region.

Due to the above factors, full mapping is unnecessary and beyond the scope of this project, and this means that the mapping was restricted to grey lava areas at all altitudes on the eastern side of the island. The areas that were mapped stretch southwards from Long Ridge to the Sfinks, which constitutes the eastern boundary of the Santa Rosa Valley (Fig. 3.1). For further analysis on spatial distribution of features the survey area has been divided into five sectors in which the altitudinal distribution of features was identified. In addition to the altitudinal distribution of features, landforms were also analysed on distribution by slope aspect in the various sectors

3.2 Study Procedure

In the construction of the maps the ITC working procedure, outlined by Boelhouwers (1988), adapted from Verstappen (1970) and Verstappen and van Zuidam (1975), has been adapted to suit this study (see Fig. 3.2) An adaptation from the ITC working procedure as outlined by Boelhouwers (1988) includes the state of the preliminary maps which are constructed after geomorphological photo interpretation and topographical map analysis. However in this study, most of the landforms are too small to identify from aerial photographs. Preliminary maps therefore, are constructed after field surveying.

The strategy adopted for this study was to compile existing background information where available, in the form of existing literature, maps and aerial photographs. The most successful approach to mapping is to combine field inspection with air-photo interpretation (Cooke and Doornkamp, 1990) and a base map of the selected area was drawn up using aerial photographs and consisting of the morphology of the selected area. This was complemented by a field survey and mapping of periglacial, glacial and mass movement features in the relevant areas. The final thematic inventory was compiled to incorporate all the information.

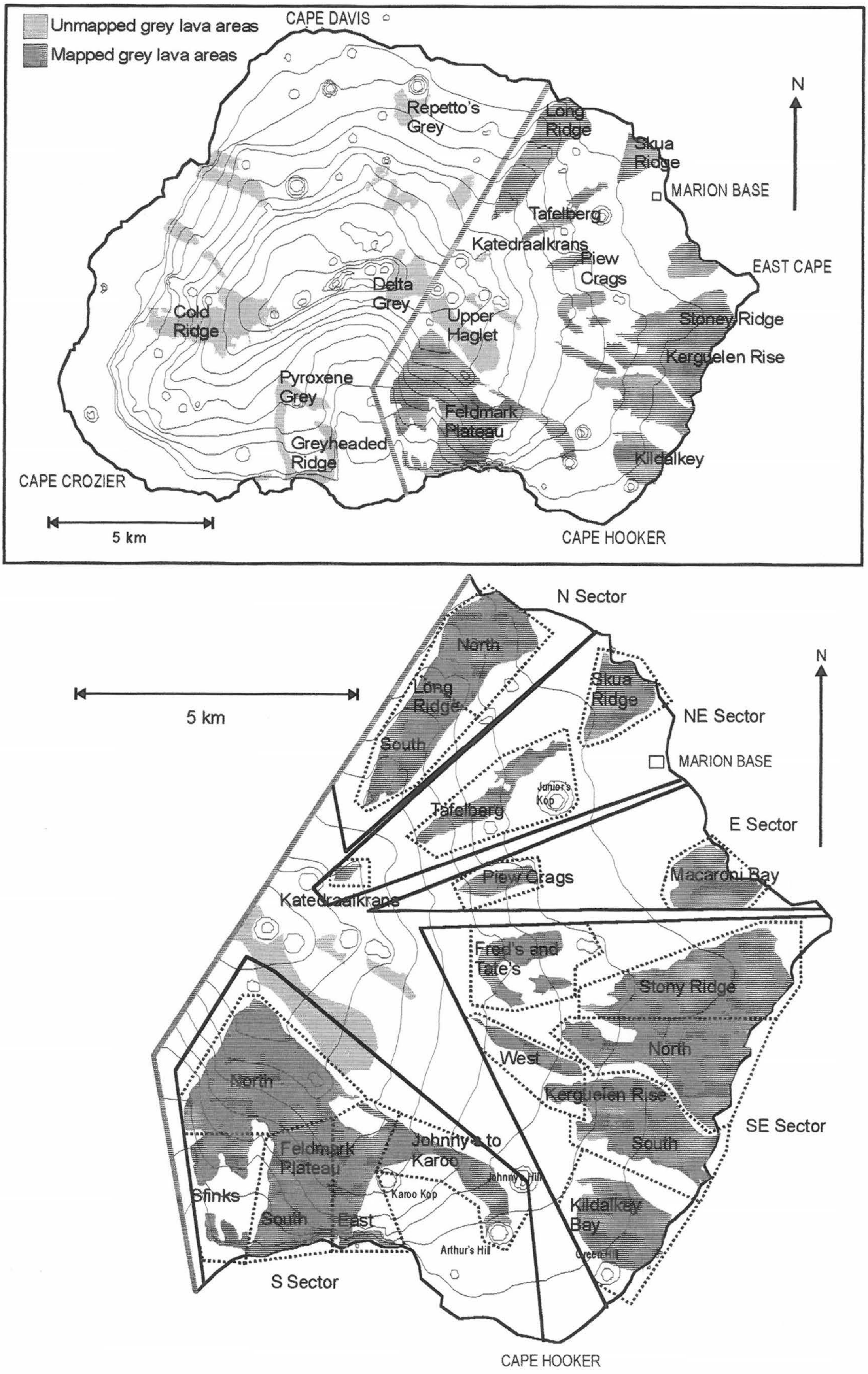

Figure: 3.1: Areas mapped on eastern side of Marion Island.

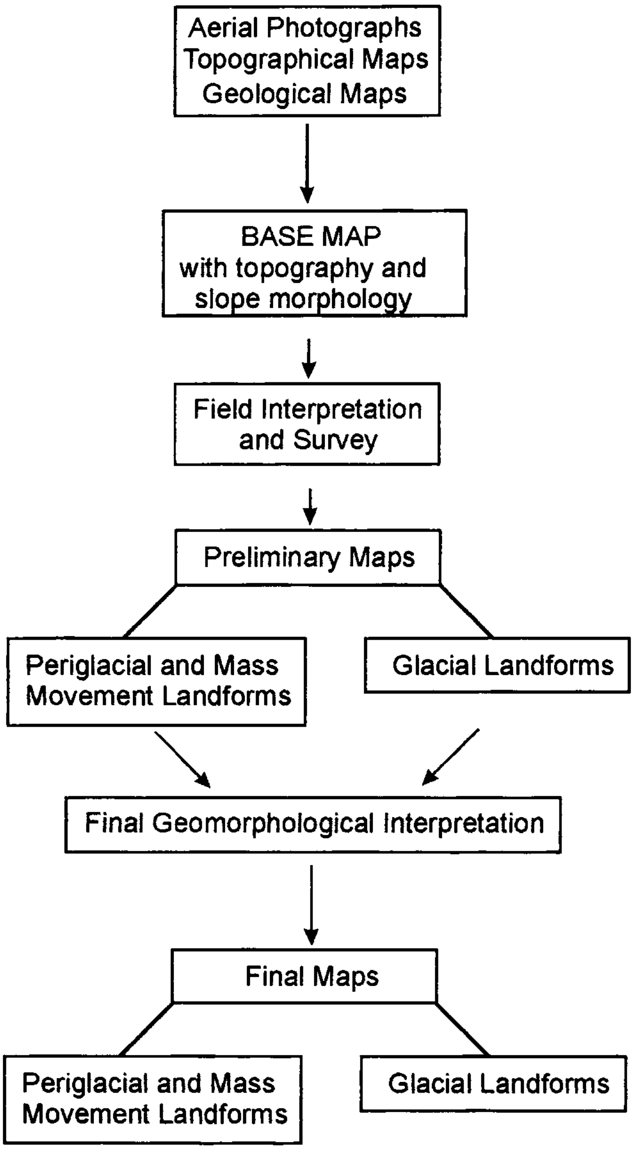

Figure: 3.2 Flow diagram of the working procedure for the mapping of grey lava on the eastern side of Marion Island adapted from the ITC procedure (Adapted from Boelhouwers, 1988).

To compile the base maps, all existing information was analysed. Information that existed prior to the study undertaken for this dissertation include:

- All existing maps and photographs, including the contour maps of Marion Island (Langenegger and Verwoerd, 1971), geology map (Verwoerd, 1971); (Chevallier *et al*, 1992) and aerial photographs.
- Previous glacial and periglacial studies (Verwoerd (1971); Hall (1978; 1980); (Holness & Boelhouwers, 1998).

The spatial distribution of grey lava, black lava and scoria described by Verwoerd (1971) and Chevallier *et al* (1992), were used to identify the relevant grey lava areas. Following, aerial photographs were used to determine the morphology of the selected areas and contours were added to provide a representation of relief. Location of coastal moraines and till on the eastern side of the island was determined from previous glacial studies (Hall, 1978; 1980). Previous and ongoing periglacial studies (Hall, 1981; 1983a); (Holness & Boelhouwers, 1998); (Boelhouwers *et al*, 2001) indicated the location of some landforms as well as identification of forms present and their characteristics.

To verify the landforms identify in previous studies, as well as identifying landforms previously unknown, periglacial, glacial and mass movement landforms were mapped in the field using the base map for the selected grey lava areas. A systematic field survey covering the relevant areas, paying special attention to bare rock surfaces for glacial evidence, as well as the size and distribution of periglacial features and mass movement landforms, was undertaken. The directions of striations on glacially moulded bedrock were also measured, and till was identified.

Further geomorphological interpretation was undertaken and final maps were compiled. The final maps were digitally compiled and consist of the glacial, periglacial and mass movement landforms identified in the area. Further analysis of these maps, with respect to the spatial distribution of these landforms as well as morphology, density, and altitudinal trends, were undertaken.

Individual maps produced from the study do not indicate each individual feature but rather the area where features are located. In other words, if the symbol of a large stone-banked lobe is situated on a certain point on the map, large stone-banked lobes will be found in that specific area. The same system was utilised for depositional features like till and platey till where the shaded area with the symbol for till covers the area in which till can be found. The symbols also indicate where features are superimposed on each other (i.e. sorted stripes on the tread of lobes). Coastal moraines that were included in the inventory are the features identified and described by Hall (1978), with the exception of one well developed end moraine reported in Boelhouwers *et al.* (2001) at the lower end of a relict glacial cirque at Snok. Hall (1978) described and mapped some striated surfaces, these surfaces with the exception of a few sites were found by the author and mapped. Previously unrecorded striated surfaces were also recorded. However, the exception to the above relates to the location of peat slides. This was individually mapped. The symbol for a specific mass movement feature does not indicate a uniform area but each individual feature. Some of the maps demarcating landslide features can be inaccurate due to a heavy rainfall period in the beginning of January 2000. Most areas had already been surveyed and mapped before this time and some peat slides did occur during the rainfall period after the areas were surveyed. Late corrections have been made, but some areas could have new peat slides that have not been mapped by the author.

No distinction is drawn between relict and active landforms in the periglacial map legends. The distinction rather relates to morphology where the stone-banked lobes, stone-banked terraces, *Azorella*-banked lobes and *Azorella*-banked terraces have been divided up into three categories. These sizes relate to riser heights and not horizontal extent or the measurement of the tread. Small features have a riser height of under 50 cm. Medium sized features have riser heights of between 50cm and 1m, and large features have riser heights of over a metre. However, based on the comprehensive process studies by Boelhouwers *et al.,* (2001), medium and large forms must be considered relict at all altitudes. Further due to the process study on periglacial features having already been completed, the scope of this research is not to investigate the processes involved that are responsible for the features, like frost action, cryoturbation or solifluction but purely to map and describe the distribution of landforms.

3.3 Description of Glacial, Periglacial and Mass Movement Features

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

3.3.1 Moraines and till

Till is the highly variable deposit laid down by ice, and moraines are the landforms produced by such deposits (Summerfield, 1991). Hall (1978) undertook fabric analysis on till and identified and described end moraines and lateral moraines on Marion Island. Most of the end moraines on Marion are of the push type, which are considered to result from the advancing of an ice front that bulldozes loose material in its path and pushed it into a ridge form (Hall, 1980b). This loose material as well as the moving ice, scrapes the underlying bedrock and forms striations (Fig. 3.3). The direction of the striations is directly related to the direction of the palaeo-ice flow (Hall, 1978). Lateral moraines are formed parallel to the direction of ice flow (Summerfield, 1991), and depict the lateral extent of the palaeo-ice flow on Marion Island (Hall, 1978).

Figure 3.3: Striated bedrock at Tafelberg, Marion Island

3.3.2 Stone and Azorella- banked lobes and terraces

Stone-banked lobes are described as "lobate masses of rocky debris underlain by relatively stone-free, fine-textured, moving soil" (Benedict, 1970:176). Embleton and King (1975) describe these landforms as "deposits confined by crescent shaped stony embankments". Lobes are relatively well known phenomena and have been reported to occur in most periglacial environments (French, 1996). French (1996) indicates that lobate features give rise to a stepped, tread-like slope which may range in angle from 3-5° upwards to 15-20° and that the micro-relief of such slopes varies from vertical turf risers of 2-3m in height, down to small *Dryas*-baked risers only a few centimetres high. Hall (1981; 1983a) as well as Holness and Boelhouwers (1998) have described and measured stone and *Azorella* -banked lobes on Marion Island. 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, 1981) (Fig. 3.4). Holness and Boelhouwers (1998) divided stone-banked lobes into two groups based on material composition. Lobes with blocky risers are associated with a material supply from bedrock outcrops, while those with platy fronts appear to be the result of transport processes in the till. Lobate forms that have a larger horizontal extent as tread length are mapped as terraces. On Marion Island the vegetation-banked lobes have the hard cushion plant *Azorella selago* as risers. Therefore, all lobes and terraces with *Azorella selago* as risers are mapped as *Azorella*-banked lobes/terraces.

Figure 3.4: Medium stone-banked lobe on Long Ridge, Marion Island

3.3.3 Patterned ground

Sorted stripes, (Hall, 1979) circles, polygons and nets (Hall, 1983b; Holness and Boelhouwers, 1998) have been previously observed on Marion Island. Washburn (1956) describes patterned ground as the term given for more or less symmetrical forms, such as circles, polygons, nets, steps and stripes that are characteristic of, but not necessarily, due to frost action. He also 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". These features are known as sorted circles, and as sorted polygons when the adjacent coarse margins merge (Derbyshire, et al. 1979).

The descriptions of sorted patterned ground tend to be arbitrary and subjective. Therefore, to keep the maps objective and constant all sorted circular patterned ground (mounds of fines bordered by coarser material) have been named and mapped as sorted polygons (Fig. 3.5) while sorted stripes are made up of lines of alternating coarse and fine debris orientated down the steepest available slope (Washburn, 1956).

Figure 3.5: Sorted circle on Marion Island (Photograph, S. Holness)

3.3.4. Rapid mass movement

Only specific rapid mass movement features (screes and peat slides) were mapped. Scree is the term given for open block deposits from rockfall origin and is superimposed on the slope material. Peat slides is the term given to several types of phenomena that depend upon the shear failure along a plane below the ground surface (Derbyshire, et al. 1979). The types of peat slides that were mapped and commonly present on Marion Island are also observed on Macquarie Island (Selkirk, 1996) and are translational, with the primary failure mostly occurring in vegetated peaty soil.

CHAPTER 4: SPATIAL DISTRIBUTION OF FEATURES

As discussed in Chapter 3, surveys and mapping were restricted to grey lava areas on the eastern side of the island. The areas that were surveyed extend southwards from Long Ridge to the Sfinks, which constitutes the eastern boundary of the Santa Rosa Valley (Fig. 3.1). A glacial and periglacial landform inventory (see Appendix A) was completed in the field on base maps compiled from the topographic and geological map of the island as well as aerial photos. The study area was divided into survey units, based on the distribution of grey lava outcrops (Fig. 3.1). The glacial and periglacial information for each survey unit was mapped on 36 separate diagrams (Appendix B). Each survey unit is outlined and described below:

4.1 Long Ridge North

Long Ridge constitutes a horst (Hall, 1978), west of the meteorology station (Fig. 4.1); it is a 5km long ridge, which runs from sea level to about 600m a.s.l. and is delimited by the Diving Petrel stream in the west and the Fairy Prion Valley in the east. Long Ridge is divided into two sections, north and south. Long Ridge North is the area between Bill Briggs and the coast, which stretches from sea level to approximately 400m a.s.l. The ridge has steep north and south facing slopes with high free faces. Long Ridge is till covered from recent glaciation (Hall, 1978), and the hard cushion plant *Azorella selago* occurs on top of the ridge, while *Poa cookii* is found on the steep slopes.

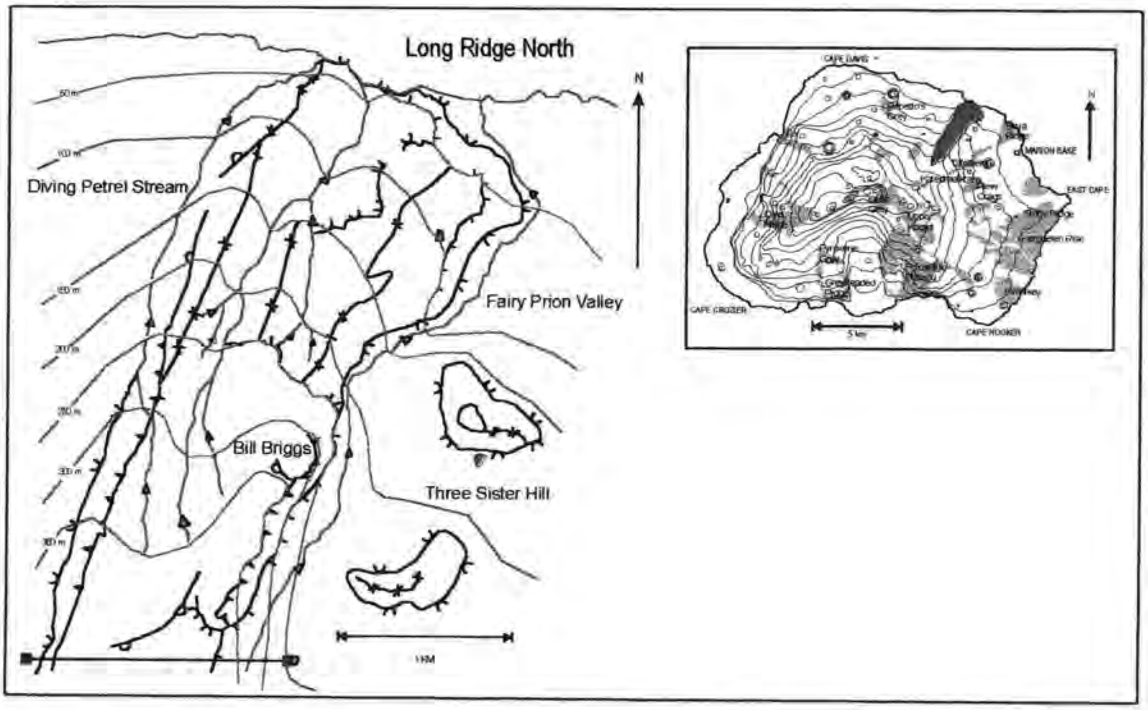

Figure 4.1: Locality and morphology of Long Ridge North

4.1.1 Glacial features

The most prominent glacial landform on Long Ridge North is an outer moraine, which follows the south-eastern curve of the ridge (Appendix B: Fig. 1). Hall, (1978) described this moraine as one that exhibits a shallow proximal slope and a steep distal one (11° and 21° respectively). The moraine projects some 40m above the surrounding area and is about 200m in width. Till covers the western end of the ridge and there are no glacio-erosional features like striated bedrock in the area.

4.1.2 Periglacial features

Active and relict periglacial landforms on Long Ridge have been identified and described by Holness & Boelhouwers (1998). The dominant periglacial features on Long Ridge North are small *Azorella* banked lobes (riser height < 50 cm) and micro patterned ground (Appendix B: Fig. 2). The patterned ground in this area comprises of sorted polygons, as well as some sorted stripes. Small vegetation-banked terraces also occur north and south of Bill Briggs (Appendix B: Fig. 2).

4.1.3 Rapid mass movement

Rapid mass movement features on Long Ridge North include screes and peat slides. On the east facing slopes below the cliffs some peat slides occur (Appendix B: Fig. 2). West facing slopes, however, have no screes but peat slides are common. The high cliffs above the west facing slopes are covered by thick peaty vegetation and the peat slides occur in this thick homogeneous soil. A single peat slide was found below 250m a.s.l.. (Appendix B: Fig. 2), and the scarcity of slides here is ascribed to low slope angles. Above 250m a.s.l. the slope angle becomes steeper and this with the thick soil account for the high distribution of peat slides observed in this area.

4.2 Long Ridge South

Long Ridge South stretches from approximately 400m a.s.l. to the termination of the grey lava at 550m a.s.l. (Fig. 4.2). Steep slope angles occur on the north and south facing sides of the ridge but the area on top of the ridge is mostly level. Till cover in areas is platey and the hard cushion plant *Azorella selago* occurs on top of the ridge, and *Poa cookii* on the steep slopes.

4.2.1 Glacial features

In the initial survey of the area as part of the first scientific expedition lead by Van Zinderen Bakker, Verwoerd (1971) found no striations at Long Ridge South. Even though this is also the case for this study, bedrock that seems to be glacially moulded is found at approximately 500m a.s.l. (Appendix B: Fig.3) but probably due to intense weathering no striations are visible.

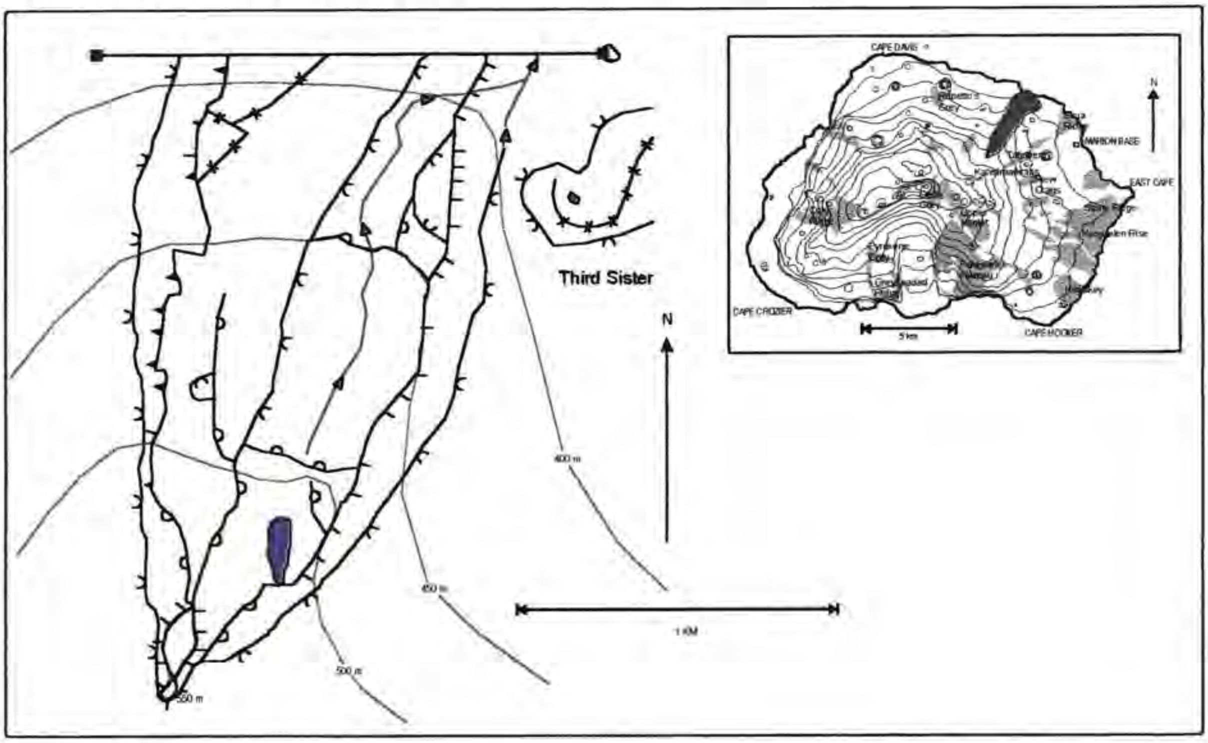

Figure 4.2: Locality and morphology of Long Ridge South

4.2.2 Periglacial features

Lobate features and patterned ground occur on Long Ridge South. At 400m a.s.l. the *Azorella* banked lobes and stone banked lobes are small, but with increase in altitude, the lobe riser height is predominantly between 50cm and 1m (medium). Some large (riser height > 1m) stone-banked lobes are located close to the lake in the far south and between 450m and 500m a.s.l. (Appendix B: Fig.4). Stone-banked lobes associated with blocky material from rock outcrops tend to have large to very large blocky fronts up to 5m high (Holness and Boelhouwers, 1998). The above stone-banked lobes and the large lobes and terraces at 450m a.s.l. east of the river bisecting the ridge, are bedrock associated. The material in the lobe is therefore made up of broken up bedrock. The large stone-banked lobes between 450m and 500m a.s.l. west of the river are not bedrock associated and have riser heights between 1.8m and 4.1m (Holness, *unpublished data*). Stone banked lobes that are not immediately associated with the disintegration of rocky outcrops have developed in the till material and tend to be smaller than the blocky front lobes (Holness and Boelhouwers, 1988). Medium sized *Azorella* banked terraces also occur throughout the whole altitudinal range of Long Ridge South interspersed with one or two large terraces at approximately 475m and 525m a.s.l. respectively. Patterned ground in the form of sorted stripes and polygons is present in the whole area on the fines-rich tread of most lobes and terraces.

4.2.3 Rapid mass movement

Screes east and west of Long Ridge South between 400m and 500m a.s.l. dominate the slopes below the high cliffs (Appendix B: Fig.4). Downslope movement of the clasts in the debris accumulations was unrestricted at the top of the slope, but further down the movement became restricted and the clasts became imbricated. The orientation of the clasts at the bottom of the slope is perpendicular to the slope, and the scree simulates a lobate front. Only three peat slides occur between 400m and 450m a.s.l. and no peat slides occur above 450m a.s.l. due to the lack of peat at these altitudes.

4.3 Skua Ridge

Skua Ridge is a small horst located 1.5 km north of the base (Fig. 4.3). It is triangular in shape, and is bounded by faults at the northern and southern extremities that are surrounded by black lavas (Hall, 1978). The sea is to the east with Ships Cove on the northern coast, and the Van den Boogaardt River is to the south (Fig. 4.3). Skua Ridge ranges in altitude from approximately 100m a.s.l. in the west, to sea level at the coast. The area has low slope angles and most of the area is covered in thick vegetation and mires.

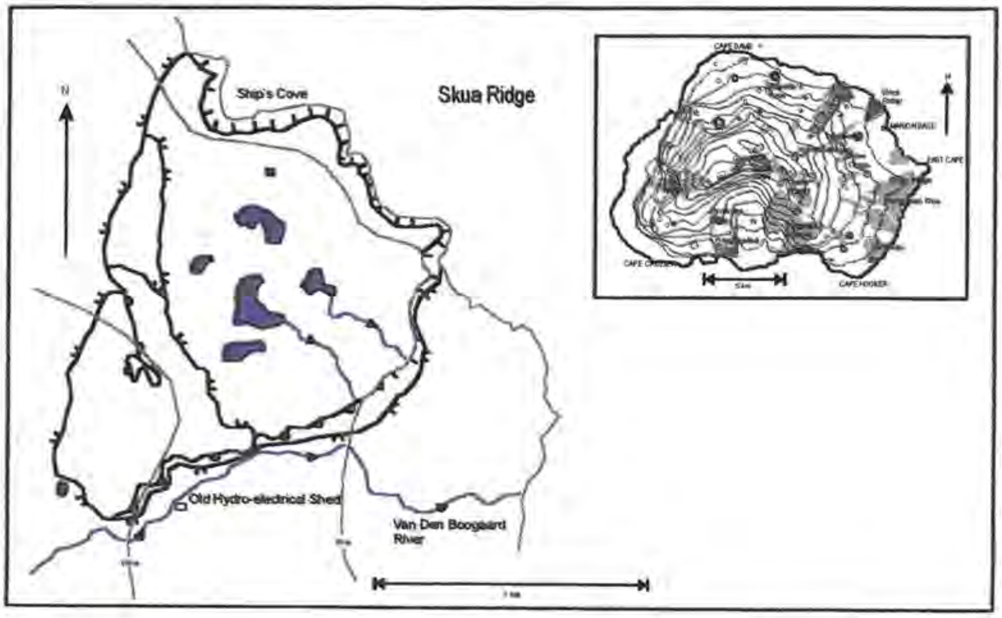

Figure 4.3: Locality and morphology of Skua Ridge

4.3.1 Glacial features

The moraines at Skua Ridge are of the push type (Hall, 1980), and are considered to result from and advancing ice front that bulldozes loose material in its path and push it into a ridge form.

Skua Ridge is divided into five physiographic units (Hall, 1978); from the coast inland these are (Appendix B: Fig.5):

- area of till, with small debris mounds and ponds,
- a broad moraine,
- an area immediately inland of the proximal edge of the moraine,
- an undulating till cover,
- a broad, high moraine with convex slopes.

The moraine closest to the coast is not a continuous feature and is broken up into small till covered outcrops. This moraine consists of a 200m wide belt of ridges and mounds with small, irregular shaped ponds in between (Hall, 1978). The majority of the ridges constituting the moraine are elongated in a north-south direction, but a number, small in size, were observed orientated east-west (Hall, 1978) (Appendix B: Fig.5).

The area immediately inland of the broad moraine closest to the coast has one large lake that is ponded against the moraine and a number of smaller ones further inland. Behind this there is an area of till, relatively free of ponds. This area slowly rises inland, with some hummocky mounds of till, until the inland moraine is met (Hall, 1978) (Appendix B: Fig.5). Hall (1978) describes the inland moraine as one that has convex slopes with a steeper proximal (25°) than distal (11°) slope. The inland moraine is terminated at its northern and southern ends by the faults. The moraine surface is relatively unvegetated and is covered with angular clasts often of boulder size.

4.3.2 Periglacial features

Skua Ridge is uniform with respect to periglacial features. Micro patterned ground in the form of sorted polygons and circles dominate the plateau on the southern edge of the grey lava area. Small sized *Azorella* banked lobes do occur on the south-eastern slopes north of the hydro-electrical shed (Appendix B: Fig.6), as well as around the lake areas. Most of the area is covered in thick vegetation and mires, and periglacial features are therefore only visible on the moraine areas not covered by vegetation.

4.3.3 Rapid mass movement

No rapid mass movement features occur in this area even though the depth of peat is quite considerable, due to the low slope angles. The lack of cliffs in the area also limits scree production.

4.4 Tafelberg

Tafelberg is an area of grey lava that is elongated from east to west. It stretches from an altitude of 150m to approximately 600m a.s.l. (Fig. 4.4) and is bounded by black lava. The Van den Boogaardt River demarcate the southern end of the area. Tafelberg is till covered, and sparsely vegetated. Thick vegetation and mires, however, occurs next to the river and these areas are free of till.

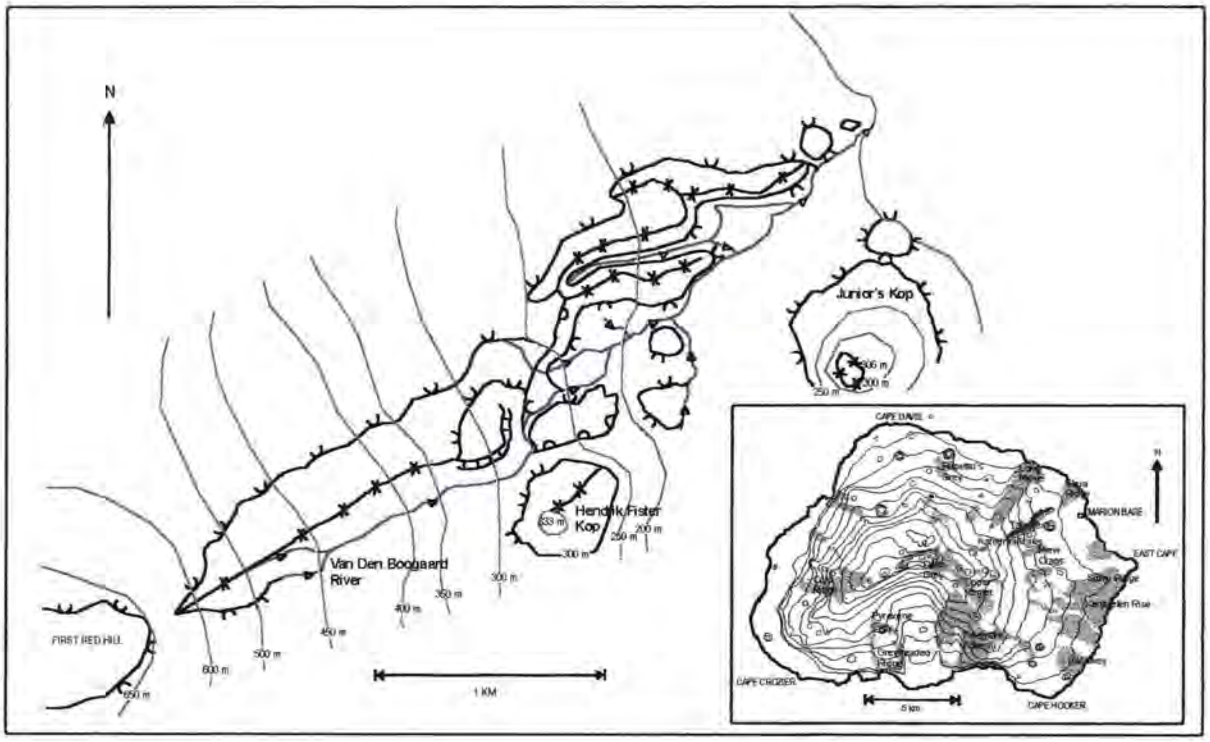

Figure 4.4: Locality and morphology of Tafelberg

4.4.1 Glacial features

Verwoerd (1971) notes the occurrence of striated pavements and roche moutonnées within the Tafelberg area but several new glacial pavements have since been identified by Hall (1978) and during the current study. Hall (1978) described the striations as being consistent over the whole area with a mean orientation of 60°. Striated bedrock is found between 200m and 600m a.s.l. and the higher altitude striated outcrops found in this study, have a mean direction between 50° and 60° (Appendix B: Fig.7). This above mentioned striation orientation correlates well with the direction of the striations at lower altitudes described by Hall (1978).

4.4.2 Periglacial features

Small *Azorella* and stone-banked lobes occur throughout the whole altitudinal range of Tafelberg with some medium sized lobes at approximately 300m and between 450m and 500m a.s.l. respectively. Some bedrock associated medium lobes do occur lower down at 200m and 275m a.s.l. (Appendix B: Fig.8). The large stone banked lobes between 300m and 350m a.s.l. have riser heights greater than 1.5m but these are bedrock associated. Some medium terraces also exist at 450m, 400m and 300m a.s.l. Sorted polygons and stripes are present throughout the whole area.

4.4.3 Rapid mass movement

One peat slide exists in the Tafelberg grey lava area at an altitude of 425m a.s.l. This slide occurred after heavy rainfall in the beginning of January 2000 (Appendix B: Fig.8).

4.5 Macaroni Bay

The Macaroni Bay area comprises a broad expanse of till immediately behind the bay and is bordered in the north and south by distinctive faults (Fig. 4.5) (Hall, 1978). The till is completely surrounded by black lava and some glacial outcrops around Macaroni Bay projecting above the black lava are also incorporated into this area. The altitude of the Macaroni Bay study site ranges from approximately 100m a.s.l. to the coast and the area has low slope angles and most of the area is covered in thick vegetation and mires

4.5.1 Glacial features

End moraines found at Macaroni Bay are of the push type (Hall, 1980). To the south of Albatross lakes two remnants of a lateral moraine are found (Hall, 1978). Moraine 2 (Appendix B: Fig.9) as described by Hall (1978) is very large and pronounced, especially in the south. It is the widest and highest moraine in the area and has a number of ponds on its crest. Much of this moraine is removed by faulting.

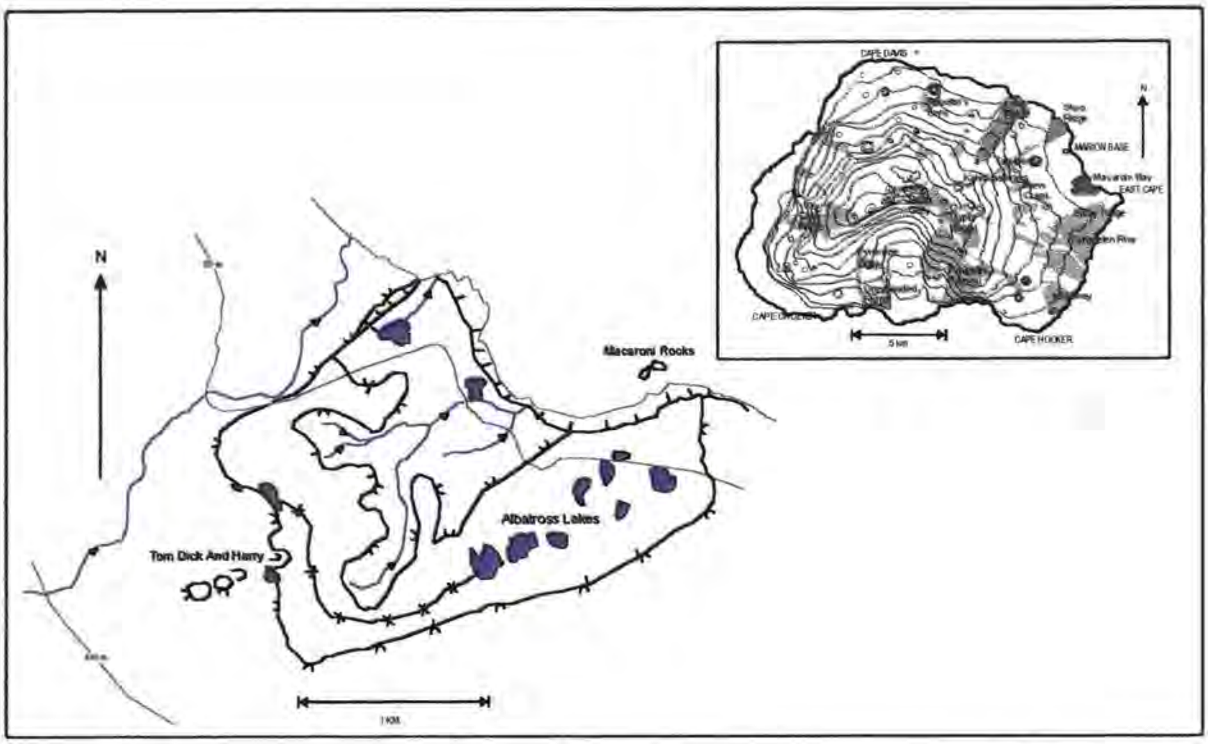

Figure 4.5: Locality and morphology of Macaroni Bay

Hall (1978) found two exposures of glacial striations to the north of the bay. On the cliff-top an area of highly polished lava with striations with a mean orientation of 37° were observed. The second exposure has striations, which indicate a mean ice-flow direction of 81°, and it is on the grey lava platform just above sea level north of the centre of the bay (Appendix B: Fig.9). The grey lava at Macaroni Bay has been dated at 276 000 BP, and is the oldest dated lava on the island (McDougall, 1971).

4.5.2 Periglacial features

The same situation exist at Macaroni Bay as on Skua Ridge where the periglacial features are common on the moraine, but the rest of the area is vegetated so no periglacial features either exist or are visible. As on Skua Ridge the features at Macaroni Bay are small, not very dense, and very uniform (Appendix B: Fig. 10).

4.5.3 Rapid mass movement

As on Skua Ridge, no rapid mass movement features occur in the Macaroni Bay area due to the low slope angles even though the depth of peat is quite considerable. The lack of cliffs in the area also limits scree production.

4.6 Piew Crags

The grey lava area at Piew Crags is approximately 1,5km long and 500m wide. Piew Crags lies between 250m and 400m a.s.l. (Fig. 4.6). A river to the south and high cliffs in the north demarcates the grey lava area and a high percentage of the grey lava surface area constitutes bedrock, but till does occur. No vegetation exists in this area except below the high north facing cliffs.

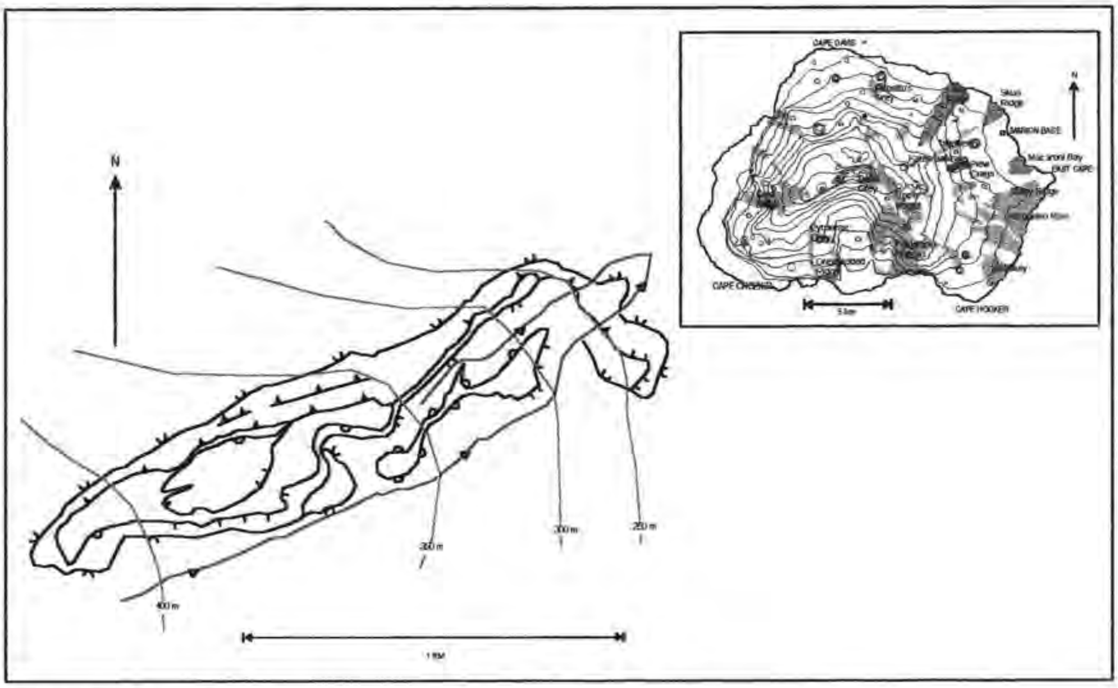

Figure 4.6: Locality and morphology of Piew Crags

4.6.1 Glacial features

The whole area mainly compromises bedrock outcrops and is covered with till and platey till. Hall (1978) described the striations as fairly consistent over the whole area with a mean orientation of 52°, and a large number of grooves were found on the glacially moulded landforms that have a mean strike of 67°. Several new pavements have been identified in this study and the direction of the striations shows a mean between 50° and 60° (Appendix B: Fig. 11). This supports the orientation of the striated pavements found by Hall (1978).

4.6.2 Periglacial features

The density of the periglacial features in the Piew Crags area is not high due to the high percentage of bedrock and the lack of material for features to form in. The high percentage of bedrock in the area also influences the lack of patterned ground. However Hall (1983a) did observe some circles and nets developed in fine-rich till only 0,15m deep at 300m a.s.l.. Sorted stripes occur 400m a.s.l. (Appendix B: Fig. 12).

Sorted polygons just below 400m a.s.l. are in material that has a strong resemblance to black lava. It is possible that the black lava has been splashed on the grey lava during the Holocene lava flows, and the sorted stripes developed in these sediments.

4.6.3 Rapid mass movement

Although the whole of the north facing side of Piew crags consist of high cliffs, with some cliff faces higher than 30m, screes are not common. Peat slides exist in the vegetated slope and some screes do occur on the north-facing slope of the crag at an altitude of between 350m and 365m a.s.l. (Appendix B: Fig. 12). Some small screes also occur below the south facing cliffs.

4.7 Katedraalkrans

Katedraalkrans is a small grey lava area approximately 1km long and 500m wide (Fig. 4.7). The area is surrounded by black lava and lies between 700m and 800m a.s.l. The study site is therefore one of the higher altitude grey lava sites. The central part of Katedraalkrans is flat, and high cliffs bound it. No vegetation, except for a few mosses, exists in this area.

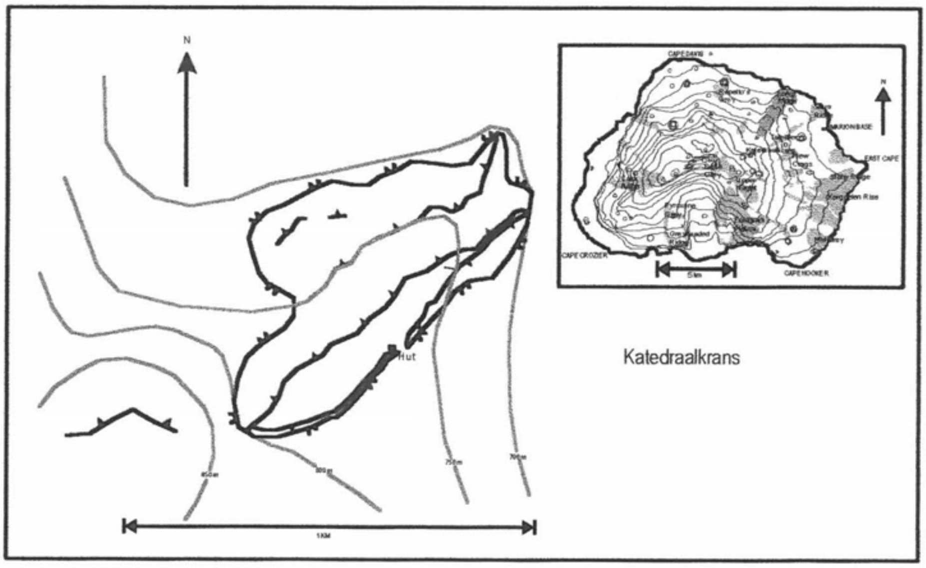

Figure 4.7: Locality and morphology of Katedraalkrans

4.7.1 Glacial features

At Katedraalkrans striations having an orientation of 40° were described (Hall, 1978). These striations were the only ones described by Hall (1978) that could not be found or verified in the current study, although rounded bedrock outcrops of apparent glacial origin were found (Appendix B: Fig. 13).

4.7.2 Periglacial features

The periglacial features at Katedraal are predominantly medium and large stone-banked lobes and terraces (Appendix B: Fig. 14). Some of the large lobes and terraces especially those just west of the hut have riser heights of over 2m. However most of these lobes have blocky fronts and are bedrock associated. Patterned ground in the form of sorted polygons and stripes are present, but not over the whole area. Most of the area consists of large plates and blocks, and the sorted polygons and stripes only occur in the areas that consist of finer materials.

4.7.3 Rapid mass movement

Scree slopes are common under the high north-facing cliff faces (+ 25m in height) (Appendix B: Fig. 14). However screes also occur under the low south-facing cliffs and under the cliffs at the eastern tip of the grey lava area. No vegetation, except for a few mosses, exists in this area and therefore no peat slides results.

4.8 Fred's and Tate's

Fred's and Tate's Hill are both scoria cones situated at 300m and 400m a.s.l. respectively. Fred's Hill bounds the grey lava area in the north-east, and the grey lava stretches around Tate's and is bounded by rivers to the north and south (Fig. 4.8). Around the scoria cones the area is till covered, predominantly flat and no vegetation exists except patches of *Azorella selago*.

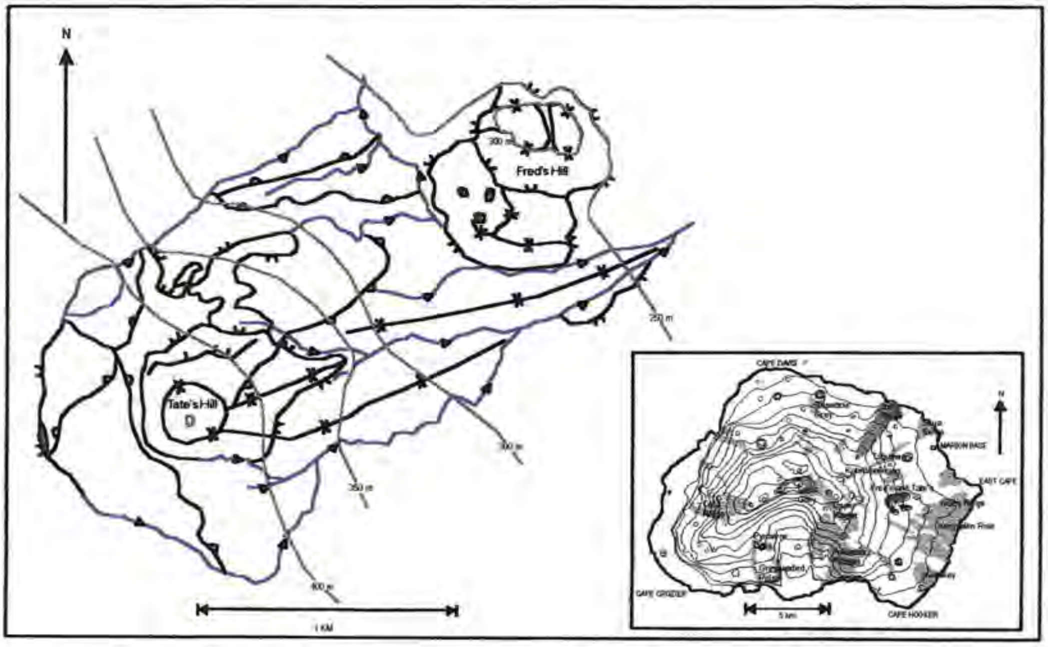

Figure 4.8: Locality and morphology of Fred's and Tate's Hills

4.8.1 Glacial features

To the west of Fred's Hill and north of Tate's Hill, striations and glacially moulded bedrock were found (Hall 1978). The striations west of Fred's Hill have an orientation of 87°, and those west of Tate's have an orientation of 82° (Appendix B: Fig. 15). In this study striations were identified south of Fred's (orientation 85°) that correlates well with the striations found at higher altitudes.

To the south of Tate's, however, the striae orientation is rather different and Hall (1978) measured a mean orientation of 125° for these striations. This evidence suggests that a splitting of the ice flow occurred in this region to produce two separate glaciers (Hall 1978) (see Chapter 5).

4.8.2 Periglacial features

Small stone-banked lobes and *Azorella* banked lobes are present in the lower regions of this particular area (Appendix B: Fig. 16). These features dominate to about 350m a.s.l. Above 350m a.s.l. medium sized lobes are dominant. Some large stone-banked lobes exist in the higher altitudinal zones. The stone-banked lobes just north of the crest of Tate's Hill are bedrock associated and have riser heights in excess of 2m. The large lobes at the south-western tip of the area, at approximately 435m a.s.l., are not bedrock associated and have riser heights between 1.2m and 1.9m. Patterned ground is not common in this area, but do occur.

4.8.3 Rapid mass movement

No screes and peat slides exist in this area (Appendix B: Fig. 16).

4.9 Stoney Ridge

Stoney Ridge extends from the coast to an altitude of approximately 200m a.s.l. (Fig. 4.9). The area is till covered but vegetation and mires dominate the area up to 100m a.s.l., and few grey lava outcrops are visible up to this altitude.

4.9.1 Glacial features

Stoney Ridge is a lateral moraine demarcating the northern boundary glacier D (see Chapter 5). The moraine is approximately 3km in length and rises to a height of 50 to 60m above the surrounding landscape (Hall, 1978) (Appendix B: Fig. 17). The area is till covered and no moulded bedrock or striations occur.

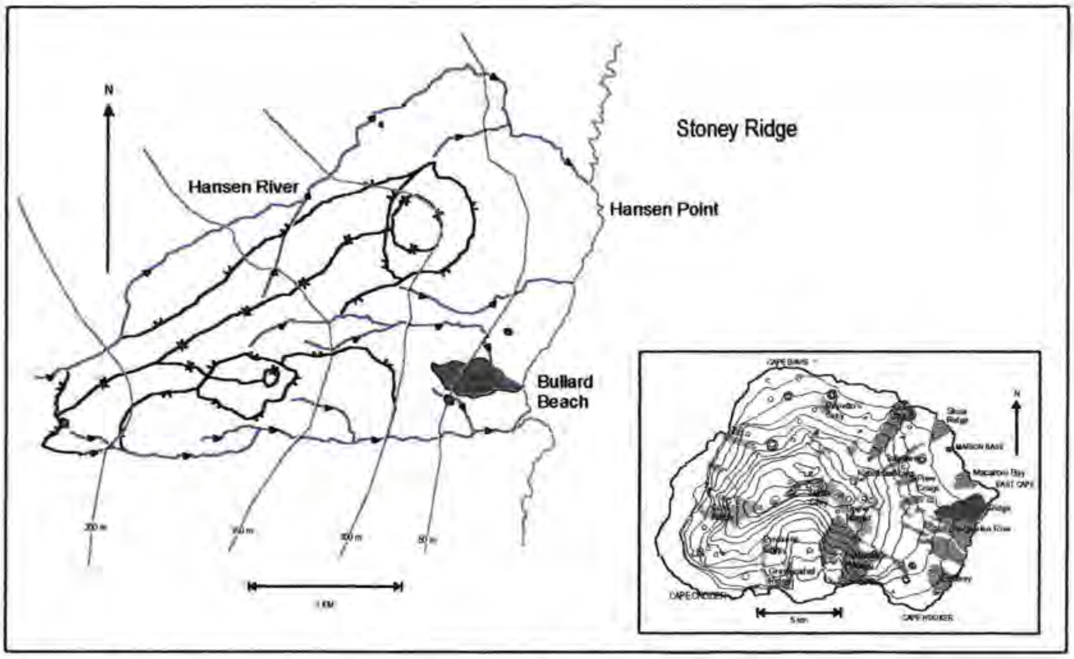

Figure 4.9: Locality and morphology of Stoney Ridge

4.9.2 Periglacial features

As at the other coastal regions, the predominate periglacial landforms are small lobes and micro patterned ground (Appendix B: Fig. 18). However some large stone-banked lobes with riser heights just over 1m are present at approximately 175m a.s.l. on the south-facing slope of the ridge.

4.9.3 Rapid mass movement

Some peat slides are present at 150m a.s.l. (Appendix B: Fig. 18). These peat slides are on the steeper north facing part of the ridge. The slope also consists of thick peat rich soil, and this together with the steep slope angle could contribute to the locality of these peat slides. As with all the other coastal sites no ridgelines with free faces are present, therefore no production of screes occur in these regions.

4.10 Kergeulen Rise North

Kergeulen Rise is a flat grey lava area that stretches from Stoney Ridge in the north to Kildalkey Bay in the south (Fig. 4.10). Due to the size of the area and the effect this has on the resolution of the maps, Kergeulen rise is divided up into three sections: Kergeulen Rise North, Kergeulen Rise South and Kergeulen Rise West (Fig. 4.10). The whole Kergeulen Rise grey lava area consists of long ridges extending from east to west with low slope angles and no cliffs. Therefore no rapid mass movement features occur in this area. Kergeulen Rise North is the grey lava section from Stoney

Ridge in the north to the Soft Plume River in the south. It stretches from the coast to approximately 250m a.s.l. It is till covered, has no bedrock outcrops and vegetation and mires are present on the coastal slopes, and an abundance of rivers bisect the area.

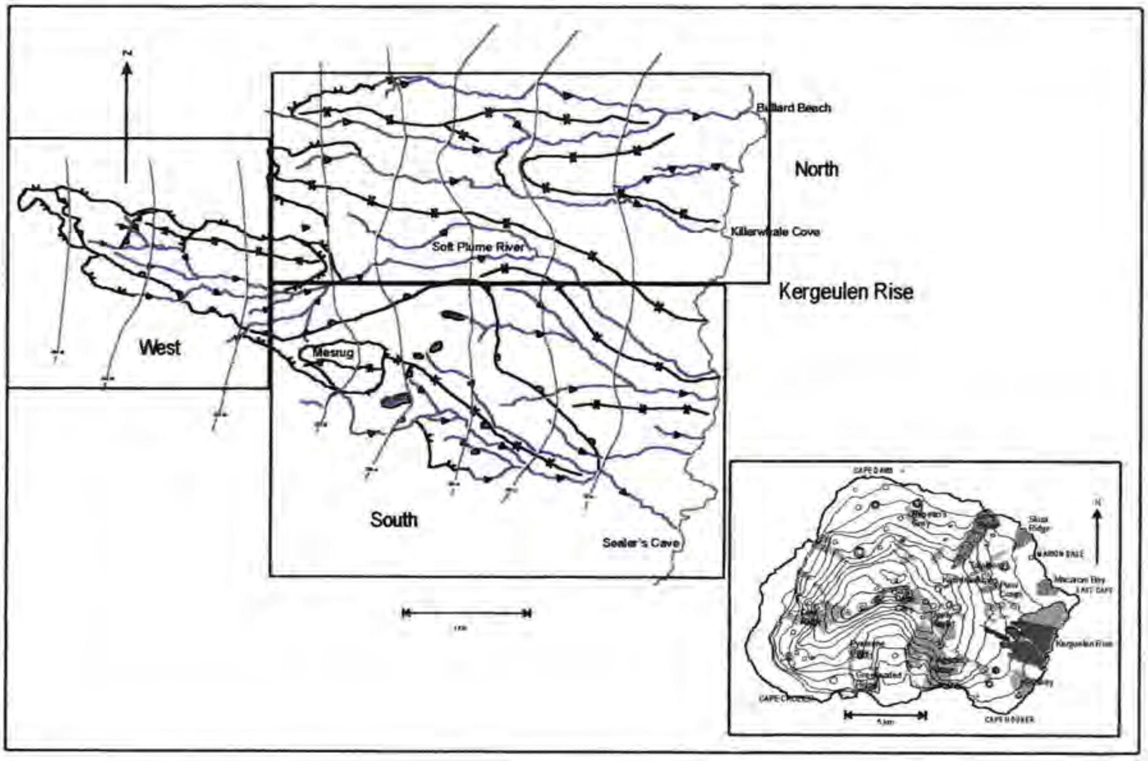

Figure 4.10: Locality and morphology of Kergeulen Rise

4.10.1 Glacial features

Kergeulen Rise North compromises two moraines. The northern moraine terminates about a kilometre from the coast (Hall, 1978), and the southern moraine's terminus swings slightly northwards (Appendix B: Fig. 19) and is surfaced by many angular clasts.

4.10.2 Periglacial features

Kergeulen Rise North is a typical coastal grey lava area with regards to periglacial features. Small lobes and micro patterned ground dominate the area (Appendix B: Fig. 20). The sorted stripes and polygons are situated predominantly on the crest lines of the subsequent ridges. However, some large stone-banked lobes with riser heights just over 1m are present at approximately 200m a.s.l. on the south-facing slope of the southern ridge. These stone-banked lobes are bedrock associated with the lobate form consisting of broken bedrock material.

4.11 Kergeulen Rise South

Kergeulen Rise South is the grey lava section demarcated by the Soft Plume River in the north and Kildalkey Bay grey lava area in the south (Fig. 4.10). In the west the site is confined to Mesrug, at an altitude of approximately 250m a.s.l. Vegetation and mires are present on the coastal slopes and an abundance of rivers and small lakes also bisect the area.

4.11.1 Glacial features

Kergeulen Rise South is till covered and no moulded bedrock or striations occur (Appendix B: Fig. 21). A broad hummocky lateral moraine occurs in this area, which marks the northern boundary of glacier B (see Chapter 5) and the seaward side of the moraine swings inward but no terminal moraine can be found (Hall, 1978).

4.11.2 Periglacial features

Kergeulen Rise South is also a typical coastal grey lava area, but some medium sized stone banked lobes do occur at an altitude of approximately 150m a.s.l. (Appendix B: Fig. 22) possibly due to higher local slope angles at those specific places.

4.12 Kergeulen Rise West

Kergeulen Rise West stretches from Mesrug in the east to the extent of the grey lava at about 400m a.s.l. (Fig. 4.10). Kergeulen Rise West is a flat expanse of till deposit and no vegetation except some patches of *Azorella selago* exist.

4.12.1 Glacial features

In the area above and to the west of Mesrug, several exposures of grey lava were found exhibiting striations and glacial smoothing (Appendix B: Fig. 23). To the northwest of Mesrug the striations have a mean direction of 91° and to the southwest of Mesrug the strike is 126° (Hall, 1978). Directly west of Mesrug close to Hoë Rooikop are striations with a bearing of 121° (Hall, 1978). These striations correlates well with the striations found just west of Tate's Hill, (Appendix B: Fig. 15). suggesting a splitting of the ice flow to produce two separate glaciers (Hall 1978) (see Chapter 5).

4.12.2 Periglacial features

As with most mid-altitudinal areas small features (riser heights < 50cm) dominate the lower regions but above ,350m a.s.l., the occurrence of medium sized features (riser heights between 50cm and 1m) are more frequent and at the highest altitude, large lobes (riser heights > 1m) are also present (Appendix B: Fig. 24). At 400m a.s.l. some medium sized lobes with riser heights just less than 1m are present as well as bedrock associated stone banked lobes with riser heights in the region of 1.8m. The large stone-banked lobes at 350m a.s.l. are bedrock associated and have riser heights of just above 1m. The local slope is also very steep. At 375m a.s.l. the large stone-banked lobes have riser heights of about 2m and are not bedrock associated, but steep local slopes do exist. Most of the sorted stripes and polygons in this area are situated on the crest of the predominant crest line of the ridge in the north, but some patterned ground features are also present in other sections.

4.13 Kildalkey Bay

Kildalkey Bay is a grey lava section just south of Kergeulen Rise. Only a small strip of black lava divides these two areas. Green Hill, a low-lying scoria cone, demarcates the area in the south (Fig. 4.11). It ranges from the coast to 150m a.s.l. A large Macaroni and King penguin colony is located at the bay and this colony is surrounded by vegetation and mires which is also present on the coastal slopes, and an abundance of rivers bisect the area.

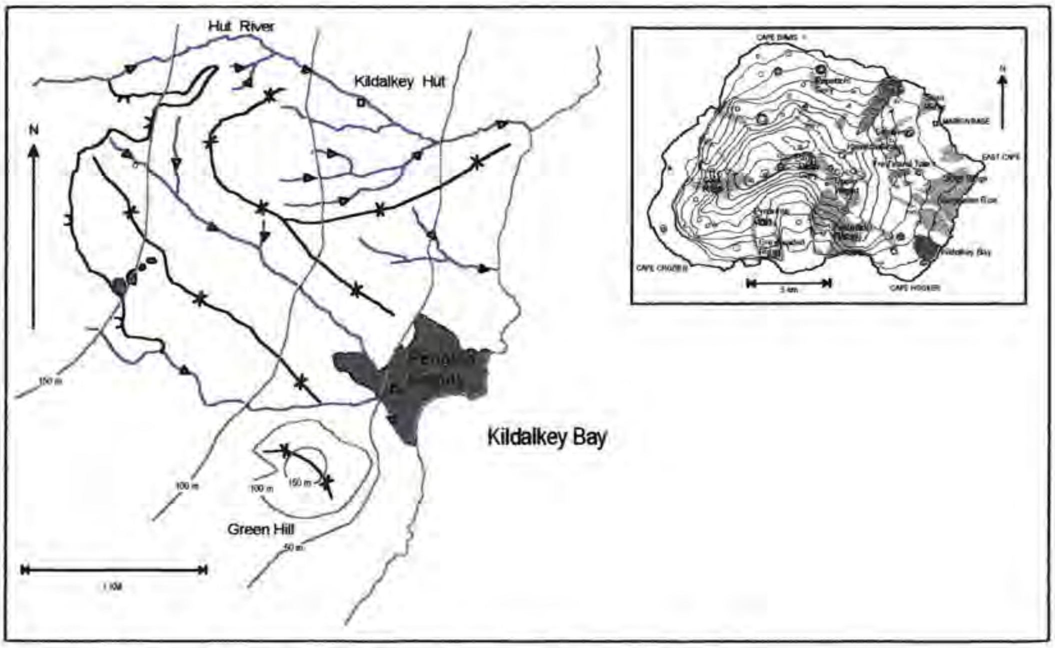

Figure 4.11: Locality and morphology of Kildalkey Bay

4.13.1 Glacial features

At Kildalkey Bay there is a lateral moraine close to Green Hill and a very broad lateral moraine (Appendix B: Fig. 25) that demarcates the southern limit of a glacier (Hall, 1978) (see Chapter 5). Hall (1978) also describes a very small but distinct end moraine between the two lateral moraines. As with the other coastal grey lava sites, the area is till covered and no moulded bedrock or striations occur.

4.13.2 Periglacial features

Kildalkey Bay like most coastal grey lava areas is made up exclusively of small lobes and patterned ground (Appendix B: Fig. 26). The patterned ground in the form of sorted stripes and polygons are present predominantly on the crest line of most of the ridges as well as on the tread of most lobes and terraces in the south-facing slope of the southern ridge.

4.14 Johnny's Hill to Karoo Kop

The grey lava area that commences between Johnny's Hill and Arthur's Hill and ends at the Feldmark Plateau's eastern boundary is a thin strip demarcated by the Black Haglet Valley in the north and an unnamed river in the south (Fig. 4.12). This area stretches over 300m of altitudinal gain, from 200m to 500m a.s.l., and no vegetation occurs in this area except some patches of *Azorella selago*.

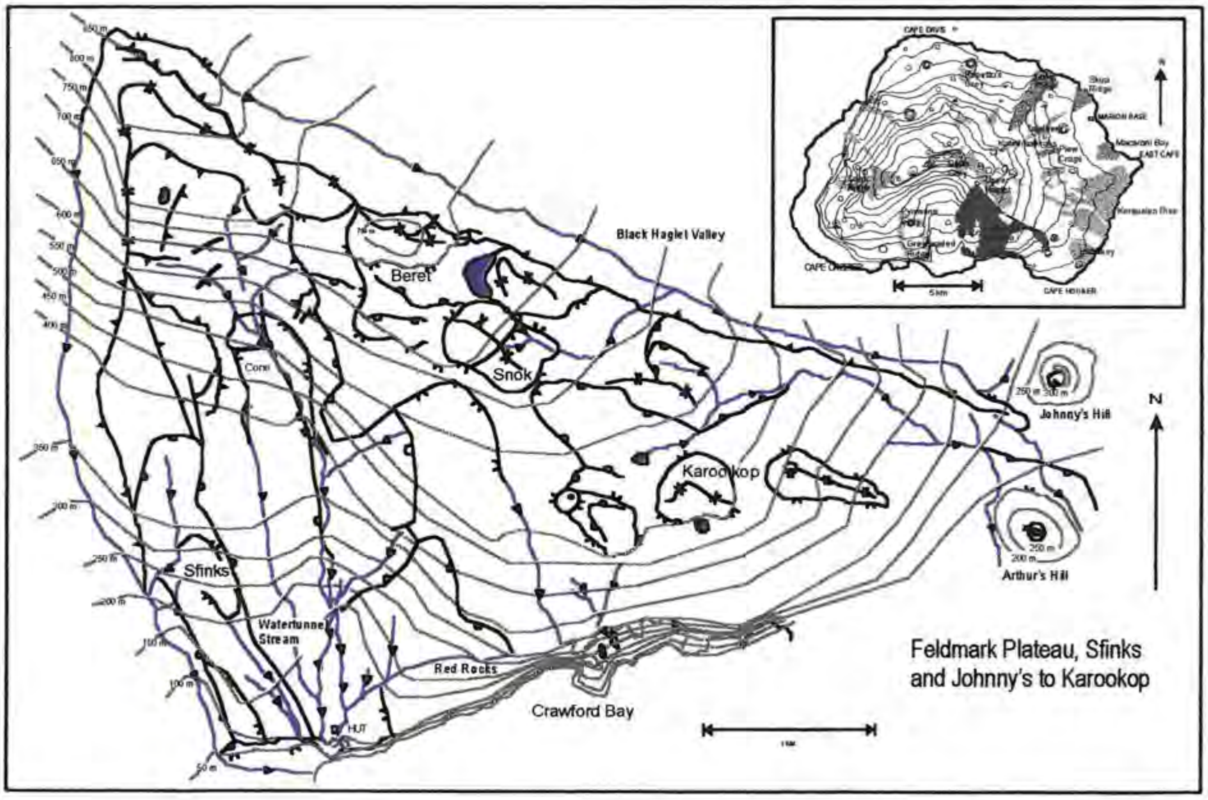

Figure 4.12: Locality and morphology of Feldmark Plateau, Sfinks and Johnny's to Karookop

4.14.1 Glacial features

No prominent glacial features exist in this area (Appendix B: Fig. 27). The only feature that could be discerned is one rounded bedrock outcrop, with no striations. The interpretation of this feature is highly dubious and it is possible that this feature is not of glacial origin.

4.14.2 Periglacial features

As mentioned before this area stretches over 300m of altitudinal gain and due to this one can expect the same situation exist as some of the other mid-latitudinal areas (Tafelberg, Fred's and Tate's, Kergeulen Rise West) where a whole range of different size of periglacial features is present. Small stone-banked lobes and Azorella banked lobes are the predominant features in the lower regions of this area (Appendix B: Fig. 28). These features are prevalent to about 300m a.s.l. Higher than 300m a.s.l., the principal feature is medium sized lobes. Some medium sized stone-banked lobes are however present at a lower altitude (200m a.s.l.), due to a steeper local slope at that particular location. Sorted stripes are present on the tread of these features. Some large stone-banked and *Azorella*-banked lobes exist in the higher altitudinal zones. These stone-banked and *Azorella*-banked lobes and terraces are located at 500m a.s.l. (Appendix B: Fig. 28). Sorted polygons are also present on the tread of these south facing stone-banked lobe and terrace features. Some patterned ground also exists on the crest line of the dominant ridge.

4.14.3 Rapid mass movement

Rapid mass movement features in this area are exclusively on the north facing slopes (Appendix B: Fig. 28) and although there are high cliffs above the north facing slopes, debris accumulation underneath these faces is not considerable and no screes exist. However, these slopes are vegetated and the same situation as on Long Ridge North could exist where vegetation cover could obscure all previous scree production. A few peat slides do exist on these north facing slopes with two being present next to each other at 250m a.s.l. and one peat slide occurring at 450m a.s.l.

4.15 Feldmark Plateau East

The Feldmark Plateau is the name given to a grey lava area from the Sfinks/Santa Rosa Valley in the west to Karoo Kop in the east (Fig. 4.12). As the name suggests it is a wind desert or feldmark complex, which are dominated by the hard cushion plant *Azorella selago*. Due to the nature of this environment no peat exist and no slides occur. The Crawford Bay area is demarcated in the south and the top of the

Black Haglet Valley in the north. It is quite an extensive area and it is divided into three sections (Fig. 4.12). Feldmark Plateau East is the grey lava area from Karoo Kop to the unnamed river south of Snok. It stretches from the coast to approximately 600m a.s.l.

4.15.1 Glacial features

In the Feldmark Plateau East area a glacial cirque basin at Snok (550m a.s.l.) with well-developed end moraine not previously recognised, was identified (Appendix B: Fig. 29) and it is suggested to have been active until the mid-Holocene (7k BP) when final deglaciation took place (Boelhouwers *et al*, 2001) (see Chapter 5).

4.15.2 Periglacial features

The coastal cliffs of Crawford Bay, which demarcate the area in the south, are approximately 300m high (Appendix B: Fig. 30). Therefore, although the periglacial features start at the coast it is already at an altitude of close to 350m a.s.l. This area is very uniform with regard to type of feature and size (Appendix B: Fig. 30) and stone banked lobes and Azorella banked lobes dominate. In regards to the size of periglacial features, the area can be divided into three sections. Small lobes are present up to 350m a.s.l. Medium lobes occur between 350m and 500m a.s.l. and large lobes are predominant in the higher altitude. Some patterned ground in the form of sorted stripes exists at approximately 550m a.s.l., just to the north of a small scoria cone.

4.15.3 Rapid mass movement

On the north-facing slope below the high cliffs at 550m a.s.l. screes and a peat slide are present (Appendix B: Fig. 30). Just to the east of Snok, below the cliffs, some debris accumulation also occurs. This accumulation is in the bowl of the cirque (see Chapter 5). This part of the area is quite flat and no cliffs exist except the coastal cliffs and the cliffs facing the Black Haglet Valley.

4.16 Feldmark Plateau South

Feldmark Plateau South is the area bounded by the Watertunnel Stream in the west, Snok in the north and the unnamed river dividing Feldmark Plateau South and Feldmark Plateau East to the east (Fig. 4.12).

4.16.1 Glacial features

This study has found no glacial landforms in this area except till (Appendix B: Fig. 31). Neither Verwoerd (1971) nor Hall (1978) has identified any glacial landforms in this area.

4.16.2 Periglacial features

Just east of the Watertunnel hut, a small flat area exists with small lobes, these small lobes are the only small stone banked and Azorella banked lobes in the entire demarcated area (Appendix B: Fig. 32). East of the Watertunnel Stream from approximately 150m a.s.l. to the end of the demarcated area at 450m a.s.l. the slopes are very steep and large stone-banked and *Azorella* banked lobes are present on these slopes. These lobate features consist of material derived from debris production from the earlier cliffs. Some remnants of these cliffs can still be seen above the slopes. East of the Watertunnel Stream and below the convex break of slope, medium sized lobes are dominant. These medium lobes are in the upper limit of the size range, close to 1m riser height, while some lobes on these slopes do exceed this height. Medium lobes also occur in the area just west of the unnamed river dividing Feldmark Plateau South and Feldmark Plateau East (Appendix B: Fig. 32). Above 450m a.s.l. the slope angles decrease but the lobe and terrace riser heights increases. The area has a slope angle of less than 10° and most of the stone banked terraces have riser heights in excess of 2m and they are horizontally extensive. Two of the terraces found in this area have riser heights of approximately 4m and 5m respectively. As can be expected the stone banked and *Azorella* banked lobes are also very large. Patterned ground is also very common on this plateau. Some of the largest sorted polygons and stripes that have been mapped are found in this area.

4.16.3 Rapid mass movement

As mentioned before, east of the Watertunnel Stream from approximately 150m a.s.l. northwards towards to the end of the demarcated area at 450m a.s.l. the slopes are very steep, but no screes exist on these slopes (Appendix B: Fig. 32).

4.17 Feldmark Plateau North

Feldmark Plateau North stretches from Snok in the east, towards the extent of the grey lava in the north, and down towards the Sfinks in the south (Fig. 4.12). This area is to the east of the Santa Rosa Valley and ranges from 400m to 850m a.s.l.

4.17.1 Glacial features

No glacial landforms other than till exist in this area (Appendix B: Fig. 33).

4.17.2 Periglacial features

Periglacially this area, together with Feldmark Plateau East, is unique. No other grey lava area that has been mapped has features of such magnitude, as those found here. None of the large lobes and terraces in this area is bedrock associated, but the riser heights of most are in excess of 2m, and one or two stone-banked lobes have riser heights of approximately 6m. These features are prevalent at approximately 550m a.s.l. to 750m a.s.l. (Appendix B: Fig. 34). Blockstreams has also been identified in this area (Boelhouwers *et al.*, 2001 (Appendix B: Fig. 34). The size of the sorted polygons and stripes are also large. The width of the crest to crest measurements of the sorted material of these stripes as well as the stripes found at Feldmark Plateau East are some of the largest in all the mapped grey lava areas of Marion Island. West of the Watertunnel Stream at approximately 400m a.s.l. to 500m a.s.l., large lobes and terraces with riser height in excess of 2m exist (Appendix B: Fig. 34).

4.17.3 Rapid mass movement

No grey lava area that has been mapped has such an extensive degree of scree production from the cliffs, especially the cliffs surrounding the Watertunnel Stream Valley as well as the screes on the west-facing slope on the other side of the crest (Appendix B: Fig. 34). The vertical extent of some of the scree slopes is in excess of 300m, and this is directly related to the vertical extent of the cliff faces above. However, some cliff faces are not very high, but the debris accumulation below it is quite extensive, and thus the cliffs that can be seen now could be the remnants of high cliffs that must have been present earlier in the Holocene (see Chapter 7).

4.18 Sfinks

The Sfinks is the name given for the grey lava area around the scoria cone called by the same name south of the Feldmark Plateau North and west of the Watertunnel Stream (Fig. 4.12).

4.18.1 Glacial features

Just to the west of Watertunnel Stream, Hall (1978) identified two lateral moraines separated by a distance of approximately 40m (Appendix B: Fig. 35). The two moraines parallel the fault, which demarcates the eastern boundary of Santa Rosa Valley, and are truncated at their seaward end by the coastal fault escarpment.

4.18.2 Periglacial features

At the coast the periglacial features are predominantly small lobes. Medium size lobes are predominant from 300m a.s.l. However from 375m a.s.l. onwards the frequency of large stone banked and Azorella banked lobes is higher than the medium sized features (Appendix B: Fig. 36).

4.18.3 Rapid mass movement

No screes or peat slides are present in this area (Appendix B: Fig. 36).

4.19 Summary

The glacial survey largely supports the interpretations made by Hall (1978). All glacial moraines, glacially polished and striated bedrock surfaces were verified and some new sites with striated surfaces were added (Table 4.1). An interesting exception is that of Katedraalkrans where no striated surfaces could be identified. However, the glacially polished surfaces, as well as relative age dating results (Sumner *et al, in press*), support an interpretation that the site was glaciated and not a nunatak. In addition to Hall's work, a glacial cirque at Snok (550m a.s.l.) with well-developed end moraine, not previously recognised has been identified (Boelhouwers *et al*, 2001). This feature is suggested to have been active until the mid-Holocene (7k BP) when final deglaciation took place (Boelhouwers *et al.*, 2001). Glacial landforms occur on all the grey lava areas that were mapped, except Feldmark Plateau South. However the glacial evidence at Feldmark Plateau North as well as the area between Johnny's Hill and Karoo Kop is inconclusive. The lack of glacial landforms in the Feldmark Plateau area is an apparent anomaly and is likely to be important for palaeoenvironmental interpretation (see Chapter 5).

Table 4.1: Summary of the orientations of the striations found in grey lava areas on Marion Island

Site	**Striations orientation**	**Author**
Tafelberg	60°, 61°	(Hall, 1978)
	60°, 60°, 55°, 60°, 50°, 60°	(Current study)
Piew Crags	52°, 67°	(Hall, 1978)
	75°, 65°, 65°, 60°, 55°, 65°, 67°, 55°	(Current study)
Fred's and Tate's Hill	87°, 82°, 125°	(Hall, 1978)
	85°, 82°, 80°, 80°, 85°, 85°, 90°, 90° 90°, 90°, 85°, 85°, 125°	(Current study)
Kergeulen Rise West	91°, 126°, 121°	(Hall, 1978)
	120°, 126°, 121°	(Current study)

Katedraalkrans	40°	(Hall, 1978)
Macaroni Bay	42°, 82°	(Hall, 1978)
	42°, 82°	(Current study)

The distribution of periglacial landforms has been the focus of current and established studies on Marion Island (Hall, 1979; 1981; 1983a; Holness & Boelhouwers, 1998). Hall (1979; 1981) reported on the widespread occurrence of periglacial landforms and observed that some are relict and, therefore, are indicative of colder than present post-glacial conditions (Hall, 1984). In their study, Holness & Boelhouwers (1998) investigated the Holocene changes in periglacial activity at Long Ridge, and showed evidence for a colder than present condition earlier in the Holocene.

Periglacial landforms occur on all the grey lava areas that were mapped. The features are present throughout the whole altitudinal range, and a definite trend can be discerned. The features on coastal grey lava areas are small, uniform and the predominantly small lobes (riser height < 50 cm) and micro patterned ground. At approximately 350m a.s.l. medium sized lobes (riser height between 50cm and 1m) emerge. Large lobes (riser height>1m) also occur frequently from about 400m a.s.l. (See Chapter 6 for a detailed analysis).

Holness and Boelhouwers (1998) found that bedrock-associated stone-banked lobes on Long Ridge have large very blocky fronts and are larger than those lobes not immediately associated with rocky outcrops. The periglacial survey of the eastern side of Marion Island supports this interpretation.

The periglacial features on the Feldmark Plateau are distinctly different than those found in other areas with respect to their size. Most of the lobes and terraces on the Feldmark Plateau have riser heights in excess of 2m and therefore are relatively much larger than the same periglacial features in other sectors at the same altitude. The magnitude of the patterned ground is also very extensive. The width of the crest to crest measurements of the sorted material of these stripes is in excess of 20cm, and the magnitude of the diameter of the polygons are some of the largest in all the grey lava areas surveyed (See Chapter 6).

Rapid mass movement features are present in most grey lava areas, except where the area consists of long ridges with low slope angles and no cliffs. . Screes are mostly found in areas with high free faces, which is part of the major faults (Hall, 1978; 1980a) at an altitudinal range of between 350m and 800m a.s.l. The extent of the screes is related to the morphology of the cliffs above. However, some cliff faces are not high, but the debris below it is extensive. It is possible that the cliffs that can be seen now, could be the remnants of the high cliffs that must have been present earlier in the Holocene or Late Pleistocene (see Chapter 7).

Peat slides are common in the altitudinal range between 150m a.s.l. and 450m a.s.l. where thick soil and steep slopes are present. This does not include the feldmark environments where peat slides do not occur. Most of the observed peat slides occur on the north facing slopes of the major ridgelines as the slope angle of these slopes is higher than the south facing slopes and this, together with vegetation and soil cover, which are also thicker on these slopes, are the apparent reasons for the north facing preference. However, on Long Ridge peat slides occur on both sides of the ridge, with the peat slides on the northwest facing slopes being more extensive (see Chapter 7).

CHAPTER 5: GLACIAL LANDFORMS AND INFERRED PALAEO ICE-FLOW

5.1 Previous studies

Prior to the study by Hall (1978), very little information was available regarding the glacial history of Marion Island. Schalke and Van Zinderen Bakker (1971) showed from palynological evidence that the region experienced a cold period that was approximately coeval with the Würm of the Northern Hemisphere and ended about 12 000 B.P (Hall, 1980a). The existence of striated bedrock outcrops first found by Verwoerd (1971) showed that ice had existed during the cold periods described by Schalke and Van Zinderen Bakker (1971) (Hall, 1980a).

Hall (1978) performed palaeoreconstruction of the glacial events of Marion Island through investigating the stratigraphy of cliff exposures at nine sites around the island. These sites were described in terms of the palaeosols, interbedded rhythmites, gravel, tills and other depositional sediments. Of the three glacials that are considered to have affected the island (see Chapter 2) the deposits of the first two are exposed along the coastal cliffs and incised stream courses (Hall, 1980). However, it is believed that most of the eastern side of the island have been affected through either glacio-depositional or glacio-erosional features resulting from the most recent glacial (Würm-age, 70 000-11 000 BP) (Hall, 1980). Depositional and erosional landforms in the form of moraines from this glacial, are also described by Hall (1978), and they are thought to be part of a sequence resulting from periods of major ice advance within the Würm-age glacial (Hall, 1980a). These moraines are therefore indicative of active glaciers on Marion Island in the Late Pleistocene.

Till fabric analysis was undertaken at all coastal and inland till exposures except Crawford Bay (Feldmark Plateau) to obtain additional information on palaeo-ice flow directions and their spatial and temporal variations (Hall, 1980a). Striated bedrock and glacially moulded landforms are further indications of the directions of palaeo- ice flows. Numerous striations have been described and mapped on Marion Island (Verwoerd, 1971; Hall, 1978). Hall (1978) assumes that the situation on the island during the glacials was the same as it is now, with a central ice cap, but from out which glaciers radiated. Most of the glacial striations described by Hall (1978) were identified and other previously unidentified striations were located to test his findings (Table 4.1). It is, however worth noting that it will be poor judgement to base palaeo ice- flow direction on striations alone, but that together with the till fabric analysis and locality and description of moraines, the palaeo- ice flow and glacial environment on Marion Island can be attained (Fig. 5.1).

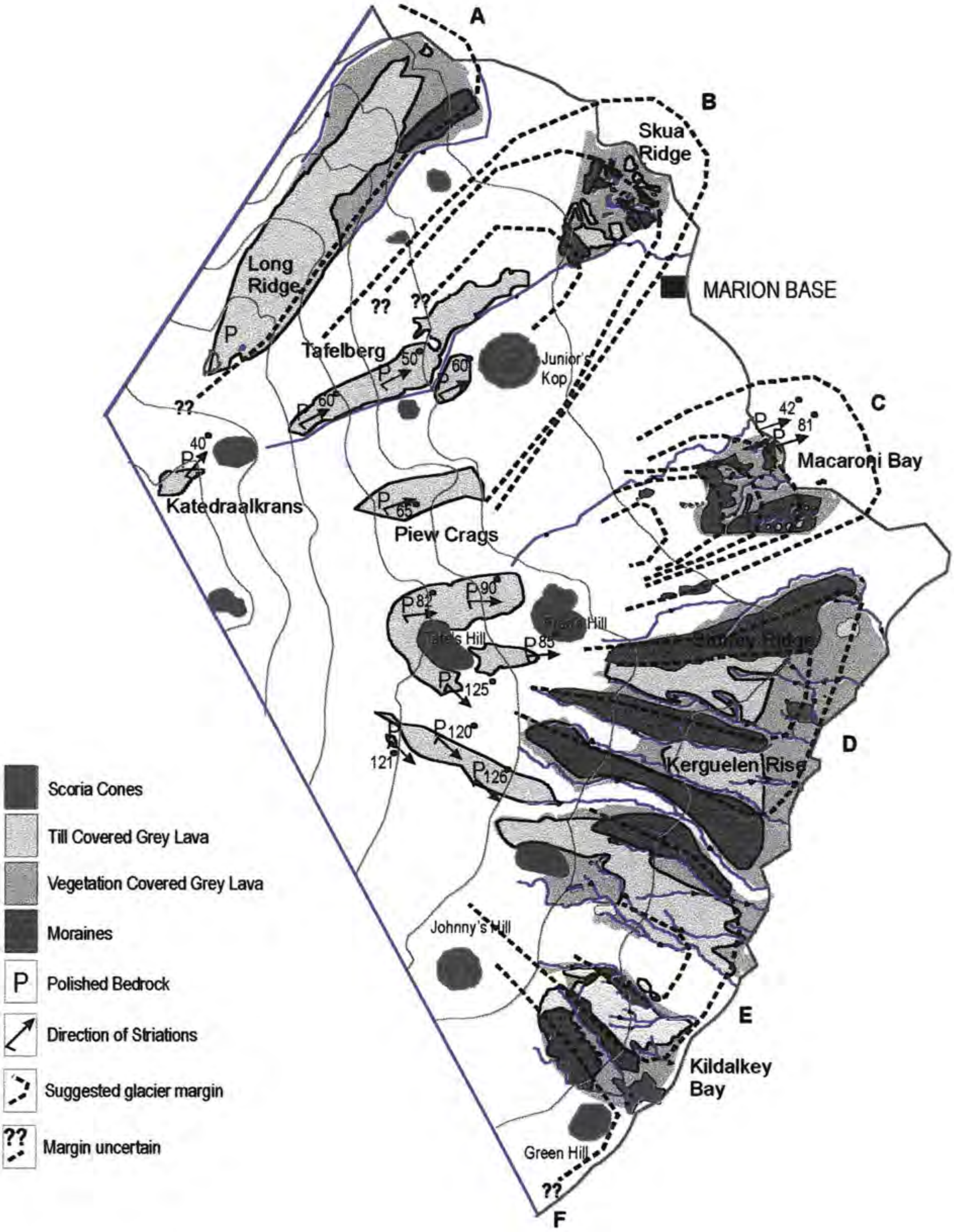

Figure 5.1: Palaeo-reconstruction of the ice cover on Marion Island (Hall, 1978)

The available information presented by Hall (1978; 1980a) provides a continuum whereby an attempt was made to reconstruct a number of the former glaciers on the eastern side of Marion Island Inland the striations and till fabric analysis give some idea of the direction of the ice flow, and the moraines demarcate the boundaries of the glaciers (Hall, 1980a). This evidence from extensive research from Hall (1978) suggests the positions of several former glaciers (Fig. 5.1). While Hall (1978) reconstructed glaciers D and E fairly rigorously, the margins of A, B and C are hypothesised to a large extent (Hall, 1980a). For a detailed study and analysis of the palaeoenvironmental reconstruction of the ice cover refer to Hall (1978; 1980a; 1983c; 1990b). Hall (1978; 1980a) further reconstructed the glacial-maximum temperatures from the altitudinal range of the palaeo-snowlines as evident in their relationship with the position and altitude of the lateral moraines. Thus, it was construed that the mean annual air temperatures of Marion Island fell by only 2 – 4°C in the last glacial and that the glaciation of the island was effected by an increase in the amount of precipitation falling as snow (Hall, 1982). As mentioned earlier, the reconstruction proposed by Hall (1978; 1980a; 1982) was contested in part by Kent and Gribnitz (1983) and Gribnitz *et al* (1986). This contesting of Hall's reconstruction is based, during two short visits to a limited part of the island, on one palaeosol, which they describe as a tuff of volcanic origin (Gribnitz *et al*, 1986). The dating of Quaternary climate change based on an assumed uniform rate of peat accumulation in a mire is also questioned (Gribnitz *et al*, 1986). These authors describe some interesting but often contradictory evidence, and although they agreed that the island had been glaciated, they did not explain why no glacial deposits other than moraines exist (Hall, 1990b). However, in the light of the amount of meticulous and sound research undertaken by Hall (1978; 1980a; 1982) (that was in part confirmed by this study), it is impossible to refute the evidence and inferred interpretation by Hall (1978; 1980a; 1982) on the palaeoreconstruction and glacial succession of Marion Island.

Notwithstanding this interpretation, there are some problems regarding certain areas, especially the areas where evidence for glacial activity is vague or not available. Further, in this study of the periglacial landforms, a number of possible problems associated with the glacial reconstruction are highlighted and are further discussed below.

5. 2 Problematic areas with regards to glacial activity and extent of ice cover

Discrepancies exist with regards to the boundaries and extent of the ice cover of the area demarcated as the Feldmark Plateau (Fig. 3.1; 5.2) (see Hall, 1977; 1978;

1980a; 1982; 1983c; 1990b). Only one margin with respect to glacier F (a small lateral moraine at Green Hill) (Fig. 5.1) is known (Hall, 1980a). With respect to glacier G (Fig. 5.2), Hall (1980a, pp. 253) states that it is "only the presence of ice which can be construed". However, in the construction of the glacier, Hall (1977) first reconstructed glacier F and G as one glacier. Later the same author constructed F and G as separate glaciers (Hall, 1978; 1980a; 1982, 1990b) but with unknown extent and margins. Though Hall (1982, pp. 50) suggests that because the "locations where the glacier is reconstructed as extending beyond the present margin of the island there is peripheral coastal faulting", and "conversely areas such as Stoney ridge to near Green Hill where there is no evidence to indicate ice extending off-shore exhibit only low cliffs with no signs of coastal faults". Hall further states "at Crawford Bay (Feldmark Plateau) where the ice did extend off-shore and which exhibits one of the highest cliff exposures on the island (+/- 350m), there are found dykes, cutting through the whole vertical sequence of beds, formed along post-glacial faults" (Hall, 1982, pp. 50). If this observation is correct and off-shore extent is directly related to the height of coastal cliffs, then the ice cover beyond Crawford Bay, which is the area demarcated as Feldmark Plateau, must have been extensive. Nevertheless, no irrefutable evidence for glacial activity has been found in this area (Fig. 5.2). A small lateral moraine was identified in the Watertunnel area (Hall, 1978; 1980a), but the bedrock outcrops that exist in this area show no sign of rounding or striations. This area is the biggest area of unbroken grey lava on the island, and surely, if the ice cover was as extensive as the cliffs, and the size of the unbroken grey lava area suggests, then some proxy-evidence should be present, but is conspicuous by it's absence.

Conversely, the Feldmark Plateau area is bounded by faults (Hall, 1978; 1982), and the whole area is raised which can only, due to a lack of evidence on the contrary, be due to isostatic uplift on deglaciation as suggested by Hall (1978; 1982) and is therefore a horst. Also, evidence for Holocenic glacial activity in the form of a cirque basin (Fig. 5.2) with a well-developed end moraine, were identified at Snok (550m a.s.l) (Boelhouwers *et al.*, 2001). This is the only known evidence for glacial activity in the Holocene on Marion Island. Given this support, and the fact that the Feldmark Plateau is in the colder southern sector, it can be construed that this area is likely to be affected by conditions that are favourable for any glacial activity.

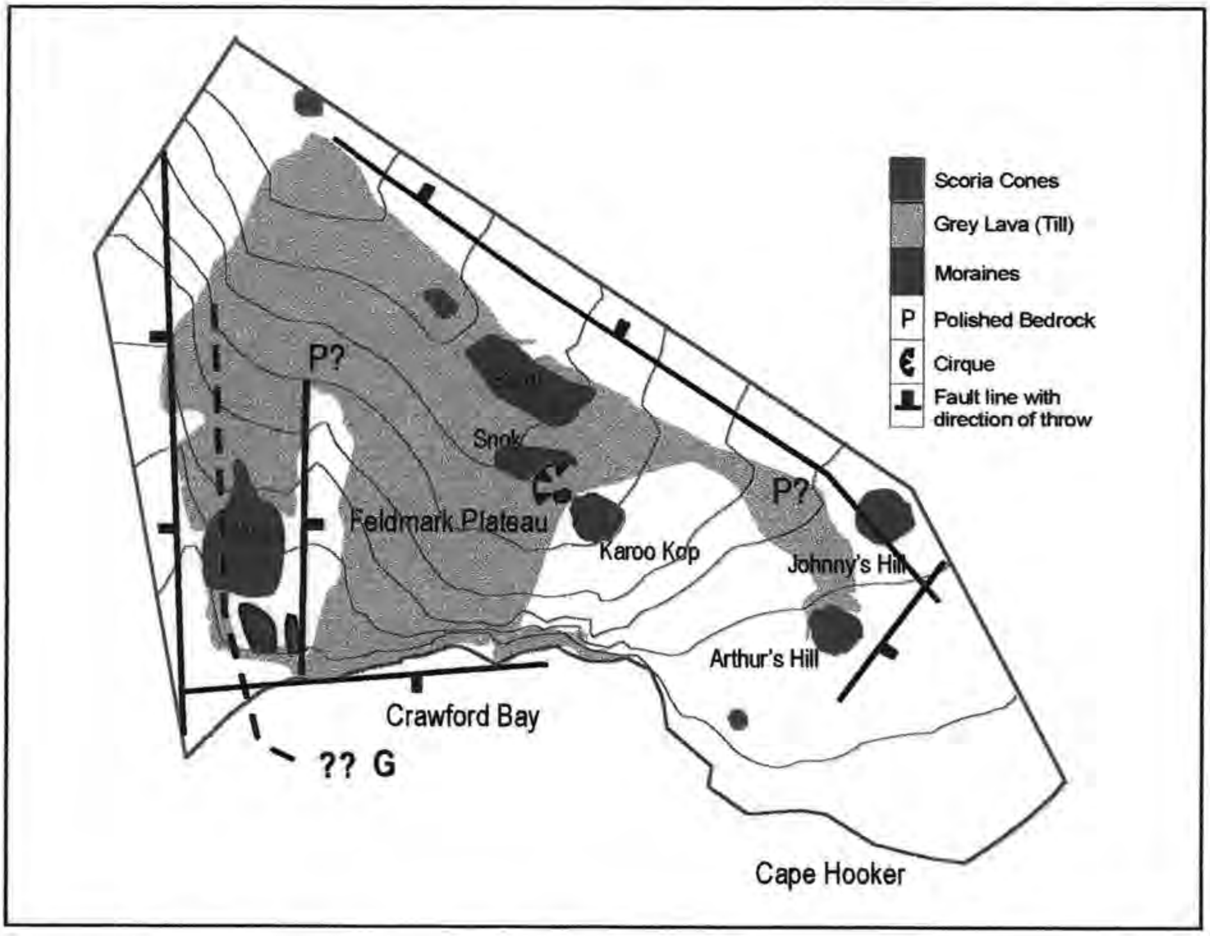

Figure 5.2: Glacial evidence and fault lines at Feldmark Plateau

The Feldmark Plateau area is unique with regards to periglacial landforms. Nowhere else on the grey lava areas on Marion Island are there features of such magnitude, as those found here (see Chapters 4 and 6). None of the large lobes and terraces in this area are bedrock associated, but the riser heights of most of them are in excess of 2m, and one or two stone-banked lobes have riser heights of approximately 6m. These features are prevalent at approximately 550m a.s.l to 750m a.s.l. Blockstreams have also been identified (Boelhouwers *et al.*, 2001) in this area. However, it should be noted that all slopes of the Feldmark Plateau are south facing and thus receive less insolation than north-facing slopes. In addition, the slopes occupy the southern sector of the island, which may further add to cooler conditions (Boelhouwers *et al.*, 2001). These two factors could contribute to the large relative magnitude of both active and relict periglacial forms found in this area. Conversely, the occurrence of larger slow mass wasting landforms at this site, could also suggest that these features either formed in ice free areas during the glacial period, or that these areas became ice-free considerably earlier than other sites at similar altitudes. This suggests that the ice cover experienced on Marion Island may have been less continuous and extensive than previously suggested by Hall, (1978) (Boelhouwers *et al.*, 2001).

It is obvious that conflicting evidence exists to the glacial activity and the extent of the ice cover on the Feldmark Plateau; further research is therefore suggested. Till fabric analysis and relative age dating (Sumner *et al., in press*) of slow mass wasting landforms is much needed and will possibly aid in establishing the palaeoenvironment of the Feldmark Plateau in the Late Pleistocene and/or early Holocene with some degree of certainty.

Boelhouwers *et al.,* (2001) suggest that the occurrence of larger slow mass wasting landforms at Long Ridge South (Appendix B: Fig. 4) indicate that features were either formed in ice free areas during the glacial period, or that this area became ice-free considerably earlier than other parts of the island. Even though Hall (1978) and Verwoerd (1971), in their surveys of the area, found no striations, a rounded bedrock outcrop with no striations, but what looks like a roche moutonnée was found by the author at 525m a.s.l. (Appendix B: Fig. 3). Also, platy material was found at 550m a.s.l on top of the proposed "nunatak". This material could have been formed due to *in situ* weathering, or it could be a till deposit. It is, therefore, ineffectual to produce a conclusion on the extent of the ice cover on Long Ridge South, especially the higher reaches, with the evidence presented here. Again, as with the Feldmark Plateau, further research is needed.

5.3 Chapter summary

Palaeoreconstruction on Marion Island with regards to glaciology was undertaken by Hall (1978) looking at the stratigraphy of cliff exposures, depositional and erosional landforms in the form of moraines, till fabric analysis and analysis of striated bedrock and glacially moulded landforms. Hall (1978) assumes that the situation on the island was the same as it is now with a central ice cap, but from which glaciers radiated. Marion Island was subject to multiple glaciation during the last 300 000 years (Hall, 1978) and that Marion Island were subjected to three glacial events, which were named "Oldest", "Penultimate" and "Würm-age". Overall the geochronology of Marion Island is described by Hall (1978) and can be seen as a grey lava volcanic stage around 276 000 BP. Subsequent to the early volcanic episode a glacial event (Oldest) occurred, which was followed by an extensive eruption of lava and pyroclasts and it is suggested that this was a major event of some duration (Hall, 1978). After this, interglacial volcanic stage the world temperature decreased, the Antarctic Polar Convergence moved northwards and a next glacial stage was initiated (penultimate). Termination of this glacial stage is marked by extensive outpours of grey lavas (Hall, 1978). Then, before the black lava stage a final Würm–age glacial episode occurred. Evidence for this is the striated grey lavas from this glacial episode, which were successfully dated by McDougall (1971) and it indicates a glaciation post-dating the grey lava stage and pre-dating the black lavas.

It is concluded that the palaeoreconstruction of Marion Island in respect to ice cover and glacial activity by Hall (1978; 1980a; 1983c; 1990b) seems to be accurate. However, there are some problems regarding certain areas, especially the areas where evidence for glacial activity is vague or not available.

5.4 Further Research

In the area demarcated as Feldmark Plateau, some morphological evidence exist that indicate that the ice cover in this region must have been extensive. However, no irrefutable proxy-evidence for glacial activity has been found here. Also, Boelhouwers *et al.* (2001) suggest that the occurrence of larger slow mass wasting landforms at Long Ridge South (Appendix B: Fig. 4) were either formed in ice-free areas during the glacial period, or that this area became ice-free considerably earlier, than previously suggested by Hall (1978). However, a feature that is apparently a roche moutonnée was identified at 525m a.s.l. and platy material on top of the proposed “nunatak” could indicate glacial activity in this area.

Conflicting evidence exists to the glacial activity and the extent of the ice cover on certain areas on Marion Island. It is, therefore, not possible to produce a conclusion on the extent of the ice cover. Further research in the form of relative age dating, analysis of the depth of sorting and soil temperature monitoring is suggested, and will possibly aid in establishing the palaeoenvironment of the relevant areas in the Late Pleistocene early Holocene with some degree of certainty.

CHAPTER 6: ALTITUDINAL RANGE AND SLOPE ASPECT OF PERIGLACIAL FEATURES

Previous studies have assessed periglacial landforms on Marion Island and their environmental implications (Hall, 1981; 1983a; Holness and Boelhouwers, 1998; Boelhouwers *et al*, 2001). These studies present the first detailed quantitative descriptions of relict periglacial slow mass wasting landforms (stone-banked lobes, stone-banked terraces, vegetation-banked terraces and blockstreams) dating from the Late Pleistocene and early Holocene. Extensive evidence of Holocene periglacial activity on Marion Island, as well as evidence for considerably colder conditions earlier in the Holocene were found. Evidence that was based on the altitudinal trend of periglacial features on Long Ridge is advanced for a steeper periglacial gradient than at present (Holness and Boelhouwers, 1998).

For further analysis on the spatial distribution of periglacial features, the survey area has been divided into five sectors in which the altitudinal distribution of features was identified (Fig. 3.1). Each landform present in the relevant sector was analysed for minimum and maximum altitude and these values of each landform were plotted against altitude. In addition to the altitudinal distribution of features, landforms were also analysed on distribution by slope aspect in the various sectors.

6.1 Altitudinal range of periglacial features

The survey area has been divided into five sectors, and for each sector the altitudinal range was plotted (Fig. 6.1)

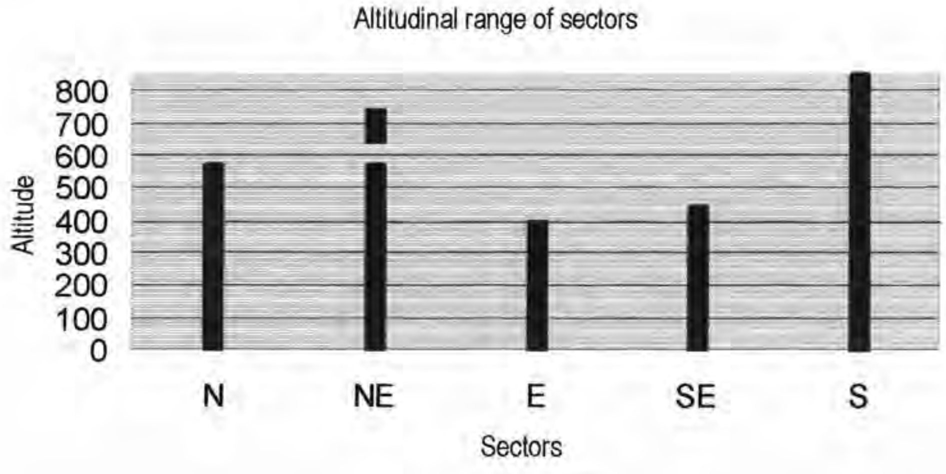

Figure 6.1: Altitudinal range of each sector in metres above sea level

6.1.1 Northern sector

The altitudinal range of the northern sector ranges from 0 to 550m a.s.l. and constitutes Long Ridge North and Long Ridge South (Fig. 6.1). It is clear that a definite altitudinal trend for the northern sector exist (Fig. 6.2), with the smaller features distributed through the whole altitudinal range, but the larger features are only present at higher altitude. Patterned ground features are distributed unevenly through the altitudinal range, and a gap exists between 200m a.s.l. and 400m a.s.l. for sorted stripes, and between 350m and 450m a.s.l. for polygons. A possible reason for the above observation could be that the type of surface materials is not conducive for patterned ground formation.

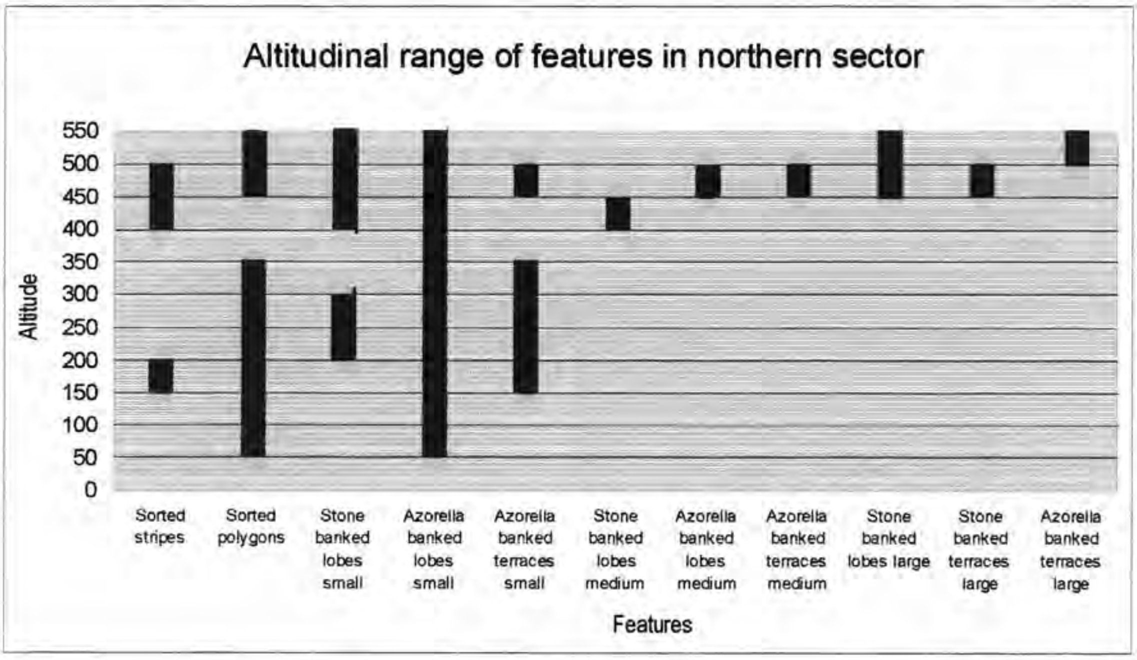

Figure 6.2: Altitudinal range of features in northern sector (LRN, LRS)

No other sector that has been studied shows this pronounced altitudinal trend with regards to size of features. This highlights the importance of Long Ridge as a study area for Holocenic periglacial studies, (e.g. Holness & Boelhouwers, 1998).

6.1.2 North-eastern sector

The north-eastern sector ranges from the coast to 100m a.s.l., 150m to 500m a.s.l. and 700m to 800m a.s.l. (Fig. 6.1). The altitudinal trend is not pronounced in this sector (Fig. 6.3) due to the nature of the area. The coastal area has low slope angles and most of the area is covered in thick vegetation and mires. At high altitudes no vegetation exist, therefore, *Azorella* banked features at high altitude are non-existent.

Another reason for the lack of a clear altitudinal trend, is the high frequency of bedrock-associated lobes. As discussed earlier, bedrock associated lobes tend to be bigger than the lobes adjacent to them, due to the increased availability of material; this explains the fact that medium sized lobes do occur at lower altitude (200m and 275m a.s.l.) and large stone banked lobes with riser heights greater than 1.5m between 300m and 350m a.s.l. Patterned ground is prominent throughout the whole altitudinal range.

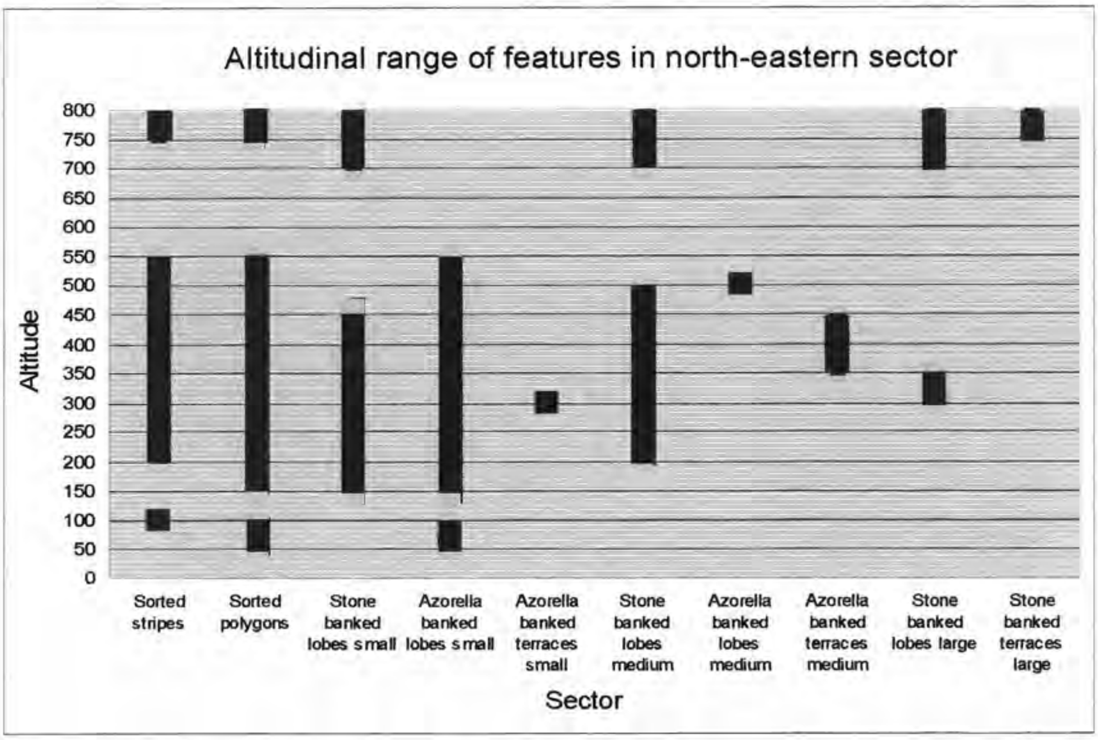

Figure 6.3: Altitudinal range of features in north-eastern sector (Skua Ridge, Tafelberg, Katedraal)

6.1.3 Eastern sector

The eastern sector constitutes Macaroni Bay and Piew Crags and ranges from the coast to 100m a.s.l. and 250m to 400m a.s.l. (Fig. 6.1). The altitudinal trend with respect to periglacial features is also pronounced in this sector with a clear increase in altitude with feature size (Fig. 6.4). Small *Azorella* banked lobes occur through the whole range, but medium and larger features only at higher altitudes. With regards to patterned ground sorted polygons dominate at all altitudes and sorted stripes only occur in a small patch at 400m a.s.l.

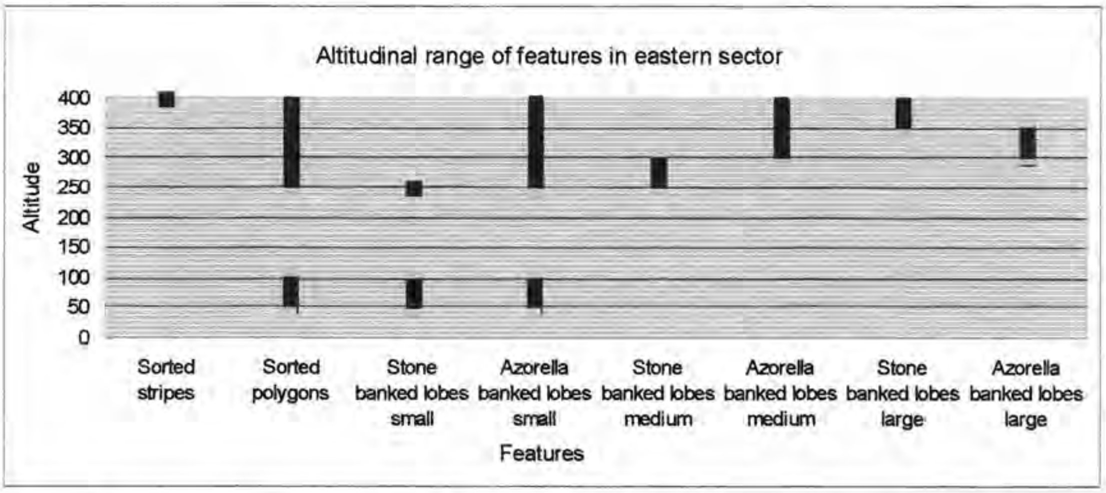

Figure 6.4: Altitudinal range of features in eastern sector (Macaroni Bay, Piew crags)

6.1.4 South-eastern sector

The south-eastern sector of Marion Island constitutes Kergeulen Rise, Kildalkey Bay and Fred's and Tate's and ranges from the coast to 425m a.s.l. (Fig. 6.1). Small features exist throughout the whole altitudinal range and the altitudinal trend with respect to feature size for this sector would have been distinct if not for the occurrence of medium and large features between 150m and 200m a.s.l. (Fig. 6.5) Reasons for the occurrence of these features are discussed later in this Chapter.

The medium stone banked lobes that occur at an altitude of approximately 150m a.s.l. is due to higher local slope angles at those specific sites. The large stone-banked lobes with riser heights just over 1m at approximately 200m a.s.l. on Kergeulen Rise, are bedrock associated and also on the colder south-facing slope. Large stone-banked lobes with riser heights just of over 1m are present at approximately 175m a.s.l on the south-facing slope of Stoney Ridge are difficult to explain, because these lobes are not bedrock associated. However, the local slope on which these lobes occur are steeper than the average slope angle for that particular area and together with the fact that these lobes are on the colder south-facing slope, could explain the uncommon large riser heights for that low altitude (see section on slope aspect for further explanation of this and alternate hypothesis). Sorted stripes and polygons are distributed throughout the whole altitudinal range and are situated predominantly on the crest lines of the ridges.

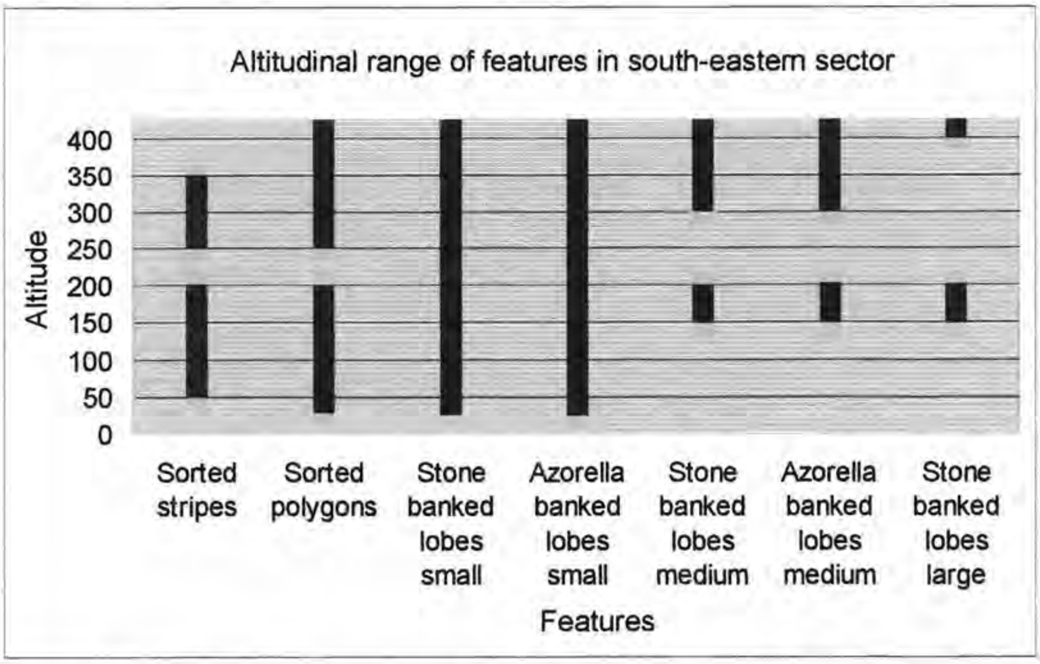

Figure 6.5: Altitudinal range of features in south-eastern sector (Kergeulen Rise, Kildalkey Bay, Fred's and Tate's)

6.1.5 Southern sector

The southern sector of Marion Island constitutes Johnny's Hill to Karookop and the whole of the Feldmark Plateau, and this sector ranges from the coast to 850m a.s.l (Fig. 6.1).

This sector has the highest altitudinal gain as well as range of all sectors in this study. One can expect a situation where a whole range of different size of periglacial features is present as well as a definite altitudinal trend. Small stone-banked lobes and Azorella banked lobes are predominant from a 100m a.s.l. to an altitude of 550m a.s.l. Medium sized stone-banked lobes are however present at a lower altitude (200m a.s.l.), than at any other sector. This is also the case for large stone-banked and *Azorella*-banked lobes where the minimum altitude of occurrence is lower than anywhere else on Marion Island. Also, most of the large features have riser heights in excess of 2m and they are horizontally extensive. Two of the terraces found in this area have riser heights of approximately 4m and 5m respectively. Patterned ground is also common on the Feldmark Plateau. Some of the largest sorted polygons and stripes that have been mapped can be found in this area.

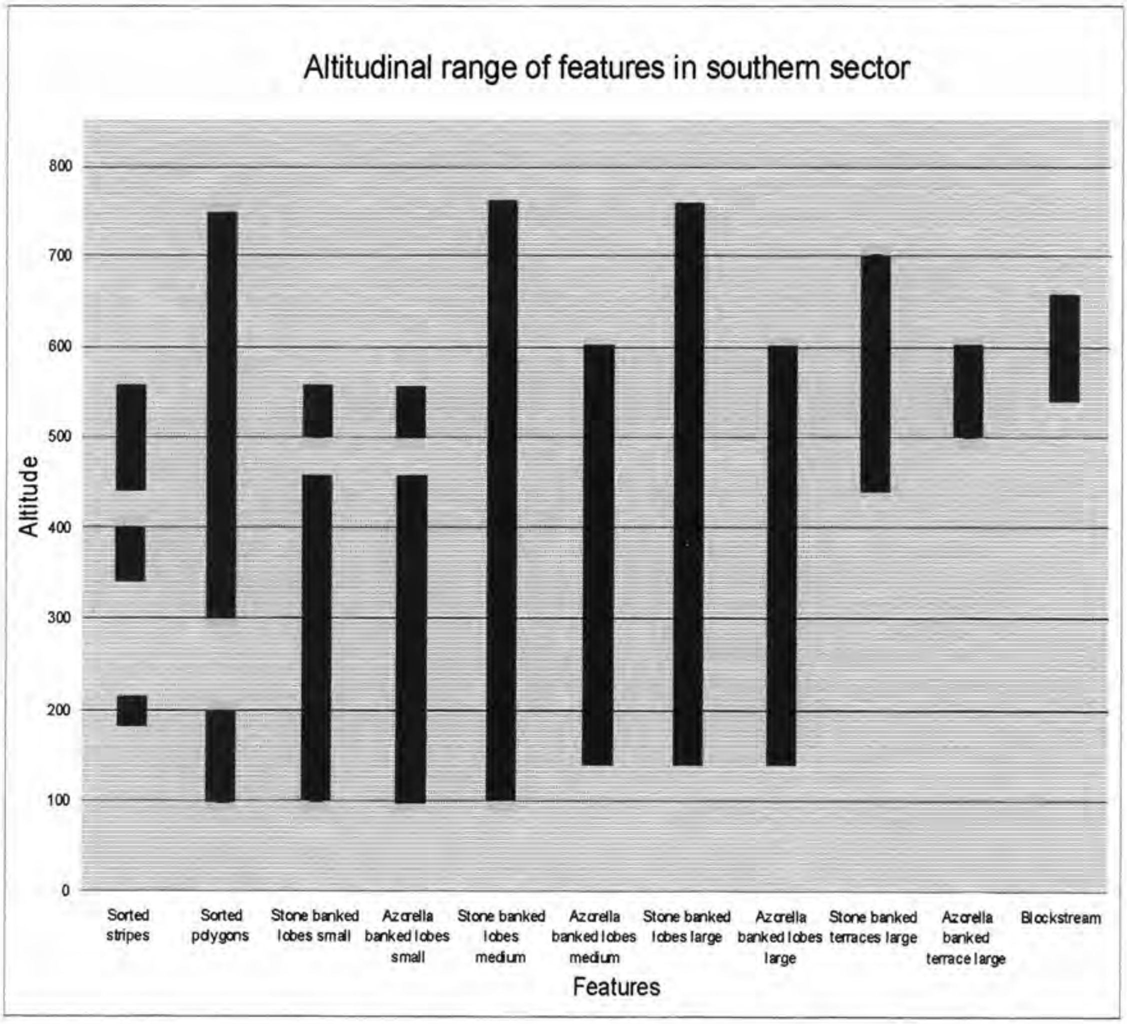

Figure 6.6: Altitudinal range of features in southern sector (Feldmark Plateau, Johnny's to Karookop)

The southern sector of Marion Island is unique with respect to periglacial features. Nowhere else on the grey lava area that has been mapped are there features of such magnitude as those found here. None of the large lobes and terraces in this area are bedrock associated, but the riser heights of most of them are in excess of 2m, and some stone-banked lobes have riser heights of approximately 6m. These features are prevalent at approximately 550m a.s.l to 750m a.s.l. Medium sized stone-banked lobes are present at a lower altitude than anywhere else on the island, therefore, the lower altitudinal limit for medium sized features (200m a.s.l) (Fig. 6.6), are also the lowest for all the sectors. It should however be noted that 750m a.s.l demarcates the upper limit of the periglacial features due to high slope angles and extensive screes above this altitude.

6.2 Discussion

Azorella and stone-banked terraces and *Azorella* banked lobes are not common on Marion Island. It must be noted that *Azorella* banked features do not occur above 600m a.s.l as conditions above this altitude become unfavourable for this type of vegetation. Although not all sectors have grey lava sites up to high altitude, some patterns emerge. First, active patterned ground forms and small lobes and terraces occur at most altitudes on the island. Sorted stripes and stone-banked lobes minimum altitudes increase somewhat from 50 to 200m a.s.l. from a southern to northern direction on the island (Boelhouwers *et al.*, 2001). No upper boundary of active forms appears to exist other than imposed by grey lava outcrops.

Medium lobes and terraces occur above 200m a.s.l in the south-eastern quadrant of the island but minimum altitudes increase to above 450m a.s.l in the north-eastern quadrant. A similar trend exists for large *Azorella* and stone banked lobes. This consistent variation in minimum altitudes may point at somewhat cooler conditions on the southern and south-eastern slopes of the island, relative to its north-eastern sector (Boelhouwers *et al.*, 2001). No ground climate records exist to test this hypothesis. Interpretation of the relict forms in terms of palaeoclimatic significance is discussed in Chapter 6 and Holness and Boelhouwers (1998).

Some large stone-banked lobes with riser heights just over 1m are present at approximately 175m a.s.l on the south-facing slope of Stoney Ridge and some stone banked lobes with riser heights of just over 1m are present at approximately 200m a.s.l on the south-facing slope of the southern ridge on Kergeulen Rise North. Although these lobes are on the colder south-facing slope, the local slope on which these lobes reside are steeper than the average slope angle for the surrounding slopes. It was found that the influence of slope aspect alone on the size of the periglacial features on Marion Island is limited (see section 6.4), but slope aspects can have a possible influence on the size of the features if it coexist with other influencing factors like bedrock association and/or steeper local slope. These large landforms at low altitude suggest an alternative hypothesis where slopes were not glaciated and that these large forms may be simply relict and reminiscent of former more severe environment. However, this is not the case, for these landforms are superimposed on moraines identified by Hall (1978). The material in the lobate forms therefore is of glacial origin, and post dates the last glacial stage. (Hall, 1978) suggest the occurrence of seasonal freezing in low altitude areas of Marion Island, with a sea level temperature depression of 4 to 5.5°C for the Late Pleistocene. However, stone-banked lobes identified at

Albatross Lakes (50m a.s.l.) (Boelhouwers *et al.,* 2001) on an end moraine dating from between 17-15kBP and 12kBP as well as the other large features at low altitude, could suggest a greater temperature depression for the Last Glacial than has previously been proposed.

As mentioned previously the periglacial features on the Feldmark Plateau are also distinctly different from the features on other areas of the same altitudinal range. The lobes and terraces have riser heights between 2 and 4m and that is twice and sometimes three times the size of features in other sectors at the same altitude, and the magnitude of the patterned ground is also extensive. Possible reasons for this could be that the Feldmark Plateau was not glaciated in the Pleistocene (see section 5.3), and these features could develop under a very cold, but ice-free environment. However, it should be noted that all slopes of the Feldmark Plateau are south facing and thus receive less insolation than north-facing slopes. In addition, the slopes occupy the southern sector of the island, which may further suggest cooler conditions (Boelhouwers *et al.*, 2001). These two factors could contribute to the large relative magnitude of both active and relict periglacial forms found in this area. But as mentioned in Chapter 5 further research has to be done to investigate this issue.

The increase in periglacial activity with altitude clearly points to an increase in frequency and/or intensity of frost induced processes with altitude (Holness & Boelhouwers, 1998). Therefore relict landforms have clear palaeoclimatic indicators, which are further discussed below.

6.3 Relict periglacial landforms and their implications

Relict stone-banked lobes appeared to be the most widespread relict slow mass movement landforms present on Marion Island, and were identified at all the study sites examined. Significant spatial and altitudinal variation in terrace morphology occurred, with generally smaller features occurring at low altitude (<300m a.s.l.) and larger features at high altitude (>300m a.s.l.) and vegetation growth on openwork risers suggests that the features are stable under present conditions (Boelhouwers *et al.*, 2001). Stone-banked terraces are less widely distributed than stone-banked lobes, with terraces being either absent or less numerous than stone-banked lobes at the majority of the study sites. Stone-banked terraces appeared to be best developed on low slope angles, with terraces on 6-11° slopes showing the greatest terrace lengths and highest risers (Boelhouwers *et al.*, 2001). As with stone-banked lobes, no active downslope movement of terrace risers appears to be occurring under present conditions, though terrace treads are affected by surficial present day soil frost activity (Boelhouwers *et al.*, 2001). Few *Azorella*-banked terraces were identified in this study, with terraces only being identified in the northern (475m a.s.l, 525m a.s.l), north-eastern (300m a.s.l, 400m a.s.l, 450m a.s.l) and southern (500m a.s.l) sectors.

A clear altitudinal trend exists with regards to *Azorella*-banked terraces, with the larger terraces located at higher altitudes. Relict blockstreams are present at a number of middle to high altitude sites such as Bill Briggs on Long Ridge North, Long Ridge South and Beret Grey on the Feldmark Plateau (Holness and Boelhouwers, 1998; Boelhouwers *et al.*, 2001). It is suggested by Boelhouwers *et al.* (2001) that the blockstreams were formed by the downslope movement of a diamict by solifluction under conditions of deep seasonal freezing, with the subsequent eluviation of fines.

The conditions required for the formation of the relict landforms on Marion Island, have significant palaeoenvironmental implications. Relict stone-banked lobes, stone-banked terraces, vegetation-banked lobes and blockstreams identified in this study cannot be explained by present day soil frost activity (Boelhouwers *et al.*, 2001). These features indicate and confirm conclusions from previous studies (Hall, 1981; 1983a; Holness and Boelhouwers, 1988) that Marion Island experienced a more severe periglacial environment than under present conditions.

The large relict periglacial features identified on the island suggest the occurrence of seasonal freezing throughout much of the island, with high altitude areas experiencing deep seasonal freezing and Mean Annual Air Temperatures of 0°C or below (Boelhouwers *et al.*, 2001). The occurrence of relict slow mass wasting landforms in previously glaciated areas such as Tafelberg, Stony Ridge and Long Ridge North, indicate a period of more intensive periglacial activity during the early Holocene and comparisons with other palaeoenvironmental data sources suggest that this period of intensive periglacial activity lasted from 12kPB until 7kBP (Boelhouwers *et al.*, 2001). These observations confirm previous suggestions of a post-glacial period of intense periglacial activity made by Hall (1981, 1983a) and Holness and Boelhouwers (1998).

6.4 Slope aspect of periglacial features

In addition to the altitudinal distribution of features, landforms were also analysed on distribution by slope aspect in the various sectors. Figure 6.7 depicts the distribution of features with regards to slope aspect for each sector in three altitudinal belts; 100m –300m a.s.l, 400m –500m a.s.l and 600m –800m a.s.l.

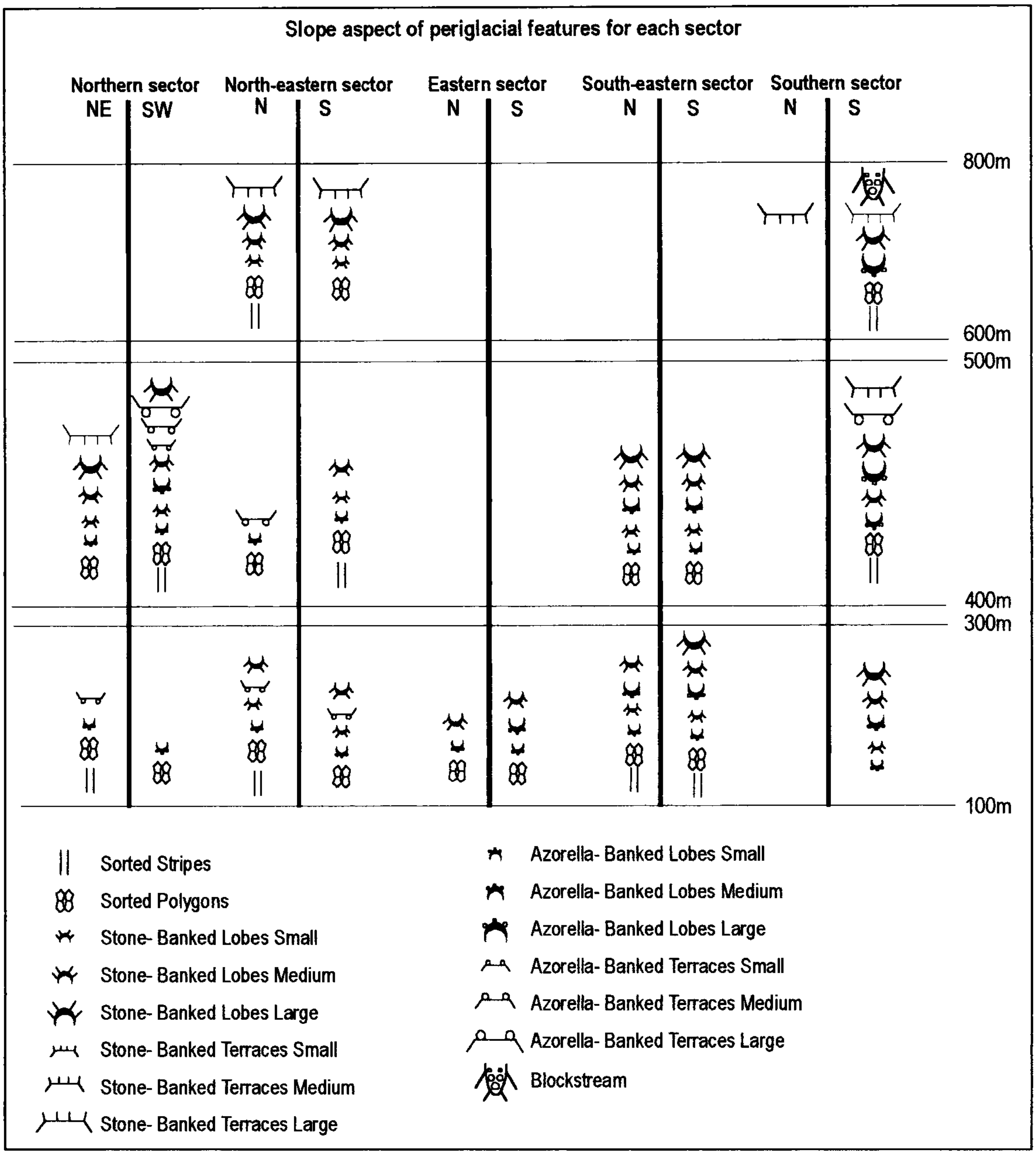

Figure 6.7: Slope aspect of periglacial features for each sector

No major difference, with respect to the size of periglacial features at all altitudes, can be discerned between the colder south and warmer north facing slopes. However, some impressions on the influence of slope aspect are noted. The topography of the Feldmark Plateau is such that all the slopes are south facing except between 600m and 800m a.s.l where some north facing local slopes exists, therefore no comparative data can be extrapolated from that sector. As mentioned before, however, the magnitude of the features in this sector is greater than in any other sector and it is possible that slope aspect does indeed play a role. Some large stone-banked lobes with riser heights just over 1m are present at approximately 200m a.s.l on the south-facing slope of the south-eastern sector. Although these lobes occur only on the colder south-facing slope they are bedrock associated with the lobe consisting of broken bedrock material and this feature as well as the other large features at low altitude could suggest a greater temperature depression for the Last Glacial than has previously been proposed.

This study has found that no significant differences appear to exist between the warmer north-facing and colder south-facing slopes with regards to the size distribution of periglacial features on Marion Island. The relative low insolation on Marion Island and high cloudiness (6 oktas) (Schulze, 1971) limits the effect that slope aspect has on the formation, and size of periglacial features.

CHAPTER 7: RAPID MASS MOVEMENT FEATURES

As mentioned before rapid mass movement features in the form of screes and peat slides are common on Marion Island. Screes are predominantly in grey lava areas, where recent glacial activity has left oversteepend slopes and loose glacial debris (Nel, 2000), both of which are conducive to the development of screes (French, 1996). Peat slides that were mapped and commonly present on Marion Island are translational, with the primary failure occurring in vegetated peaty soil. Very little research however, has been undertaken on rapid mass movement features on Marion Island. Some research has been conducted on the characteristics of small debris flows (Boelhouwers *et al*, 1999) but no maps or an inventory exists that describes the spatial distribution of rapid mass wasting landforms. Rapid mass movement features are described in this study, with respect to their spatial distribution, slope aspect and possible palaeoclimatic implications

7.1 Spatial distribution and slope aspect of peat slides

Peat slides occur in all the sectors in middle and low altitudinal areas in the altitudinal range of between 150m a.s.l and 450m a.s.l (Table 7.1) where thick soil and steeper slopes are present. This does not include the feldmark environments where peat slides do not occur. The lower limit for peat slides seems to be 150m a.s.l, and the upper 550m a.s.l (Table 7.1). Coastal areas are normally flat; therefore no peat slides exist below 150m a.s.l and above 550m a.s.l only feldmark type vegetation exist, therefore no peat slides occur above this altitude.

Table 7.1: Summary of altitudinal range and slope aspect of peat slides on eastern side of Marion Island

Study site	**Altitudinal range**	**Sector**	**Min altitude**	**Max altitude**	**Slope aspect**
Long Ridge North	0-400m	N	150	400	NE AND SW facing
Long Ridge South	400-550m	N	400	450	NE AND SW facing
Tafelberg	150-550m	NE	400	400	South facing
Piew crags	250-400m	E	350	350	North facing
Stoney Ridge	0-200m	SE	150	200	North facing
Johnny's to Karookop	200-500m	S	450	450	North facing
Feldmark Plateau	0-600m	S	550	550	North facing

On Marion Island major ridgelines extending east to west exist, and peat slides predominantly occur on the north facing slopes of these ridges, except at Tafelberg (Table 7.1). However, the Tafelberg peat slide as mentioned before occurred after heavy rainfall in the beginning of January 2000. It is also situated at a spring, which was the probable cause of the slide. On Long Ridge peat slides occur on both sides of the ridge, but the peat slides on the north-west facing slopes are more extensive.

7.1.1 Discussion

The slope angle of the north facing slopes is higher than the south facing slopes and this together with possibly thicker vegetation and soil cover, could be the reason for the north facing preference. The distribution of peat slides (150 – 450m a.s.l) appears mostly controlled by the presence of steep slopes with sufficient material for failure. As all peat slides are associated with peaty soil, an upper altitudinal limit of 600m a.s.l exists. Selkirk (1996) attributes the occurrence of peat slides on Macquarie Island to gradual build up of organic slope materials up to point of failure. Peat slide failure mechanisms on Marion appear similar and further analysis is much warranted, but falls outside the scope of this project.

7.2 Spatial distribution of screes

Screes are the term given for debris accumulations on steep slopes on Marion Island that are of apparent rockfall origin and are superimposed on the slope material. Downslope movement after the initial fall of clasts, in most of the scree accumulations, is over finer material. Soil below two of the screes on the south-facing slopes on Long Ridge is not needle ice susceptible under present day conditions (Nel, 2000), but could have been under a colder climate.

Screes are found on slopes with angles of between 20° and 40°, and the scree shows no preferred orientation (Table 7.2). The location, orientation and distribution of this rapid mass movement feature is only due to the morphology of the slope and the scree accumulation development and the length of the scree is directly related to the amount of material available for debris production and, therefore, to the height of the cliffs above the slopes (Table 7.2). However, some cliff faces in certain part of the Feldmark and Long Ridge areas are not high, but the debris below it is extensive (Table 7.2). Even though other factors like rock mass strength, joint density and slope length can also play a role in scree production and morphology; the cliffs that can be seen now, could be the remnants of the high cliffs that must have been present earlier in the Holocene or Late Pleistocene.

Table 7.2: Summary of a number of screes on the eastern side of Marion Island

Area	Altitude	Slope length (m)	Orientation	Slope angle	Scree length (m)	Scree width (m)	Cliff height
Long Ridge	400m	83	S	35	83	11.3	<5m
Long Ridge	425m	83	SE	40	46	11.4	<5m
Long Ridge	430m	101.6	SE	40	91	13.8	5-10m
Long Ridge	475m	65	NW	32	65	18	>15m
Long Ridge	480m	55	NW	35	55	20.4	>15m
Long Ridge	490m	55	NW	30	55	13	>15m
Long Ridge	500m	50	NW	30	35	13	>15m
Long Ridge	500m	58	NW	30	58	7.5	10-15m
Katedraal	730m	66	N	35	66	250	>25m
Katedraal	755m	6.3	S	25	6.3	7.9	<5m
Katedraal	760m	9.5	S	20	9.5	12	<5m
Katedraal	765m	8.4	S	20	8.4	9	5-10m
Katedraal	770m	13	S	45	13	13.5	10-15m
Katedraal	775m	20	S	35	20	15	5-10m
Piew Crags	350m	50.5	N	40	40	20.1	<5m
Piew Crags	360m	34.7	N	20	25.7	15.8	<5m
Piew Crags	365m	52.2	N	25	52.2	23	5-10m
Feldmark	400m	195	E	35	160	11.9	10-15m
Feldmark	400m	215	E	33	180	8.7	10-15m
Feldmark	400m	270	W	40	270	36	>15m
Feldmark	400m	290	W	40	290	43	10-15m
Feldmark	420m	266	W	35	266	55	>15m
Feldmark	425m	305	W	35	305	40.5	>15m
Feldmark	450m	286	W	30	286	55	>15m

Lichen cover on the larger clasts in the scree also suggest that the scree accumulations are inactive under present day conditions, although some scree from the cliffs are still added to the slope, the rate of accumulation is slower and the size of the fresh material much smaller than the relict clasts.

7.3 Palaeoclimatic implications

Observations from this study produced possible evidence that major scree production occurred during the period of more intensive periglacial activity during the early Holocene lasting from 12kPB until 7kBP. These observations confirm previous suggestions of a post-glacial period of intense periglacial activity made by Hall (1981, 1983a), Holness and Boelhouwers (1998) and Boelhouwers *et al*, (2001). Downslope movement of the clasts were probably over finer material and when climatic conditions became warmer and unfavourable for intense frost action, downslope movement stopped, and the fine material were washed away. Screes are mostly found in areas with high free faces, which is part of the major faults (Hall, 1978; 1980a) and the extent of the screes can be related to the morphology of the cliffs above. However some cliff faces are not high, but the scree below it is quite extensive, and thus the cliffs that can be seen now, could be the remnants of the high cliffs that must have been present earlier during the Late Pleistocene just after the last glacial event.

In the Feldmark Plateau area scree production was intense especially on the slopes overlooking Santa Rosa Valley and Watertunnel Valley (Appendix B: Fig. 34, Table 7.2). Nowhere else on the island is there so much scree overlying the slopes, as in this area. If the hypothesis holds true that intense scree production during the early Holocene lasting from 12kPB until 7kBP, than this is manifested in the scree on the slopes of the Feldmark. Therefore during this period of more intensive scree production the Feldmark Plateau area must have been ice-free. After glaciation, oversteepend slopes are also conducive to intense scree production. It can, therefore, be concluded that the Feldmark Plateau, if glaciated, (see Chapters 5 and 6) became ice-free very rapidly after glaciation, so that the intense periglacial activity, plus the oversteepend slopes left by the glacial activity, produced large amount of scree from the cliffs.

The processes causing peat slides on Marion Island took place after these events during the Late Holocene when conditions like the gradual build up of organic slope materials up to point of failure became favourable for sliding. Therefore peat sliding is the only active rapid mass movement process on Marion Island. Although the grey lava cliffs are still producing some scree debris, the rate of accumulation is slow and the size of the fresh material small.

CHAPTER 8: CONCLUSION

The glacial survey on Marion Island largely supports the interpretations made by Hall (1978). All glacial moraines, glacially polished and striated bedrock surfaces were verified and some new sites with striated surfaces were added. In addition to Hall's work, Boelhouwers *et al.*, (2001) identified a glacial cirque at Snok (550m a.s.l) with a well-developed end moraine, not previously recognised. This feature is suggested to have been active until the mid-Holocene (7k BP) when final deglaciation took place.

Periglacial landforms occur on all the grey lava areas that were mapped. The features are present throughout the whole altitudinal range, and a definite trend can be discerned. The features on coastal grey lava areas are uniform and predominantly small (riser height < 50 cm) lobes and micro patterned ground. At approximately 350m a.s.l medium sized lobes (riser height between 50cm and 1m) do emerge. Large lobes (riser height>1m) also occur frequently from about 400m a.s.l Medium lobes and terraces occur above 200m a.s.l in the south-eastern quadrant of the island but minimum altitudes increase to above 450m a.s.l in the north-eastern quadrant. A similar trend exists for large *Azorella* and stone banked lobes. This consistent variation in minimum altitudes may point towards somewhat cooler conditions on the southern and south-eastern slopes of the island relative to its north-eastern sector (Boelhouwers *et al.*, 2001). No ground climate records exist to test this hypothesis.

The increase in periglacial activity with altitude clearly points to an increase in frequency and/or intensity of frost induced processes with altitude (Holness & Boelhouwers, 1998). The conditions required for the formation of the relict landforms on Marion Island, have significant palaeoenvironmental implications. Relict stone-banked lobes, stone-banked terraces, vegetation-banked lobes and blockstreams identified in this study cannot be explained by present day soil frost activity (Boelhouwers *et al*, 2001). These features indicate and confirm conclusions from previous studies (Hall, 1981; 1983a; Holness and Boelhouwers, 1988) that Marion Island experienced a more severe periglacial environment than present. The large relict periglacial features identified on the island suggest the occurrence of seasonal freezing throughout much of the island, with high altitude areas experiencing deep seasonal freezing and Mean Annual Air Temperatures of 0°C or below (Boelhouwers *et al.*, 2001). The occurrence of relict slow mass wasting landforms in previously glaciated areas such as Tafelberg, Stony Ridge and Long Ridge North, indicate a period of more intensive periglacial activity during the early Holocene and comparisons with other palaeoenvironmental data sources suggest that this period of intensive periglacial activity lasted from 12kPB until 7kBP (Boelhouwers *et al.*, 2001). These observations confirm previous suggestions of a post-glacial period of intense periglacial activity made by Hall (1981, 1983a) and Holness and Boelhouwers (1998). (Hall, 1978) suggest the occurrence of seasonal freezing in low altitude areas of Marion Island, with a sea level temperature depression of 4 to 5.5°C below present, for the Late Pleistocene. However stone-banked lobes identified on an end moraine dating from between 17-15kBP and 12kBP (Boelhouwers et al., 2001) as well as other large features at low altitude could suggest a greater temperature depression for the Last Glacial than has previously been proposed.

Holness and Boelhouwers (1998) in their study of the periglacial features on Long ridge found that bedrock-associated stone-banked lobes have large very blocky fronts and are larger than those lobes not immediately associated with rocky outcrops. The periglacial survey of the eastern side of Marion Island supports this interpretation. It was observed that bedrock-associated stone-banked lobes, due to the readily availability of materials, tend to be larger than the features in the vicinity.

This study has found that no significant differences appear to exist between the warmer north-facing and colder south facing slopes with regards to the size distribution of periglacial features on Marion Island. The relative low insolation on Marion Island and high cloud cover (6 oktas) (Schulze, 1971) limits the effect that slope aspect has on the formation, and size of periglacial features. Some observations however, suggest that if features are on the south-facing slope, and other factors influencing size coexist, then this can collectively influence the size of periglacial features.

Rapid mass movement features are present in most grey lava areas, except where the area consists of long ridges with low slope angles and no cliffs. Screes are mostly found in areas with high free faces and the extent of the screes can be related to the morphology of the cliffs above. However, some cliff faces are not high, but the scree below it is quite extensive, and thus the cliffs that can be seen now could be the remnants of the high cliffs that must have been present earlier in the Holocene or Late Pleistocene.

Peat slides are common in middle and low altitudinal areas in the altitudinal range of between 150m a.s.l. and 450m a.s.l. where thick soil and steeper slopes are present. This does not include the feldmark environments where peat slides do not occur. Most of these peat slides predominantly occur on the north facing slopes of the major ridgelines as the slope angle of these slopes is higher than the south facing slopes and this together with vegetation and soil cover which are also thicker on these slopes, must be the reason for the north facing preference.

From this study it is concluded from observations that major scree production occurred during the period of more intensive periglacial activity during the early Holocene lasting from 12kPB until 7kBP. These observations confirm previous suggestions of a post-glacial period of intense periglacial activity made by Hall (1981, 1983a), Holness and Boelhouwers (1998) and Boelhouwers *et al*, (2001). Downslope movement of the clasts was probably over finer material and when climatic conditions became warmer and unfavourable for intense frost action, downslope movement stopped, and the fine material were washed away. Screes are mostly found in areas with high free faces, which is part of the major faults (Hall, 1978; 1980a) and the extent of the screes can be related to the morphology of the cliffs above.

Constructing the palaeoenvironmental situation, with regards to the glacial activity and the extent of the ice cover on certain areas on Marion Island, are problematic. In the area demarcated as Feldmark Plateau some morphological evidence exist that indicates that the ice cover in this region must have been extensive. Nevertheless no irrefutable proxy-evidence for glacial activity has been found in this area. Further more periglacial features in this area are relatively much larger than the same periglacial features in other sectors at the same altitude. Possible reasons for this could be that the Feldmark Plateau was not glaciated in the Pleistocene, and therefore these features could develop under a very cold, but ice-free environment. However, it should be noted that all slopes of the Feldmark Plateau are south facing and thus receive less insolation than north-facing slopes. In addition the slopes occupy the southern sector of the island, which may further add to cooler conditions (Boelhouwers *et al.*, 2001). These two factors could contribute to the large relative magnitude of both active and relict periglacial forms found in this area. Further, in the Feldmark Plateau area scree production were intense especially on the slopes overlooking Santa Rosa Valley and Watertunnel Valley. If the hypothesis holds true that intense scree production during the early Holocene lasting from 12kPB until 7kBP, than this is manifested in the scree on the slopes of the Feldmark. Therefore during this period of more intensive scree production the Feldmark Plateau area must have been ice-free. After glaciation, oversteepend slopes are also conducive to intense scree production. It can therefore be concluded that the Feldmark Plateau, if glaciated, became ice-free very rapidly after glaciation, so that the intense periglacial activity, plus the oversteepend slopes left by the glacial activity, produced large amount of scree from the cliffs.

But as mentioned previously further research has to be done to investigate this issue. It is therefore ineffectual to produce a conclusion on the extent of the ice cover in this area, with the evidence presented here. Further research is therefore much warranted, and will possibly aid in establishing the palaeoenvironment of the relevant areas in the Late Pleistocene early Holocene with some degree of certainty.

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10. APPENDIX

10.1 Appendix A: Summary and inventory of spatial distribution and altitudinal range of periglacial features on eastern side of Marion Island.

Study site	**Altitudinal range**	**Sector**	**Periglacial landforms present in area**	**Min altitude**	**Max altitude**
Long Ridge North	0-400m	N	Sorted stripes	150	200
			Sorted polygons	50	350
			Stone banked lobes small	200	300
			Azorella banked lobes small	50	400
			Azorella banked terraces small	150	350
Long Ridge South	400-550m	N	Sorted stripes	400	500
			Sorted polygons	450	550
			Stone banked lobes small	400	550
			Azorella banked lobes small	400	550
			Azorella banked terraces small	450	500
			Stone banked lobes medium	400	450
			Azorella banked lobes medium	450	500
			Azorella banked terraces medium	450	500
			Stone banked lobes large	450	550
			Stone banked terraces large	450	500

Study site	**Altitudinal range**	**Sector**	**Periglacial landforms present in area**	**Min altitude**	**Max altitude**
Long Ridge South	400-550m	N	Azorella banked terraces large	500	550
Skua Ridge	0-100m	NE	Sorted stripes	100	100
			Sorted polygons	50	100
			Azorella banked lobes small	50	100
Tafelberg	150-550m	NE	Sorted stripes	200	550
			Sorted polygons	150	550
			Stone banked lobes small	150	450
			Azorella banked lobes small	150	550
			Azorella banked terraces small	300	300
			Stone banked lobes medium	200	500
			Azorella banked lobes medium	500	500
			Azorella banked terraces medium	350	450
			Stone banked lobes large	300	350
Katedraalkrans	700-800m	NE	Sorted stripes	750	800
			Sorted polygons	750	800
			Stone banked lobes small	700	800
			Stone banked lobes medium	700	800
			Stone banked lobes large	700	800

Study site	**Altitudinal range**	**Sector**	**Periglacial landforms present in area**	**Min altitude**	**Max altitude**
Katedraalkrans	700-800m	NE	Stone banked terraces large	750	800
Macaroni Bay	0-100m	E	Sorted polygons	50	100
			Azorella banked lobes small	50	100
Piew crags	250-400m	E	Sorted stripes	400	400
			Sorted polygons	250	400
			Stone banked lobes small	250	250
			Azorella banked lobes small	250	400
			Stone banked lobes medium	250	300
			Azorella banked lobes medium	300	400
			Stone banked lobes large	350	400
			Azorella banked lobes large	300	350
Stoney Ridge	0-200m	SE	Sorted stripes	150	200
			Sorted polygons	100	200
			Stone banked lobes small	50	200
			Azorella banked lobes small	100	200
			Azorella banked lobes medium	150	200
			Stone banked lobes large	150	200

Study site	**Altitudinal range**	**Sector**	**Periglacial landforms present in area**	**Min altitude**	**Max altitude**
Kergeulen Rise North	0-200m	SE	Sorted stripes	50	200
			Sorted polygons	100	200
			Stone banked lobes small	25	200
			Azorella banked lobes small	25	200
			Stone banked lobes large	200	200
Kergeulen Rise South	0-250m	SE	Sorted stripes	200	200
			Sorted polygons	25	200
			Stone banked lobes small	25	250
			Azorella banked lobes small	25	250
			Stone banked lobes medium	150	200
			Azorella banked lobes medium	150	150
Fred's and Tate's	250-425m	SE	Sorted stripes	250	350
			Sorted polygons	250	425
			Stone banked lobes small	250	350
			Azorella banked lobes small	250	425
			Stone banked lobes medium	300	425
			Stone banked lobes large	400	425

Study site	Altitudinal range	Sector	Periglacial landforms present in area	Min altitude	Max altitude
Fred's and Tate's	250-425m	SE	Azorella banked lobes medium	300	425
Kergeulen Rise West	250-400m	SE	Sorted stripes	300	350
			Sorted polygons	300	400
			Stone banked lobes small	250	400
			Azorella banked lobes small	250	400
			Stone banked lobes medium	350	400
			Azorella banked lobes medium	350	400
			Stone banked lobes large	350	400
Kildalkey Bay	0-150m	SE	Sorted stripes	100	150
			Sorted polygons	50	150
			Stone banked lobes small	50	150
			Azorella banked lobes small	50	150
Johnny's to Karookop	200-500m	S	Sorted stripes	200	200
			Sorted polygons	300	500
			Stone banked lobes small	200	450
			Azorella banked lobes small	200	450
			Stone banked lobes medium	200	500
			Azorella banked lobes medium	450	500

Study site	**Altitudinal range**	**Sector**	**Periglacial landforms present in area**	**Min altitude**	**Max altitude**
Johnny's to Karookop	200-500m	S	Stone banked lobes large	350	500
			Azorella banked lobes large	500	500
			Stone banked terraces large	500	500
Feldmark Plateau East	0-600m	S	Sorted stripes	550	550
			Sorted polygons	600	600
			Stone banked lobes small	350	400
			Azorella banked lobes small	350	400
			Stone banked lobes medium	400	600
			Azorella banked lobes medium	400	600
			Stone banked lobes large	500	600
			Azorella banked lobes large	500	600
Feldmark Plateau South	0-600m	S	Sorted stripes	450	550
			Sorted polygons	400	600
			Stone banked lobes small	100	150
			Azorella banked lobes small	100	150
			Stone banked lobes medium	150	500
			Azorella banked lobes medium	150	500

Study site	Altitudinal range	Sector	Periglacial landforms present in area	Min altitude	Max altitude
Feldmark Plateau South	0-600m	S	Stone banked lobes large	150	500
			Azorella banked lobes large	150	500
			Stone banked terraces large	450	550
			Azorella banked terrace large	500	500
Feldmark Plateau North	400-850m	S	Sorted stripes	550	750
			Sorted polygons	550	750
			Stone banked lobes small	500	550
			Azorella banked lobes small	500	550
			Stone banked lobes medium	500	750
			Azorella banked lobes medium	500	550
			Stone banked lobes large	550	750
			Azorella banked lobes large	600	600
			Stone banked terraces large	550	700
			Azorella banked terrace large	600	600
			Blockstream	550	650
Sfinks	0-400m	S	Sorted stripes	350	400
			Stone banked lobes small	100	200

Study site	**Altitudinal range**	**Sector**	**Periglacial landforms present in area**	**Min altitude**	**Max altitude**
Sfinks	0-400m	S	Azorella banked lobes small	100	200
			Stone banked lobes medium	100	400
			Azorella banked lobes medium	100	400
			Stone banked lobes large	350	400
			Azorella banked lobes large	350	400

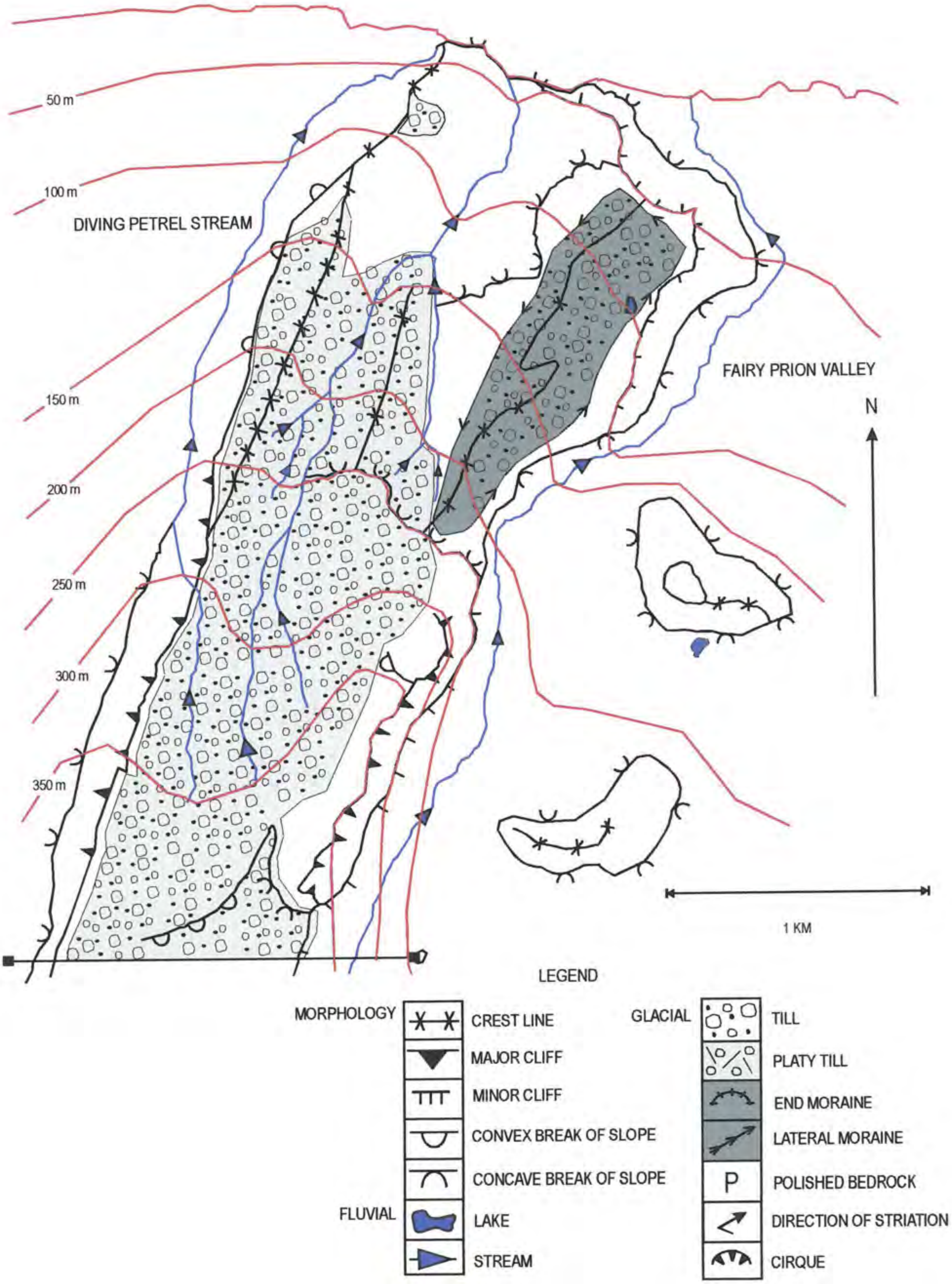

Figure 1: Long Ridge North Glacial Features

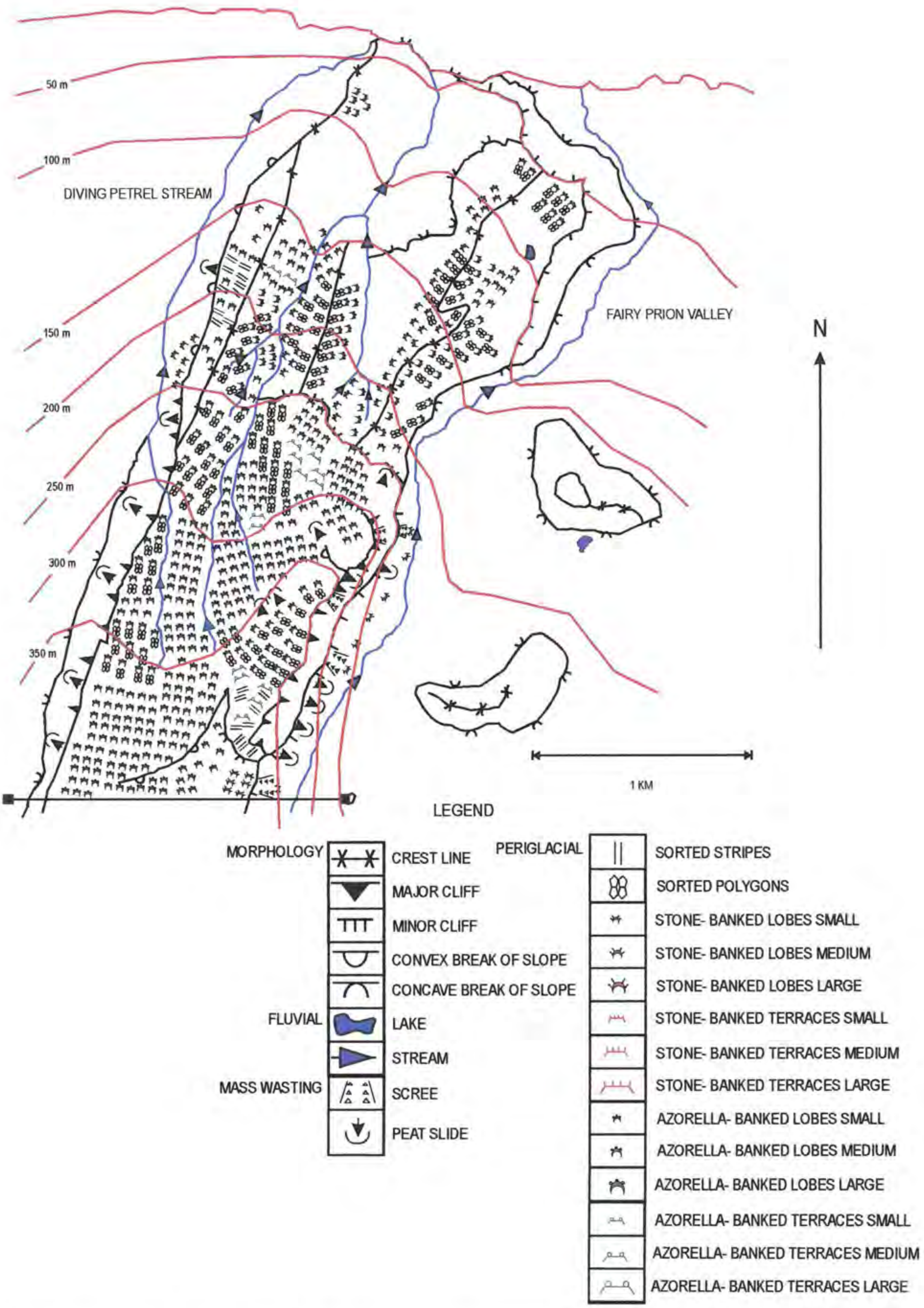

Figure 2: Long Ridge North Periglacial and Mass Movement Features

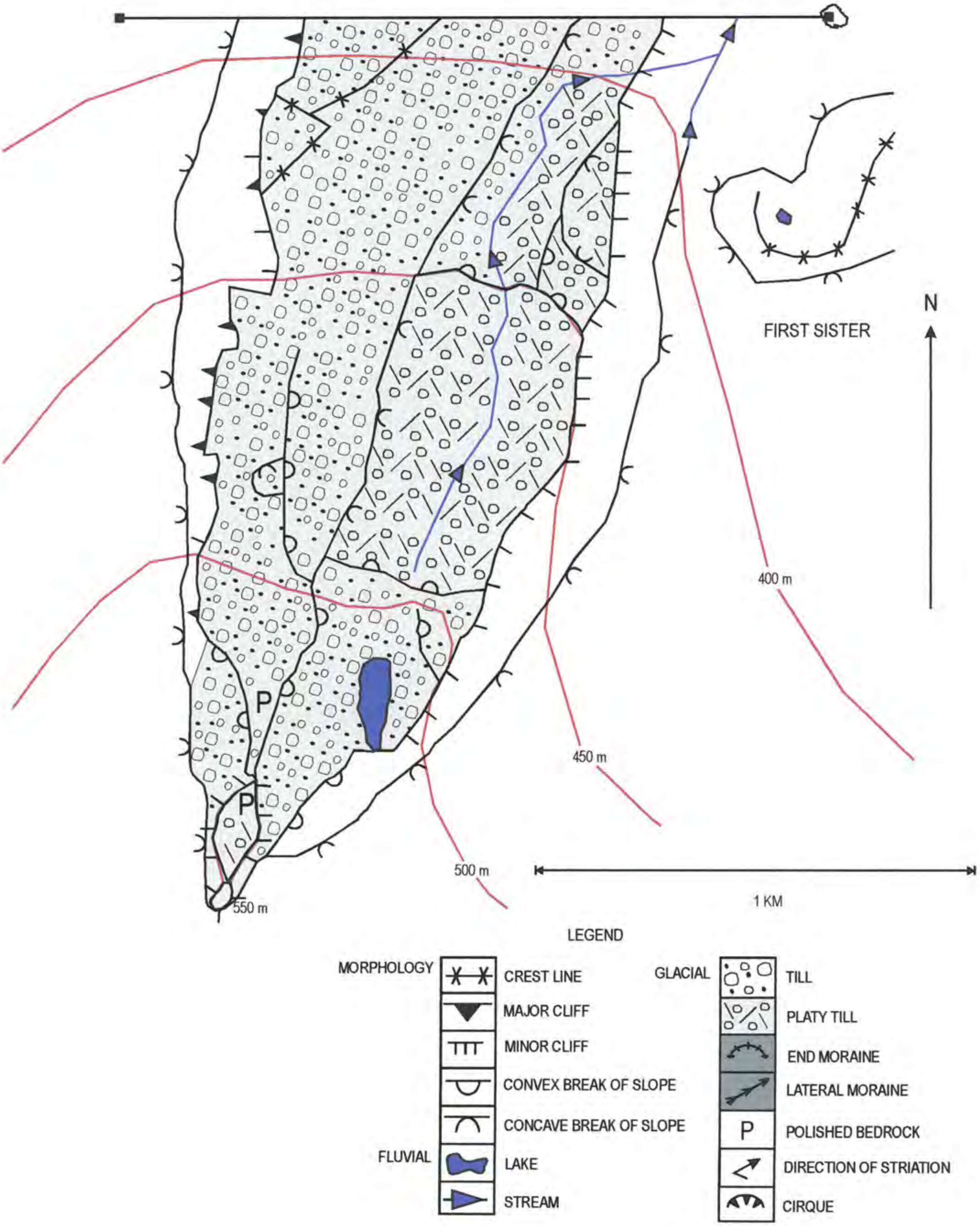

Figure 3: Long Ridge South Glacial Features

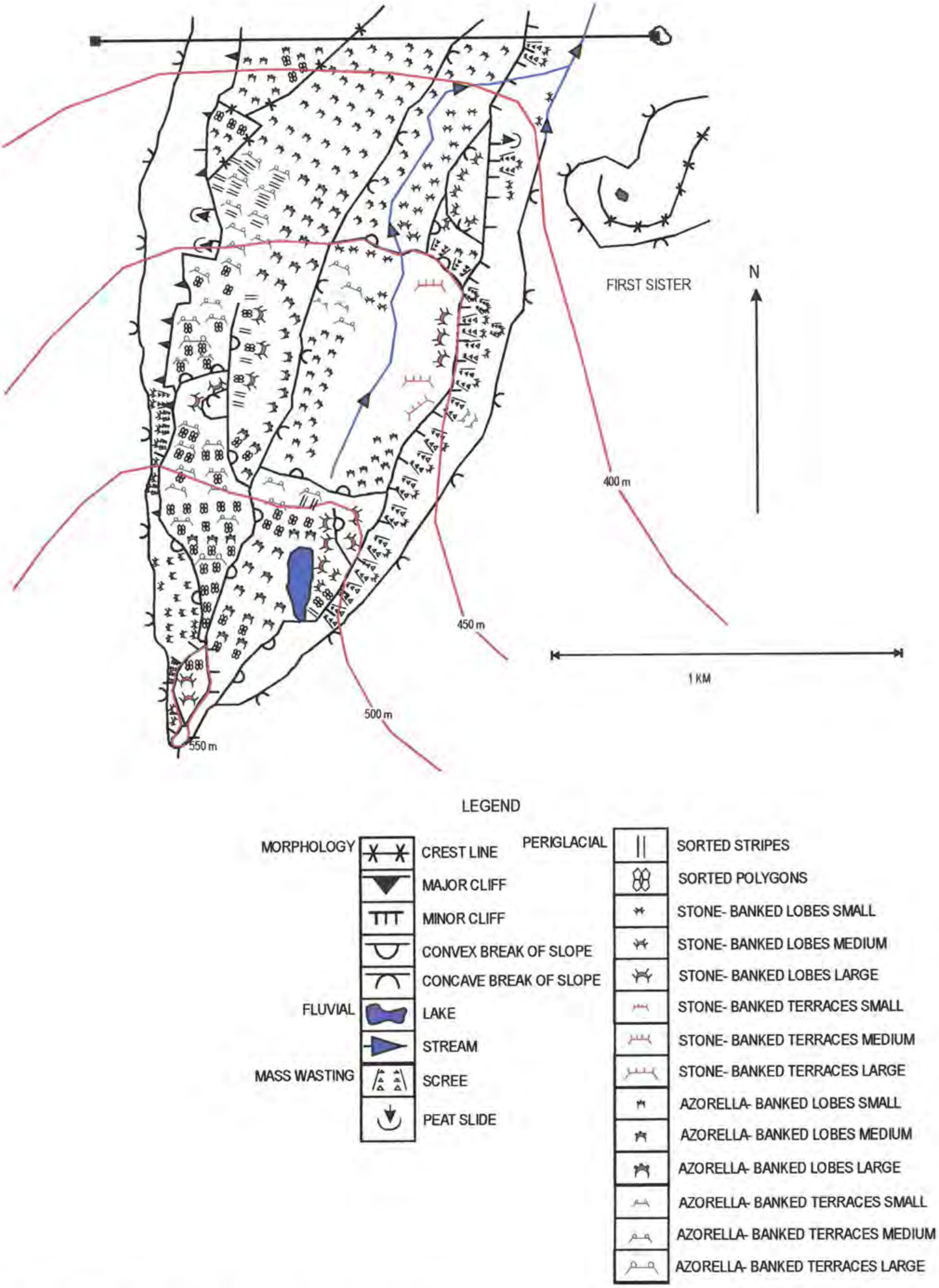

Figure 4: Long Ridge South Periglacial and Mass Movement Features

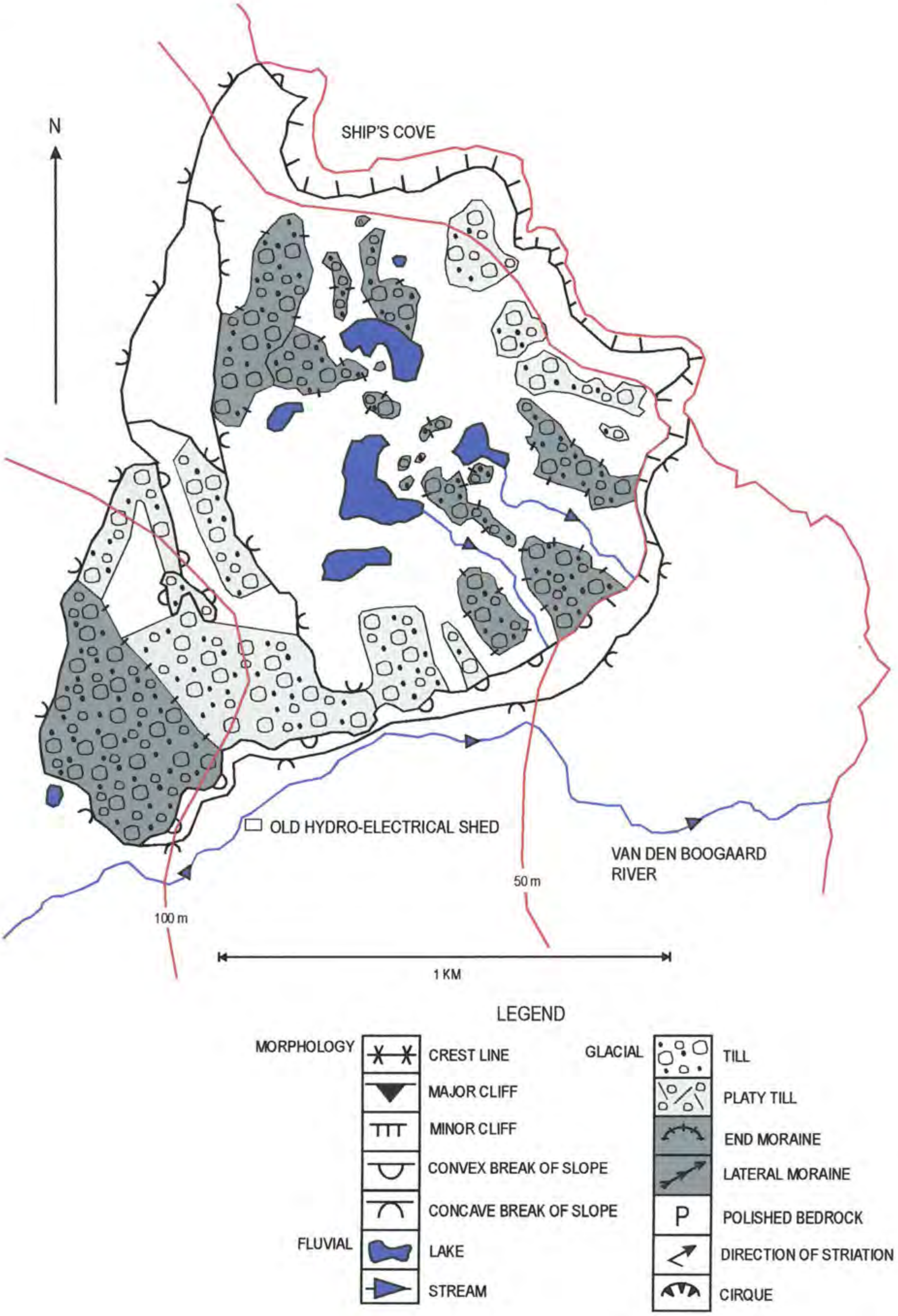

Figure 5: Skua Ridge Glacial Features

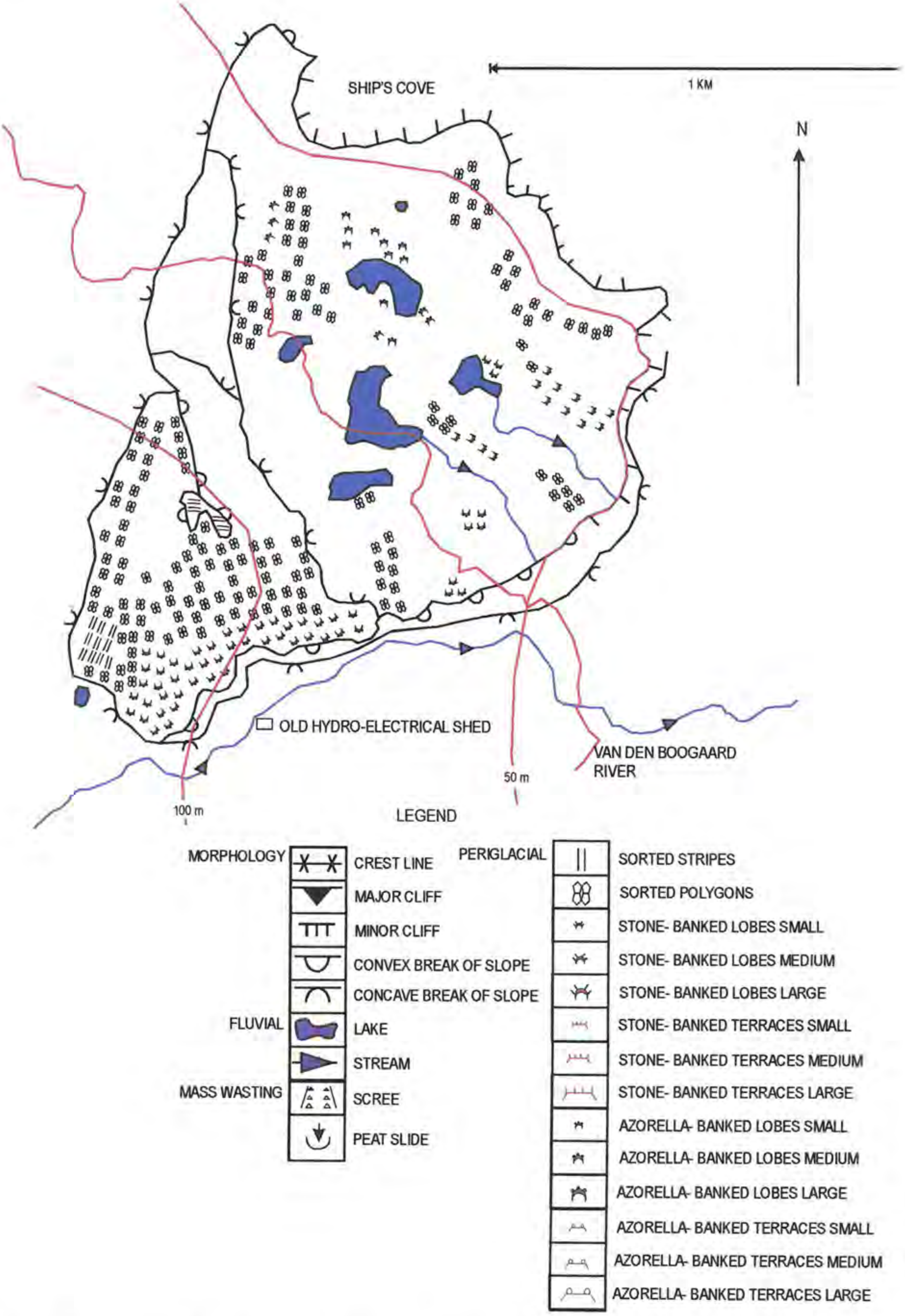

Figure 6: Skua Ridge Periglacial and Mass Movement Features

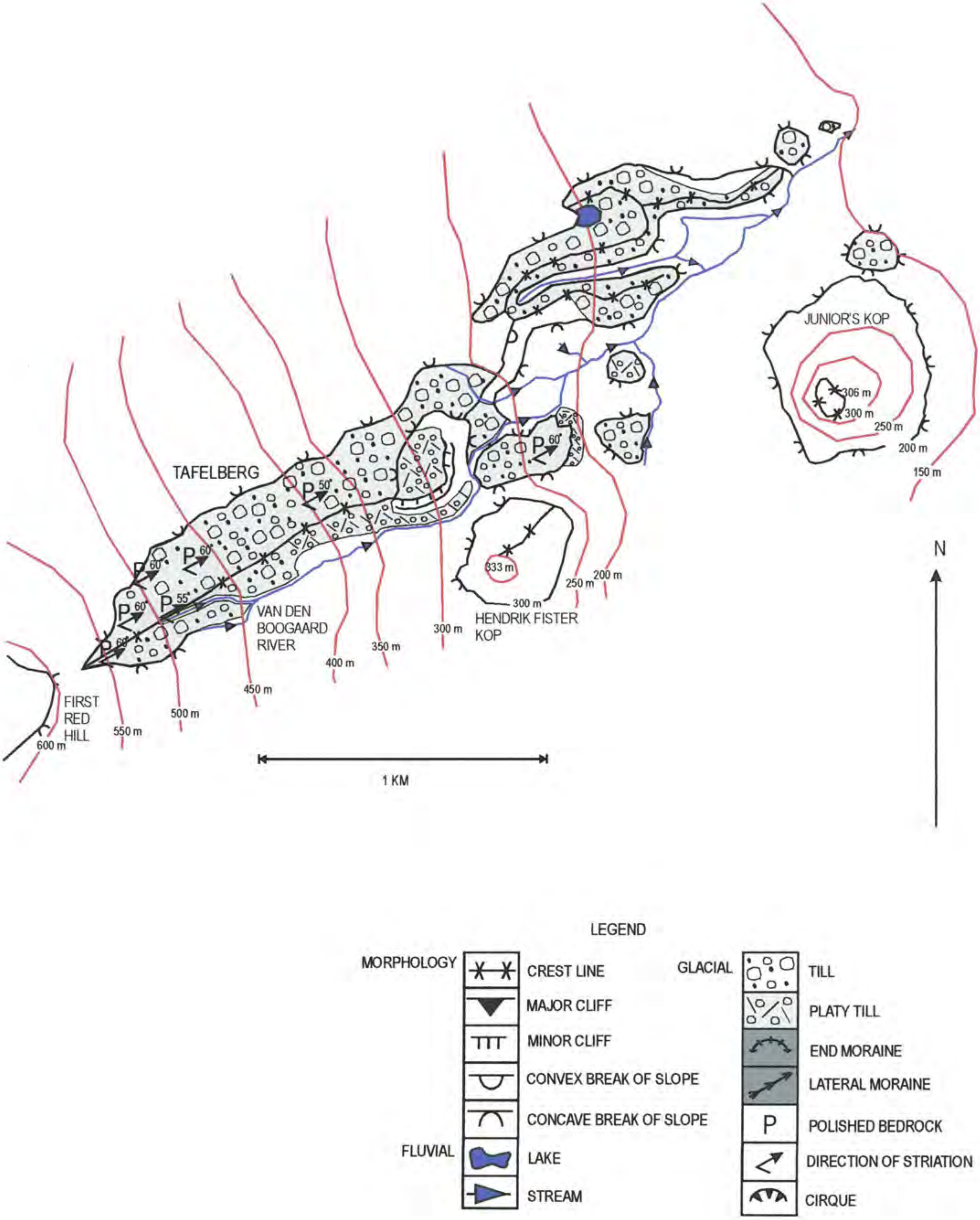

Figure 7: Tafelberg Glacial Features

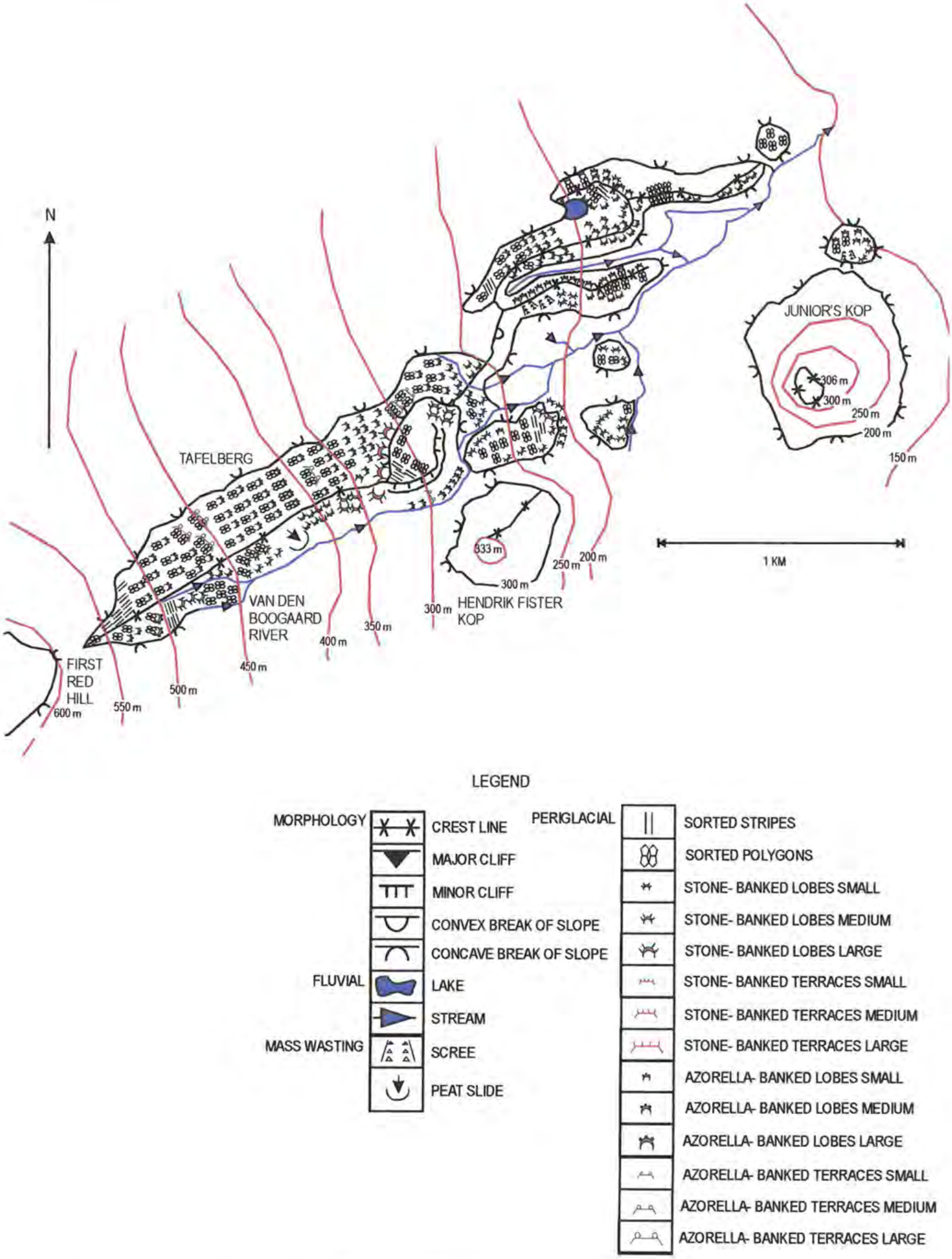

Figure 8: Tafelberg Periglacial and Mass Movement Features

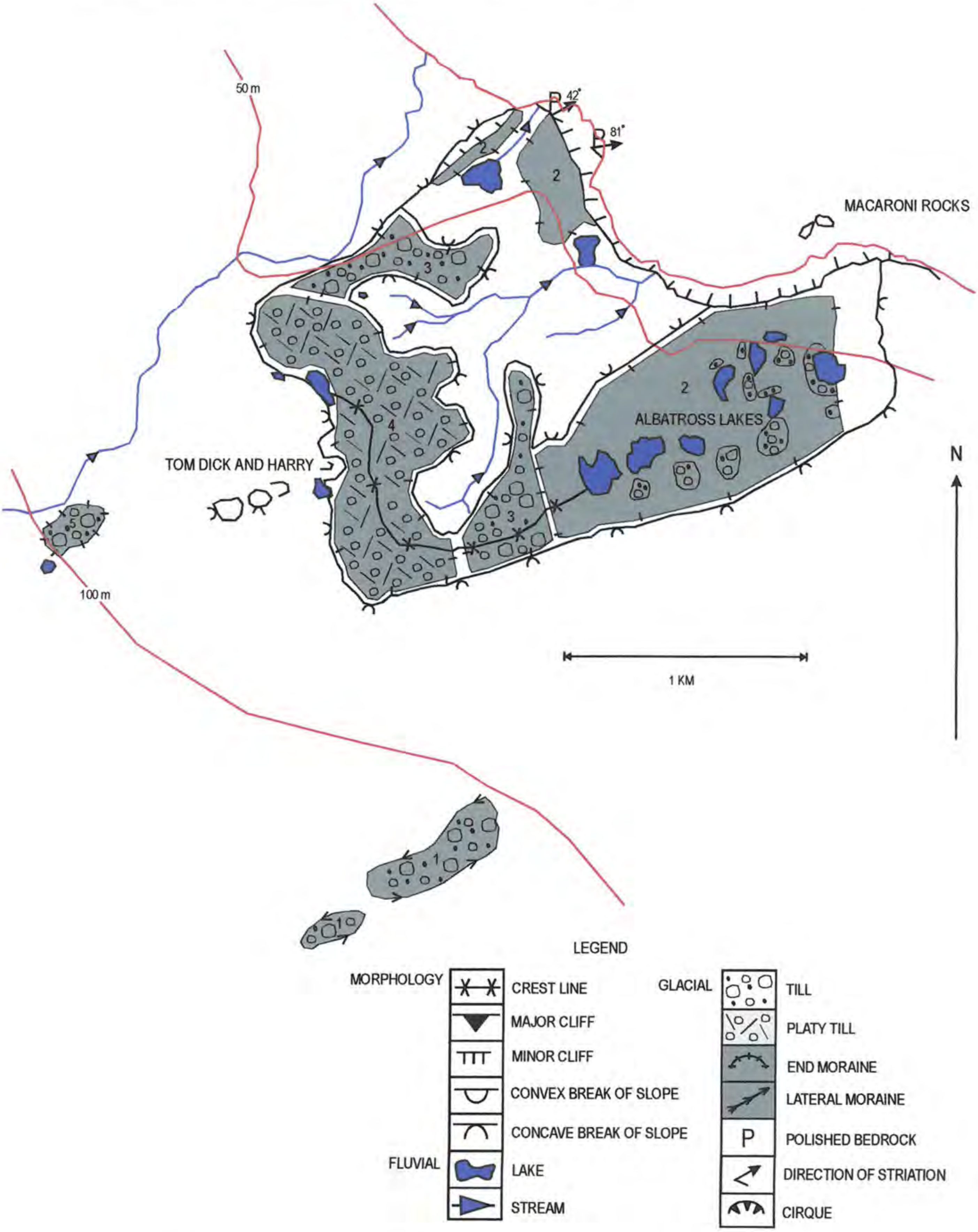

Figure 9: Macaroni Bay Glacial Features

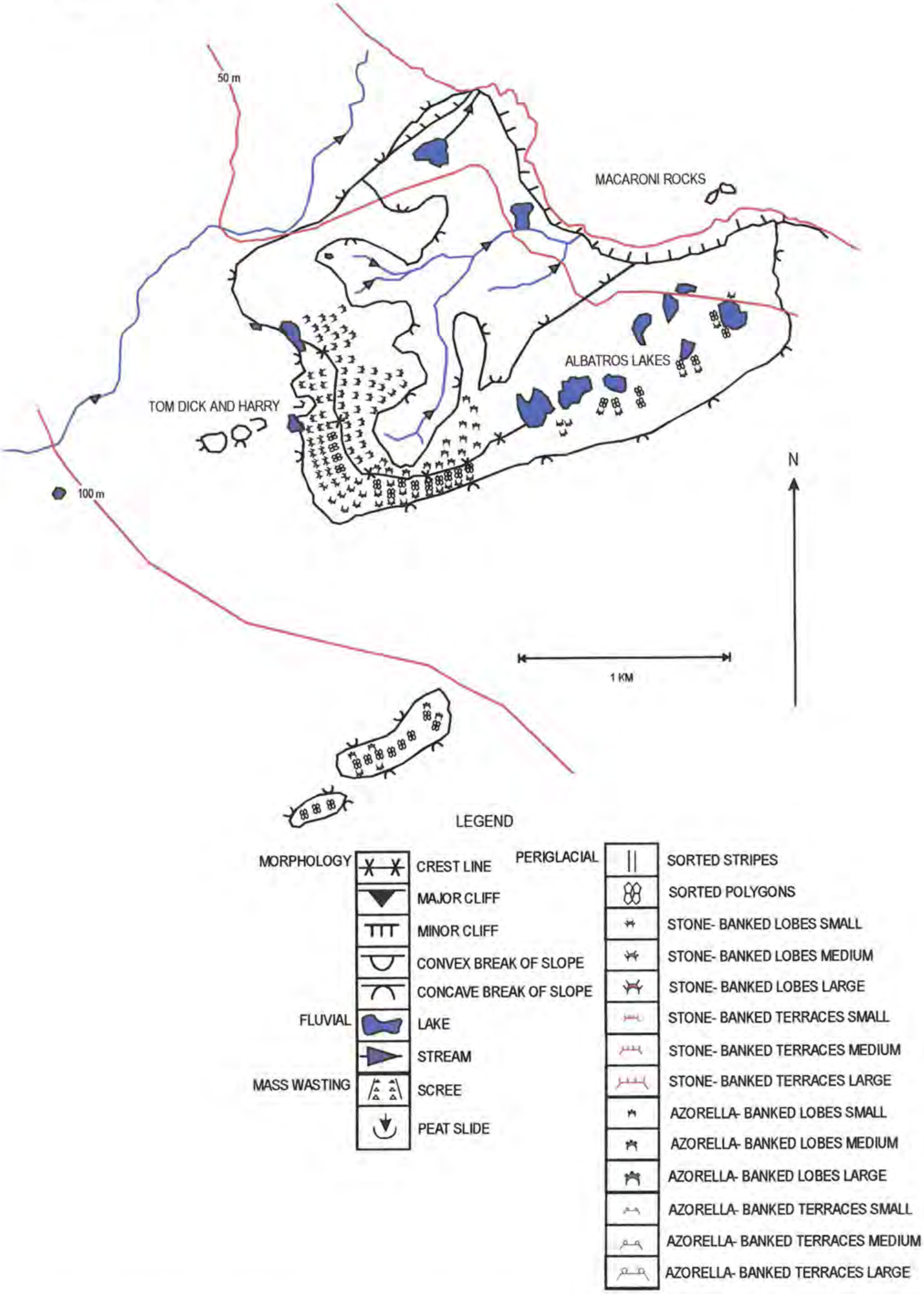

Figure 10: Macaroni Bay Periglacial and Mass Movement Features

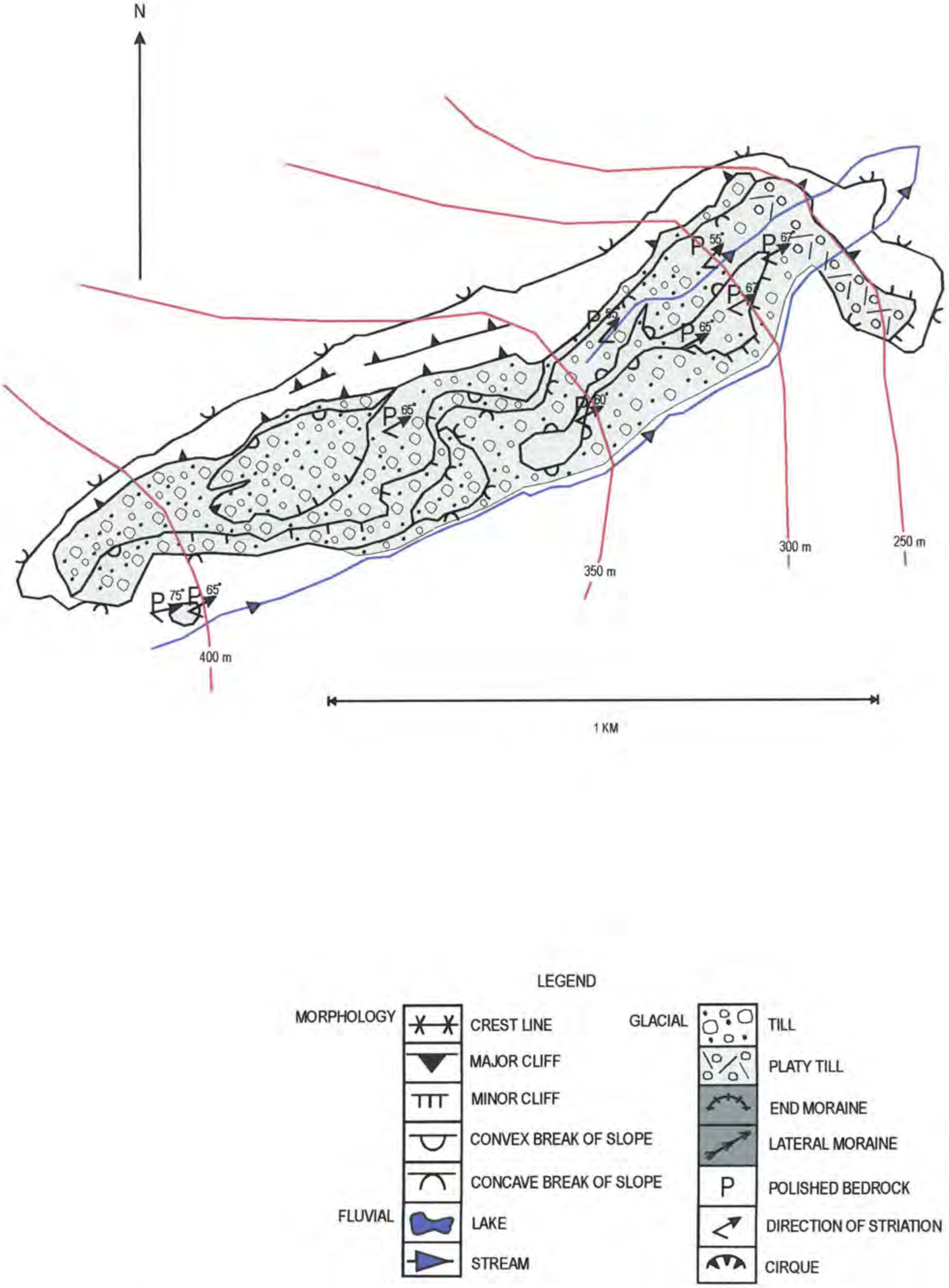

Figure 11: Piew Crags Glacial Features

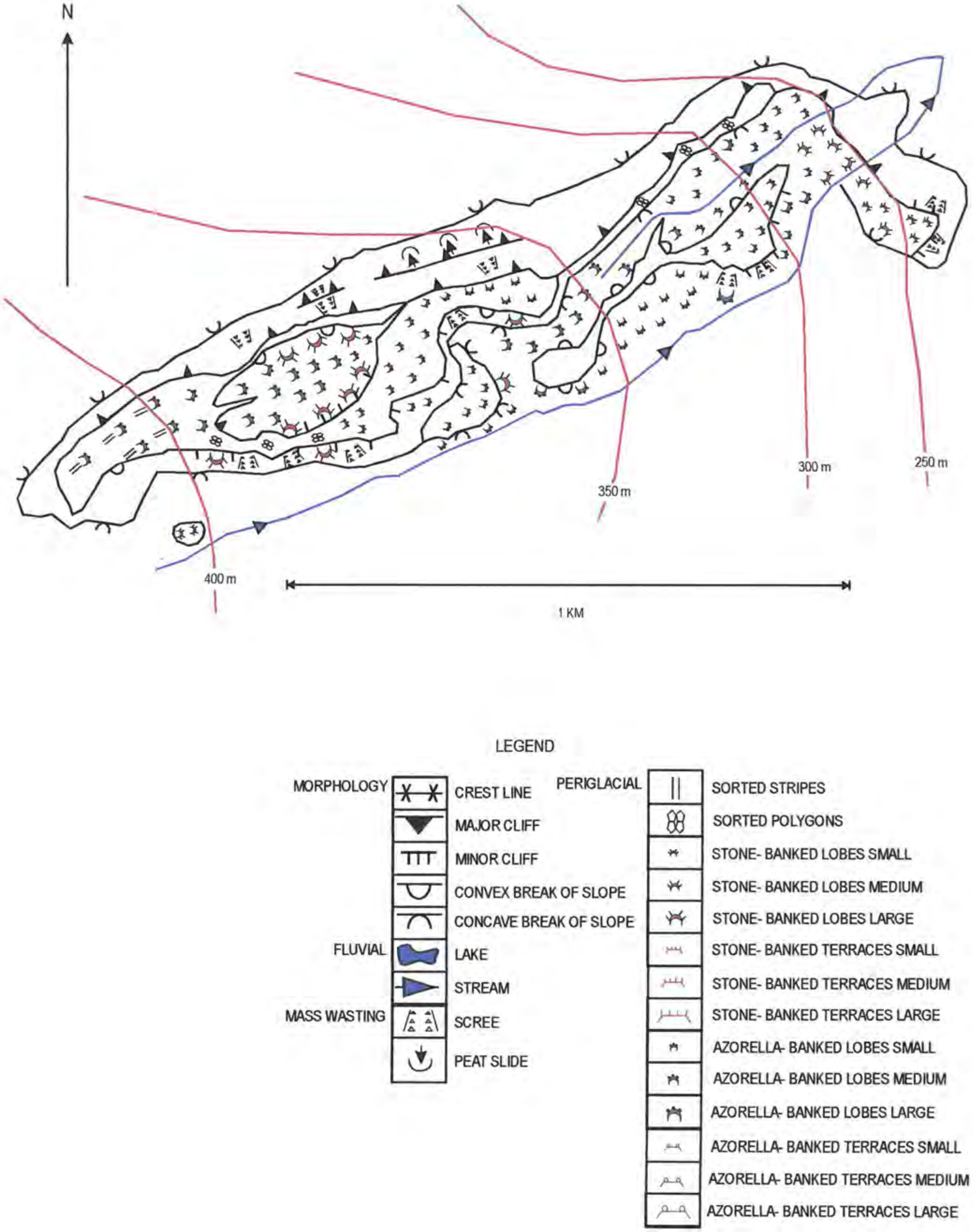

Figure 12: Piew Crags Periglacial and Mass Movement Features

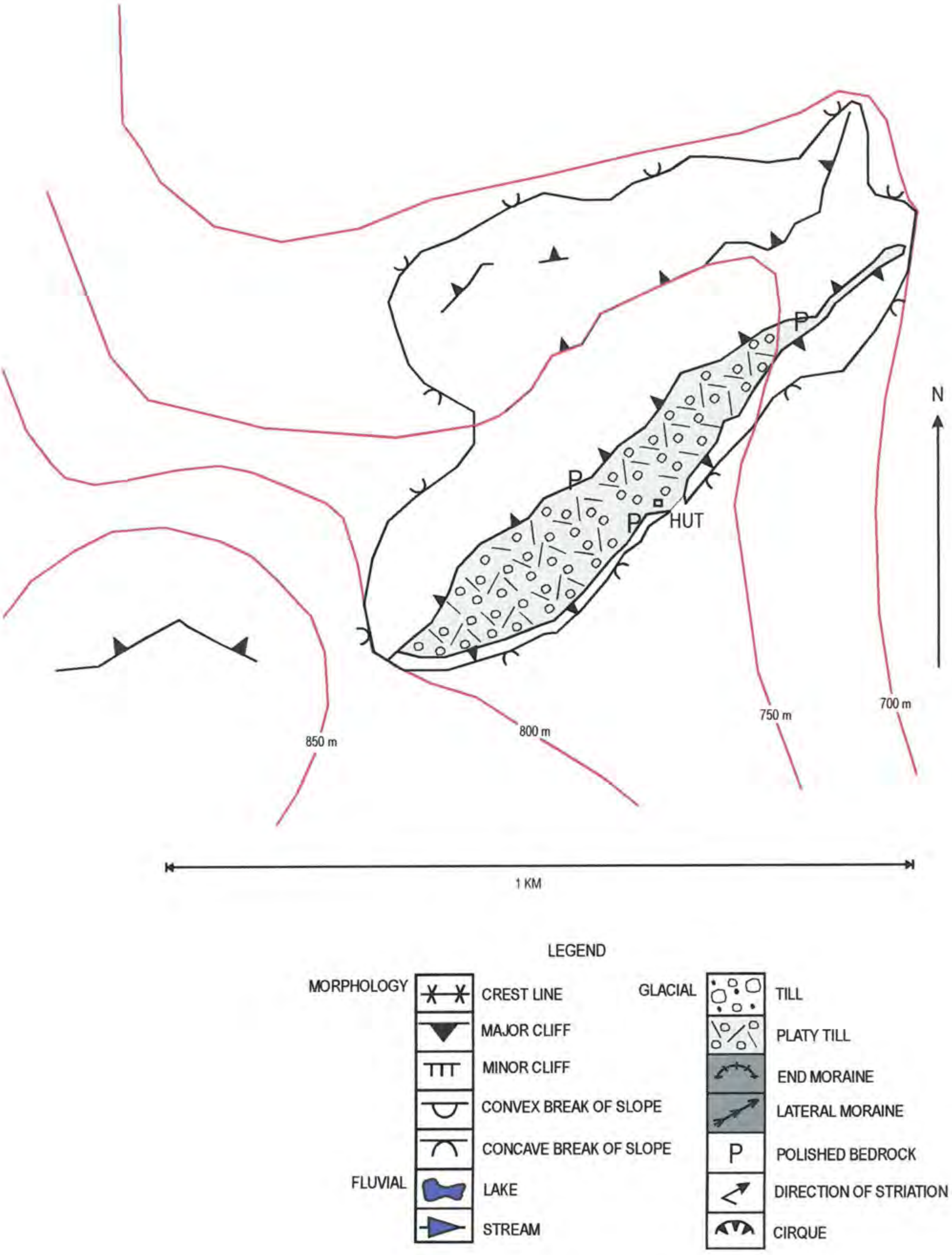

Figure 13: Katedraal Glacial Features

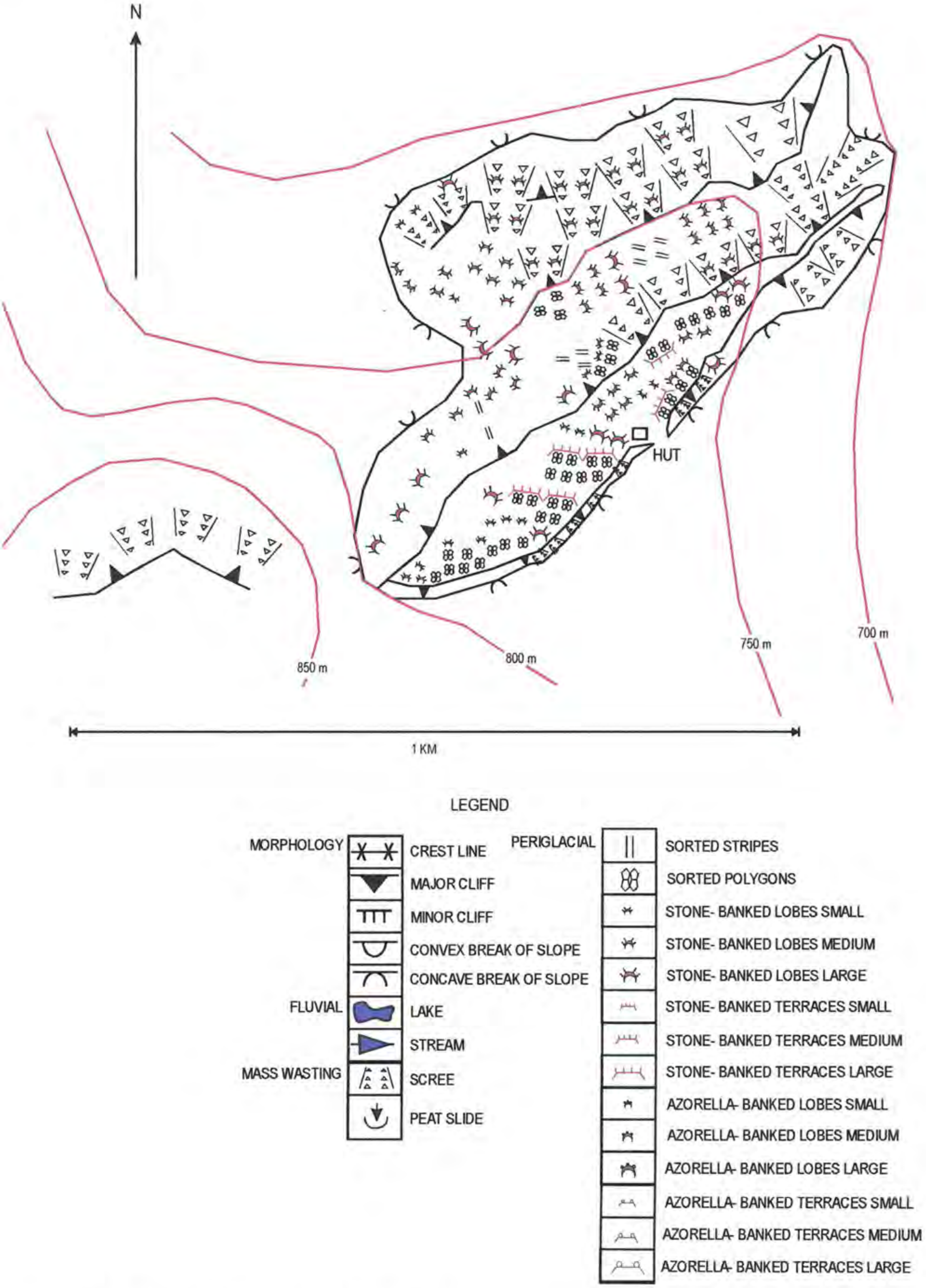

Figure 14: Katedraal Periglacial and Mass Movement Features

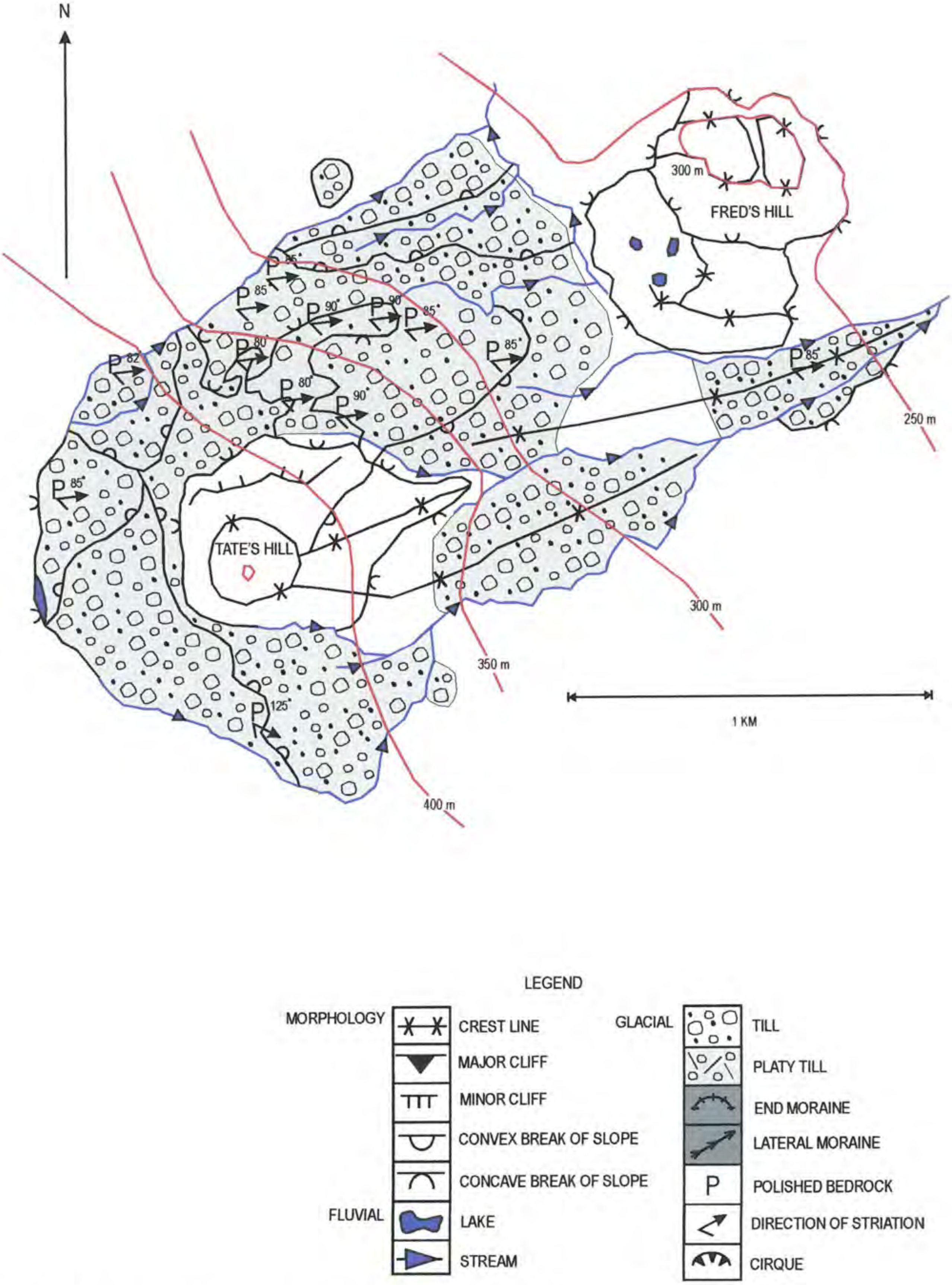

Figure 15: Fred's and Tate's Hill Glacial Features

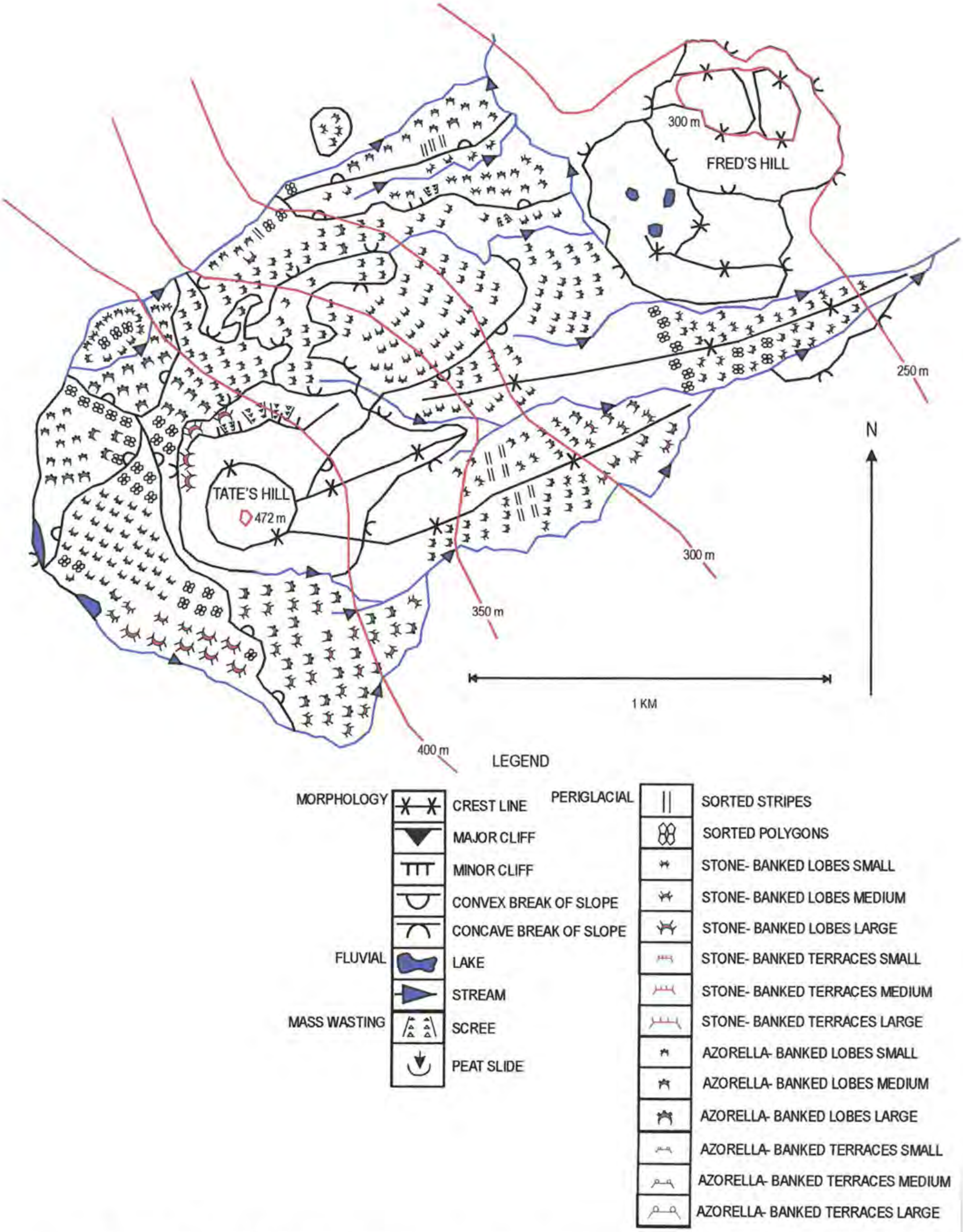

Figure 16: Fred's and Tate's Hill Periglacial and Mass Movement Features

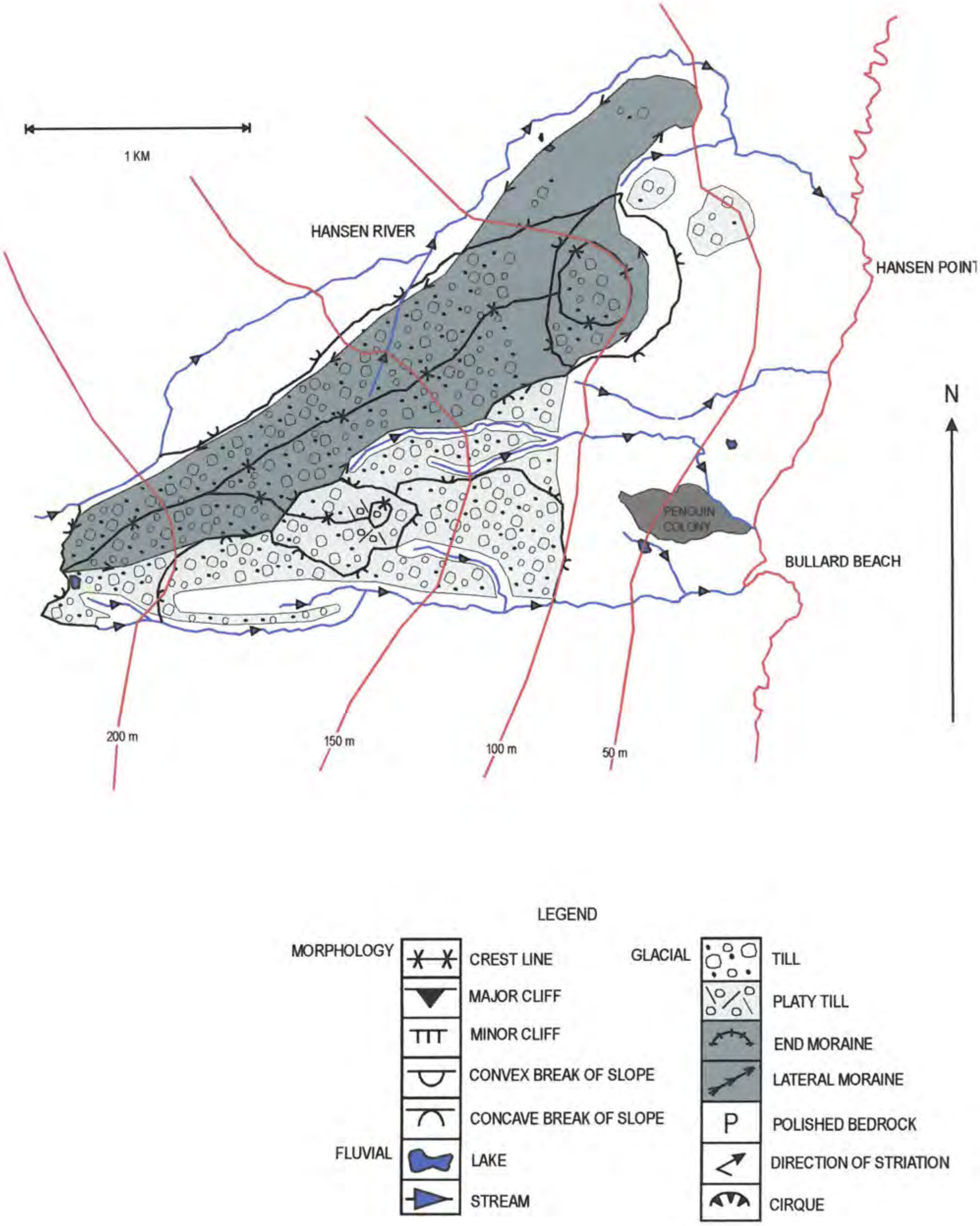

Figure 17: Stoney Ridge Glacial Features

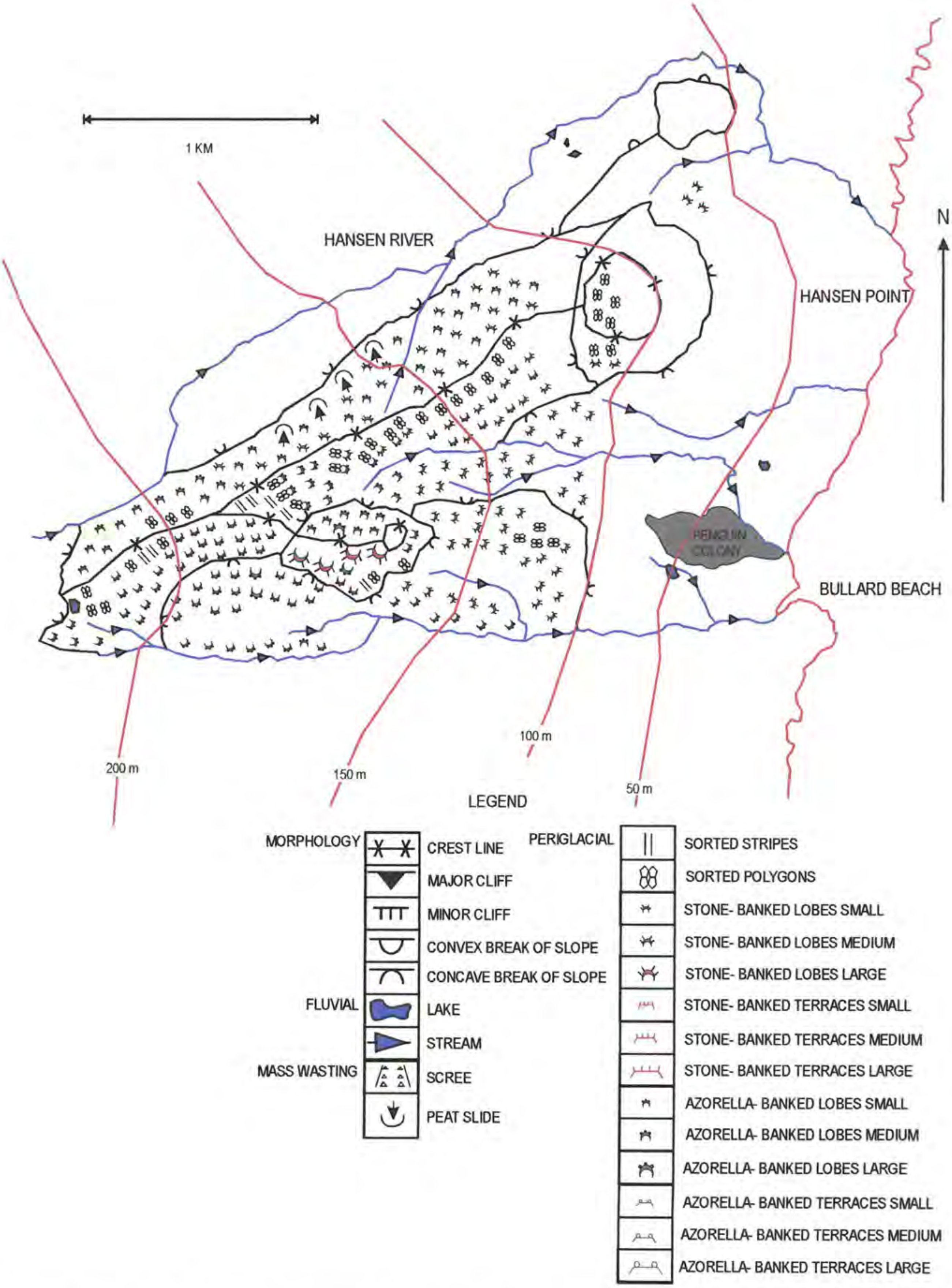

Figure 18: Stoney Ridge Periglacial and Mass Movement Features

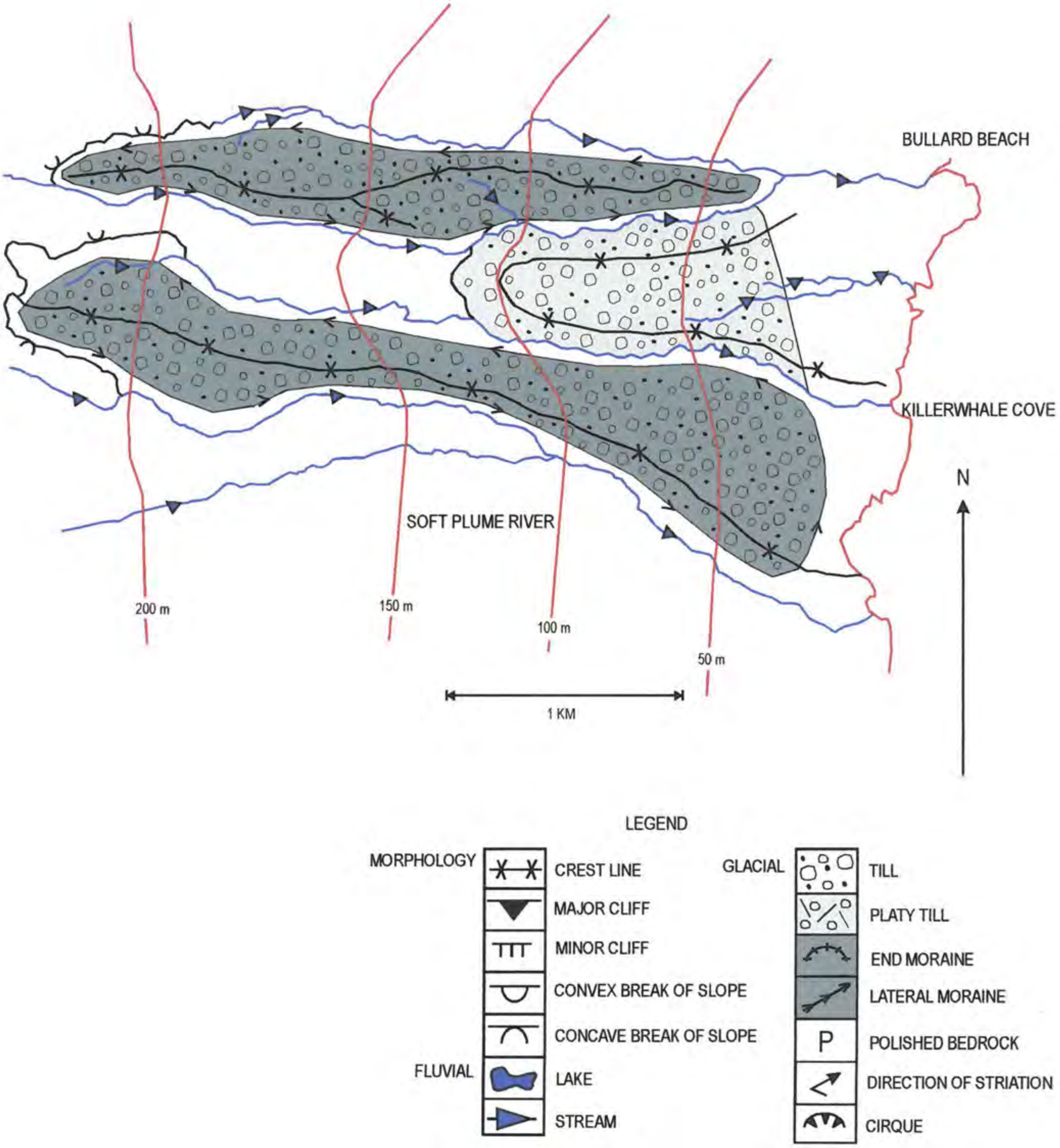

Figure 19: Kergeulen Rise North Glacial Features

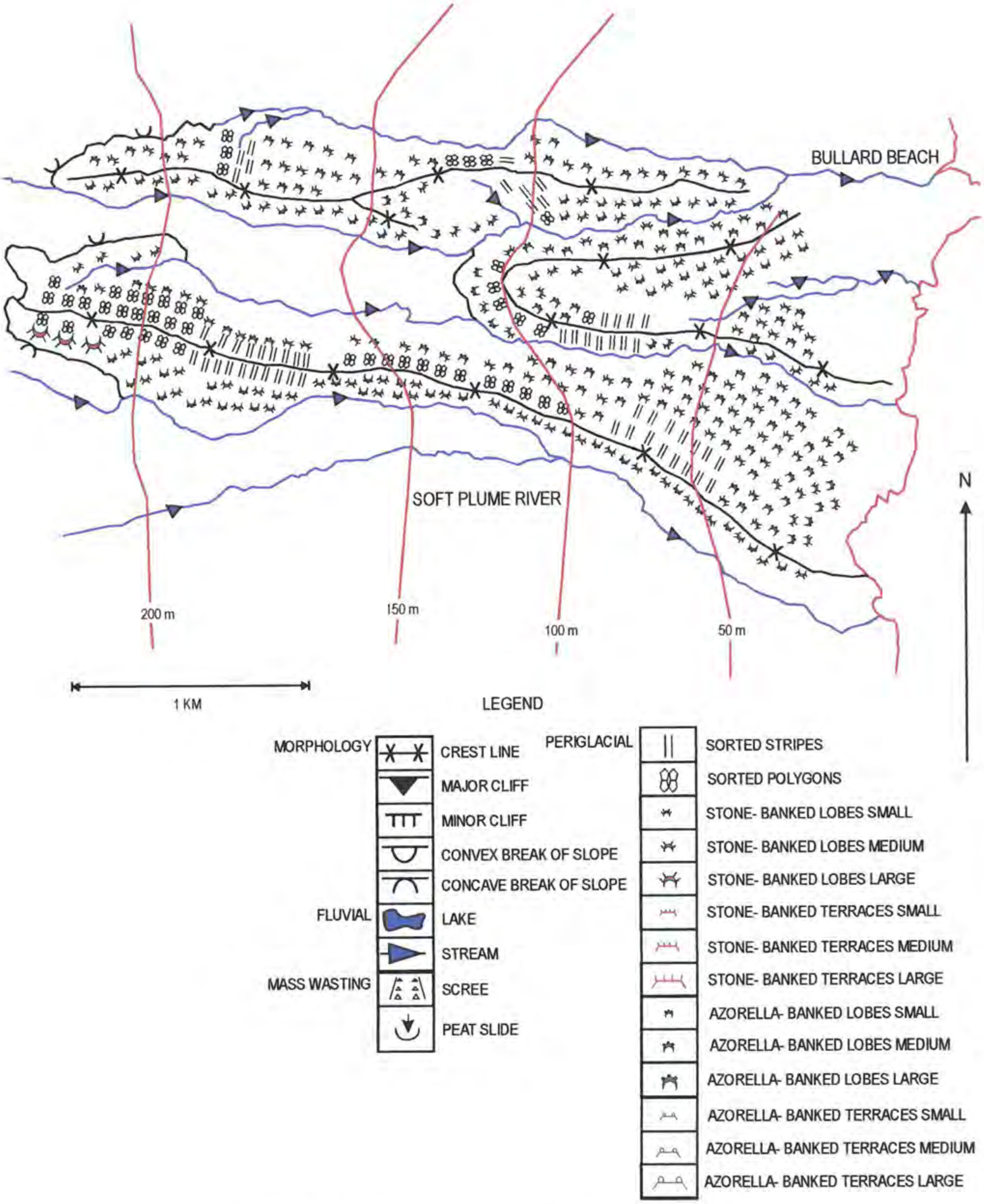

Figure 20: Kergeulen Rise North Periglacial and Mass Movement Features

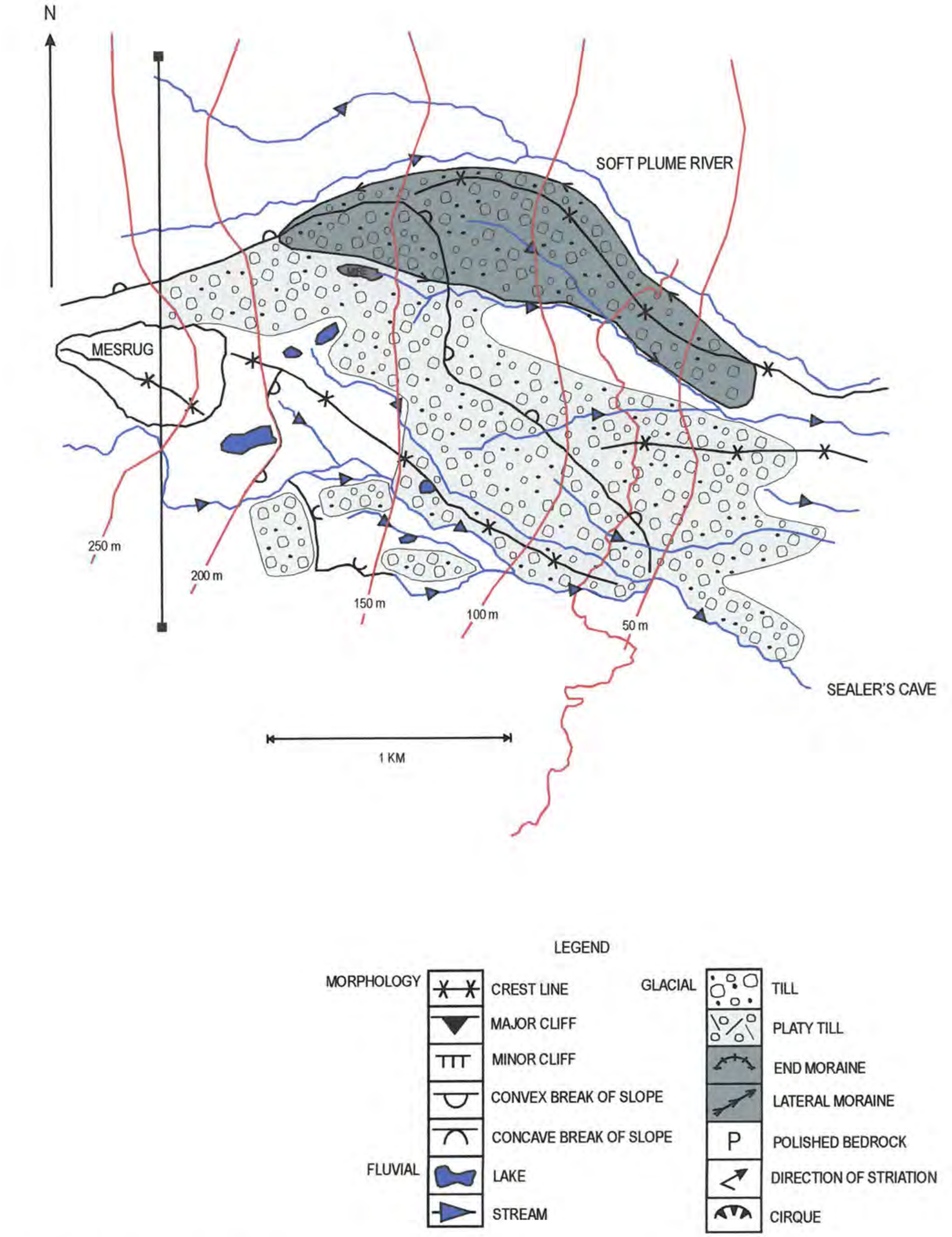

Figure 21: Kergeulen Rise South Glacial Features

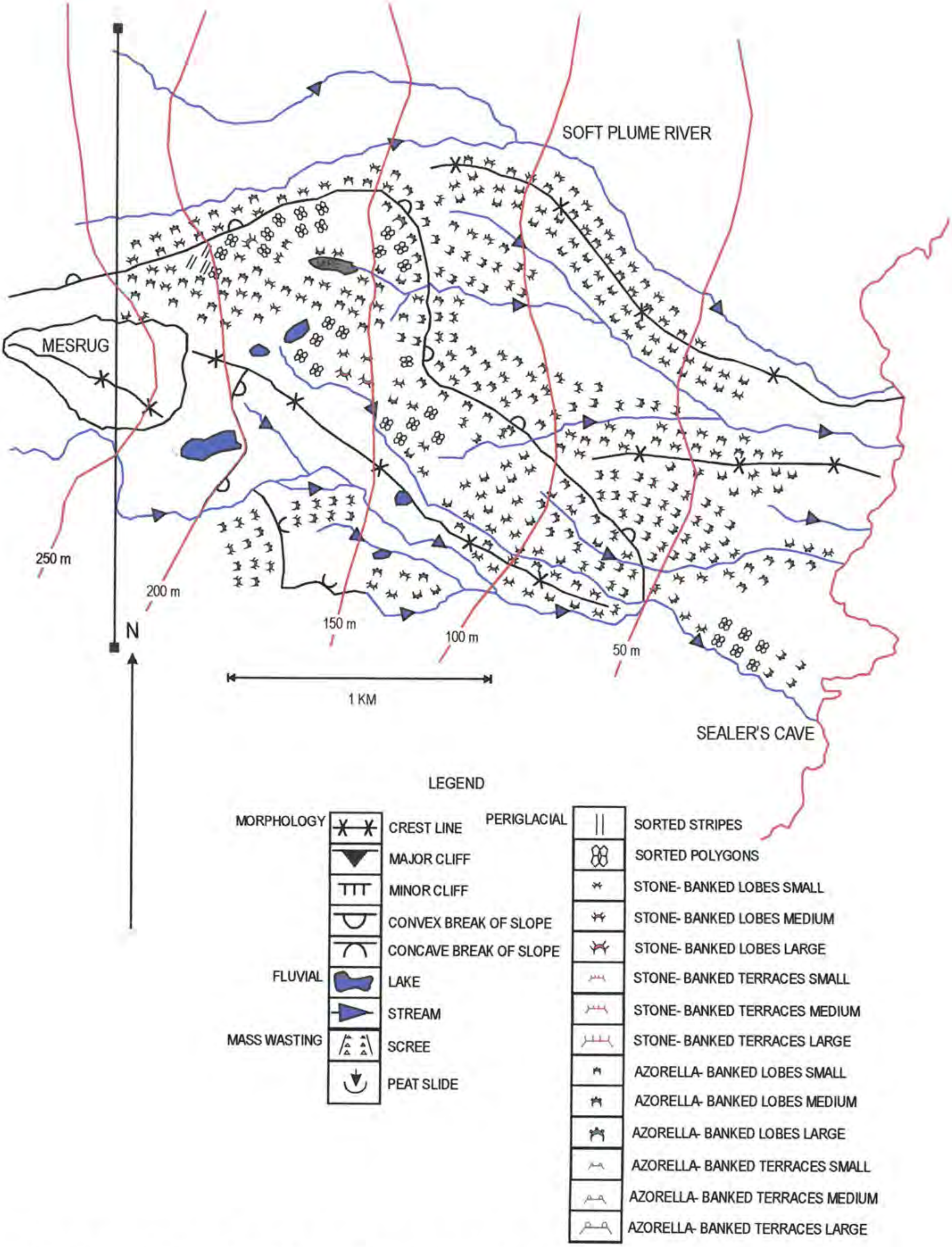

Figure 22: Kergeulen Rise South Periglacial and Mass Movement Features

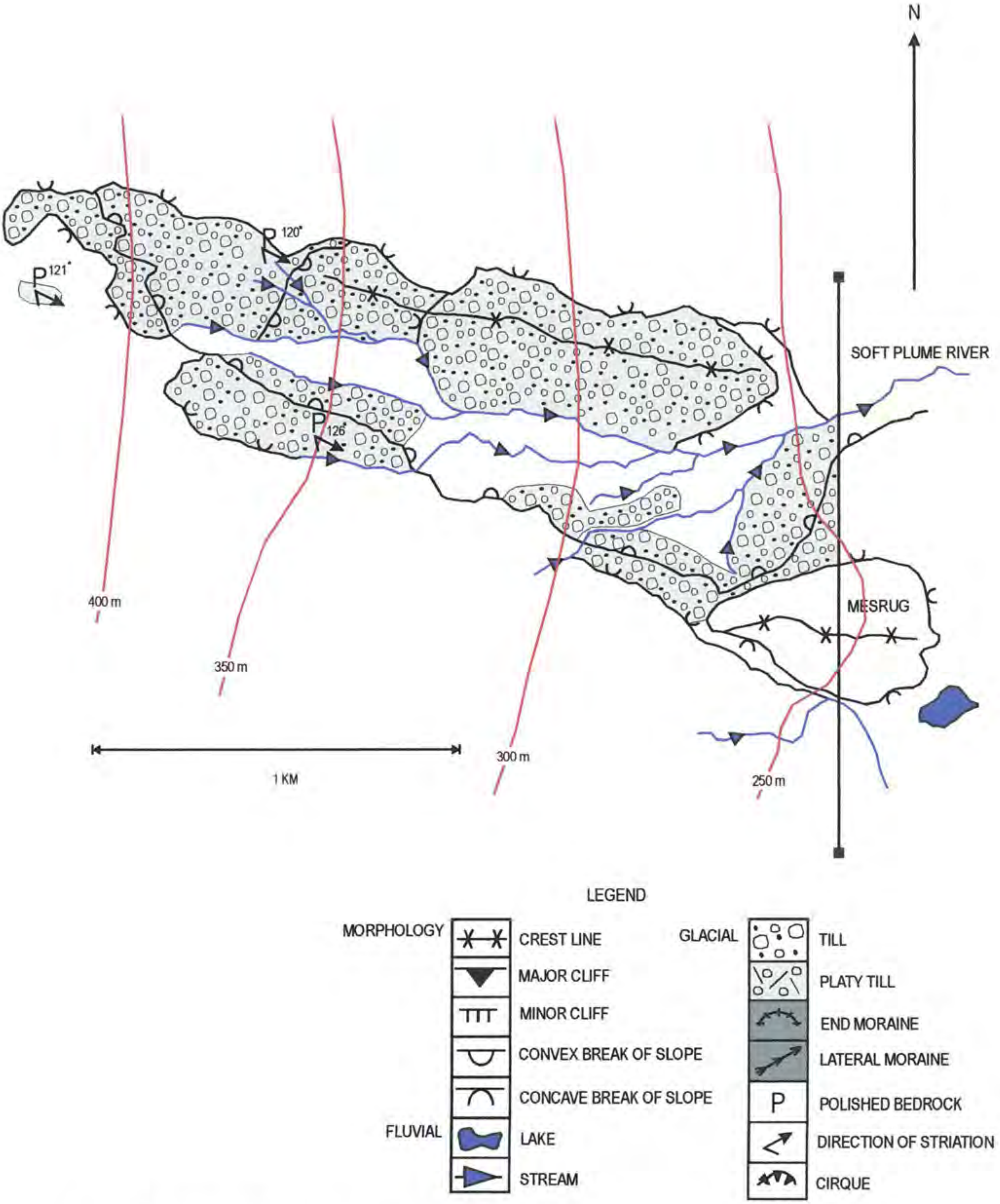

Figure 23: Kergeulen Rise West Glacial Features

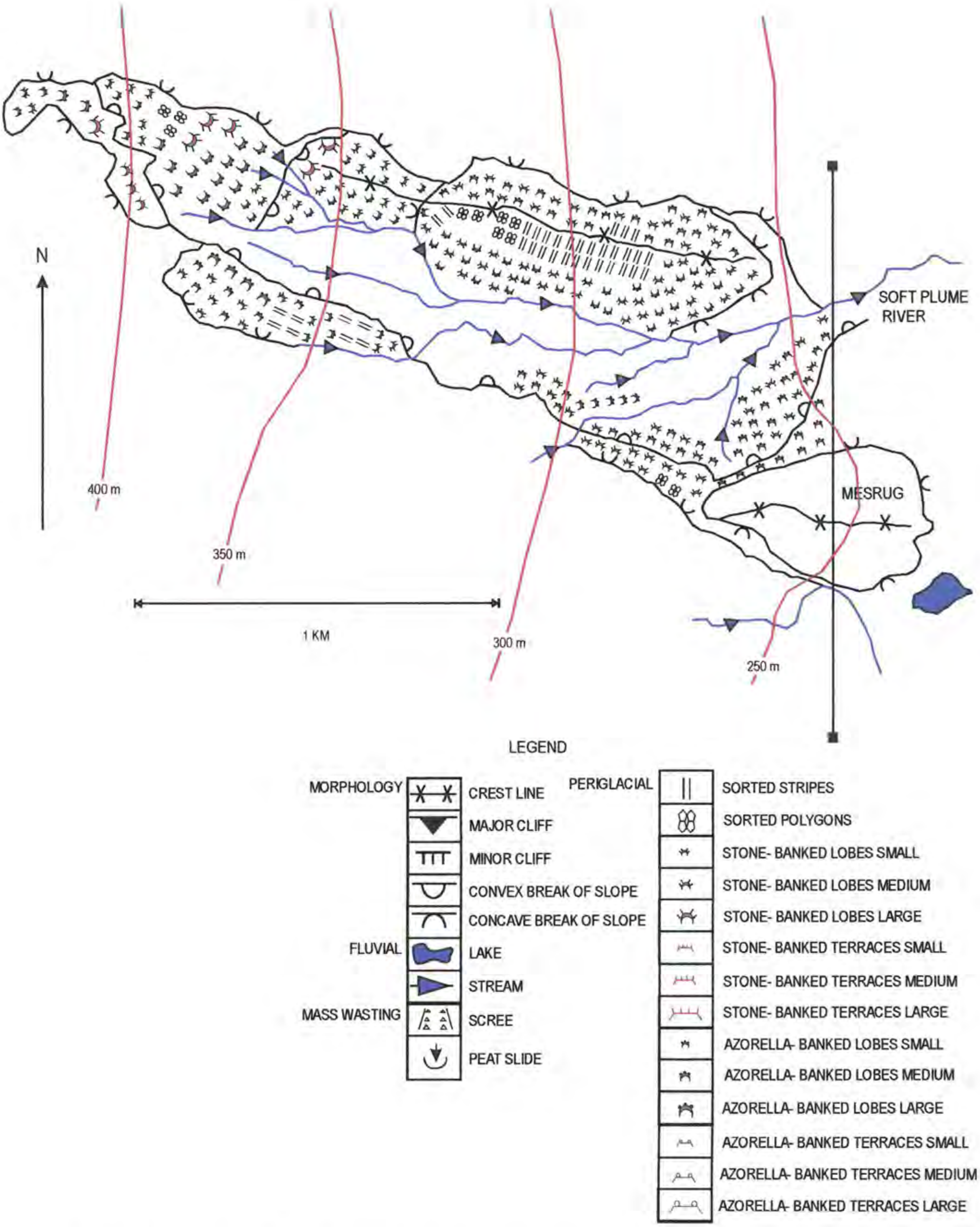

Figure 24: Kergeulen Rise West Periglacial and Mass Movement Features

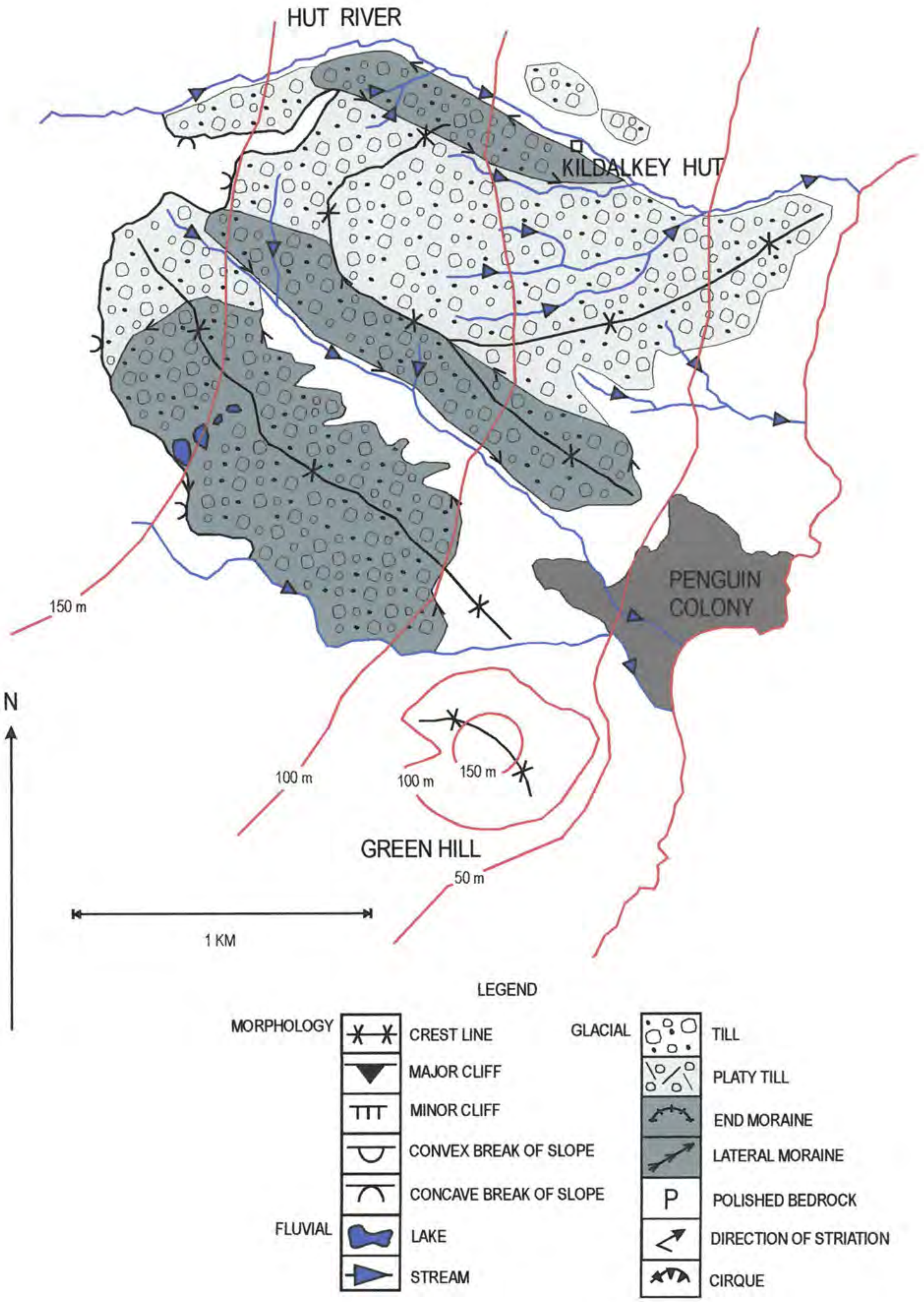

Figure 25: Kildalkey Bay Glacial Features

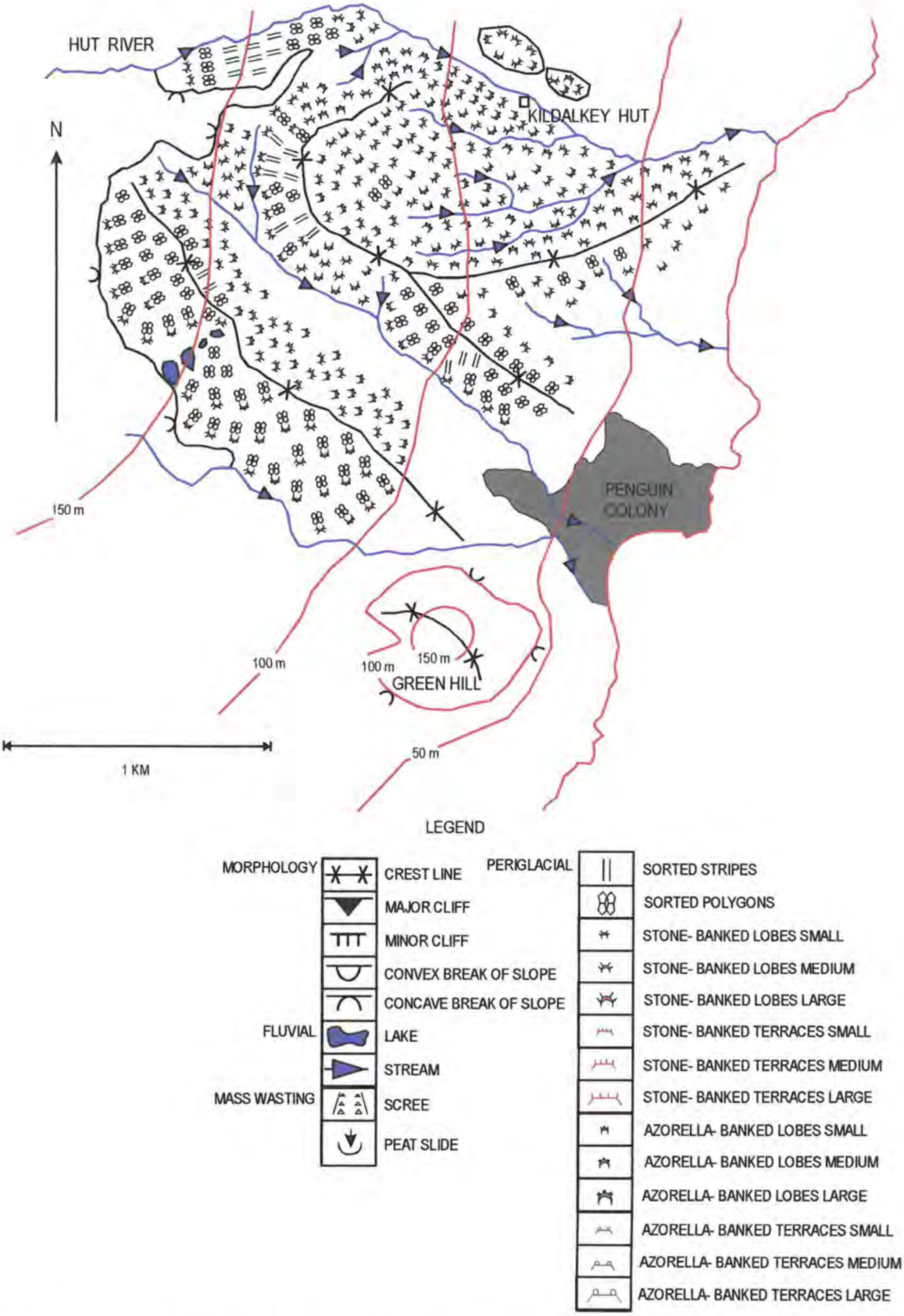

Figure 26: Kildalkey Bay Periglacial and Mass Movement Features

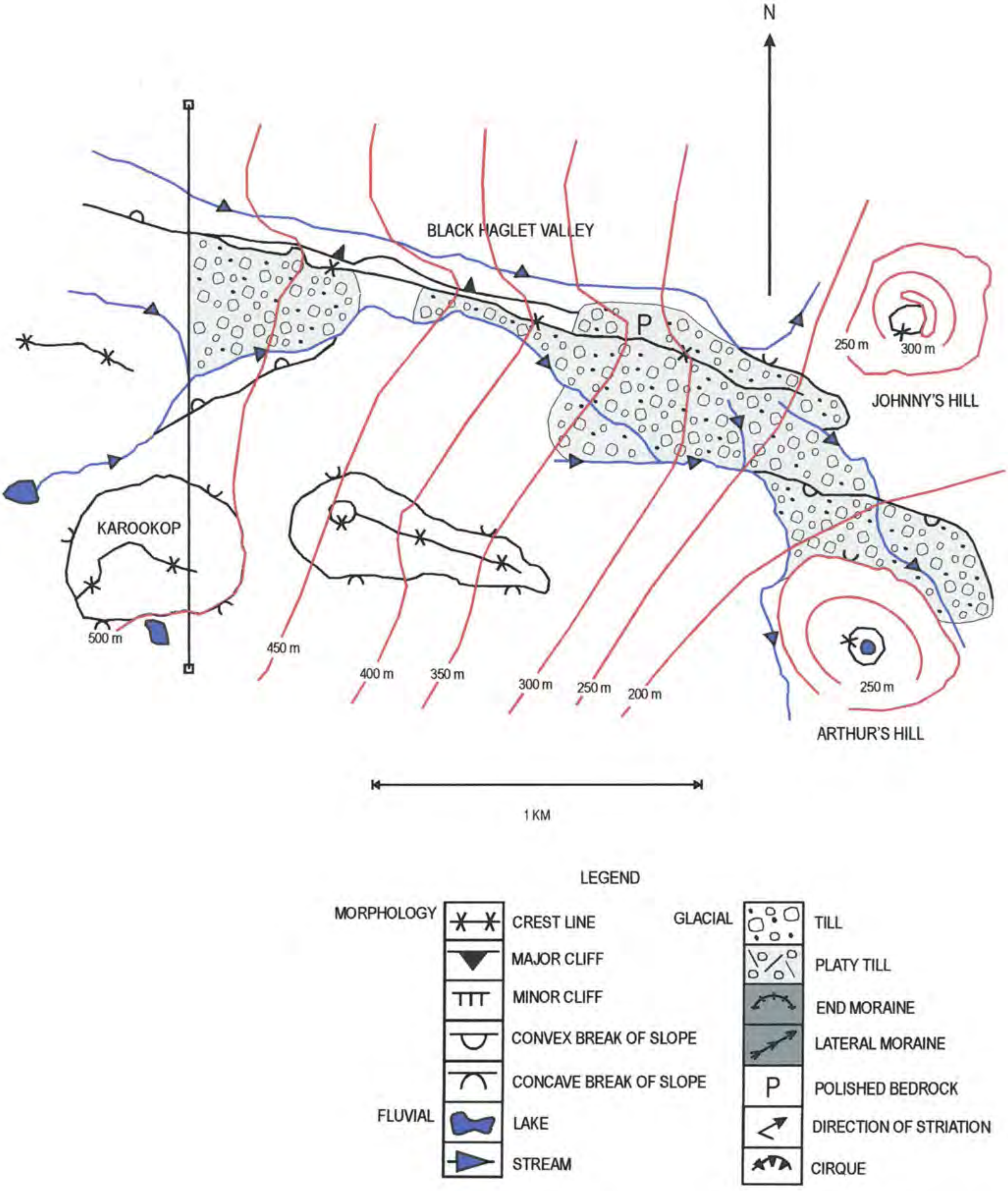

Figure 27: Johnny's Hill to Karookop Glacial Features

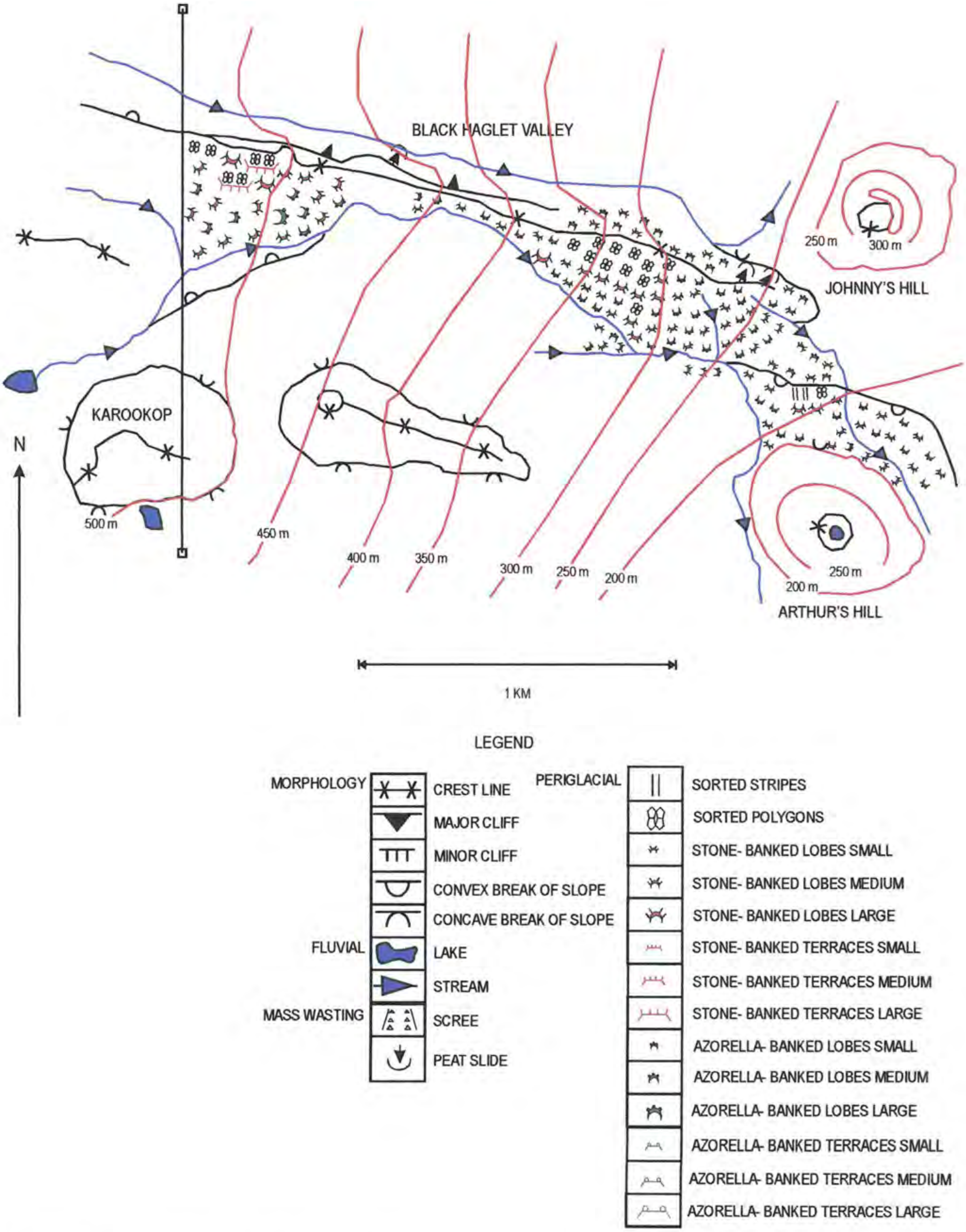

Figure 28: Johnny's Hill to Karookop Periglacial and Mass Movement Features

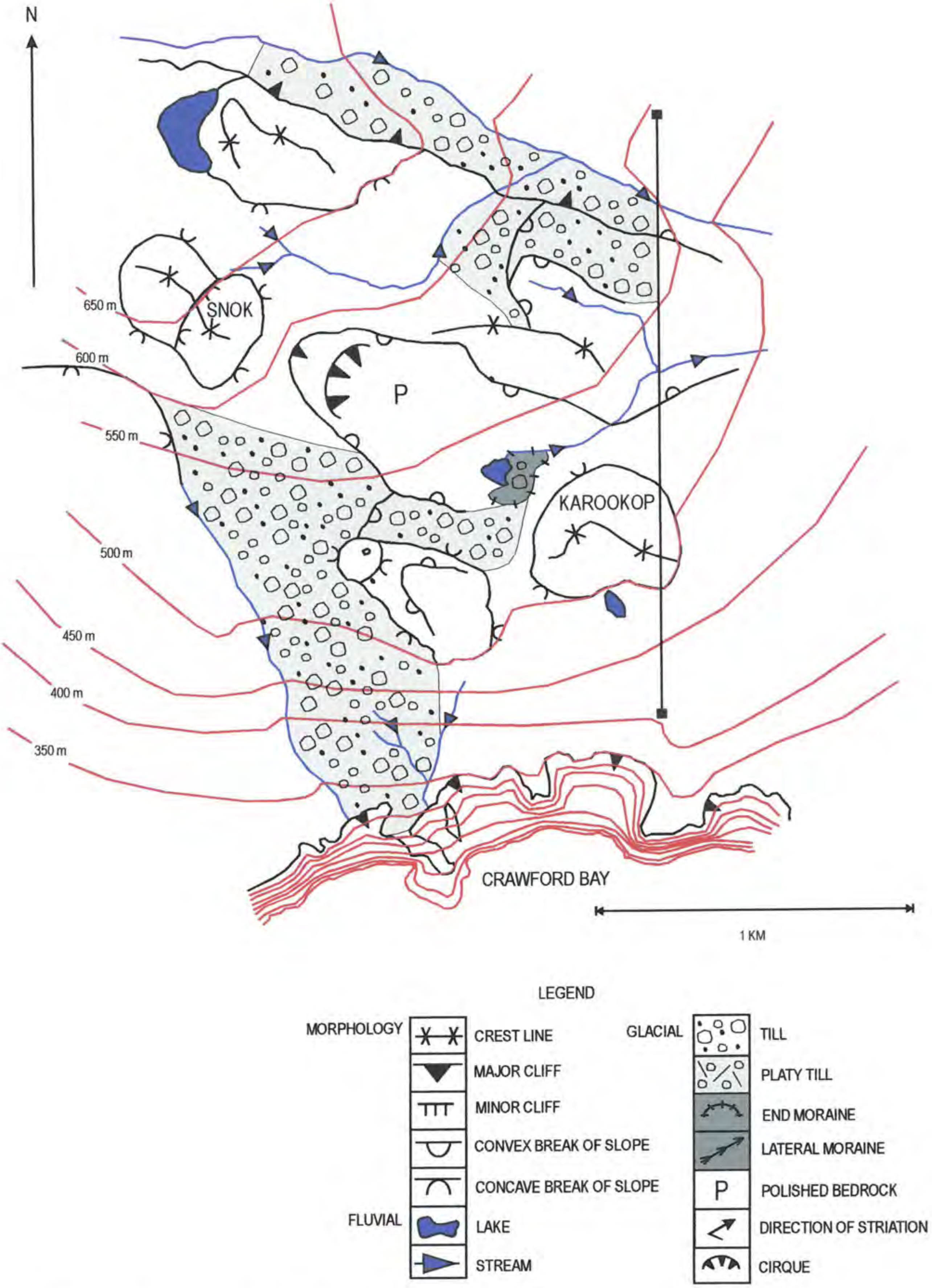

Figure 29: Feldmark Plateau East Glacial Features

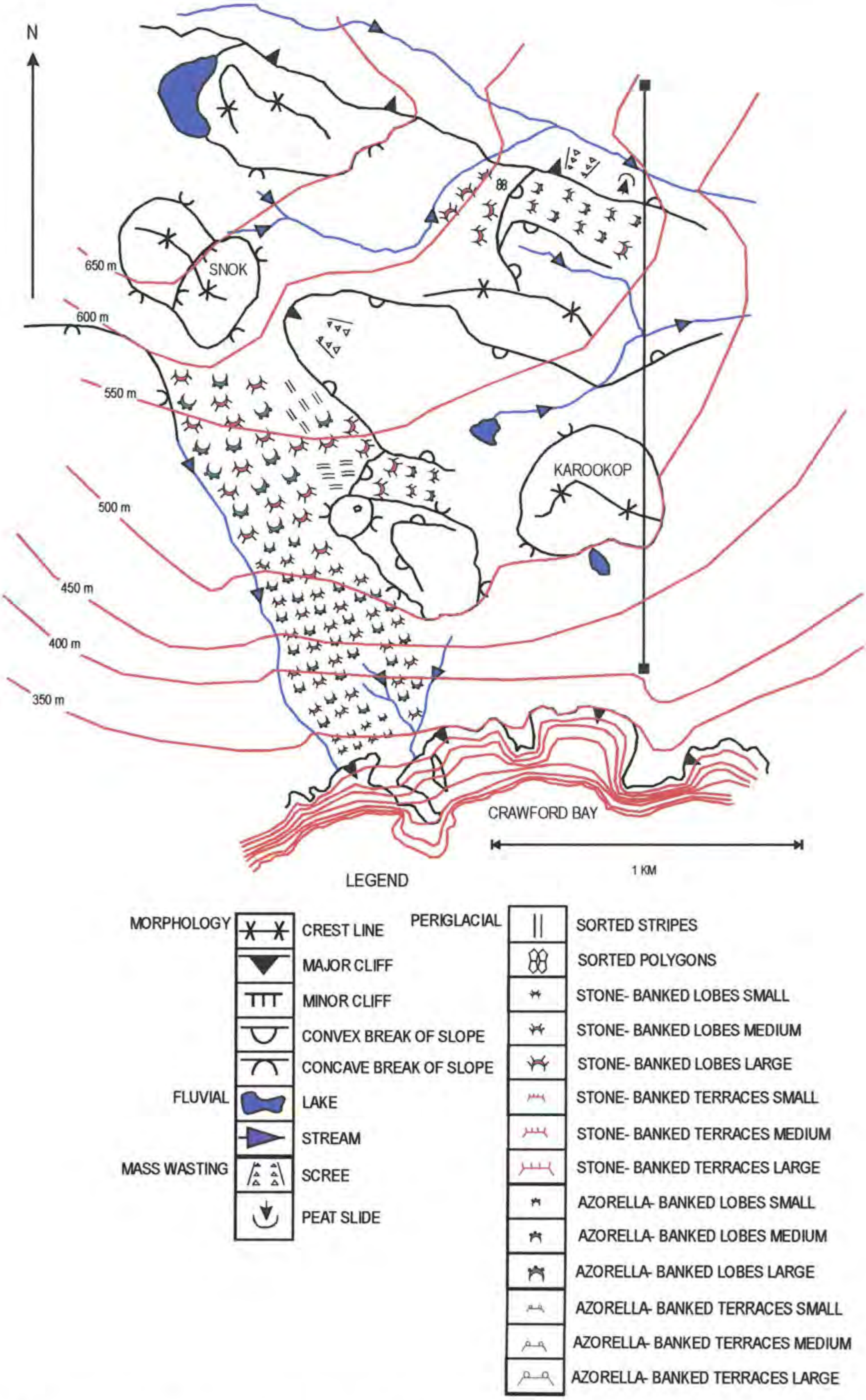

Figure 30: Feldmark Plateau East Periglacial and Mass Movement Features

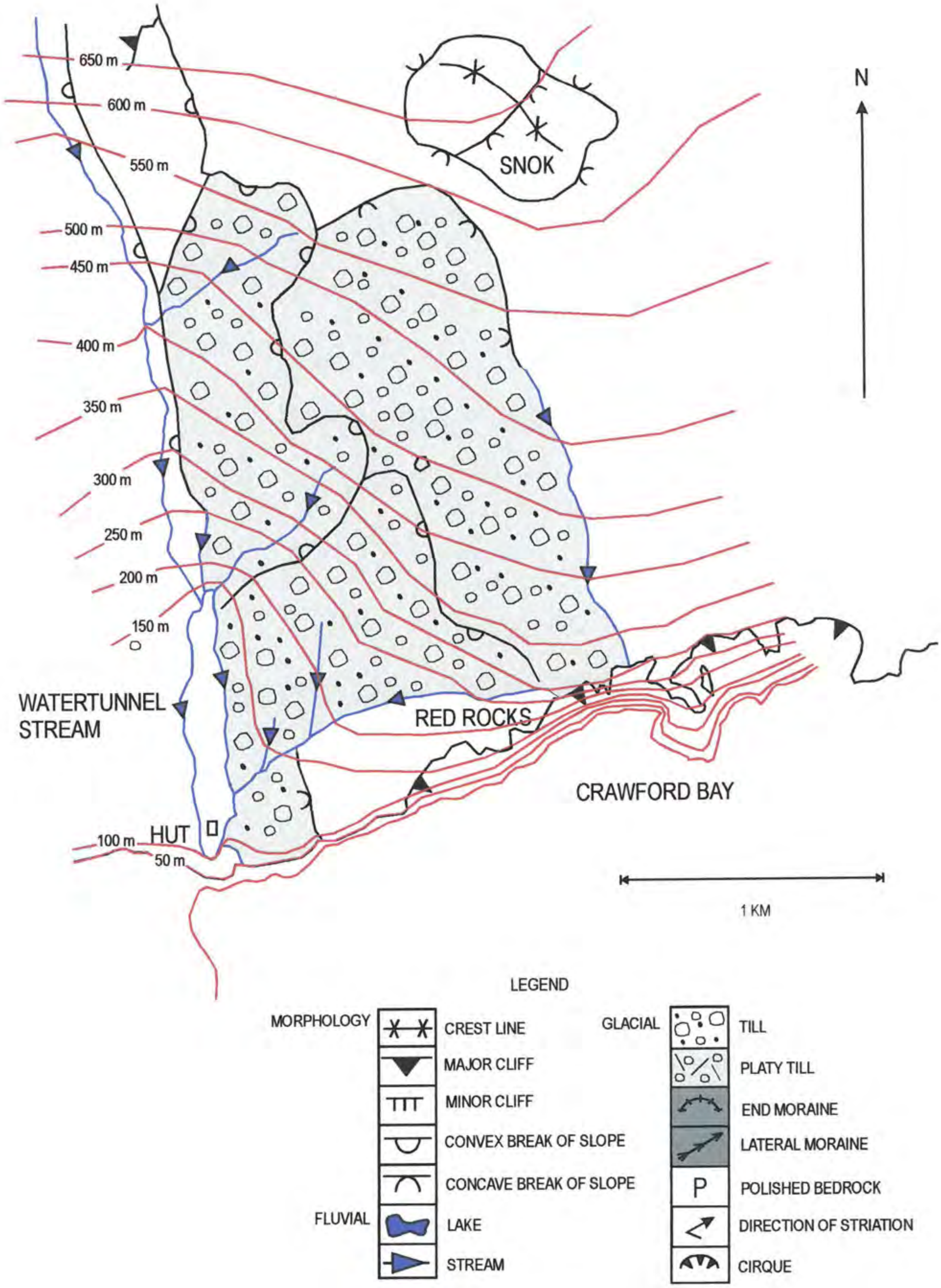

Figure 31: Feldmark Plateau South Glacial Features

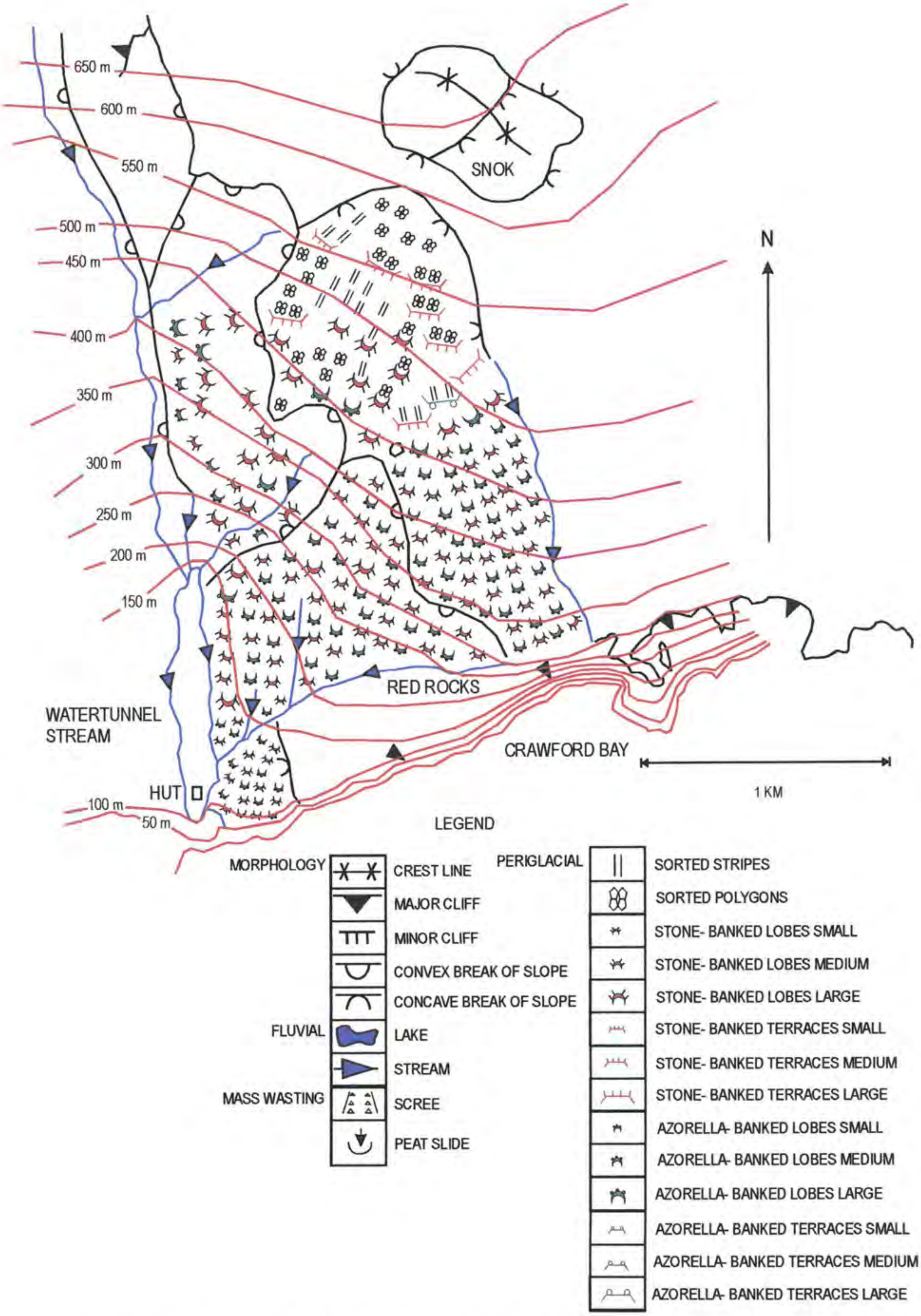

Figure 32: Feldmark Plateau South Periglacial and Mass Movement Features

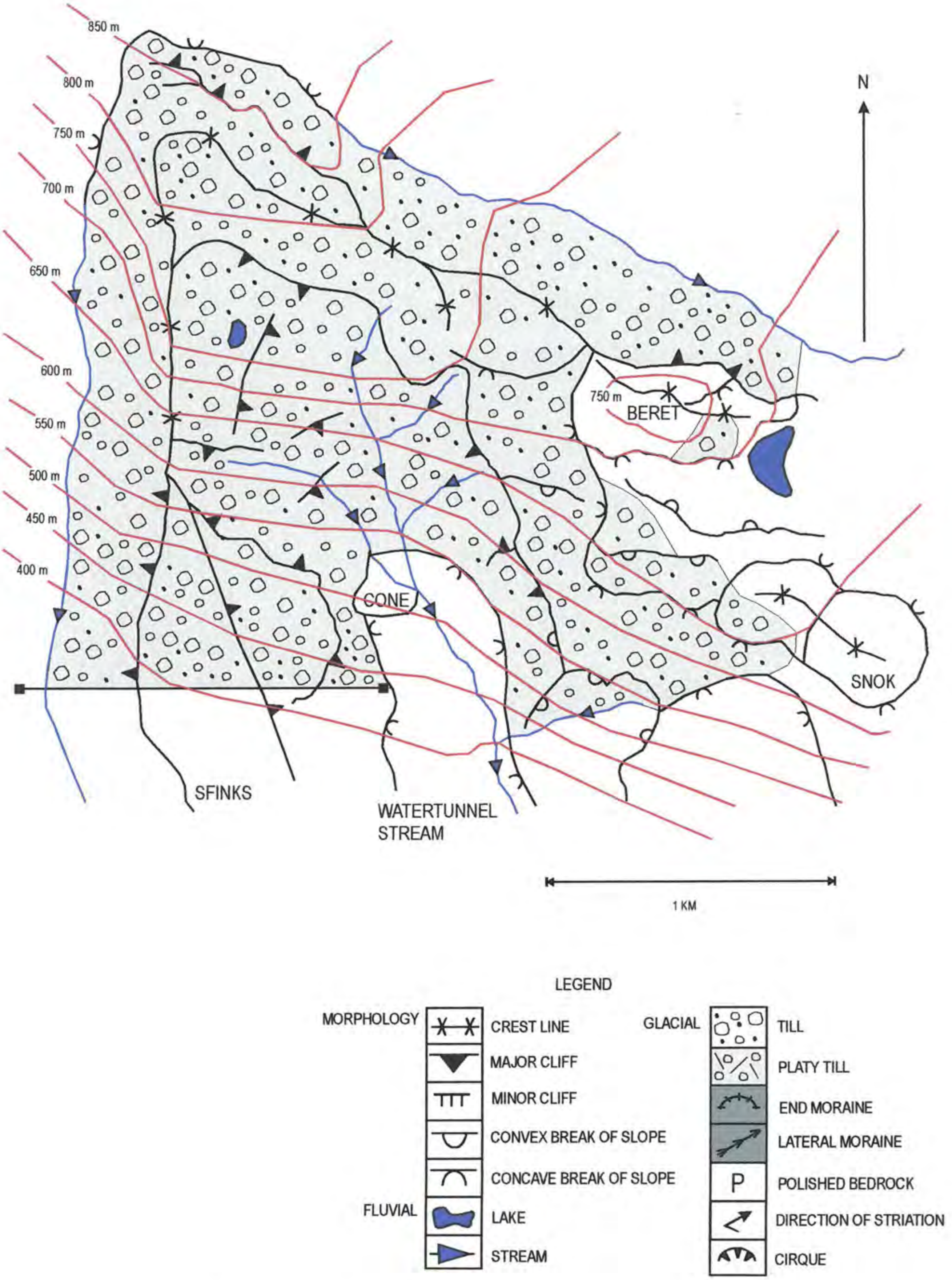

Figure 33: Feldmark Plateau North Glacial Features

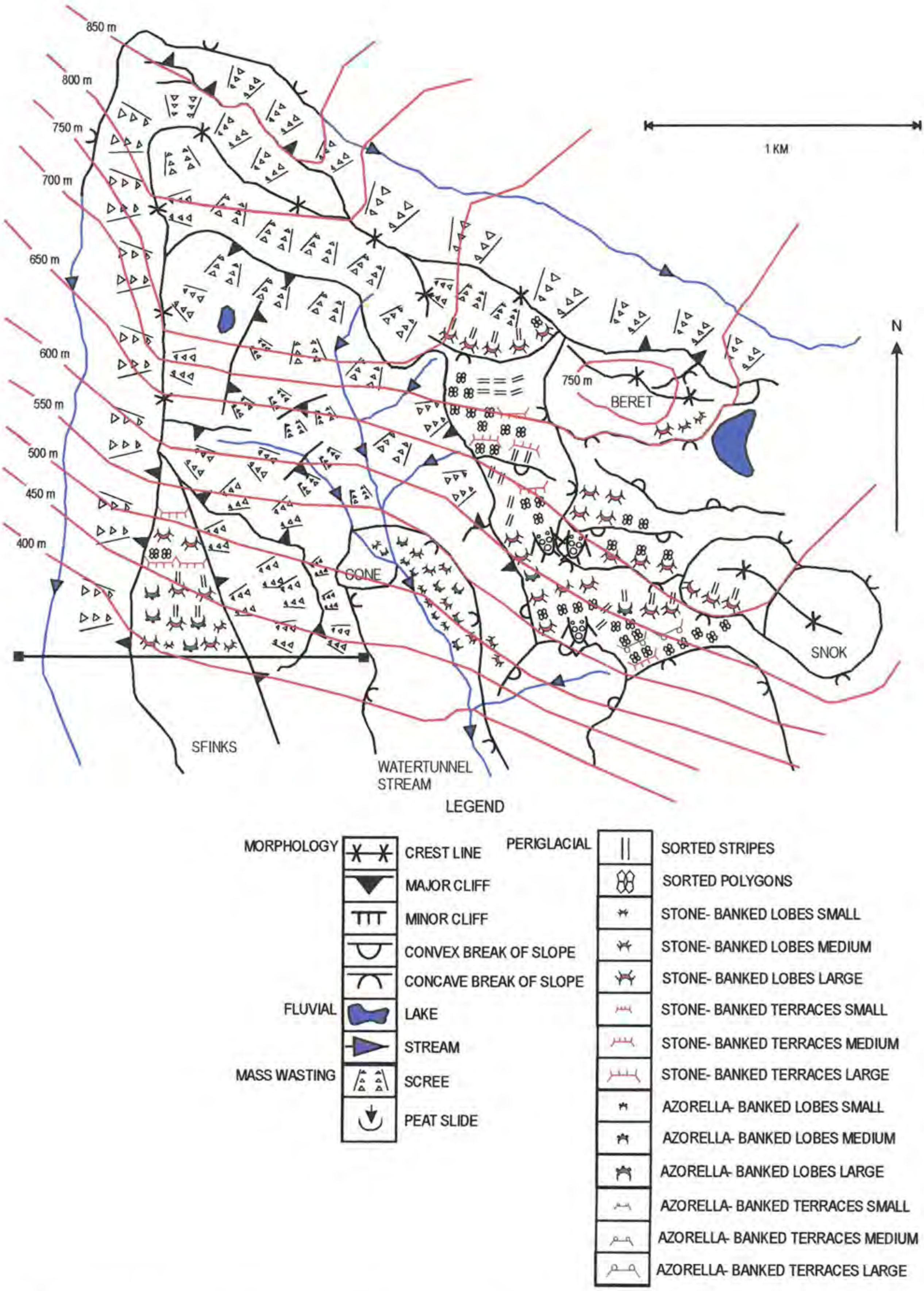

Figure 34: Feldmark Plateau North Periglacial and Mass Movement Features

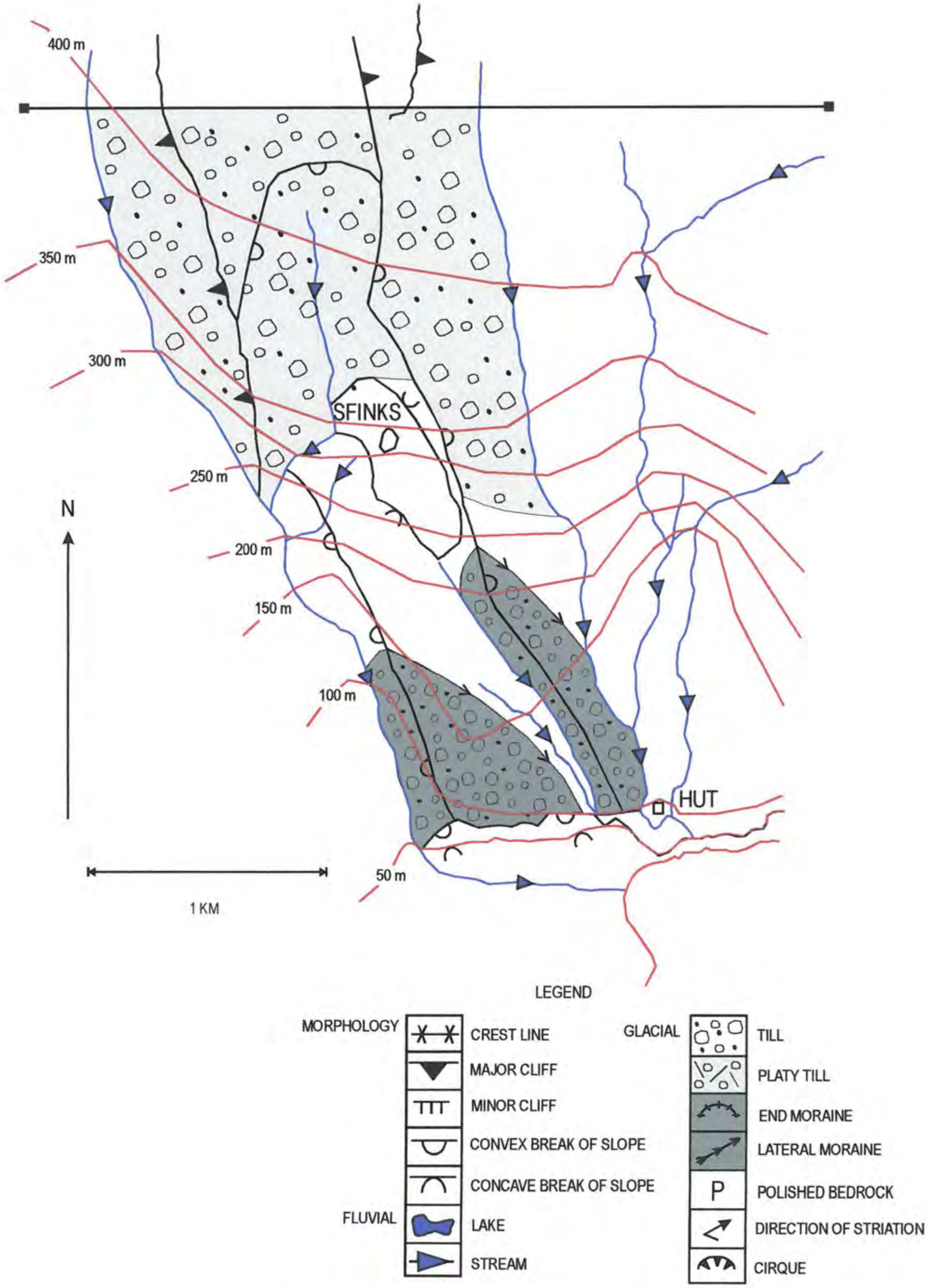

Figure 35: Sfinks Glacial Features

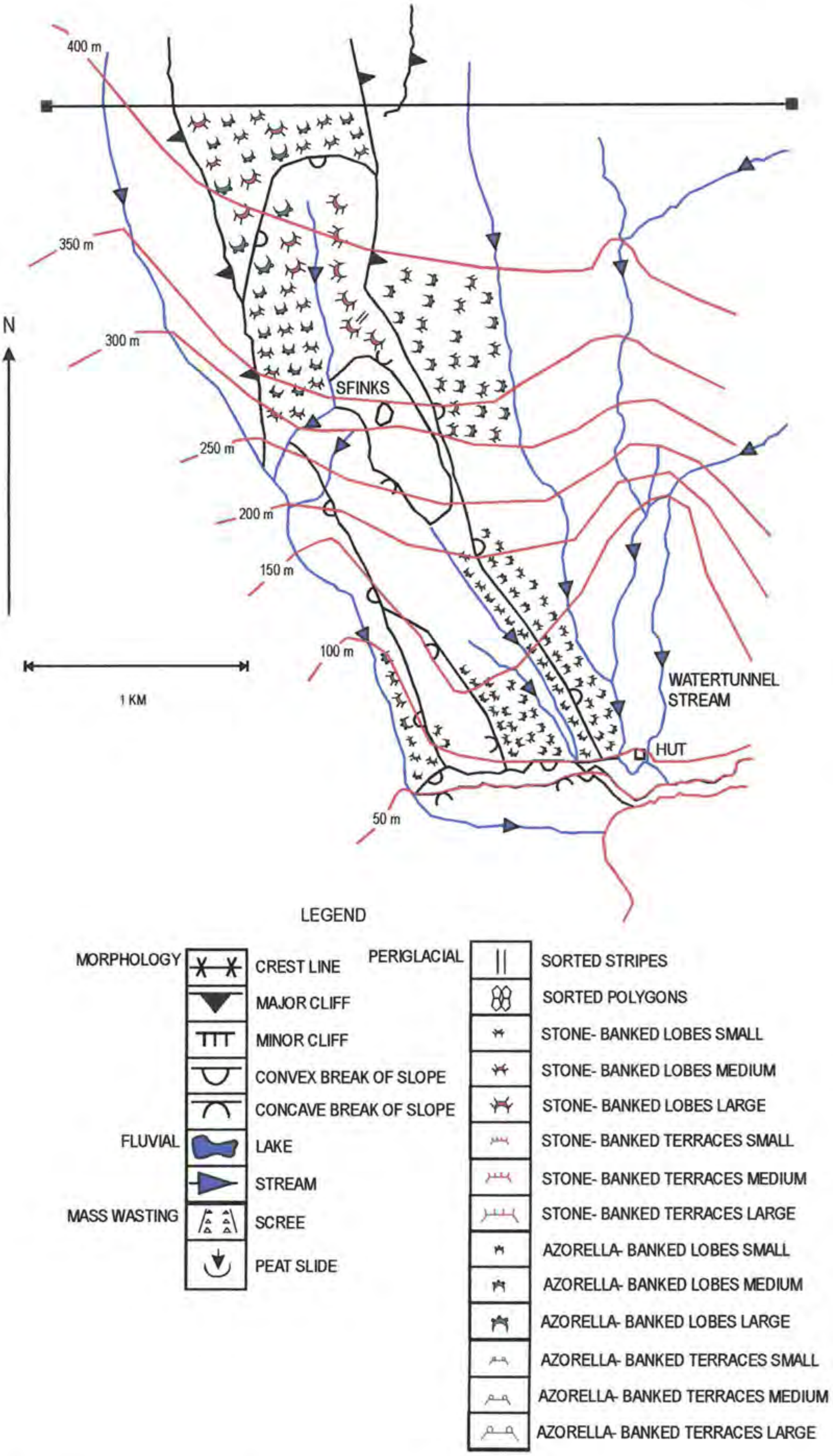

Figure 36: Sfinks Periglacial and Mass Movement Features