CHAPTER 1

Background, setting and research problem

1.1 Introduction

Over the last decade (1989-1999) there has been an increase in the number of studies of both past and current geocryological activities and landforms in southern Africa (Grab, 1998, 1999). These studies are concerned with the way particular cryogenic processes have modified, and continue to modify, the high summit regions of the subcontinent. Following Troll's (1944) paper on southern African geocryology, the importance of cryogenic studies in southern Africa was realised, leading to a substantial increase in publications after 1960 (Fig. 1.1).

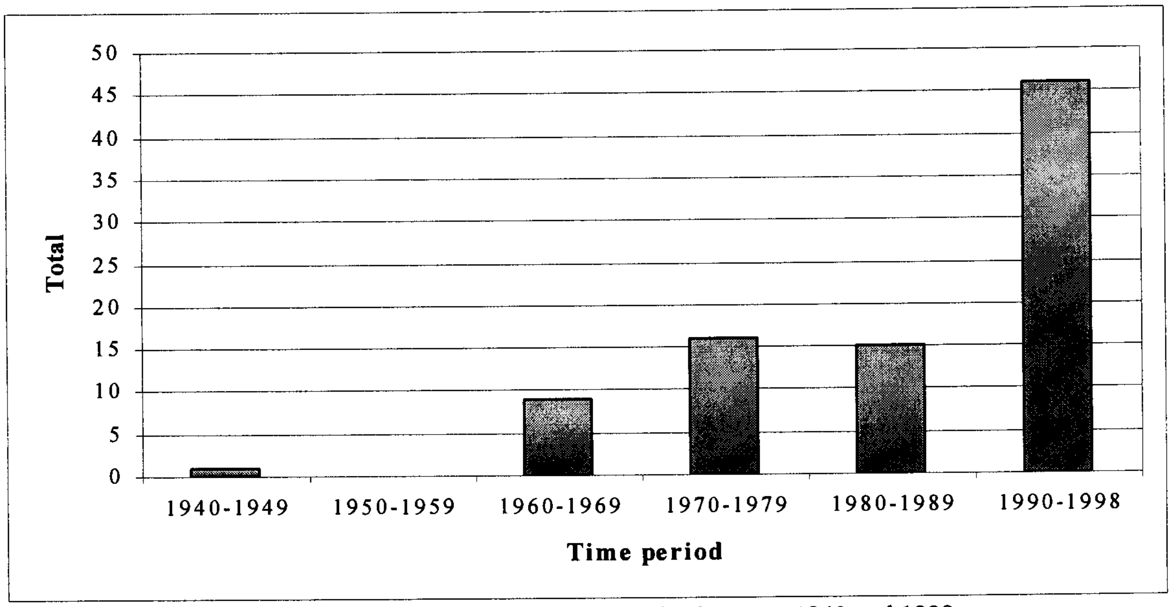

Figure 1.1: Cryogenic research publications in southern Africa between 1940 and 1998.

While contemporary activity is useful in the broader context of current environmental and earth science, palaeoenvironmental studies are important for the reconstruction of past climates. Superficial features are widespread throughout southern Africa (Grab, 1997a) and when sufficiently well preserved (Dewey, 1988), are used by researchers to establish:

- Pleistocene palaeoclimatic sequences (e.g. Sparrow, 1971),
- temperature fluctuations of the Quaternary (e.g. Hall, 1991a; Boelhouwers, 1994),
- the intensity and specific conditions of past climates (e.g. Marker, 1994a; Grab, 1999), and
- the reconstruction of a Pleistocene snowline elevation for the subcontinent (e.g. Hastenrath, 1972; Fitzpatrick, 1978).

Cryogenic research can thus be viewed within the broader context of climate change studies where assessing the past ultimately helps researchers to predict future trends. Climate has always been a major determinant of human activities, but over the last two centuries the activities of humankind have increasingly become a determinant of climate on global scale (Tyson, 1993; February, 1994a). Therefore, it has become important to understand the processes involved in climatic change and the nature of the changes taking place to forecast future events (Tyson, 1993), and in refining General Circulation Models currently used to predict atmospheric responses to global warming (Partridge, 1990; Partridge *et al.*, 1990; Hecht, 1997). Despite current research, there is a need to develop other methods of establishing longer climatic records than presently at our disposal (February, 1994a), and this involves many disciplines, e.g. biology, biogeography, climatology, pedology, palynology, botany, zoology and geomorphology (Partridge *et al.*, 1990; Grab, 1997a). Geomorphology is important in this context as the landscape responds to climatic fluctuations by generating processes which, in turn, produce products deposited as recognisable superficial forms (Dewey, 1988). It is logical to assume that landscapes react even more rapidly to extreme climatic oscillations, such as that of the Last Glacial Maximum (LGM).

1.2 The research problem

Because of a general lack of knowledge of palaeoclimates in southern Africa, more information relating climatic and geomorphic conditions during the Quaternary is required (Hall, 1991a, 1994; Le Roux, 1991; Marker, 1991a). In this regard research has focussed on cryogenic geomorphology in the high summit areas of southern Africa to establish the extent of contemporary and relict features in these regions (Sumner & Meiklejohn, 2000).

However, problems exist in interpreting surviving relict forms (Grab, 1996a). A number of superficial cryogenic features have been recognised and attributed to either Pleistocene glaciation or periglacial activity (e.g. Linton, 1969; Borchert & Sänger, 1981; Lewis, 1987;

Marker, 1992; Lewis & Hanvey, 1993; Grab, 1996a). However, supportive evidence for a glacial hypothesis is insufficient and Pleistocene periglacial activity is subject to considerable debate (e.g. Le Roux 1990, 1991; Marker, 1990a, 1991b; Hall, 1991a, 1994; Sumner, 1995). The arguments and difficulties currently facing southern African glacial and periglacial research will be discussed in Chapter 2, but are summarised as follows:

- Despite the relatively large body of research, the significance of many relict landforms remains difficult to interpret.
- The spatial extent of specific features and their associative processes are unknown.
- There is insufficient data regarding cryogenic activity during the Quaternary, which has resulted in contradicting qualitative interpretations of the palaeoclimate.
- The origin of relict landforms has seldom been interpreted within a larger palaeo-environmental context.
- There is an apparent lack of rigour in palaeocryogenic research.
- Spatial and temporal resolution of Quaternary cryogenic activity is poor.

Certain specific problems associated with cryogenic research in southern Africa can be identified and summarised as follows:

- Many relict landforms have been identified and are believed to be indicators of cold past conditions, while the significance of these features is difficult to interpret. This is mainly because the intensity and spatial distribution of past processes, whether glacial, periglacial or otherwise, are unknown.

- There are no conclusive data that suggest glacial conditions in the Drakensberg/Lesotho Mountains and along the Great Escarpment during the Quaternary.

- The spatial and temporal extent of both palaeoglacial and palaeoperiglacial activity has not previously been described.

- The uncertainty surrounding southern African cryogenic studies can be coupled to poor spatial and temporal resolution of data, contradictory quantitative and qualitative interpretations, and to a lesser extent, a lack of simple self-evident terminology for southern African conditions (see Chapter 2).

- There is a need to explain the origin of landforms ascribed to periglacial and glacial environments within a larger, sound theoretical framework and to shift from a single-cause perspective to an interactive perspective (see Chapter 3).

It is evident that there is a need for a more rigorous approach in southern African cryogenic studies (as also noted by Hall, 1992), as well as better understanding of relict features and processes and the palaeoenvironment in which they have developed. An objective data source of existing knowledge of the Quaternary in southern Africa will facilitate this process of understanding by providing a comprehensive overview of the current situation from which the scientific community can identify areas for future research.

1.3 Aims and objectives

The general aim of the study will be to expand on current knowledge of relict features and processes, thereby facilitating the reconstruction of the Pleistocene environment by means of a reliable data source for future verification. Specific aims and objectives are:

- to provide an objective data source to challenge specific research problems, thus adding to existing Quaternary knowledge;

- to gain a better understanding of the intensity and spatial distribution of relict features and processes, and ultimately contribute towards a reconstruction of the southern African Quaternary palaeoenvironment.

In addition, the study aims to create avenues for future research that will contribute towards a better understanding of the processes produced by climate change. Precipitation, snowline elevation and altitudinal zonation for relict features of the Pleistocene in southern Africa are important issues that need further research.

It is appropriate to focus attention on past episodes of climatic change as analogues for likely future changes (Partridge, 1990; Partridge *et al.*, 1990; February, 1994a, 1994b). In the face of human induced global climate changes, it is imperative to establish longer climatic data records. Given the dependence of cryogenic activity on the climate, it is reasonable to assume that periglacial and glacial research will provide an important avenue for Quaternary studies in southern Africa.

1.4 Study area

The study area, as defined by the literature, comprises the High Drakensberg, Lesotho Mountains, the Great Escarpment, the Eastern Cape Mountains, and the Western Cape Mountains (Fig. 1.2). These areas represent the highest elevations in southern Africa and hold the key in assessment of large-scale altitudinal zonation. Mountain environments react sensitively to climatic changes, which manifests itself in a variety of phenomena (Hastenrath & Wilkinson, 1973; see Chapter 2).

The different parts of the study area each display its own characteristic lithology, climate and temperature regimes. The dominant lithology of the Drakensberg and Lesotho Mountains is basalt, which overlies sandstones and forms part of the Karoo Sequence (Fig. 1.3, 1.4 and Table 1.1; SACS[1], 1980; Moon & Dardis, 1988). The basalts are particularly prone to chemical weathering (Van Rooy & Nixon, 1990; Hall, 1992; Van Rooy, 1992; Van Rooy & Van Schalkwyk, 1993). Prominent dolerite dykes are a familiar sight and the drainage pattern is complex and deeply incised (Nicol, 1973; SACS, 1980; Boelhouwers, 1991a; Marker, 1991b; Meiklejohn, 1994; Grab, 1996a). The dominant lithology of the Eastern Cape Mountains is quartzite with several resistant dolerite dykes and sills, such as those comprising Elandsberg, Hogsback, Katberg and Gaika's Kop (SACS, 1980; Moon & Dardis, 1988; Meadows & Meadows, 1988). The Western Cape Mountains consist of the Tafelberg Group sandstones, with subordinate shales, quartzites and conglomerates (SACS, 1980; Moon & Dardis, 1988).

Lesotho, the Kwa-Zulu Natal Drakensberg Escarpment and parts of the Western Cape Mountains receive the highest annual rainfall for the study area, approximately 1 800 to 3 300mm p.a. (Fig. 1.5). The High Drakensberg and Lesotho Mountains are located in a summer rainfall area with cold and dry winters and mild and wet summers (Schulze, 1965; Schmitz & Rooyani, 1987; Hanvey & Marker, 1992; Grab, 1996b). Snow sometimes accumulates on the high slopes and cutbacks during colder months (Marker, 1991b; Hanvey & Marker, 1992; Grab, 1996a). The Eastern Cape climate is relatively moist with an all-year precipitation regime and average annual totals in excess of 1 000mm (Fig. 1.5). Snow may fall in winter on peaks above 900m (Meadows & Meadows, 1988). The Western Cape Mountains receive winter precipitation with totals exceeding 2 000mm (Fig. 1.5). The whole of the study area is subject to regular frost occurrences between April and September (Schulze, 1965; Meadows & Meadows, 1988; Grab, 1996b, 1997a).

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[1] South African Committee for Stratigraphy.

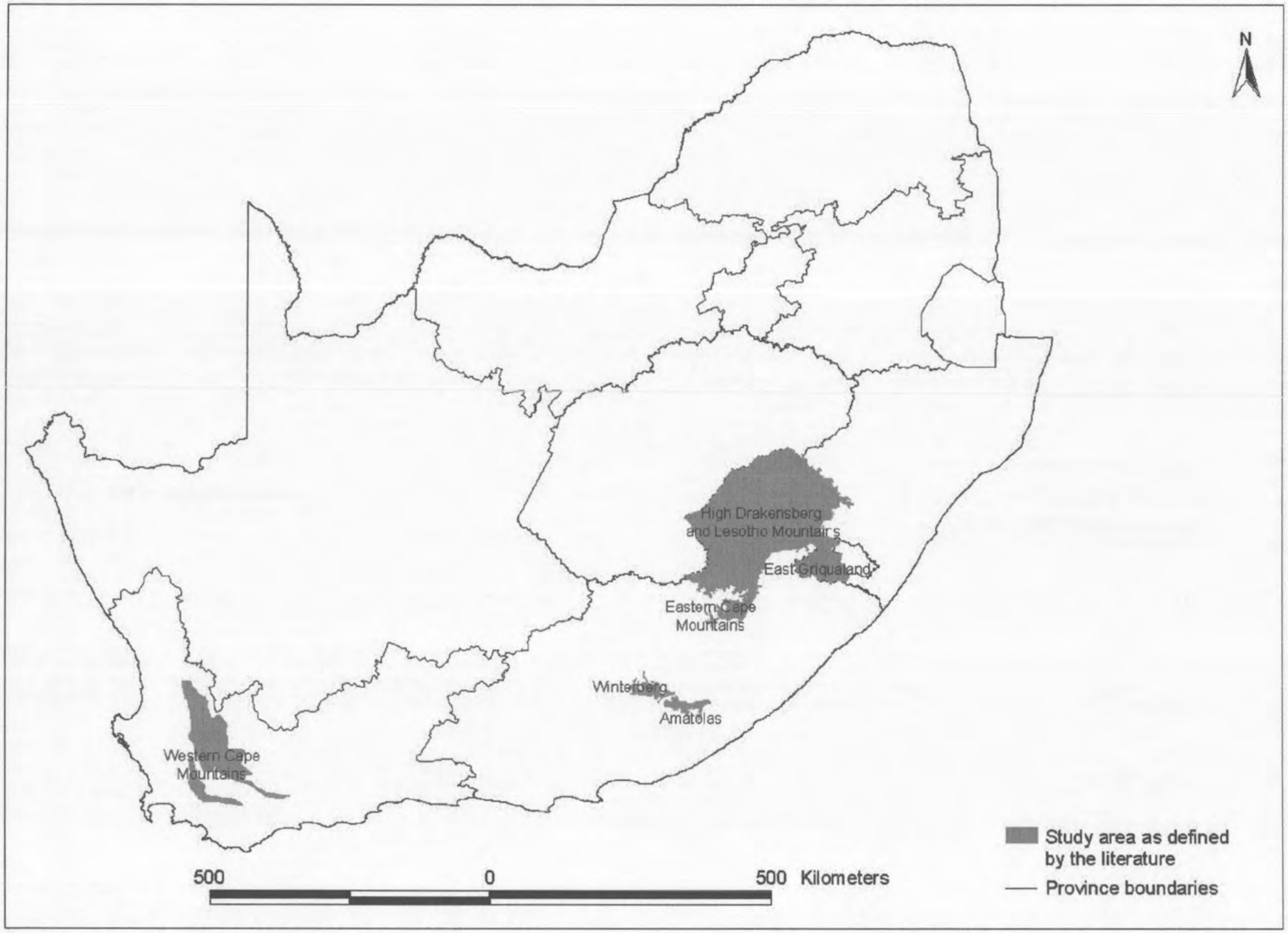

Figure 1.2: The study area(s) as defined by the literature.

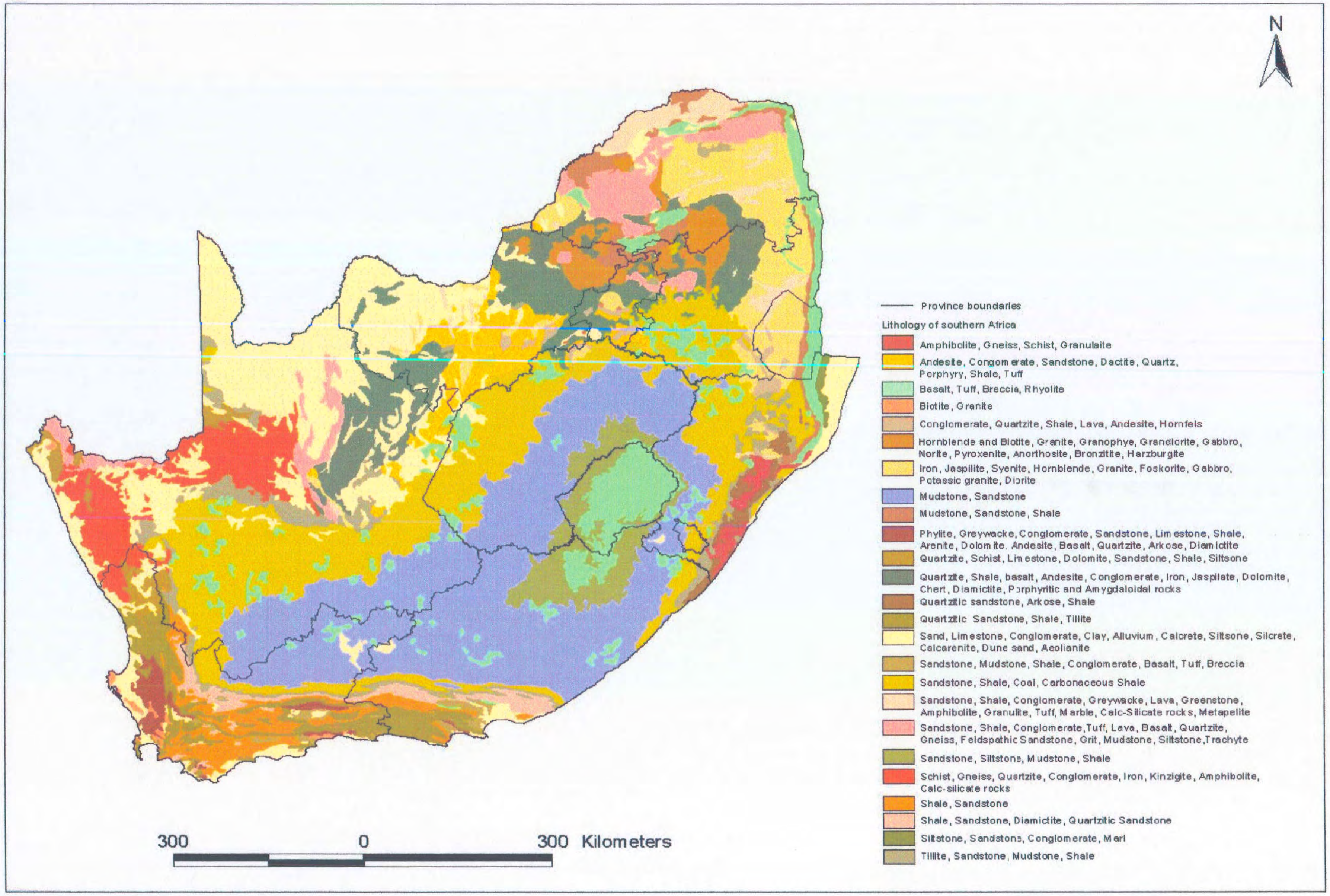

Figure 1.3: Lithology of southern Africa (Enpat).

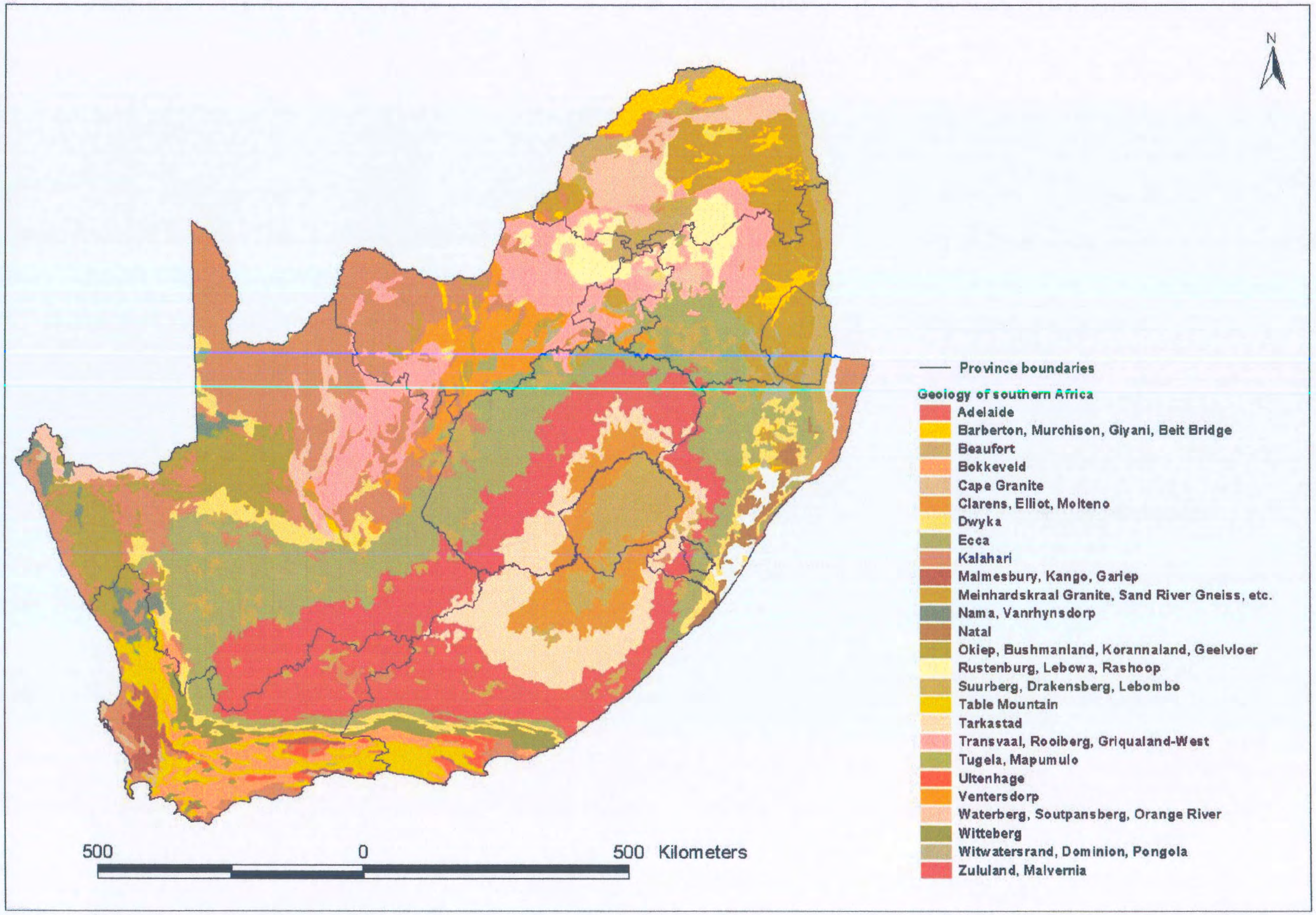

Figure 1.4: Geology of southern Africa (Enpat).

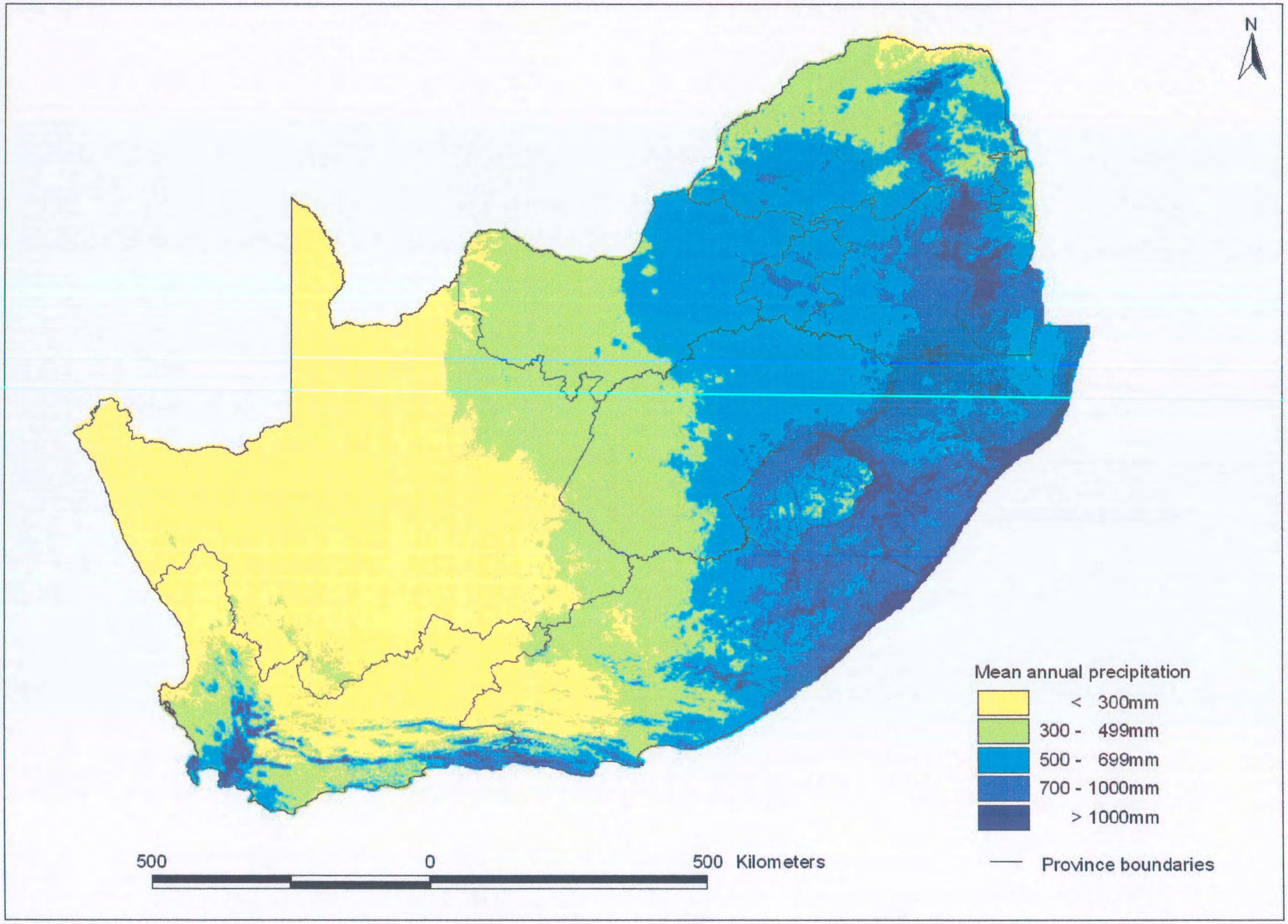

Figure 1.5: Mean annual precipitation for southern Africa (Schulze, 1998).

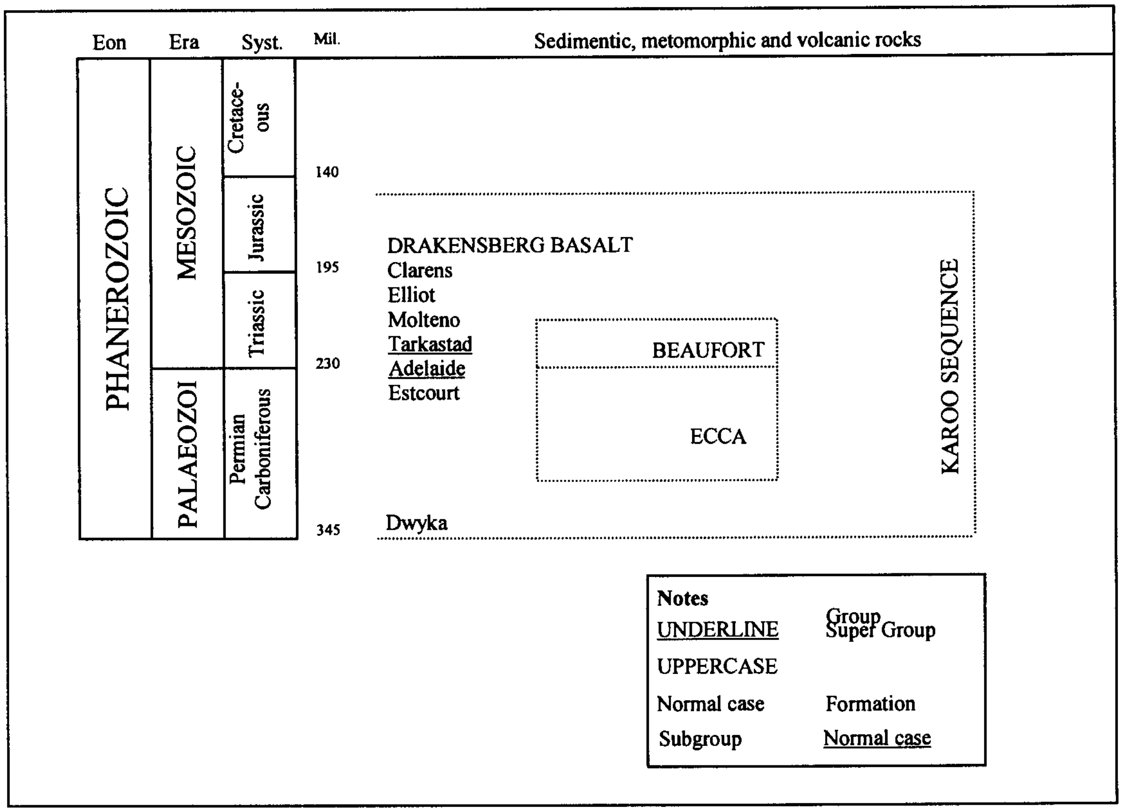

Table 1.1: Part of the geological time scale of southern Africa (after Wellington, 1955; King, 1963; SACS, 1980).

Mean annual air temperatures (MAAT) for the High Drakensberg and Lesotho Mountains as well as the Eastern Cape Mountains are relatively low, ranging between 1° and 12°C (Fig. 1.6). Along the main Escarpment and elevations above 2 800m, a MAAT of between 1° and 4°C occur (Backéus, 1989; Grab, 1996a, 1997a). The Western Cape Mountains have higher MAAT of between 10° and 20°C (Fig. 1.6).

Southern African mountain areas currently experience a *sub-periglacial* climate (Lewis, 1987; Meiklejohn, 1992; Boelhouwers, 1991b, 1995a; Hanvey & Marker, 1992; Marker, 1992, 1994b, 1995a). Seasonal frost action, generating micro-periglacial forms, prevails at altitudes above 1 900m a.s.l. (Boelhouwers, 1988; Marker, 1992; Hanvey & Marker, 1992), but cryogenic action is limited somewhat during dry periods in winter (Marker, 1992). The resultant cryogenic features are located along or adjacent to the Lesotho/Natal Drakensberg and Eastern Cape Escarpments (Lewis, 1987). No current permafrost has been recorded in southern Africa (Marker, 1995a; Lewis, 1996a).

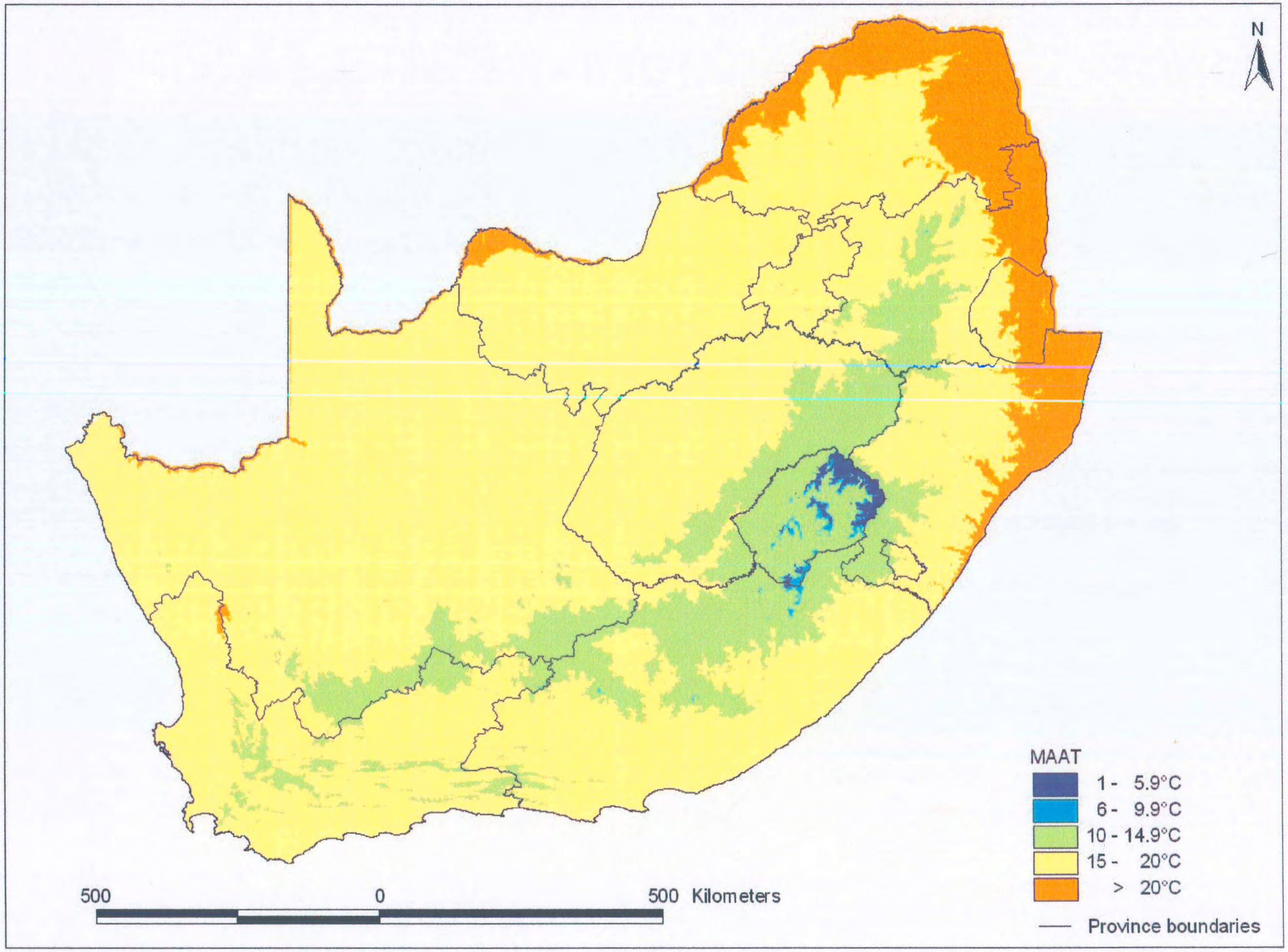

Figure 1.6: Mean annual air temperatures for southern Africa (Schulze, 1998).

To accomplish the study aims and objectives aforementioned, a database system approach within a geographical information system (GIS) framework was chosen (Chapter 3). Such a system can arrange and classify data and is a reliable and objective aid in problem solving. Through GIS-based analysis techniques it is hoped to achieve a better understanding of palaeocryological processes and potentially calculate prevailing moisture conditions, the Pleistocene snowline elevation and altitudinal zonation for relict periglacial features in southern Africa. The spatial database will serve as an information source for future research. Specific problems and hypotheses within current research will be addressed through the database and GIS-techniques in Chapter 5.

CHAPTER 2

Cryogenic research in southern Africa: geomorphic evidence and problems experienced within the discipline

This chapter is a review of studies in the high summit regions of southern Africa focusing on the main debates and problems. Research can roughly be divided into two groups (Fig. 2.1), namely research about present-day cryogenic features and processes, and studies of relict cryogenic processes and forms. Little is known of the formative processes of relict forms in southern Africa, and existing theories, hypotheses and views are apparently contradictory. These will be discussed in detail below.

2.1 The southern African cryogenic landscape in world context

Present glacial landscapes are landscapes covered with, or consisting of, glaciers or glacial ice that are remnants of the Last Glacial Maximum (LGM) (Sugden & John, 1976; Van der Meer, 1997; Ahnert, 1998). Glacial landscapes are subject to active glaciation and glacial processes recognisable in a variety of phenomena (Goudie *et al.*, 1985; Clark, 1998). Current glaciers are usually in transit and inclined to erode the underlying and surrounding topography (Van der Meer, 1997; Clark, 1998). There are several types of present-day glaciers and icecaps, normally categorised according to size (Table 2.1). The largest glaciers today are those covering Greenland and Antarctica.

The geological history of the earth has known several ice ages that included a number of glacials and interglacials. The last ice age, which ended about 14 000B.P. (Broecker & Denton, 1989; Marker, 1994b, 1995a; 1998; Hanvey & Marker, 1994; Lewis, 1996b; Partridge, 1997 etc.) saw large sections of the Northern Hemisphere covered in extensive ice sheets (Embleton & King, 1975; Lewis, 1996b; Van der Meer, 1997; Ahnert, 1998 etc.). Southern Africa experienced at least seven glaciations of which the greatest one was the Permo-Carboniferous Dwyka glaciation that occurred 300 million B.P. (Table 1.1; Du Toit, 1922; Truswell, 1977; SACS, 1980; Lewis, 1996b). Some researchers argue for at least one Pleistocene glaciation on the highest mountains, since southern Africa experienced periods of depressed temperatures apparently more or less concurrent with Northern Hemisphere temperature shifts (Harper, 1969; Hanvey & Marker, 1994; Marker, 1998).

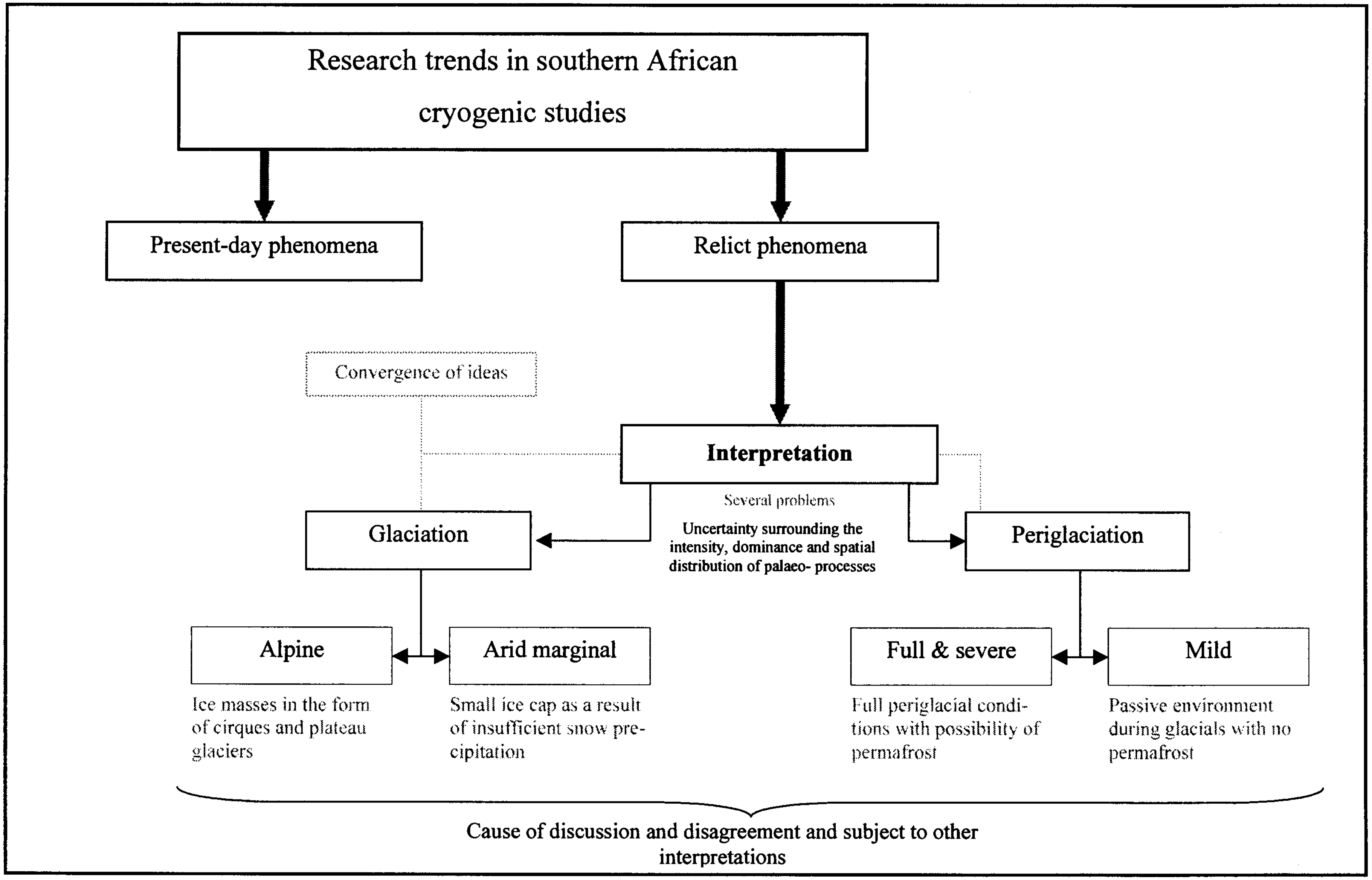

Figure 2.1: Cryogenic research in southern Africa.

Type of glacier	General description
Ice sheets	A continuous mass of ice and snow of considerable thickness and covering large areas of rock or water. Ice sheets occupy most of the continent of Antarctica and Greenland at present and are not influenced by underlying topography.
Icecaps	A dome-shaped glacier, smaller than an ice sheet, covering high altitude areas. Icecaps are not influenced by the underlying topography.
Valley glaciers	A glacier that occupies an existing valley. Valley glaciers are widespread in the Rocky Mountains, Himalayas and Alps.
Alpine glacier	A valley glacier formed in an amphitheatre among mountain summits descending a mountain valley and ending by melting or spreading out into a piedmont glacier.
Outlet glacier	A valley glacier originating from the margin of an icecap or ice sheet.
Cirque glacier	Cirque glaciers form in mountains in hollows called *cirques*.
Névé field	A névé field is not much more than a snow patch in which the snow has scarcely been turned to ice (névé). Usually there is not much movement in such ice patches.
Other	
Volcano glaciers	Aprons of glaciers on and around isolated volcanoes, e.g. Andes Mountains, Rocky Mountains.
Regenerated glaciers	Found below very steep slopes. A glacier at the edge of a precipice may discharge large blocks of ice which fall down. At the bottom of the precipice the ice blocks freeze back together again and the glacier flows further. These glaciers are found in all high mountain regions on earth.
Piedmont glaciers	Piedmont glaciers are found especially in arctic regions and also called ice tongues. Piedmont glaciers begin life as part of an icecap. These glaciers are long and thin and lie in shallow valleys.

Table 2.1: A summary of the types of glaciers found in current glacial landscapes (after Van der Meer, 1997; Clark, 1998).

Current periglacial environments are characterised by cryogenic conditions, processes and landforms (Fig. 2.2) associated with cold, nonglacial environments (Dylik, 1964; French, 1976, 1996; Washburn, 1979), regardless of their proximity to a glacier (Washburn, 1979; French, 1996). Most (but not all) periglacial environments are characterised by permafrost, and are dominated by frost action (Dylik, 1964; French, 1976, 1996; Washburn, 1979; Goudie *et al.*, 1985; Clowes & Comfort, 1987; Thorn, 1991). Periglacial environments are prevalent in high altitudinal and tundra regions, but may be encountered below the tree line and in alpine regions of temperate latitudes, such as the High Drakensberg and Lesotho Mountains (French, 1996). Frost action and/or permafrost are the most important indicators of a periglacial environment (Embleton & King, 1975; French, 1976, 1996), but permafrost is not a necessary attribute of periglacial regions (Thorn, 1991). Other processes not restricted to, but important on account of their high frequency in periglacial regions, are ice segregation, seasonal frost action, frost (cryogenic) weathering, and rapid mass movements (Embleton & King, 1975; Goudie *et al.*, 1985; French, 1996).

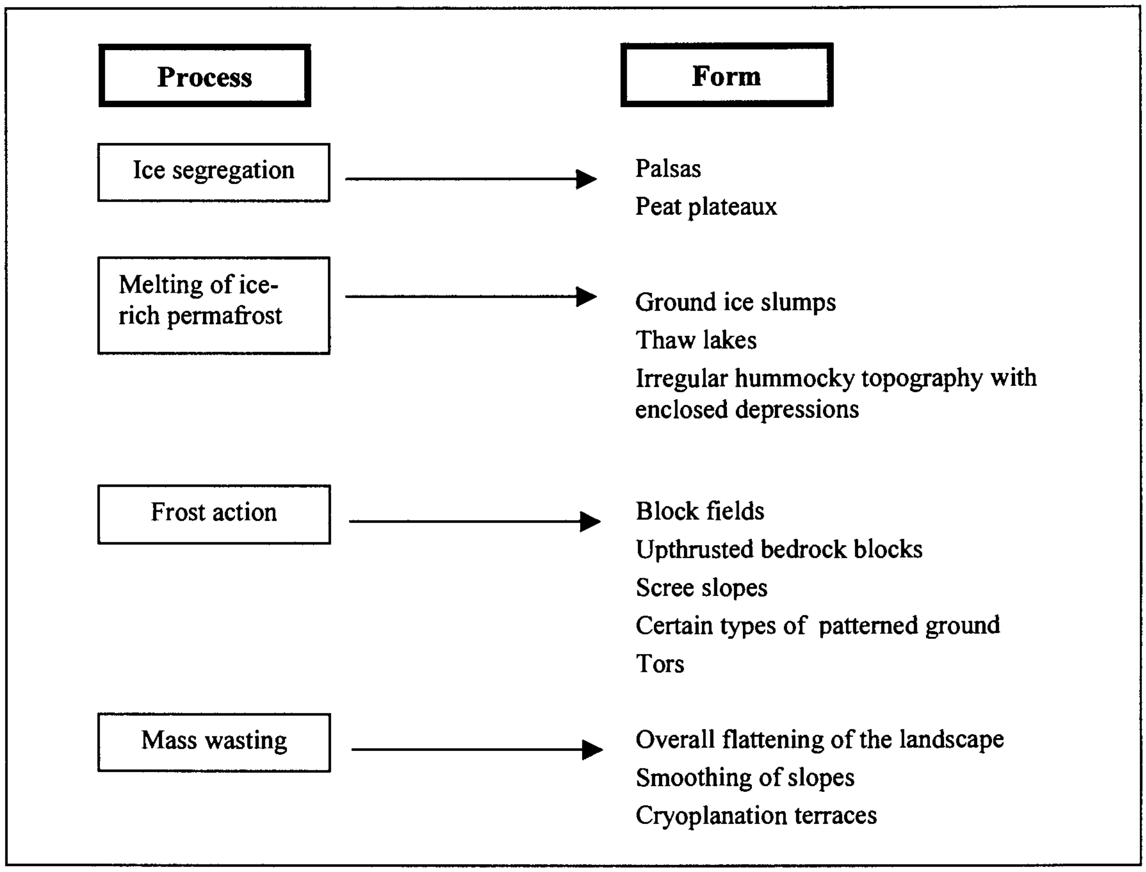

Figure 2.2: A summary of aggradational features commonly found, but not exclusive to, periglacial environments (after Goudie *et al.*, 1985).

2.2 Present-day periglacial phenomena in southern Africa

The High Drakensberg and Lesotho Mountains consist of the highest elevations of the Great Escarpment of southern Africa and separate the high interior from the low coastal regions (King, 1963; Hastenrath & Wilkinson, 1973; Boelhouwers, 1991a). The mountains reach heights of 3 000m (King, 1972; Watson, 1988) and reacts most sensitively to climatic change (Hastenrath & Wilkinson, 1973). Present-day high mountain areas on the subcontinent display a *sub-periglacial* nature (Lewis, 1987; Meiklejohn, 1992; Boelhouwers, 1991b, 1995a; Hanvey & Marker, 1992; Marker, 1992, 1994b, 1995a) despite their relatively low altitude and latitude (Hastenrath, 1972; Lewis, 1987; Marker, 1992, 1998), and have also been classified as:

- Marginal montane periglacial (Lewis, 1987; Boelhouwers, 1991a).
- Borderline periglacial (Boelhouwers, 1991b; Hall, 1994).
- Marginal frost action environment (Boelhouwers, 1994, 1995a; Grab, 1997a, 1997b).

For the purposes of this study the term *sub-periglacial* will be used. Sub-periglacial features cluster along or adjacent to the Drakensberg Escarpment of Lesotho, Kwa-Zulu Natal, the Eastern and the Western Cape, but may be more widespread than is generally assumed (Lewis, 1987). In northern Lesotho it appears that the sub-periglacial zone exists above 2 900m a.s.l. (Hanvey & Marker, 1992), lowering down to about 2 800m at 30°30'S (Boelhouwers & Hall, 1990), 1 900m a.s.l. in the Northeast Cape, 1 800m a.s.l. on the Matroosberg, and at 1 700m a.s.l. on the Waaihoek Mountains in the Western Cape (Boelhouwers, 1991b). The lower limit of the present-day sub-periglacial zone shows a decline in altitude with higher latitude (Marker, 1995a). Knowledge of periglacial environments in southern Africa, however, is still very much in its infancy (Hall, 1992; Grab, 1994), and the exact extent of the modern periglacial environment remains to be established (Lewis, 1987; Meiklejohn, 1992; Grab, 1997a). Little is known about the spatial and temporal variations of these sub-periglacial phenomena and of variability of local environmental controls other than climate (Boelhouwers, 1991a; Grab, 1997a).

It is interesting to note that active periglacial processes occur at lower altitudes (1 000 to 1 500m a.s.l. lower than in other periglacial regions of the world), in areas that receive strong insolation and have mean annual temperatures (MAAT) of between +4°C and +7°C, at least 6°C higher than postulated for a sub-periglacial zone (Boelhouwers, 1991a; Hanvey & Marker, 1992). Hanvey & Marker (1992) contribute this to the reduction of vegetation cover by fire and overgrazing, which, in turn, promotes frost action. Of course this observation warrants further discussion, but at this stage it is beyond the scope of the present study. It is more important, however, to realise that the existence of active periglacial microforms demonstrates that conditions at present are favourable for the formation of marginal periglacial phenomena (Boelhouwers, 1991a; Hanvey & Marker, 1992). Phenomena that have been studied and classified as current periglacial in origin are summarised in Table 2.2 and Table 2.3.

PRESENT-DAY PERIGLACIAL FEATURES		
Category	**Type of feature**	**Author**
Patterned ground	Sorted circles	Dardis & Granger (1986) Boelhouwers (1991a; 1994; 1995b)
	Nonsorted circles	Harper (1969) Hastenrath & Wilkinson (1973) Borchert & Sänger (1981) Boelhouwers (1991a)
	Thufur (nonsorted circles)	Harper (1969) Hastenrath (1972) Hastenrath & Wilkinson (1973) Lewis (1987; 1996b) Boelhouwers (1991a) Hanvey & Marker (1992) Grab (1994; 1997b)
	Sorted nets	Hastenrath & Wilkinson (1973) Boelhouwers (1991a)
	Sorted polygons	Harper (1969) Hastenrath & Wilkinson (1973) Lewis (1987) Boelhouwers (1991a; 1995b) Hanvey & Marker (1992)
	Nonsorted polygons	Harper (1969) Hastenrath (1972) Lewis (1987; 1996b) Hanvey & Marker (1992)
	Nonsorted stripes	Lewis (1987) Boelhouwers (1991a; 1994; 1995b)
	Sorted step	Borchert & Sänger (1981)
	Nonsorted step	Boelhouwers (1991a; 1995b)
	Sorting (gravel)	Hastenrath (1972)
Snow and ice features	Ground ice	Dardis & Granger (1986) Hanvey & Marker (1992)
	Ice-wedges	Harper (1969)
	Needle ice	Hastenrath (1972) Hastenrath & Wilkinson (1973) Lewis (1987) Sänger (1988) Hanvey & Marker (1992)
	Segregation ice	Grab (1996b)
	Turf exfoliation	Hastenrath (1972)
Solifluction features	Solifluctional overforming or smoothing	Hastenrath & Wilkinson (1973)
	Stone-banked terraces	Dardis & Granger (1986) Boelhouwers (1991b; 1994; 1995b) Lewis (1996a)
Other features	Dislocation of stones	Borchert & Sänger (1981)
	Slip scars	Harper (1969)
	Terracettes	Harper (1969) Hastenrath (1972) Hastenrath & Wilkinson (1973) Dardis & Granger (1986) Verster & Van Rooyen (1988) Watson (1988) Boelhouwers (1991a; 1991b) Boelhouwers & Hall (1990) Hanvey & Marker (1992)

Table 2.2: Present-day periglacial features in southern Africa.

PRESENT-DAY PERIGLACIAL PROCESSES		
Category	**Type of process**	**Author**
Freeze-thaw	Freeze-thaw	Harper (1969) Hanvey & Marker (1992)
	Periglacial processes	Hastenrath (1972) Borchert & Sänger (1981) Hanvey & Marker (1992)
	Ground freeze	Boelhouwers (1995b) Grab (1997b)
Frost and cryogenic action	Frost heave	Hastenrath (1972) Dardis & Granger (1986) Hanvey & Marker (1992)
	Frost action	Harper (1969) Hastenrath (1972) Hastenrath & Wilkinson (1973) Lewis (1987; 1996b) Grab (1994)
	Frost wedging	Harper (1969) Hastenrath & Wilkinson (1973) Borchert & Sänger (1981)
	Frost creep	Hanvey & Marker (1992) Boelhouwers (1994; 1995b)
	Frost shattering	Hanvey & Marker (1992)
	Frost creep	Boelhouwers (1991a)
	Cryoturbation	Borchert & Sänger (1981)
Gelifluction	Gelifluction	Dardis & Granger (1986) Hanvey & Marker (1992) Boelhouwers (1994) Lewis (1996a)
Solifluction	Solifluction	Hastenrath (1972) Hastenrath & Wilkinson (1973) Borchert & Sänger (1981) Sänger (1988) Boelhouwers (1991a; 1995b)
	Solifluctional smoothing	Hastenrath & Wilkinson (1973)
Soil and mass movement	Mass movement	Hastenrath (1972) Verster & Van Rooyen (1988)
	Surface creep	Sänger (1988)
	Soil creep	Borchert & Sänger (1981) Verster & Van Rooyen (1988) Boelhouwers (1991a)
	Sheet-wash	Watson (1988)
Other processes	Contraction	Hanvey & Marker (1992)
	Solution	Verster & Van Rooyen (1988)
	Desiccation	Hanvey & Marker (1992)

Table 2.3: Present-day periglacial processes in southern Africa.

2.3 Relict phenomena in southern Africa

The High Drakensberg and Lesotho Mountains also display a wide range of relict features (Fig. 2.1; Tables 2.4 and 2.5) of which most are believed to have formed during the LGM between 16 000 and 30 000B.P. (Lewis, 1996b). However, there are features older than 30 000B.P. (Lewis, & Dardis, 1985; Marker, 1992, 1994b; Lewis, 1996b), possibly deposited during the Quaternary cold phases before the LGM (Tyson *et al.*, 1976; Partridge, 1997). During the LGM temperatures were probably 5° to 6°C colder than today[1,2], and experienced several colder and warmer periods with a glacial maximum between ±14 000 and 21 000B.P. (Van Zinderen Bakker, 1963, 1964, 1966; Hastenrath, 1972; Deacon *et al.*, 1984; Vogel, 1985; Partridge *et al.*, 1990; Marker, 1991b, 1995a, 1998; Meiklejohn, 1992; Hanvey & Marker, 1992; Partridge, 1997). During the Quaternary cold spells, and especially the LGM, cryogenic processes must have been more widespread and severe on the subcontinent (Meiklejohn, 1992). It is generally accepted that the physical environment was thus changed, apparent from ample evidence that has been accumulated from a variety of palaeoecological sources, although the nature and extent of the Late Quaternary and Early Holocene environmental change remains unclear for most of the subcontinent (Dewey, 1988). If one considers that global temperatures were colder 18 000B.P. than present and large areas of the world in middle and high latitudes were inundated by glacial ice (Lewis, 1996b), this theory seems viable.

The LGM ended suddenly and simultaneously in both hemispheres at ±14 000B.P. with a rapid amelioration in annual temperatures (Broecker & Denton, 1989; Marker, 1995b; Hanvey & Marker, 1994). During the early southern African Holocene (5 000 to 8 000B.P.) warmer and wetter conditions followed (Partridge *et al.*, 1990; Marker, 1994b; Partridge, 1997). After 5 000B.P. little variation in temperature is identified, and from 2 000 to 1 000B.P. wetter conditions again dominated, as illustrated in Table 2.6 (Tyson, 1993; February, 1994a; Hanvey & Marker, 1994; Marker, 1994b, 1995a, 1998; Partridge, 1997).

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[1] Van Zinderen Bakker (1964; 1976), Harper (1969) and Vogel (1983) have extrapolated a 5.5°C to 9°C late-Pleistocene temperature drop for the highlands of Lesotho. Talma *et al.* (1974) extrapolated an 8°C to 9.5°C drop for the Wolkberg caves at 19 800B.P. Grab (1996a) and Talma (1989) calculated temperature drops of 7.5° at 33°30'S and 5°C at 24°15'S for the period between 16 000 and 20 000B.P. However, the most conservative estimate is usually accepted and cited as between 5° and 6°C (Sparrow, 1971; Deacon *et al.*, 1984; Hanvey & Marker, 1992; Marker, 1992 etc.).

[2] The reconstruction of a temperature decrease of higher altitudes is only possible under the assumption of a constant lapse rate (6.5°C km^{-1}) (Hastenrath, 1972).

RELICT FEATURES		
Category	**Type of feature**	**Author**
Large hollows and associated features	Hollows reminiscent of nivation cirques	Harper (1969) Marker & Whittington (1971) Sparrow (1971)
	Cirque-like hollows	Sparrow (1964) Dyer & Marker (1979)
	Cirques	Sparrow (1967a) Harper (1969) Hastenrath (1972) Borchert & Sänger (1981) Sänger (1988)
	Erosional hollows	Hastenrath & Wilkinson (1973) Nicol (1973) Marker (1989; 1991a) Lewis & Hanvey (1991) Marker (1990a, 1990b) Hanvey & Marker (1994)
	Protalus rampart	Marker (1989) Lewis (1994; 1996a)
	Trough-like valleys	Lewis (1996b)
	Trough's end	Lewis (1996b)
Glacial features	Avalanche deposits	Lewis & Dardis (1985) Marker (1990a)
	Glacial deposits	Sänger (1988)
	Glacial pavements	Sänger (1988)
	Glacial polished surfaces	Harper (1969) Borchert & Sänger (1981) Sänger (1988) Marker (1989)
	Hanging valleys	Lewis (1996b)
	Pinnacles	Borchert & Sänger (1981)
	Arêtes	Sparrow (1967b) Sänger (1988)
	Glacial striations	Borchert & Sänger (1981) Lewis (1996b)
	Cutbacks	Hall (1994) Grab (1996a)
	Glaciers Cirque glaciers Valley glaciers Plateau glaciers	 Borchert & Sänger (1981) Sänger (1988) Sänger (1988) Sänger (1988)
	Moraines Cirque or terminal moraine Kame moraine Kame-terrace deposit Moraine	 Lewis (1996b) Lewis (1996b) Lewis (1996b) Sparrow (1967a) Borchert & Sänger (1981) Sänger (1988)
	Fluvio-glacial deposits	Sänger (1988) Lewis (1996b)
	Truncated spurs	Lewis (1996b)
Accumulations of coarse debris	Blockfields	Linton (1969) Sparrow (1971) Borchert & Sänger (1981) Sänger (1988)
	Blockstreams	Hagedorn (1984) Lewis (1996b)

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Accumulations of coarse debris- cont.	Screes	Sparrow (1967a) Marker (1986)
	Debris lobe & ridges	Sparrow (1967a) Nicol (1973) Lewis & Hanvey (1991) Grab (1996a)
	Rock glacier	Lewis & Hanvey (1993) Lewis (1996b)
Relict patterned ground	Sorted stripes	Boelhouwers (1994) Grab (1996b)
Snow and ice features	Fossilised permafrost layers	Fitzpatrick (1978)
	Ice-stripped areas	Sparrow (1967a)
	Ice-wedge casts	Lewis & Dardis (1985) Lewis (1996b)
	Ice-shattered ridges	Sparrow (1967a)
	Cryoplanation terraces	Hagedorn (1984)
Gelifluction features	Gelifluction sheets	Boelhouwers (1994)
	Head	Nicol (1973) Lewis & Dardis (1985) Lewis (1987)
Solifluction features	Geliflual deposits	Linton (1969)
	Solifluction lobes	Sparrow (1971) Marker (1989; 1992)
	Solifluction terraces	Harper (1969)
	Solifluctional mantles	Hastenrath (1972)
	Stone-banked lobe	Boelhouwers (1991a; 1991b; 1994)
	Solifluctional overforming	Hastenrath (1972)
Other features	Basalt steps	Harper (1969)
	Frozen ground phenomena	Borchert & Sänger (1981)
	Valley asymmetry	Sparrow (1964; 1967a) Harper (1969) Marker (1989) Meiklejohn (1992)
	Planation surfaces	Sänger (1988)
	Relict terracettes	Marker (1989)
	Grézes liteés	Lewis & Dardis (1985) Lewis & Hanvey (1988)

Table 2.4: The most important cryogenic relict features of southern Africa.

RELICT PROCESSES		
Category	**Type of process**	**Author**
Geliflual and gelifluction	Geliflual action	Linton (1969)
Snow and ice processes	Perennial snowbed growth	Nicol (1973) Dyer & Marker (1979) Lewis (1994)
	Nivation	Dyer & Marker (1979) Marker (1990b) Hall (1994) Lewis (1994)
Glacial processes	Glacial meltwaters	Nicol (1973) Hall (1994)
	Glaciation Glaciation Marginal (arid) glaciation Niche glaciation	Borchert & Sänger (1981) Marker (1991a; 1998) Hall (1994) Grab (1996a)
Frost and cryogenic action	Frost wedging	Harper (1969)
	Frost climate	Borchert & Sänger (1981)
	Cryogenic action	Hanvey & Marker (1994)
	Frost action	Nicol (1973)
Solifluction	Solifluction	Hanvey & Marker (1994)
Other processes	Inversion of the weathering profile	Linton (1969)

Table 2.5: Important processes thought to have modified the high summit areas of southern Africa.

Ages	**Palaeoclimates as compared to the present**
Before the LGM	Cold, but warmer than preceding cryogenic period.
24 000– 13 500B.P.	The LGM Sever cold prevailed.
13 500– 9 000B.P.	Temperature amelioration. This period of warmer and wetter conditions and temperature increase started suddenly and concurrently in both hemispheres.
9 000– 5 000B.P.	Early Holocene, which experienced drier conditions.
5 000– 3 000B.P.	Wetter and warmer conditions.
3 000– 2 400B.P.	Wetter conditions.
2 400B.P.– 900A.D.	Warmer and wetter conditions.
900– 1300A.D.	Warmer conditions, but with much variability. The highest temperatures are recorded for the 10th and 11th centuries. Between 600 and 900 AD temperature were variable, whilst between 250 and 600AD it was warmer. Between 100 and 200AD cooler conditions prevailed.
1300– 1850A.D. (650B.P.)	The Little Ice Age. Major instability and variability in temperatures are recorded. 1300 to 1500 was the coldest phase with an increase in temperatures between 1500 and 1675.
1850A.D. – present (100B.P.)	The Post Little Ice Age, which is the period of recovery and amelioration. However, anthropogenically induced temperature increases owing to greenhouse gases and global warming may be superimposed.

Table 2.6: A synopsis of Late Quaternary and early Holocene climatic changes in southern Africa (after Marker, 1995b; February, 1994a and Tyson, 1993).

Southern Africa had several climatic oscillations during the Quaternary and, with the possibility of a 5° to 6°C drop in MAAT and the existence of relict landforms, past conditions were probably cold enough for widespread cryogenic activity, particularly during the LGM (Hanvey & Marker, 1992). However, the subcontinental dimensions of southern Africa makes it unlikely for a uniform climate to have existed (Sparrow, 1971; Butzer, 1973; Grab, 1996a). Uncertainty stems from disputes over the intensity, dominance and spatial distribution of past processes (Boelhouwers, 1988). To explain what may have happened thousands of years ago, and to understand the processes responsible for the creation of relict forms, two opinions emerge in the literature, namely that of a *glacial origin*, and that of a *periglacial origin* for relict phenomena (Fig. 2.1), while many earth scientists in southern Africa remain sceptical about either (Le Roux, 1991, Tyson, 1986, Deacon & Lancaster, 1988 etc.).

2.3.1 A glacial origin for relict phenomena

Some researchers believe that southern Africa experienced some form of glaciation during the Pleistocene (e.g. Sparrow, 1964; Dyer & Marker, 1979; Borchert & Sänger, 1981; Lewis, 1987; 1996a; Hall, 1994; Grab, 1996a, etc.). Several factors are taken into account that may prove, or disprove, glaciation on the subcontinent but supporting evidence for glaciation remains unclear. Two views on Pleistocene glaciation in southern Africa have been proposed, namely an *alpine glaciation* and, alternatively, an arid *marginal glaciation* (Fig. 2.1).

2.3.1.1 <u>An alpine glaciation</u>

By an alpine glaciation (Fig. 2.1) it is presumed that the mountain areas of southern Africa were covered by ice masses (in the form of plateau glaciers), feeding several shorter valley glaciers (Borchert & Sänger, 1981; Maud & Partridge, 1987; Sänger, 1988; Hall, 1994; Lewis, 1996b) that would have formed at insolation-protected sites (Hall, 1991a; Le Roux, 1991; Marker, 1991a; Grab, 1996a). The ice would have eroded the plateau summits and the Escarpment edge (Grab, 1996a). Along the Escarpment sidewalls pre-existing drainage lines would have been enlarged, forming funnel-shaped hollows and cirques (Grab, 1996a). Several relict features are said to support this theory, amongst others glacial striations, moraines, kame moraines, cirques, and glacially polished surfaces (Borchert & Sänger, 1981; Lewis, 1996b).

It is maintained that if the subcontinent did experience a substantial drop in temperature during the LGM (Partridge, 1997), then it is likely that the higher mountains experienced mean annual temperatures of between –1°C and –3°C (Grab, 1996a). It is also proposed that the Antarctic polar fronts would have been displaced further north which probably increased the possibility of more winter precipitation during this time in the form of heavier snowfalls (Van Zinderen Bakker, 1975; Howard, 1985; Tyson, 1986; Marker, 1990b, 1992; Hanvey & Marker, 1992; Grab, 1996a). It is then likely that conditions during the late Pleistocene could have been favourable for localised development of glacial ice, with glaciation on the subcontinent corresponding with evidence for glaciation on Mount Kosciusko, Australia (± 20 000 to 15 000 years B.P.) and Mount Elgon, Uganda / Kenya (± 20 000 to 17 000 years B.P.) during the late Pleistocene (Grab, 1996a). After the LGM temperatures ameliorated such that much of the snow and ice would have melted over a short period of time (Vogel, 1985), resulting in an increase of surface water and runoff (Grab, 1996a). Meltwaters would have incised the glacial deposits, forming shallow gullies in pre-existing debris (Hall, 1994), and eventually transporting debris downstream (Grab, 1996a). Following this wetter phase the mountain areas became subject to periglacial activity (Sparrow, 1971).

However, conclusive evidence to confirm Pleistocene alpine glaciation remains elusive. This is mainly because of the apparent difficulty of recognising such landforms (Lewis & Hanvey, 1993; Hanvey & Marker, 1994; Lewis, 1996b). They are, for the most part, poorly preserved, partly due to the kind of material in which they are found, and partly to recent strong weathering and denudation, resulting mostly from intensive precipitation (Borchert & Sänger, 1981; Grab, 1999). Therefore, an alternative approach has been suggested that might offer better insights into the possible Pleistocene glacial history of the subcontinent, namely *arid marginal glaciation.*

2.3.1.2 Arid marginal glaciation

An arid marginal or arid continental glaciation (Fig. 2.1) is defined as the consequence of insufficient snow precipitation (Marker, 1991b), and implies that glaciation could have taken place in the form of a small icecap restricted to the highest elevations (Dyer & Marker, 1979). Ice development would have been marginal and ineffective (Marker, 1992, 1994b), the affected areas characterised by arid continental glacial conditions, marked cirque orientation and low cirque density (Marker, 1991b, 1994b) with glacial ice thinly spread and moving very slowly (Marker, 1998).

Two periods of extreme cold (glacials) are suggested for southern Africa (Harper, 1969; Lewis & Dardis, 1985; Lewis, 1996b). The first (the *Older Stadial*) occurred prior to

40 000B.P. (Marker, 1994b) with a snowline calculated at 3 350m (30°S) and 3 200m (31°S) with an estimated 9°C drop in temperature (Harper, 1969; Talma *et al.*, 1974; Lewis, 1996b). The second and less severe phase (the *Younger Stadial*) experienced a drop of ± 5° to 6°C 16 000 to 20 000B.P. with a snowline at 3 770m (30°S) and 3 650m a.s.l. (31°S) (Harper, 1969; Deacon & Lancaster, 1988). During the Older Stadial some form of glaciation might have taken place on the subcontinent, covering the highest parts of Lesotho with a thin icecap (Maud & Partridge, 1987). It might be that a similar glaciation took place during the Younger Stadial. However, supporting evidence of proxy data for a cold period with an estimated 9°C prior to the LGM remains elusive.

The theory of arid marginal glaciation is used to explain the origin of certain cirque-like forms that have been noted in the Great Escarpment by Marker (1991b), who proposed that the characteristics and distribution of the hollows were in accordance with an origin under marginal glaciation. As a result, the hollows would display certain characteristics (Derbyshire & Evans, 1976), such as marked aspect, strong orientation towards the leeward side of ridges, a flatness index of glacial proportions, and a correlation between hollow density and precipitation.

Findings showed that 72.3% of the hollows studied were orientated towards the north, irrespective of topographic ridge alignment (Marker, 1991b). The orientation is believed to be consistent with leeward snow accumulation at times of lower temperatures, strong southerly winds and greater cloudiness. Marker (1991a, 1998) concluded that much of the ice must have been thin, if one is to accept these hollows as a measurement of effective glaciation, and that conditions for cirque glaciation were most favourable along the Escarpment where higher altitudes and greater precipitation were available (Marker, 1991b, 1998).

At present annual snowfall and precipitation are highly variable, and it is likely to have been the same in the past (Sparrow, 1971). During the Quaternary, however, existing synoptic conditions probably were displaced northwards (Howard, 1985), causing more frequent winter precipitation and lower freezing levels. It is proposed that the Escarpment zone and the Lesotho plateau were only marginally glaciated (Marker, 1991b, 1998).

2.3.2 Other views

The general view is that southern Africa was never glaciated (Tyson, 1986; Deacon & Lancaster, 1988; Preston-Whyte & Tyson, 1988), mainly because no direct evidence of glaciation or permanent ice has been found (Van Zinderen Bakker, 1976; Marker, 1994a; Grab, 1996a). It is difficult to verify whether or not an icecap did exist in the absence of evidence of glacial abrasion. It may be that the Lesotho Highlands, for example, was an accumulation zone where no sediments, striations or other glacial evidence were generated. Features that may have been formed by glacial abrasion could have disappeared as a result of chemical weathering and fluvial action (Boelhouwers & Hall, 1990). It is argued that if estimated temperature drops and increased snowfall are acceptable, a small icecap could have formed and cirques could have developed to the leeward side of ridges on the Lesotho plateau and along the Escarpment (Marker, 1991b, 1998; Lewis, 1996b).

2.3.3 Periglacial origin relict phenomena

At present, active periglacial microforms prove that the climate is cold enough for periglacial processes to take place (Hanvey & Marker, 1992). The presence of a sub-periglacial zone lends credence to the opinion that the southern African mountain environment was modified by periglacial action during Quaternary glacials (Hanvey & Marker, 1992; Hanvey, 1990; Marker, 1994b, 1998[3]). Superficial relict periglacial deposits are found throughout the High Drakensberg and Lesotho Mountains and have been used to establish a Pleistocene palaeoclimatic sequence (Sparrow, 1971; Hastenrath & Wilkinson, 1973; Grab, 1999). The existence of relict periglacial landforms has lead to the contention that the mountains were subject to much greater winter snowfall at times of Quaternary temperature depressions (Marker, 1990b, 1992, 1994b, 1998; Hanvey & Marker, 1992) and that at least two former phases of periglacial activity preceded the present phase of periglacial activity (Lewis, 1987; Marker, 1994b). These features are inactive under present climatic conditions, and gave rise to two palaeoperiglacial theories (Fig. 2.1):

- *Full periglacial conditions*, including the possibility of permafrost (Fitzpatrick, 1978; Lewis & Dardis, 1985; Marker, 1989; Lewis & Hanvey, 1993; Lewis, 1994) that caused cryogenic imprints recognisable in landforms (Troll, 1944; Ellenberger, 1960; Alexandré, 1962; Harper, 1969).

- A periglacial phase of *mild intensity* and *relatively short duration,* excluding the possibility of permafrost (Marker, 1995a).

[3] Some authors referenced in this discussion support both the glacial and periglacial arguments.

2.3.3.1 Full or severe periglacial activity

It has been mentioned earlier that temperatures were depressed by at least 5°C between 16 000 and 20 000B.P. (Talma *et al.*, 1974). In view of these findings it is hypothesised that if a sub-periglacial zone can exist above 3 000m altitude at present, it will only be logical that full (or more severe) periglacial conditions occurred at high altitudes during the Quaternary cold periods (Fig. 2.1) (Lewis & Dardis, 1985; Hanvey & Marker, 1992; Marker, 1992, 1994b, 1995a). The mere recognition of relict periglacial landforms indicates that past conditions were suitably cold for widespread periglacial activity (Sparrow, 1971; Hanvey & Marker, 1992). It is supposed that certain features identified in the field could only have occurred under severe climatic periglacial conditions (Marker, 1989, 1990a, 1994a, 1998). A relatively thin snow cover may have survived the summer months on shaded slopes and formed snow or ice patches in hollows and depressions (Marker, 1989). Marker (1989) suggests that snow patches probably allowed the ground to freeze solid in winter resulting in nivation by freezing and thawing. According to Marker (1987) the Pleistocene southern African landscape may well have resembled the present sub-polar regions of Marion Island (46,5°S) or Northern Norway (60°N) in certain aspects.

Marker (1995a) found that relict cryogenic landforms of southern Africa can be separated into two regions, namely the eastern Great Escarpment and the Western Cape. Despite low altitudes and latitude, the higher summits of these regions project into the current sub-periglacial zone (Lewis, 1987; Boelhouwers, 1991b, 1995a; Hanvey & Marker, 1992; Marker, 1992, 1994b, 1995a, etc.). Most identified relict landforms require increased snowfall (Hanvey & Marker, 1992; Marker, 1995a); however, it is not certain what the moisture conditions during the Quaternary were (Marker, 1992). Furthermore, it is not easy to confirm cryogenic evidence, since southern Africa has neither a present-day glaciation nor an existing snowline (Marker, 1995a). The lower altitudes, at which some of the proposed periglacial features are found, may perhaps be a function of increased continentality at times of sea level recession and may date from earlier periods of extreme cold (Marker, 1995a), such as the Older Stadial discussed earlier.

2.3.3.2 Mild periglacial activity

For other researchers the theory of severe palaeoperiglacial phases in southern Africa does not satisfactorily answer the many questions surrounding the subject, especially where conclusive evidence is absent. In light of the various problems presented by this theory, it has been proposed that, due to considerable temperature and precipitation variations during the Pleistocene, periglacial activity of mild intensity and short duration (Fig. 2.1) existed (Sparrow, 1971; Nicol, 1973; Hall, *pers. comm.*). It is accepted that conditions were cold enough for some form of periglacial activity to have taken place and that periglacial phases were concurrent with the commencement of cooler conditions in the rest of the world (Linton, 1969; Sparrow, 1971). The intensity of periglacial conditions during interstadials and stadials, however, probably resembled those of the present-day periglacial environment (Hall, *pers. comm.*; for an overview see Partridge, 1997).

2.3.4 A convergence of ideas

During the Pleistocene glacials and interglacials the subcontinent experienced temperature and precipitation oscillations comparable to and concurrent with those in the Northern Hemisphere (Linton, 1969; Sparrow, 1971; Partridge, 1997). Glacial and periglacial conditions might have co-existed (Linton, 1969; Marker, 1989; Lewis & Hanvey, 1993), or one could have been more dominant at times than the other. It is therefore important that a periglacial or a glacial origin of phenomena not be treated in isolation of each other (Fig. 2.1). The following issues still need further verification:

- The amount of moisture available for the formation of relict landforms (Marker, 1992).
- The exact Pleistocene drop in temperature for the mountain regions (Meiklejohn, 1992).
- An LGM snowline elevation to establish the extent and nature of glacial activity if Pleistocene glaciation did take place (Marker, 1995a).
- The extent of a former periglacial activity (Lewis & Dardis, 1985).

On macro-scale other difficulties arise. It is not yet known, for example, what effect the northward migration of the Antarctic polar ice had on the local climate or sea currents, or what the effect of increased continentality was (Van Zinderen Bakker, 1976; Marker, 1989, 1995a). The climate might have been only marginally suitable for snowbed or ice survival at times, thus restricting it to protected and shaded sites, or moist at other times, resulting in heavy snowfalls (Lewis, 1994). It has been suggested that glacial ice disappeared very quickly due to the sudden onslaught of warmer temperatures during the temperature amelioration after the LGM. Any glacial phenomena that may have remained would have been eroded away by fluvial and/or chemical action (Boelhouwers & Hall, 1990).

The relict landscape and its features apparently are products of more than one Pleistocene glacial period (Linton, 1969). There is no doubt that relict processes were more extensive and enhanced (Meiklejohn, 1994), as is evidenced by the widespread nature of these landforms (Linton, 1969; Marker, 1990b; Hanvey & Marker, 1992). With an estimated 5° to 6°C drop in temperature, it is possible that snow remained for longer periods (Marker, 1989) and enhanced cryoturbation, frost action, solifluction and gelifluction processes occurred (Marker, 1990b; Meiklejohn, 1992, 1994). Yet, it should be realised that if the mountainous areas were indeed glaciated, the formation of certain periglacial features (such as ice wedges) would have been highly unlikely (Hall, 1991a; Le Roux, 1991; Marker, 1991a). If the mountains were not glaciated, these regions may be true periglacial environments (as opposed to pro- or paraglacial; French, 1996), areas that have not been glaciated but subjected to cold-based processes without the provision of debris by glaciers (Hall, 1991a; Le Roux, 1991; Marker, 1991a).

2.4 Current research problems

It was mentioned elsewhere that there are several problems embedded in the study of cryogenic landscapes within southern African context. The hypotheses discussed above only serve to draw attention to the difficulties experienced in current research. It is imperative for researchers to take note of these problems since many of them in fact offer new avenues of research. The main problem currently facing cryogenic research in southern Africa is undoubtly the scarcity of useable data.

2.4.1 Data

Sufficient data, as well as self-evident terminology and interpretation, is missing in contemporary cryogenic research in southern Africa (Hall, 1992; Grab, 1999). Hypotheses on Pleistocene conditions for the subcontinent lack supportive field data (Marker & Whittington, 1971; Hall, 1988a; Meadows & Meadows, 1988; Hanvey & Marker, 1992; Grab, 1994, 1996b), inhibiting the formulation of definite conclusions. Further, knowledge of Quaternary conditions is very limited (Partridge, 1990; Hall, 1991a; Le Roux, 1991; Marker, 1991a; Hanvey & Marker, 1994; Hall, 1994; Meiklejohn, 1994). Some data are inaccurate because of too few sampling sites (Hastenrath, 1972; Butzer, 1973; Hall, 1992; Boelhouwers, 1994). The scarcity of literature is mainly due to the very small number of workers on the subject

(Hall, 1988a, 1991b; Le Roux, 1991; Marker, 1991a)[4]. As far as terminology is concerned, for thufur alone six different terms exist (e.g. Schunke & Zoltai, 1988; Harris, 1988; Gerrard, 1992). Some regard one or two terms synonymous, while others distinguish between them. Terracettes also have a wide range of terminology in international literature (Watson, 1988), and so do numerous other features (Grab, 1999). A number of terms are outdated or obsolete, e.g. *congeli-solifluction* (solifluction) and *confraction* (frost shattering) (Linton, 1969; Borchert & Sänger, 1981; Kearey, 1996). The lack of knowledge, data inaccuracy, inconsistency in field techniques, and problematic classification, result in many qualitative and contradictory presumptions being made (Butzer, 1973; Hall, 1988a, 1991b; 1992; Meadows & Meadows, 1988). Many plea that great care be taken in arriving at any judgement (Sumner, 1995; Hall, 1992, 1994) and for further testing of hypotheses in southern African context (Boelhouwers, 1991a; Grab, 1996a, 1999).

2.4.2 Feature anomalies

Feature anomalies are landforms that are found at altitudes and unexpected places anomalous to regular findings of relict features. One such feature was recognised by Marker (1990c) in Golden Gate Highlands National Park. Linton (1969) identified others:

Phenomenon	**Location**	**Altitude a.s.l.**
Gelifluction deposit	Port Alfred	445 m
Rubble drift (gelifluction)	Camps Bay, Cape Peninsula	sea level
Residual blocks from gelifluction sludges	Gydo Pass, north of Ceres	1 100m
Striped block fields	15 km south of Pretoria	1 500m
Inversion of weathering profile (gelifluction)	Magaliesburg	1 200m

Linton (1969) reached the conclusion that these residuals belong to an older phase of cryoturbation and raised the possibility of more than one glacial period in southern Africa (e.g. Harper, 1969; Lewis & Dardis, 1985; Deacon & Lancaster, 1988; Marker, 1994b; Lewis, 1996b). According to Meiklejohn (1992) and Marker (1995a), preceding cold periods were extreme and it may explain the existence of relict cryogenic features at low altitudes. These

[4] Current literature on cryogenic studies in southern Africa has been supplemented greatly by a number of new publications for the period 1999 – 2000, e.g. Grab (1999), Meiklejohn *et al.* (1999), Sumner & Meiklejohn (2000), etc.

examples signify an age (or ages) of more severe climatic conditions in southern Africa, which allowed the formation of phenomena at lower altitudes, or on slopes that are currently not conductive towards cryogenic processes.

2.4.3 Climatic, altitudinal and latitudinal design

The climate and precipitation of southern Africa are controlled by the subcontinent's geographic location and its altitude above sea level (Marker, 1998). Southern Africa extends from ± 20°00'S to 34°30'S latitude and reaches a maximum altitude of 3 482m in Lesotho (Marker, 1995a, 1998). The subcontinent is both low altitude and low latitude (Hastenrath, 1972; Marker, 1992, 1995a, 1998); this fact hampers a clear assessment of Pleistocene conditions in southern Africa (Hastenrath, 1972). At present no modern glacial activity exists (Hastenrath & Wilkinson, 1973; Boelhouwers, 1994; Marker, 1995a; Grab, 1996a). Because there is no modern glaciation, the palaeoclimatic implications of relict phenomena are poorly understood (Hastenrath, 1972; Hastenrath & Wilkinson, 1973; Marker, 1992).

Southern Africa further has no modern snowline (Boelhouwers, 1994; Marker, 1995a), which is a drawback in periglacial studies and altitudinal zonation of past climates. High mountain environments react most sensitively to climatic change (Hastenrath, 1972; Hastenrath & Wilkinson, 1973) and a snowline can be seen as the manifestation of a complicated climatic balance. In places where a permanent snowline is present, geomorphic evidence can be interpreted with confidence. During winter months, the mountain areas of the subcontinent experience roughly eight snowfalls per annum, but snow only remains a few days (Borchert & Sänger, 1981; Grab, 1997b). The absence of a modern snowline and of non-permanent snow is contributed mostly to strong prevailing winds, mild conditions and high insolation (Hastenrath & Wilkinson, 1973).

2.4.4 Dating of phenomena

Datable material from study sites in southern Africa is limited (Sparrow, 1971; Marker, 1995a, 1998), causing several features to remain undated (Grab, 1994; Marker, 1994a; Lewis, 1994, etc.). The absence of datable matter can be attributed to certain factors such as aridity (Meadows & Meadows, 1988), and rapid fluvial incision (Hanvey & Marker, 1994). Thus, many studies that contribute to the palaeoclimatic record in southern Africa can give nothing more than a relative dating (Sparrow, 1971), keeping palaeoenvironmental reconstruction in a preliminary stage (Hanvey & Lewis, 1990).

2.4.5 The onset of the Holocene and subsequent temperature amelioration

When the LGM ended simultaneously in both hemispheres after 14 000B.P., annual temperatures in southern Africa rapidly increased (Hanvey & Marker, 1994; Marker, 1994b, 1995a, 1998; Lewis, 1996b; Partridge, 1997). The climate grew warmer and extensive glacial retreat occurred (Table 2.6). It is believed that, along with the glacial ice, remnant features of glacial and/or periglacial activity, vanished (Grab, 1996a; Lewis, 1996b). Basalt weathers very quickly and during the temperature amelioration following the LGM weathering mechanisms, e.g. chemical weathering, must have been greatly enhanced. Features that might have helped researchers understand past events, have simply disappeared, diminished or changed such that they remain unrecognised (Grab, 1999).

2.4.6 Other issues in southern African cryogenic studies

There are more unresolved issues in southern African cryogenic studies that can be added to the difficulties aforementioned. Currently, these issues prevent acceptable appraisal of palaeo-processes and their extent:

- Most phenomena, e.g. patterned ground, can be *polygenetic* in origin and not necessarily related to periglacial or glacial conditions (Hanvey & Marker, 1992).

- Some phenomena *are not clearly defined* or well developed (Boelhouwers, 1995a), making it difficult to correctly classify them.

- The *lower tree line* in southern Africa is attributed to the absence of boreal species and to a long history of fire and heavy grazing. The tree line position is critical in defining effective frost processes in cold environments (Marker, 1992).

- *Biological activity*, particularly endolithic and chasmolithic bacteria and lichens, may exert an influence on freeze-thaw weathering and other cryogenic mechanisms (Hall, 1988a, 1988b).

- *Past moisture regimes are difficult to project* from modern periglacial forms (Hanvey & Marker, 1992), especially those found in the High Drakensberg and Lesotho Mountain.

- Most southern African studies attempt to classify fossil phenomena through the use of *high latitudinal and altitudinal models*. These models can not readily be applied on the southern African environment due to the many difficulties already discussed (Hall, 1994; Sumner, 1995). Models based on periglacial phenomena also fail to define the current sub-periglacial environment (Boelhouwers, 1991a; 1995a).

- Actual cryogenic landforms in the High Drakensberg and Lesotho Mountains are generally *small in size* and of *seasonal occurrence* (Lewis, 1987; Grab, 1996b, 1997a), casting doubt on their proposed origins.

- Marker & Hanvey (1994) note that many hollows have been *truncated by the Great Escarpment recession* and that fluvial incision has modified hollow floor gradients (Marker, 1994b, 1998). It is not known what influence the Escarpment recession exerts (or exerted) on other cryogenic phenomena.

- There is no evidence for the present or former existence of *permafrost* in southern Africa. This is ascribed to climatic conditions that are unfavourable for permafrost development (Lewis, 1996a). Permafrost is generally accepted as an important diagnostic indicator in periglacial environments (Embleton & King, 1975; Goudie *et al.*, 1985).

The identified problems and difficulties prompted further study by way of comparison between local features and those of other cryogenic environments, thereby attempting to classify relict phenomena (e.g. Marker, 1990b). Existing models and theories for the Northern Hemisphere have also been applied to create models for the southern African cryogenic environment, e.g. a model for valley asymmetry in southern Africa (Fig. 2.3; Meiklejohn, 1992, 1994), and the identification of two classes of erosional hollow (Fig. 2.4; Marker, 1995a). Given the need to describe the southern African palaeoclimate, it is important to understand the environment in its entirety and to engage other disciplines and techniques to supplement current cryogenic research, e.g. a vegetation cover model for the southern African Pleistocene climate (Fig. 2.5; Van Zinderen Bakker, 1976). Unfortunately, models of this nature are not unique in southern African context and do not solve the problems encountered in cryogenic research. In an attempt to elucidate critical issues in southern African periglacial and glacial research, a database comprising cryogenic literature for the subcontinent, was

Slope →	Characteristics →	Result
South-facing slope	-Lower average ground temperatures -Shallow active layer -Protective layer of snow	Result in an inactive environment with respect to weathering and mass movement. Due to this the south-facing slope maintains a steep gradient and is slow in changing profile
North-facing slope	-Greater insolation -Higher ground temperatures -Deeper active layer -Active layer more favourable to mass movement and weathering -Greater quantities of scree	Downslope movement of material is more dynamic

Figure 2.3: Contrasting processes on south- and north-facing slopes due to differing insolation receipts (after Meiklejohn, 1994).

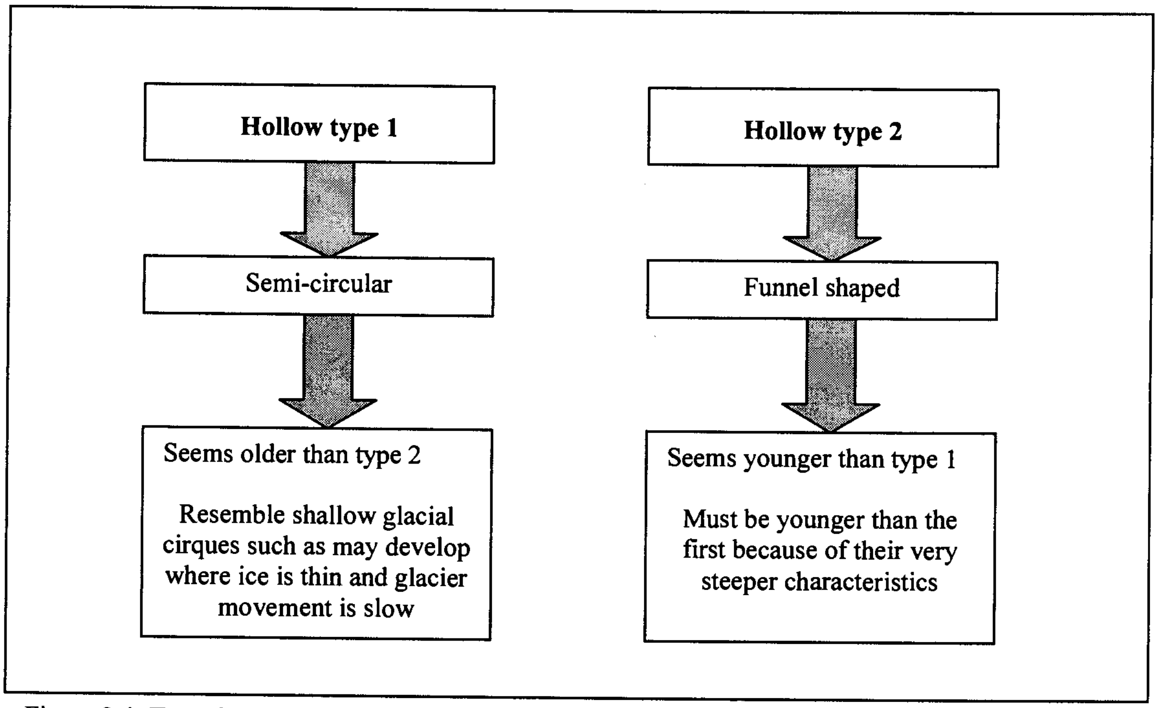


Figure 2.4: Two classes of erosional hollow as proposed by Marker (1995a).

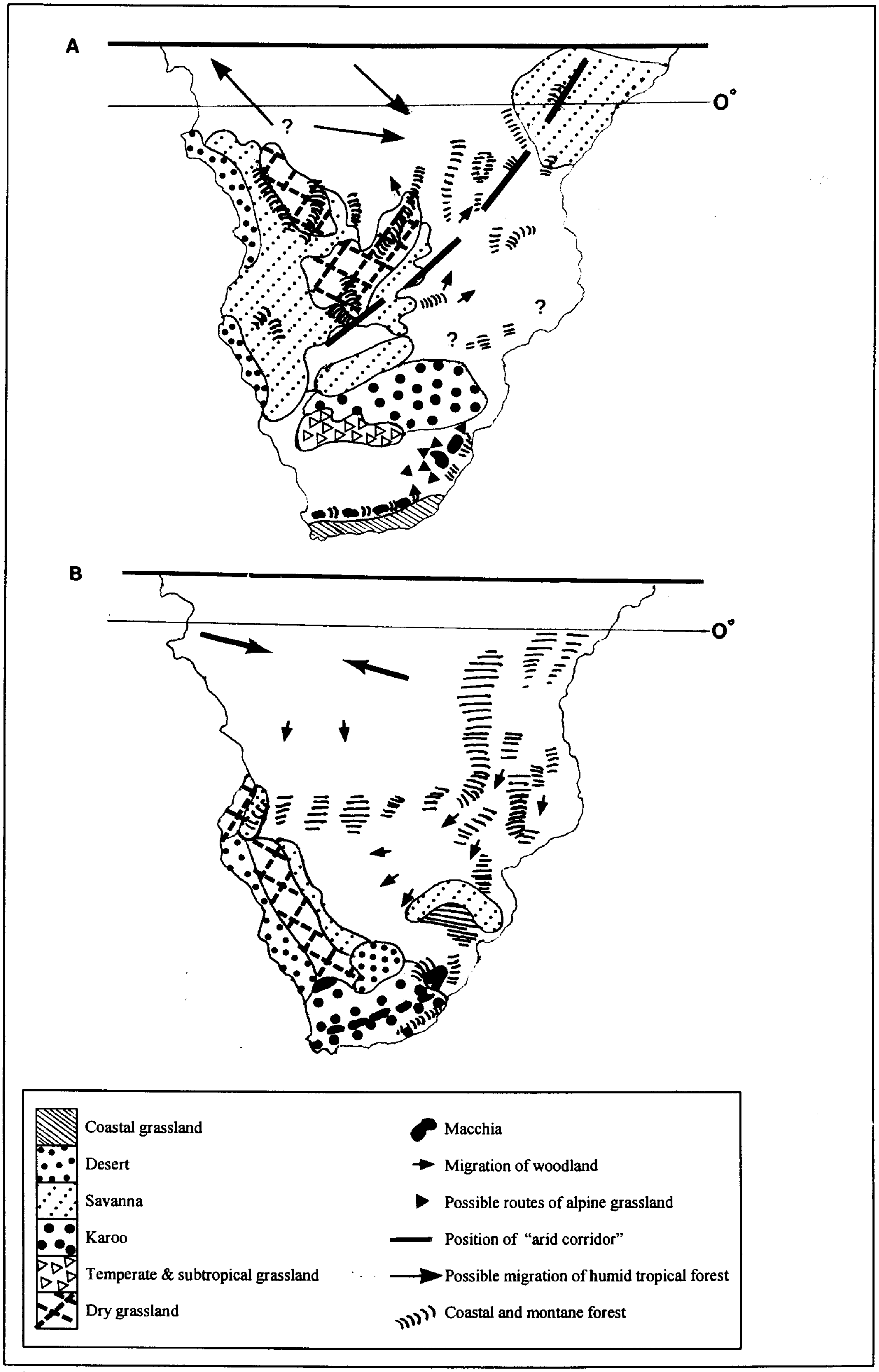


Figure 2.5: Vegetation patterns during a glacial maximum (A) and during an interglacial (B) (after Van Zinderen Bakker, 1976).

assembled. Within a GIS-system the database can be used to arrange and classify data for in-depth analysis, thus acting as a reliable and objective aid in problem solving. The spatial database will further serve as an information source for future research.

2.6 Conclusions

In this chapter different views expressed in southern African literature are presented. It was recognised that the modern environment is subject to sub-periglacial activity, but that the exact spatial extent thereof is still not certain. The mountain environment of southern Africa was exposed to widespread cryogenic activity and had experienced several temperature oscillations and depressions during the Pleistocene. In classifying cryogenic remnants of the Pleistocene, substantial controversy is evident, especially concerning the intensity, dominance and spatial distribution of past processes. Two main views were identified, namely a glacial and a periglacial origin for relict phenomena. Those who believe that glaciation took place proposed either an alpine or an arid marginal glaciation for the mountain areas of southern Africa. Those who maintain a periglacial view, either support full periglacial activity, or periods of mild periglacial action, excluding the possibility of permafrost. Both views take into account that all phenomena identified thus far require (and indicate) periods of enhanced snow cover. It was further shown that either activities should not be isolated and treated separately.

The uncertainty surrounding the classification of phenomena was indicated to be a function of several problems encountered in current research. The main problems were identified as those of data inconsistencies, phenomenon anomalies, the geographic location and climate of the subcontinent, difficulty in dating, terminology, and the effect of the temperature amelioration after the LGM on the local landscape. The need for a reliable data source in the form of a GIS-database was discussed.

CHAPTER 3

Research methodology: database components and development

3.1 Introduction

In Chapters 1 and 2 it was indicated that the significance of many relict landforms remains difficult to understand and that the exact extent of these features, as well as their associative processes, are unknown. It is evident that southern African knowledge of the Quaternary and palaeocryogenic action is insufficient, leading to contradictory quantitative and qualitative interpretations. There is a need to explain the origin of Pleistocene relict landforms within a larger framework and for a more rigorous approach towards palaeoenvironmental studies. Therefore, the aims and objectives are to gain a better understanding of relict features and processes, to establish or reconstruct the palaeoenvironment and its extent, to provide an objective data source, and supplement existing knowledge of the Quaternary.

To achieve these aims and objectives, the construction of a database system that assembles, arranges and classifies data on a less predisposed foundation was chosen. The purpose of Chapter 3 is to explain every step in the development of such a system, to reveal its advantages and to demonstrate how the database will be utilised in realising the aims and objectives of the study.

3.2 The advantages of a database system approach

Combined with the current explosion in computer technology, a database system approach offers a number of advantages to the researcher (Davies, 1996). It is not difficult to realise the potential such a system may have for current cryogenic research in southern Africa:

- Quick access to data and fast, inexpensive mapping. A database is convenient; data are very accessible with little problems in data retrieval. Existing software packages are specialised and user specific. Programmes, e.g. ArcView®, and supplementary datasets, e.g. Enpat, are created specifically for geographical use and contain most of the information needed by geographers. From the database southern African cryogenic data can easily be accessed and calculated for analysis, thus acting as both data source and data analyser.

- Modern computer programmes are able to do a wide variety of querying and the researcher will be able to do overlays and create reports at the same time within one system. This basically means that several options exist that make complex analyses of southern African cryogenic data combined with other sources in the form of spatial data, possible.

- The database will standardise the information it contains. This is necessary to secure consistent results free of the inconsistencies in southern African cryogenic data due to qualitative interpretations.

- An existing database and good software saves time and money since everything is done within one system.

- Data can be entered, upgraded, corrected and deleted. A database system is very flexible and will allow the researcher to upgrade or correct southern African cryogenic data within the database.

However, to maintain a database, regular data upgrading is necessary (Goodchild & Kemp, 1991). The next discussion will endeavour to curb this problem by presenting basic guidelines to aid researchers in the process of regular upgrading. Furthermore, definite and specific information is needed for a working database. This implies that before adding new information to the database, the researcher must first spend time in reading and interpreting the data according to the conditions and definitions stipulated for the database. The researcher must also be knowledgeable in database management and software, implying that time be set aside for training. Nevertheless, it is believed that a database system and complementing software will help clarify problems experienced in southern African cryogenic studies by utilising specialised operations such as digital mapping and mathematical analysis. The database must be as complete as possible with the definite possibility of upgrading and accessibility of information, and database operations and information contained within the structure must be easy to understand.

3.3 Development of a GIS-database for cryogenic studies in southern Africa

Database development involves several stages (Fig. 3.1), namely the input of *spatial data*, the input of *attribute data* and *linkage* between the two (Goodchild & Kemp, 1991). Digital spatial data were obtained from the Department of Environmental Affairs and Tourism, Surveyor General, Department of Land Affairs, Centre for Environmental Studies (University of Pretoria), Council for Geoscience, and the Computing Centre for Water Research (CCWR). The spatial data contain dataset information about southern African geology and lithology, vegetation patterns, mean annual, monthly and seasonal air temperatures and precipitation, international and national boundaries, and infrastructure.

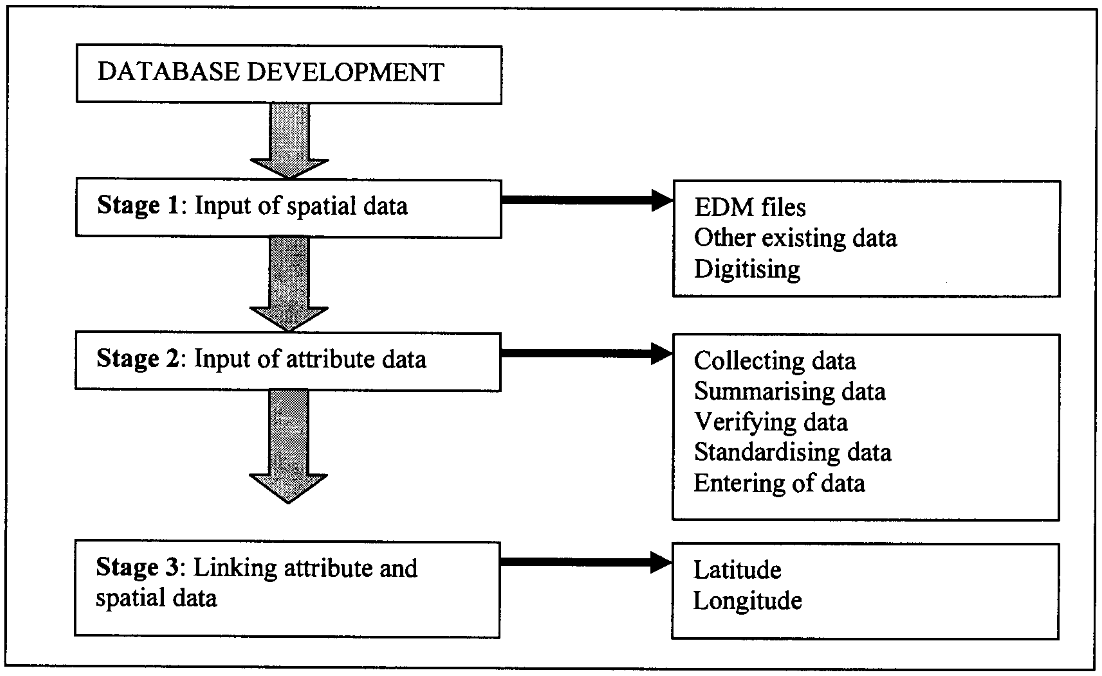


Figure 3.1: Stages in database development (after Goodchild & Kemp, 1991).

Attribute data were obtained from known relevant publications and unpublished sources. The information was summarised according to a summary list with the main points of interest (Fig. 3.2). Each entry received a reference number followed by the author(s) name(s), year of publication and specific information from research papers, theses or honours papers. Summaries were kept as true as possible to the original facts and entered into the database columns created in a database programme (Microsoft® Access$_{TM}$). New columns were added if required. The information summaries were compared with each other and with international literature to verify consistency in the use of cryogenic terminology. Background information indices regarding database terminology and data were subsequently constructed as a standar-

Reference: __________
Author(s): __________ Year of publication: __________
Feature: __________
Age: __________ Activity: __________
Altitude a.s.l.: __________
Causative: __________
Climate: __________
Consistency: __________
Count: __________
Dimensions: Width: __________
Diameter: __________
Length: __________
Height: __________
Depth: __________
Slope angle: __________
Size: __________
Slope: __________
Form: __________
Hypothesis: __________
Location: Latitude: __________
Longitude: __________
Name of place: __________
Other char.: __________

Figure 3.2: An example of a summary list used in the categorising of data.

disation measure. Additional information concerning specific cryogenic phenomena mentioned in the database as identified and contemplated by e.g. Sparrow (1974), Le Roux (1990), Hall (1988a, 1991a), Thorn (1991), Sumner (1995), French (1996), Grab & Hall (1996), Shakesby (1997), Grab (1999), Sumner & De Villiers (*in prep.*), were included. These two stages in the development of the database will be discussed further in Chapter 4.

Spatial and attribute data were linked by location (latitude and longitude). The database was imported in table format into ArcView® GIS. A more user-friendly database was created in Microsoft® Access$_{TM}$. In ArcView® GIS the database were fully employed by overlaying database attribute data on spatial data. Through simple map calculations and overlays the desired results were obtained and will be discussed in Chapter 5. The database and information are available on CD-ROM (Appendix A). The next discussion will consider the database components.

3.3.1 Main components of the database

Database components (Appendix B) were derived directly from the information summaries. Microsoft® Access$_{TM}$ automatically allocates a unique identification number for each data entry. When an entry is deleted, its identification number is never again allocated. This will allow the researcher to be sure of an entry's location in the database. It is desired that any given entry will contain as much information as possible, although it is not anticipated that all data columns will be filled. The following components were ascertained from the information summaries:

3.3.1.1 Information source

Research is acknowledged by stating the name(s) of the author(s) and the year of publication. A complete reference list of papers, theses, honours papers and personal correspondence is issued with the database on CD-ROM (Appendix A: Cryogenic Processes and Landforms Spatial Database for Southern Africa).

3.3.1.2 Identification of the phenomenon

This section is divided into the identification of the phenomenon and the processes involved in its formation (standardised version, Appendix C), and the author(s) own classification(s) (author's version). In the first component, the phenomenon and its associated processes are identified according to Appendix C. In the second part the author(s) classification(s) is (are) given to prevent possible misunderstandings.

3.3.1.3 Geographic location and processes involved in the phenomenon's formation

This category consists of the geographic location of the phenomenon, that is latitude, longitude, name of the place and altitude above sea level by which the distribution of a phenomenon can be determined. Different locations for the same phenomenon are treated as separate entries.

3.3.1.4 Geomorphic characteristics of the phenomenon

The geomorphic characteristics of a phenomenon indicate its mode of formation, whether produced under glacial or past- and present-day periglacial conditions (according to the research at hand). Closely linked with geomorphic characteristics is phenomenon activity.

Three activity levels are differentiated, namely glacial relicts, periglacial relicts and current periglacial phenomena. Of the latter most are seasonally active (mainly in winter, May to August or September), but others may be classified as currently active (phenomena active at the time of observation) or currently inactive (phenomena inactive at the time of observation, but showing distinct signs of ongoing activity).

3.3.1.5 Specific characteristics

- *Age*: sometimes it is possible to calculate a relative date for a phenomenon or at least estimate its age as before, during or after the Last Glacial Maximum (LGM). These options are provided for in the database.

- *Count* designates the number of phenomena encountered at the time of research. However, it is not possible to indicate a number for certain features, e.g. needle ice, or processes, e.g. frost action.

- *Vegetation*: in this section it is confirmed whether a phenomenon is covered with or display a fringe of vegetation (such as seen among screes).

- *Sorting* (Fig. 3.3) is the measure of the standard deviation of particles and relates to the way in which material is differentially removed by geomorphic agencies, such as wind and water (Kearey, 1996). Sorting is seen particularly among patterned ground phenomena (e.g. Harper, 1969; Hastenrath & Wilkinson, 1973; Dardis & Granger, 1986; Boelhouwers, 199a, 1994, 1995b).

- *Stratification* (Fig. 3.3) implies one layer of materials covering another layer of materials (Kearey, 1996).

- *Grading* comprises units that exhibit a vertical gradation in mean grain size (Goudie *et al.,* 1985). Normally a fining-upward sequence is present, but an inverse grading that displays an upward-coarsening sequence, may occur (Goudie *et al.,* 1985). In the database, this data column was allocated a drop-down option list.

- *Soils*: material composed of mineral particles and organic remains overlaying bedrock and usually supporting vegetation (Goudie *et al.,* 1985). If a phenomenon harbours a palaeosol (an ancient or relict soil or soil horizon), it is regarded as a soil. In the database soil names are entered, or, in the absence of specific identification, classified, e.g. *modern soils* or *subsoils*.

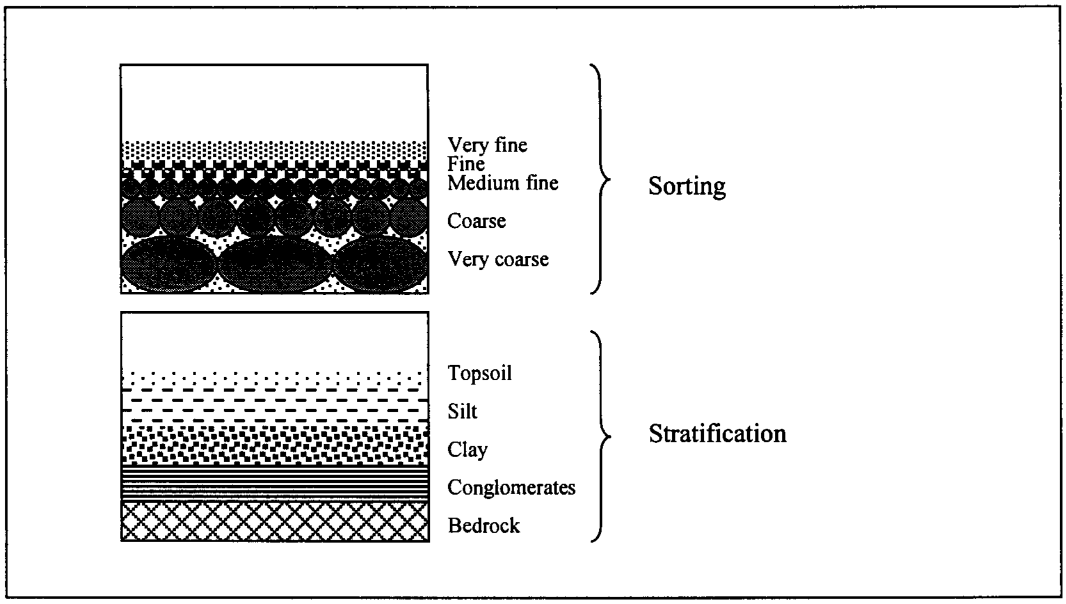


Figure 3.3: The difference between sorting and stratification.

- *Matrix and matrix supported material*: matrix is fine-grained material that separates clasts in a sedimentary rock or in which larger bodies are set (Kearey, 1996). The material it supports is called matrix-supported material. Both concepts are treated separately in the database.

- *Clasts and clast supported material*: a clast is a coarse particle of rock produced by weathering and erosion, usually larger than 4mm in diameter. Clast sizes include pebbles, cobbles and boulders (Goudie *et al.*, 1985; Kearey, 1996). Material that is clast-supported usually lacks matrix materials. These concepts are treated separately in the database.

- *Gradient* or angle of a phenomenon is its inclination in relationship to the body on which it is located, measured in degrees. Mostly a phenomenon inclines at the same angle as that of the slope or body on which it lies (Table 3.1 & Fig. 3.4).

- *Orientation* or aspect is the phenomenon's position in relation to the main points of the compass. In the database, orientation is treated as a definite compass direction (Fig. 3.4 & Fig. 3.6).

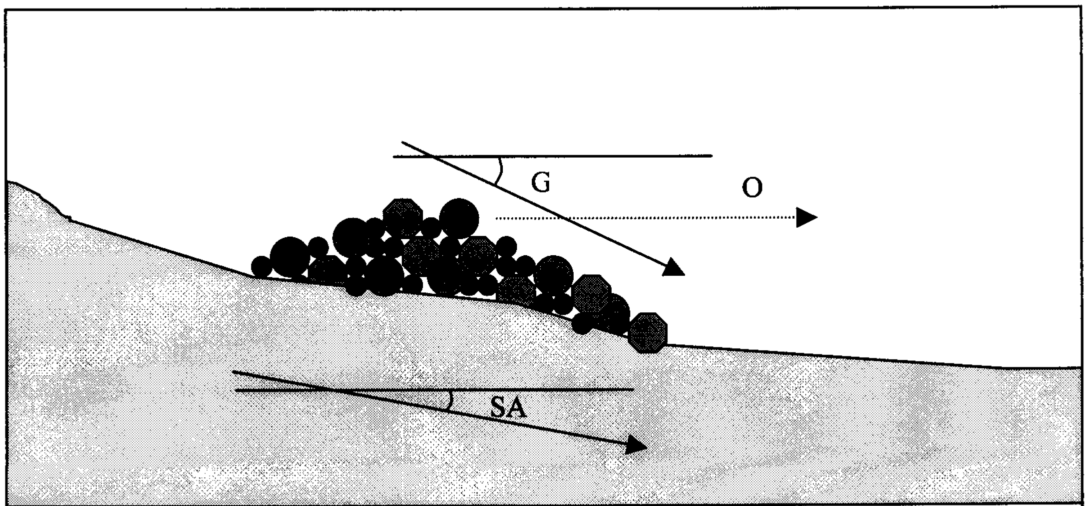
- *Slope* refers to the actual slope on which the phenomenon is located which faces a certain compass direction.

- *Slope angle* refers to the slope's inclination in degrees (Fig. 3.4).

- *Dimensions*: that is the width, length, height, depth and diameter of the phenomenon (Fig. 3.5).

Direction	Exact demarcation	Generalised demarcation	Compass direction
N	348.76° - 11.25°	348° - 10°	0°
NNE	11.26° - 33.75°	11° - 32°	22.5°
NE	33.76° - 56.25°	33° - 55°	45°
ENE	56.26° - 78.75°	56° - 77°	67.5°
E	78.76° - 101.25°	78° - 100°	90°
ESE	101.26° - 123.75°	101° - 122°	112.5°
SE	123.76° - 146.25°	123° - 145°	135°
SSE	146.26° - 168.75°	146° - 167°	157.5°
S	168.76° - 191.25°	168° - 190°	180°
SSW	191.26° - 213.75°	191° - 212°	202.5°
SW	213.76° - 236.25°	213° - 235°	225°
WSW	236.26° - 258.75°	236° - 257°	247.5°
W	258.76° - 281.25°	258° - 280°	270°
NNW	281.26° - 303.75°	281° - 302°	292.5°
NW	303.76° - 326.25°	303° - 325°	315°
NNW	326.26° - 348.75°	326° - 347°	337.5°

Table 3.1: Compass direction ranges.



G = gradient of phenomenon

O = orientation of phenomenon; this phenomenon face east and is thus located on a western slope

Figure 3.4: The differences between gradient, orientation and slope angle.

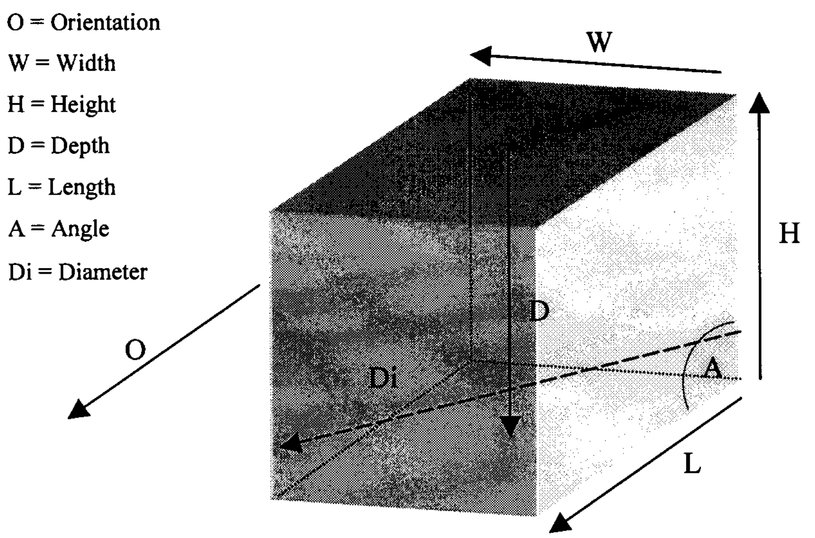


Figure 3.5: The dimenions of a three-dimensional figure.

Dimensional measurements differ from phenomenon to phenomenon. For terracettes and other step-like features, height is measured at their raised fronts, and for hollow-like features at their backwalls. Depth is applicable to features of which the distance can be measured from their "surfaces" to their bases. The measurement unit in the database (and later map analysis) is in metres.

3.3.1.6 Other characteristics

In the literature many interesting facts are discussed that can not be included in the data columns referred to above, but may be incorporated into this special category. The first subcategory encompasses other phenomena in the near vicinity of the phenomenon under discussion, e.g. tor-like features observed in close vicinity of cutbacks (Grab, 1996a). The second subcategory deals with any interesting fact or characteristic of the phenomenon, e.g. thufur "form in areas of abundant soil moisture" and "thufur break-up normally occur on the northern side of the mound" (Hastenrath, 1972).

3.3.2 Problems encountered during the development of the GIS-database

During database compilation, unforeseen difficulties came to the fore. One of the biggest problems is incomplete information. Many of the earlier papers give only a broad overview of phenomena. Sometimes the same phenomenon with the same characteristics is repeated several times, differing only in location. Because of the lack of supportive data, there are incomplete data entries in the database. One of the research aims is to provide point data locality for each phenomenon. This goal can not be achieved if data were combined to give an overall or more representative picture. The same applies for generalisation of areas where no definite latitude or longitude is given for a feature. It is important in both cases that if point data are desired, phenomena must be indicated geographically separate from each other. The problem was partially overcome by allocating a polygon (representing that specific area) to a data entry; nevertheless, the convenience of point data locality is sacrificed.

It was also found that most features and processes were not clearly defined. The way in which data are presented is sometimes confusing and a certain degree of classification becomes necessary. For this problem, a glossary of terminology and a basic reference framework were compiled (see Chapter 4).

3.4 Realising the aims and objectives of the study through database manipulation

The purpose of the Cryogenic Features and Processes Database for Southern Africa is to realise the aims and objectives of the study and to comprehend the significance of relict and present-day features and processes through specialised operations. Regarding the conditions stipulated for the database earlier in the discussion, it is certain that the database will provide an objective data source and supplement existing knowledge of the Quaternary in southern Africa. Other important prerequisites, namely database efficacy, workability and user friendliness, are tested in Chapter 5.

A further aim of the database, combined with programme accessories such as Enpat for ArcView®, is to enable researchers to create maps, interactive views and reports to assist them in future cryogenic studies in southern African. The database is a dynamic and flexible system and a valuable GIS-tool in decision making with a range of functions, outputs and operations (Davies, 1996). GIS uses geographically referenced data as well as non-spatial data, and includes operations that support spatial analysis (Goodchild & Kemp, 1991). The database is the focus of the GIS-system and embodies spatial and attribute data needed for data analysis.

The database can be manipulated to produce maps by isolating selected database elements (Eastman, 1992). A GIS-system is capable of data input and verification, data storage and database management, data output and presentation, data transformation, and interaction with the researcher (Burrough & McDonnell, 1997). It is evident that a GIS-system is dynamic, putting the latest technology and advanced information systems at the disposal of the researcher (Davis, 1996).

3.4.1 Factors affecting the reliability of spatial and attribute data

Different factors can influence the reliability of spatial and attribute data (Goodchild & Kemp, 1991; Burrough & McDonnell, 1997), especially where southern African cryogenic research is concerned. These factors not only limit the reliability of the data, but also its usefulness, credibility and efficiency:

- *Age of data*: The researcher is forced to use existing published data and in the case of the Cryogenic Features and Processes Database for Southern Africa, some information is rather old, but regarded indispensable for research.

- *Aerial coverage*: It is desirable that the whole of a study area should have a uniform information cover. If this is not possible, the researcher must be satisfied with partial levels of information. To make coverage more complete and uniform, supplementary data must be obtained or detailed data must be generalised to match less detailed data.

- *Map scale and resolution*: Most geographic resource data have been generated and stored in the form of thematic maps. It is only recently with the development of digital information system that it has been possible to have the original field observation available for further processing. In the southern African context not much has been done for cryogenic studies in the form digital mapping, implying that resolution and scale must be chosen discretely.

- *Density of observations* involves ground truth and sampling density upon which observations and data-sets are based. Some data in current cryogenic literature are seriously deficient in supportive ground truth data, which unavoidably affect data quality.

These factors affect the database system in one way or the other. However, it is hoped that the Cryogenic Features and Processes Database for Southern Africa will stimulate new research that will diminish these factors significantly.

3.4.2 Different outputs and operations

The Cryogenic Features and Processes Database for Southern Africa can be employed in different ways and through GIS-based programmes, e.g. ArcView®, to aid further cryogenic research. ArcView® is a vector and raster based GIS-system and is used to visualise attribute data for this study. The various advantages and disadvantages of raster and vector formats are outlined in Tables 3.2 and 3.3. Data can be recalled and organised to the researcher's specifications by utilising overlays, queries, map calculations, etc. By overlaying one coverage over another a multi-feature or multiple-theme coverage can be produced (Davis, 1996). Stored information can be viewed by location or by attributes through queries (Eastman, 1992). Query options, according to Goodchild & Kemp (1991), include:

- Simple recall of data.
- Showing a specified object (show me object X).
- Specifying an object (what is this object?).
- Summarising attributes of objects within a distance.
- Summarising attributes of objects within a region.
- Recommending the best route.
- Showing all objects satisfying pre-set or specified criteria.

After manipulating the data and acquiring the desired results, the outcome can be presented in text, graphic or digital format (Goodchild & Kemp, 1991). A GIS-system combined with a database offers an assortment of options for data manipulation and is one of the best methods for solving geographic problems and questions.

3.5 Conclusion

In this chapter each step in the development of the Cryogenic Features and Processes Database for Southern Africa was explained. The advantages of a GIS-based database were revealed and it was demonstrated how the database can be utilised in realising the aims and objectives of this study. Through database compilation, utilisation of GIS-techniques, data modelling and data representation, it is hoped that a better understanding of relict features and processes will be gained. By importing known Quaternary data into the database-GIS setting the reconstruction of the palaeoenvironment and its extent is possible and the insights gained from database modelling will enable prediction of future climatic events. Lastly, the database is a more reliable and objective data source and will supplement existing knowledge of the Quaternary in more than one way.

RASTER FORMAT	
Advantages	• Simple data structure: a grid with a single number in each cell. • Easy to understand and use, even for beginners. • Easy analysis. • Remote sensing imagery is obtained in raster. • Modelling which uses raster numbers, use the creation of a generalised data file or a set of universal procedures to accomplish a certain GIS task.
Disadvantage	• Spatial inaccuracies. • "Implies" truth (an implicit structure). • Relatively low resolution. • Raster systems can have very large data sets. • The general public does not usually understand raster imagery.

Table 3.2: Advantages and disadvantages of raster format (after Davies, 1996).

VECTOR FORMAT	
Advantages	• It is more map-like. • High resolution. • High spatial accuracy. • Vector data can be topological. • Takes less storage space and offer better storage capabilities than raster formats. • The general public usually understands what is shown on vector maps.
Disadvantages	• May be more difficult to manage than raster formats. • Require more powerful, high-tech machines. • More expensive.

Table 3.3: Advantages and disadvantages of vector format (after Davies, 1996).

CHAPTER 4

A discussion of database terminology and data problems encountered in the literature

In Chapter 3 the importance of background information indices regarding database terminology as part of the study methodology was mentioned. Besides the need for glossaries and indices, additional information concerning specific database features and processes prompted closer inspection. The following discussion will look at the preparation of supplementary information glossaries and will examine the difficulties regarding specific phenomena in the database.

4.1 Database terminology

Terminology usage in southern African cryogenic research is not consistent or self-evident (e.g. Hall, 1992; Grab, 1999; Chapter 2). This problem was partly overcome by compiling a glossary of terms and definitions for standardising purposes. International terminology definitions were collected in an effort to add more meaning to the often casual usage of terminology in southern African cryogenic studies (Hall, 1992). Periglacial terminology and definitions were obtained from the International Permafrost Association's Global Geocryological Database (Van Everdingen, 1998). Glacial and other geomorphological terminology were quoted from *The Encyclopaedic Dictionary of Physical Geography* (Goudie *et al*., 1985), *Earth* (Press & Siever, 1986), *Dictionary of Geography* (Clark, 1998), and *The New Penguin Dictionary of Geology* (Kearey, 1996). Where necessary, definitions were inferred from southern African papers and personal communication. The Terminology Glossary is summarised in Appendix C.

Four supplementary reference tables and lists were added to the Terminology Glossary and comprise of a *Features and Processes Table* (Appendix D), a *General Features and Processes Reference Index* (Appendix E), a *Geographic Location Reference Index* (Appendix F), and an *English/Afrikaans Terminology Index* (Appendix G). To demonstrate the function of the indices, the feature *solifluction terrace* is considered as an example. When searching through the Terminology Glossary (Appendix C) for "solifluction terrace", the following definition will be found:

Solifluction terrace:

A low step, or bench, with a straight or lobate front, the latter reflecting local differences in the rate of solifluction movement. A solifluction terrace may have bare mineral soil on the upslope part and 'folded-under' organic matter in both the seasonally thawed ground and the frozen ground. Those covered with a vegetation mat are called turf-banked (solifluction) terraces; those that are stony are called stone-banked (solifluction) terraces (Van Everdingen, 1998).

For most terminology more than one definition is given. Synonyms, southern African papers, and a short synopsis of southern African examples for "solifluction terrace" are included in the Terminology Glossary:

Solifluction terrace:

***Synonyms**: solifluction bench, solifluction step, garland terrace (obsolete)*

***Papers**: Harper (1969); Lewis (1996a)*

***Synopsis**: active & relict; 2600-2744m.a.s.l.; vegetated; unconsolidated grey, orange & red sediments, modern soils & a palaeosol; 0.5-10m wide; 1m long; 1-20cm high; 6.1-12.2m deep*

The other indices (Appendix D, E, F and G) are shorter specialised versions of the Terminology Glossary (Appendix C) and focus specifically on southern African cryogenic phenomena. The Features and Processes Table (Appendix D) was designed to standardise database term usage and rule out unnecessary synonyms or obsolete terminology, e.g.

Solifluction terrace:

Category:	*Solifluction features*
Term in database:	*Solifluction terrace*
Sub-categories:	*Turf-banked terrace*
	Stone-banked terrace
Term recognised by the IPA[1]:	*Solifluction terrace*

[1] International Permafrost Association.

Synonyms recognised by the IPA:	*Solifluction bench*
Synonyms not recommended by the IPA:	*Soliflual garland terrace*

The General Features and Processes Reference Index (Appendix E) functions as an extension of the Terminology Glossary (Appendix C) and incorporates southern African occurrences in particular, e.g.

Solifluction terrace:

Writers:	*Harper (1969); Lewis (1996a)*
Activity:	*Active & relict features*
Altitude above sea-level:	*2 600 – 2 744m*
Vegetation:	*Yes*
Sorted/nonsorted:	-
Soils and sediments:	*Unconsolidated grey, orange & red sediments, modern soils & a palaeosol.*
Matrix:	-
Width:	*0.5-10m*
Length:	*1m*
Height:	*1-20cm*
Depth:	*6.1-12.2m*

The Geographic Location Reference Index (Appendix F) is a quick reference guide to the geographic location of features and processes in southern Africa, e.g.

Solifluction terrace:

Location	***Province/region***	***Latitude***	***Longitude***
Ben MacDhui	*Eastern Cape*	*30°38'44"*	*27°56'32"*
Brandwag	*Free State*	*28°34'05"*	*28°34'36"*
Cathedral Cave valley	*Kwa-Zulu Natal*	*29°01'30"*	*29°15'00"*
Ribbok Valley	*Free State*	*28°32'22"*	*28°36'19"*
Tiffendell Ski Resort	*Eastern Cape*	*30°40'22"*	*27°56'53"*

The English/Afrikaans Terminology Index (Appendix G) acts as a quick reference list regarding database terminology, synonyms, obsoletes and suggested Afrikaans terminology, e.g.

Solifluction terrace:

Terminology	***Preferred usage***	***Afrikaans***
Garland terrace	*Solifluction terrace*	*Bodemvloeiterras*
Solifluction bench	*Solifluction terrace*	*Bodemvloeiterras*
Solifluction terrace	*Solifluction terrace*	*Bodemvloeiterras*

The main objective behind the compilation of the glossaries and indices is to standardise terminology specifically for the development and functionality of the database. In addition, the indices were compiled according to the features and processes observed in southern Africa, thus lacking other significant periglacial and glacial phenomena found in the rest of world. The reader is therefore explicitly reminded that the database is primarily an aid for researchers inquiring into cold southern African environmental phenomena.

It is further realised that the southern African cryogenic environment may be unique in its own respect and that international terminology and definitions may not be applicable or suitable in southern African context. However, since no significant original vocabulary explicitly for southern African cryogenic features and processes has been put forward, and seeing that internationally accepted terminology is widely used by researchers, the Terminology Glossary (Appendix C) and supplementary indices must be accepted as a basis for database terminology. In the words of Thorn (1991:4), "terminology issues are an important facet of the inherent conflict in science between the need for meaningful generalisation and the need for precision … it behoves every scientist to be clear-minded. Clarity of thought is dependent upon the small artefacts of the process (i.e. words) as well as the grandiose (i.e., overarching theory)."

4.2 Inconsistencies encountered in the literature

Because of the great uncertainty in southern African cryogenic studies many interpretation inconsistencies exist that have not been addressed or clarified. Southern African cryogenic geomorphology is going through a phase of acceptance (Hall, 1991a), and knowledge of the cryogenic environment is still in its early stages (Hall, 1992). Nonetheless, the problems and different views emphasised below reflect the likely *polygenetic* origin of most so-called periglacial or glacial features (Thorn, 1991). Some of the irregularities may not necessarily affect database efficiency, but cast a poor light on database reliability. It is important to be aware of the these conflicts for the following reasons:

- There are problems within current southern African cryogenic data that are often not addressed. Most of these problems, as will be revealed later on, are still under discussion internationally.
- Unconfirmed arguments and ideas influence database objectivity. Current cryogenic data interpretation are used to explain and lay the foundation for either glacial or periglacial arguments for the palaeoclimate of southern Africa. However, most proposed hypotheses and follow-up arguments have not been verified and lack back-up research and contributions from other disciplines.
- Criticism on proposed ideas is seldom constructive and rarely contributes towards the discussion.
- Due to the scarcity of cryogenic data in southern Africa, database reliability is compromised in that it is reliant on a small assortment of unverified research.

The primary intention of the following discussion is to focus attention on some irregularities and the arguments and criticism surrounding it, and not to assess database credibility.

4.2.1 Southern African erosional hollows

Southern African erosional hollows are the most debated phenomena in current cryogenic literature. Marker (1989, 1990c, 1991b, 1992, 1998) undoubtedly contributed greatly towards research concerning these much-disputed features. Erosional hollows are believed to be the products of Quaternary cold periods in southern Africa and are described as valley-type features found in the upper regions of the High Drakensberg and Lesotho Mountains resembling shallow cirques (Marker, 1989, 1990c, 1991b; Sparrow, 1971, 1973, 1974). Erosional hollows are sometimes referred to as amphitheatre-shaped hollows, cirque-like hollows and nivation cirques (Sparrow, 1964; Marker & Whittington, 1971; Hastenrath, 1972; Nicol, 1973; Hastenrath & Wilkinson, 1973; Dyer & Marker, 1979; Marker, 1989, 1990c, 1991b; Hanvey & Marker, 1994). Erosional hollows are frequent along the Great Escarpment.

4.2.1.1 The Golden Gate erosional hollows

Marker (1989) found that periglacial processes and nivation formed the Golden Gate erosional hollows, and that the characteristic niche-shape of some of these features indicates an origin under snow-patch conditions (Marker, 1990a). The contention is that the shape of the hollows was enhanced by the distinct geology of the region (resistant basalt over sandstone), but that if they were solely structural in origin they should occur on all aspects and at any elevation (Marker, 1990a). The hollows occur seemingly only on south-facing slopes and above 1 700m a.s.l. (Marker, 1990a).

Where form and shape is concerned, however, one cannot necessarily infer causes from outcomes. In addition, the hypothesis of periglacial conditions during the Pleistocene may be disputed on account of the probable aridity of the eastern Free State (and most of the subcontinent for that matter) during the Last Glacial Maximum (LGM) (Le Roux, 1990). The characteristic niche-shape hollows along south-facing slopes can form because of lithological differences, notably in basalt, which tends to be unhomogeneous (Le Roux, 1990; Van Rooy & Nixon, 1990; Van Rooy, 1992; Van Rooy & Van Schalkwyk, 1993). Different mechanisms other than nivation may have been operative in the formation of the hollows.

4.2.1.2 The High Drakensberg and Lesotho Mountains erosional hollows

Both nivation and cirque glaciation have been proposed to explain the origin of the Lesotho erosional hollows (see Chapter 2). The hollows are regarded as cold climatic features because of their strong pole-facing orientation, and are associated with other pole-facing asymmetrical slope forms and periglacial features (Sparrow, 1973). These hypotheses, however, have not yet been proven (Grab & Hall, 1996). Researchers should also note the following issues raised by Sparrow (1973), Hall (1991c), Le Roux (1991b) and Hall & Grab (1996):

- The Lesotho erosional hollows may imply a different suite of evolutionary and palaeoenvironmental events in the landscape.
- The term "nivation" has its own set of problems (see later discussion) and lacks an acceptable operating definition.
- The idea of large quantities of Pleistocene snow drifting into leeward positions seems unlikely when compared to contemporary snow drifting, which is insignificant.
- It is proposed that the hollows are of nivational/glacial origin. Erosional hollows appear to be restricted to regions above 3 000m a.s.l. and are mostly north-facing. But, if

snowfall were enhanced and remained for longer periods, it is just as valid to presume that cirques would rather have developed a preferred south-facing aspect.

- Snow-patches may accumulate in pre-existing hollows, but are unlikely to have produced the hollow itself. It is evident that the Lesotho erosional hollows developed over a long period, but it is difficult to contribute hollow formation to glacial/periglacial processes when unequivocal evidence is absent.
- It is difficult to interpret past conditions from geomorphological evidence alone. This makes it essential to support any argument in favour of former cold conditions by evidence from other disciplines.
- *Pre-existing* hollows for cirque formation and *time* for cirque development, growth and decline need more consideration.

The distinct structural disposition of the High Drakensberg and Lesotho Mountains, its superficial geomorphological impact yet unknown, may play a significant part in the natural formation and control of erosional hollows and niches (Meiklejohn, *et al.*, 1999).

An alternative approach is presented by Hall & Grab (1996) suggesting that the Lesotho erosional hollows are reminiscent of *bog cirques* as seen in north-eastern Mongolia (Dzulynski & Pekala, 1980). The regions in which bog cirques occur, display similar climatic conditions to those found in southern Africa, amongst others summer rainfall and winter drought, low mean annual air temperatures, a scarcity of snow, and intense diurnal and seasonal freeze-thaw cycles. According to Hall & Grab (1996) the Lesotho erosional hollows exhibit many prominent bog cirque characteristics:

- Hollow morphometry, like bog cirques, resembles that of nivation hollows and are prominent features of the landscape.
- Hollows are irregularly spaced, have arcuate rock benches and basin-like depressions.
- Hollows develop preferentially on the sun-exposed (north-facing) slopes.
- Hollow floors are boggy and host peat-forming vegetation.
- Hollows commonly merge into trough-like summit surfaces at high elevations.

Hall & Grab (1996) decided that the nival/glacial hypotheses for north-facing hollows harbour too many problems. They call for a revision of high altitude palaeoenvironmental theory and unequivocal evidence. Sparrow (1973) documented the same hollow characteristics as found by Marker (e.g. 1989, 1991b, 1992) and Dyer & Marker (1979). However, Sparrow (1973) perceived that the hollows are relatively shallow and display prominent head fans at their bases, both of which tend to rule out an origin by ice processes. According to Sparrow (1973), glacial evidence is lacking for the High Drakensberg and Lesotho Mountains and former cold-climate conditions may not have been either intense or necessarily long in duration to produce glacial phenomena. Thus, Sparrow (1974) argues for a non-glacial hollow developmental sequence for southern African erosional hollows.

Sparrow (1974) found that the erosional hollows form through a sequence where asymmetrical slope forms evolve either through a dry succession or a wet succession into cirques (Fig. 4.1). Dry succession landforms have a developmental sequence of their own but may graduate into the wet succession. Wet succession landforms are restricted in distance to the eastern and south-eastern parts below the main Escarpment (Sparrow, 1974). The transitional stage between dry and wet successions can evidently be seen in the strongly denticulated cliffs, pinnacles and large shallow hollow development (Sparrow, 1974).

The origin of southern African erosional hollows remains nonetheless unresolved. More research and testing of hypothesis are needed to prove or disprove current ideas on the matter. Erosional hollows are not the only cryogenic features needing further investigation as will be shown presently.

4.2.2 Valley asymmetry

Valley asymmetry is another large-scale phenomenon observed in southern Africa. The strongest manifestations occur in Lesotho and adjacent areas (Sparrow, 1964, 1967a, 1969; Boelhouwers, 1988; Marker, 1989; Meiklejohn, 1992; Grab, 1999; Meiklejohn *et al.*, 1999). In the High Drakensberg and Lesotho Mountains south-facing slopes are consistently steeper than north-facing slopes and attributed mainly to periglacial and snow processes (Meiklejohn, 1992; Grab, 1999). However, asymmetric valleys can form under almost all climatic conditions (Le Roux, 1990) and are not necessarily indicators of periglacial activity (Meiklejohn, 1994). Garland (1979), Boelhouwers (1988) and Grab (1999) pointed out that differential operation of non-periglacial processes on north- and south-facing valley sides, might account for valley asymmetry in the Drakensberg. Garland (1979) and Boelhouwers (1988) proposed that the valley-side with the highest denudation rates will develop the

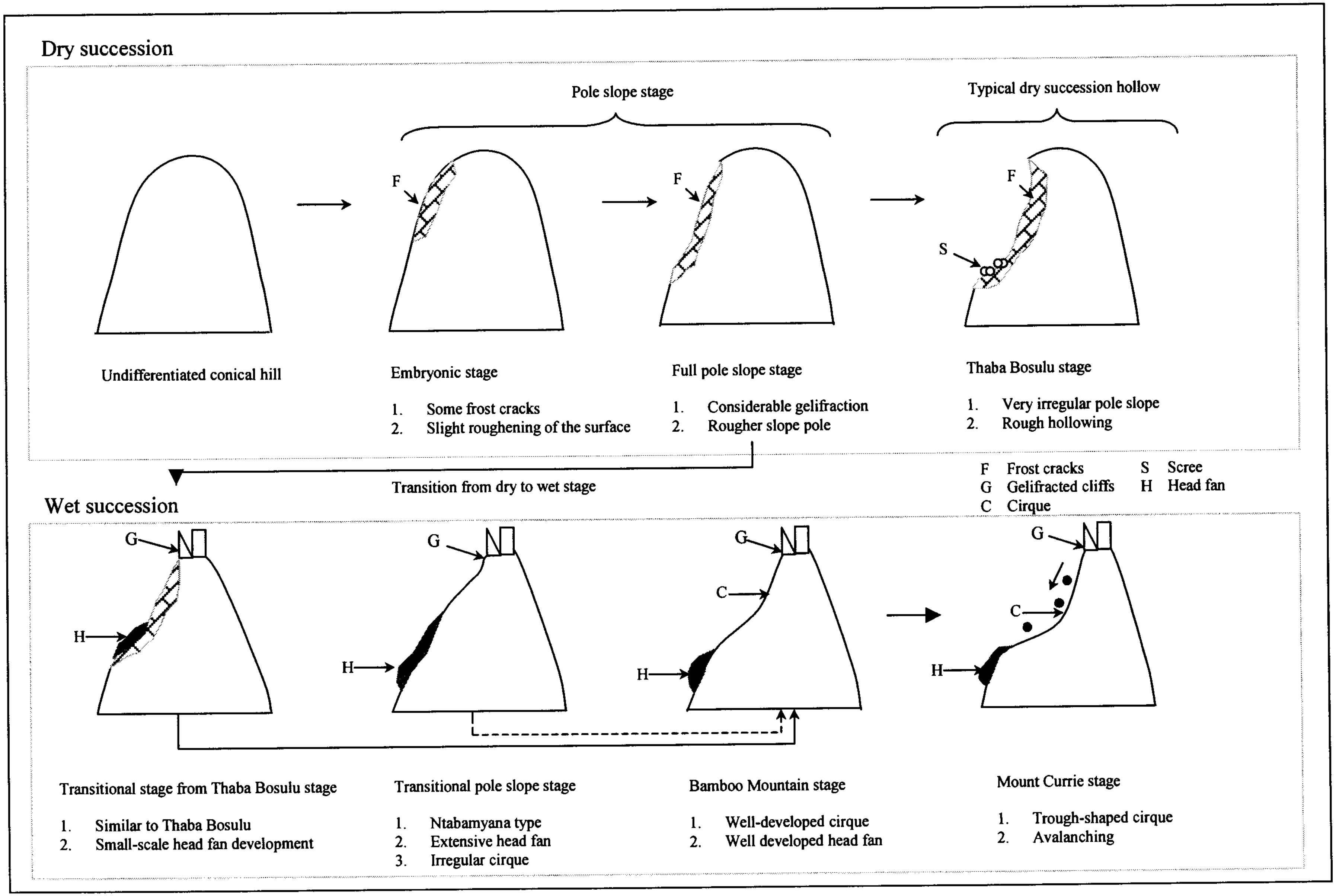


Figure 4.1: Suggested developmental sequence of non-glacial cirques (after Sparrow, 1974)

shallowest gradient, i.e. the north-facing slope, and that over time valley asymmetry will originate through the dominance of non-periglacial processes. Boelhouwers (1988) concludes that the observed valley asymmetry is the result of differing intensities of various weathering and erosion processes on opposite valley sides. No aspect of valley form in and of itself appears to be sufficient to establish a periglacial environment, and to emphasise asymmetry in and of itself cannot be considered diagnostic (Thorn, 1991; French, 1996).

4.2.3 River terraces

Marker (1989) reported a double terrace along the Little Caledon River consisting of rubble lobes evidently moved downslope by solifluction (Marker, 1989). Current drainage through the deposits do not affect the alleged solifluction material and at least five solifluction diamictons, fining upwards and showing fluvial sorting, are visible (Marker, 1989, 1990a). These unsorted sediments need not necessarily be solifluction material. During the present climate unsorted slope material creeps downslope very slowly, but during heavy rainfalls debris slides are common (Le Roux, 1990). The deposits could have accumulated during an arid phase of the LGM when the Little Caledon River might not have been able to move the unsorted sediment delivered by infrequent heavy rains (Le Roux, 1990). Thorn (1991) noticed that there are many fluvial situations in cold climates lacking diagnostic landforms that might establish a periglacial environment.

4.2.4 Large scattered boulders

Large scattered boulders are a regular phenomenon on slopes of the High Drakensberg and Lesotho Mountains. The distribution is widespread but seemingly always above 1 500m a.s.l. (Marker, 1989, 1990a). Some had slid down in a matrix of mud and boulders evidently caused by solifluction (Marker, 1989). According to Le Roux (1990) it must first be considered, before attributing the transportation and formation of the boulders to specific geomorphic events, that boulders can roll downslope from a scarp or cliff on to their present locations and can move downslope slowly in and on other debris and soil aided by gravitation and heaving. Boulders may even move due to the lubricating effects of water and the shear pressure of the debris packet above the boulder (Le Roux, 1991). Moreover, the large scattered boulders observed on the subcontinent are common tropical climate and tropical desert features. The observation that boulders are only found above 1 550m a.s.l. is accounted for by the fact that rock material of sufficient strength coupled with massivity and thickness does not occur below that elevation (Le Roux, 1990).

4.2.5 Basalt and angular clasts

Basalt is a dark igneous rock characterised by small grain sizes and containing almost equal proportions of plagioclase feldspar and calcium rich pyroxene (Mottana *et al.*, 1995; Clark, 1998). Most angular clasts in the High Drakensberg and Lesotho Mountains are contributed to freeze-thaw mechanisms (e.g. Hanvey & Marker, 1992). In a laboratory test conducted by Haskins & Bell (1995) it was shown that all the basalts tested (olivine, amygdaloidal, moderately amygdaloidal and non-amygdaloidal) had a relatively high resistance to cyclic freezing and thawing, but not to repeated wetting and drying. Basalts are much more prone to chemical weathering (Hall, 1992). In cold climates basalts and sandstones can produce angular or rounded clasts (Hall, 1992). Rounded clasts are usually found where a greater amount of water and high rock temperatures are present to produce chemical weathering (Hall, 1992). It is more likely southern African basalts produce rounded or angular clasts not necessarily due to cryogenic processes, but rather to chemical weathering and the availability of water and high temperatures (Hall, 1992). Angular clasts can also result from thermal fatigue and have no unique association with frost action (Hall, 1992).

4.2.6 Cutbacks

Cutbacks are narrow, steep-sided valleys or passes cut into the slopes of a mountain. According to Grab (1996a) they are ravines or steep, narrow valley heads. Cutbacks are commonly found in the High Drakensberg and Lesotho Mountains. Hall (1994) observed that these cutbacks have channel systems with closing borders at their lower ends consisting of rounded, cobble to boulder-sized debris. Hall (1994) envisaged large volumes of water discharging the deposits and rounding boulders during transport. The possibility of debris flows and precipitation were ruled out in favour of meltwater from an ablating ice body (Hall, 1994). Hall (1994) concluded that there was a glacial ice cover on the High Drakensberg and Lesotho Mountains that melted during the onset of the Holocene, pouring down the cutbacks and forming the deposits. It is suggested that nival processes are responsible for the origin of the cutbacks. However, basalt is predisposed to rounded clasts and in cold climates with high rock temperatures and wet conditions, weather to rounded clasts (Sarracino & Prasad, 1988;

Hall, 1992; Sumner, 1995). Basalt can already be highly rounded by weathering prior to movement (Hall, 1992). Rounded basalts are frequent on the Escarpment where no fluvial action or clast movement is taking place (Sumner, 1995). Sumner (1995) argued that nival processes couldn't fully explain the origin of the cutbacks or the large debris deposits.

4.2.7 Protalus ramparts

A protalus rampart is an accumulation of coarse angular rock debris resembling a moraine and consisting of material that has slipped down from perennial banks of snow, lying parallel to the slope that produced it (French, 1996; Shakesby, 1997; Clark, 1998). A feature resembling a protalus rampart was found in Bokspruit, Eastern Cape by Lewis (1994) and measured according to the criteria given by Ballantyne & Kirkbride (1986). The rampart is approximately 1km long and 17m high, consisting of a connected series of arcuate debris accumulations. Lewis (1994) assumed that the feature is a protalus rampart caused by snowbed growth during the LGM. Shakesby (1997), though, is of the opinion that the differences are more noteworthy than the similarities between this feature and a true protalus rampart:

- Only the relationship between the Bokspruit rampart width and thickness is similar to the findings of Ballantyne & Kirkbride (1986).
- The relationship between the protalus rampart at Bokspruit's size indices and crest-talus distance was a negative relationship, unlike the positive one found by Ballantyne & Kirkbride (1986).
- All of the Bokspruit rampart size indices lie outside the range of the British examples given by Ballantyne & Kirkbride (1986).

Shakesby (1997) likewise questions other "protalus" ramparts identified in southern Africa (e.g. Nicol, 1973; Lewis, 1987, 1994; Marker, 1989, 1990c) and resolved that they probably had alternative origins.

4.2.8 Scree deposits

Intense frost action together with periglacial slope-wash is generally believed to be the formative processes behind screes (French, 1996). Scree deposits are familiar features in the

High Drakensberg and Lesotho Mountains and especially in the Eastern Cape. They have been extensively researched by Marker (1986) and attributed to nivational and frost action processes in a cold palaeoperiglacial environment. However, subsequent research by Sumner & De Villiers (*in prep.)* has shed more light on the nature of these screes and concluded that, although there is a strong indication that cold processes were responsible for their formation, the screes can not be ascribed to any specific cold environment scenario. It was further suggested that the features were deposited over a long period pre-dating the Last Glacial Maximum (LGM) (Sumner & De Villiers, *in prep.*). French (1996) cautions that screes may possess a wide range of textural characteristics related to local bedrock conditions. Screes may also be formed by other processes totally unrelated to periglacial conditions, e.g. debris flows (French, 1996) and may therefore not be a reliable diagnostic indicator for past periglacial climates.

4.2.9 Discussion of Harper (1969) and Linton (1969)'s findings

It is essential to support any argument in favour of former cold conditions by inter-disciplinary evidence (Sparrow, 1973). Both Harper (1969) and Linton (1969) failed to produce empirically tested evidence (Sparrow, 1973). Harper (1969) and Linton (1969) reported on such diverse features and processes as basalt steps, patterned ground, erosional hollows, frost wedging, glacial polish, ice-wedges, slip scars, valley asymmetry, etc. Butzer (1973) suggested that Linton's (1969) striped blockfields near Pretoria (see Chapter 2) might actually be typical sheet-wash, creep and occasional mudflow deposits of a more colluvial nature. A more likely explanation is that the deposits are karstic or even litho-structural in origin (Butzer, 1973). The inverted weathering profile near Magaliesburg (Linton, 1969) are, according to Butzer (1973), not uncommon to the foot slope sectors of the High Veld wherever colluvial agencies have been prominent. Butzer (1973) altogether disregarded Linton's (1969) cryonival and geliflual interpretation of Western Cape features (Appendix A) and the possibility of cold climatic conditions in the northern parts of the subcontinent.

4.2.10 Comments on process terminology usage in southern African cryogenic research

It has been shown thus far that some southern African cryogenic researchers inevitably step into pitfalls because of qualitative presumptions and a lack of evidence and empirical quantitative research. Thorn (1991) specifies problems experienced world wide with certain processes that southern African researchers should take note of, especially where terminology usage is concerned. Earlier it was revealed that southern Africa is a borderline or sub-periglacial region (Chapter 2) and that little is known about the features and processes abounding there. It is difficult to discern what combinations of processes have been operative in the recent past (Hall, 1992), particularly in marginal areas (i.e. sub-periglacial regions). Therefore, considerable caution must be taken when classifying and interpreting southern African phenomena, otherwise a completely misleading picture may emerge (Hall, 1992). Thorn (1991) further comments on the terminology usage of frost wedging, frost heaving and nivation in southern African cryogenic research.

4.2.10.1 Frost wedging

Frost wedging, in the broadest sense, is weathering by freezing and thawing, yet it is not known exactly how this process works and what the main protagonists are (Thorn, 1991). Although the term is widely accepted in periglacial studies, it lacks detailed theory (Thorn, 1991). In this regard, Walder & Hallet (1985) did develop a theoretical framework, but warned that there are too many unresolved problems, e.g. the likelihood of frost wedging as a multi-component process, of which not much is known (Thorn, 1991). Frost wedging is believed to produce angular fragments, but this has already been shown as not entirely true as angularity is largely dependent on the lithology and several other mechanisms (Hall, 1992). A revision of the use of “frost wedging” is called for since this term is used too readily in southern African cryogenic literature (e.g. Harper, 1969; Borchert & Sänger, 1981).

4.2.10.2 Frost heave

Hastenrath (1972) mentions the presence of frost heave processes in the High Drakensberg and Lesotho Mountains. Frost heave of soil is produced by two primary mechanisms, namely a 9% expansion of volume during the phase change from liquid to ice, and a much more complex as well as a potentially much larger effect produced by the migration of unfrozen soil moisture to the freezing front, usually producing segregation ice. The assumption is the presence of an attractive force towards the solid-liquid interface, but there is no definitive explanation of such a force, although evidence for it does exist (Thorn, 1991). Another assumption is the presence of a *disjoining* force that separates the faces of a growing ice crystal from solids. Theoretical explanation of the formative processes of segregation ice, nevertheless, has remained difficult (Thorn, 1991).

4.2.10.3 Nivation

Matthes (1900) introduced the term nivation, defining it as the process of névé occupying a valley and changing its form from a V-shaped to a U-shaped (Thorn, 1988). Mechanical weathering, chemical weathering and mechanical transport are only a few of the processes that may be involved in nivation (Thorn, 1988). However, the term embraces many component concepts and is not defined operationally (Hall, 1991a; Thorn, 1991). According to Thorn (1978, 1991), the term "nivation" must be abandoned in favour of uncomplicated terminology and critical analysis (Grab & Hall, 1996). It is evident that southern African researchers use the term too quickly without prior knowledge of the many difficulties surrounding it (e.g. Sparrow, 1967a; Harper, 1969; Nicol, 1973; Dyer & Marker, 1979; Borchert & Sänger, 1981; Lewis & Hanvey, 1988; Marker, 1986; Hanvey & Lewis, 1991; Hall, 1994).

4.2.11 Freeze-thaw weathering

Freeze-thaw weathering, also called gelifraction (Sparrow, 1964; Hastenrath, 1972; Hastenrath & Wilkinson, 1973; Nicol, 1973), is a form of weathering in periglacial areas where the temperature stays close to freezing point, below which frost breaks up the rock and above which the ice melts, so that water flows and carries away the rock fragments (Clark, 1998). Many workers attribute their findings to freeze-thaw weathering (e.g. Sparrow, 1964; Hastenrath, 1972; Hastenrath & Wilkinson, 1973; Nicol, 1973; Marker, 1989), but findings continue to be unsubstantiated and qualitative with respect to the role of freeze-thaw weathering in nivation and of its role in the developmental sequence of hollow to cirque (Hall, 1988a; 1991b). Freeze-thaw weathering is a very complex process (Hall, 1991b) and constitutes a range of potential means by which it can take place (Fig. 4.2). Hall (1988a) remarked that although the High Drakensberg and Lesotho Mountains experience cold for part of the year and are substantially elevated above sea level, one can not justifiably say that the process of freeze-thaw weathering takes place.

Freeze-thaw weathering is a complex phenomenon and has been researched extensively. For further reading on the matter the following publications are recommended: Clark & Small (1982), Hall (1988a, 1988b, 1991a) and Matsuoka (1990).

Freeze-thaw weathering

- Hydration (water does not freeze) (White, 1976)
- Hydrofracture (force of water in front of freezing front) (Powers, 1945)
- Acoustic emission (sound waves cause fracture) (Hodder, 1976)
- 9% volumetric expansion (Hodder, 1976)
- Closed system caused by 0.1°C min^{-1} fall of *t* (Battle, 1960)
- Undirectional crystal growth of ice (Connell & Tombs, 1971)
- Ice lens growth (rock as an analogue to soil)

Figure 4.2: Some of the various mechanisms that constitute freeze-thaw weathering (after Hall, 1991b).

4.2.12 Frost action features

Frost action is frequently claimed as an important indicator of palaeocryogenic, and in particular periglacial, environments (French, 1996). Frost action has been cited as the cause of several southern African cryogenic features by Sparrow (1967a), Harper (1969), Hastenrath (1972), Hastenrath & Wilkinson (1973), Borchert & Sänger (1981), Hanvey *et al.* (1986), Lewis & Hanvey (1988), Lewis (1989, 1996a), Hanvey & Lewis (1991), and Grab (1994). The recognition and interpretation of evidence regarding frost action, however, is sometimes difficult, mostly because of the presence of contemporary frost action (French, 1996). According to French (1996), a relict feature's frost action significance is dependent on the evaluation of the susceptibility of the underlying bedrock to frost action, moisture, vegetation, and local conditions. Furthermore, features that are generally held as indicators of frost action palaeoenvironments, e.g. tors, blockfields, cryoplanation terraces, grèzes litées and head, may have been formed under non-periglacial circumstances (French, 1996). Few of these features provide unequivocal proof of palaeoperiglacial conditions and only where a number of different features occur together or in association with one another, a frost action environment may be assumed (French, 1996).

4.2.12.1 Blockfields

Southern African blockfields have been documented by Linton (1969), Sparrow (1971), Borchert & Sänger (1981), Sänger (1988) and Boelhouwers (1994). Blockfields are apparently indicators of intense frost wedging (French, 1996). However, before considering blockfields as relict cryogenic features, it must first be proven that the deposits are not being formed under present-day climatic conditions or that the current rate of weathering is insufficient to explain them (French, 1996). It is also possible that blockfields, especially in southern African context, may have formed over a long period of time (French, 1996), in which case it is difficult to pinpoint one specific geomorphic event. French (1996) warns that these features are of limited use in Pleistocene periglacial reconstruction (French, 1996).

4.2.12.2 Tors and cryoplanation terraces

Sparrow (1967a), Hagedorn (1984), and Dardis & Granger (1986) identified tors and cryoplanation terraces on the subcontinent and ascribed them to gelifluction, nivation and frost creep. French (1996) suggests that a variety of processes and environmental conditions may produce essentially the same landform, and periglacial conditions merely represent one set. With regards to cryoplanation terraces, no processes thus far demonstrate that these phenomena form under prevailing cold climate conditions (French, 1996). French (1996) concludes that it is more appropriate to stress the role of mass wasting than frost action in the periglacial interpretation of tors and cryoplanation terraces. In terms of southern Africa cryogenic research it is questioned whether these ambiguous features should be considered in palaeoenvironmental reconstruction.

4.2.12.3 Gelifluction head deposits

Gelifluction head deposits (or more commonly referred to as "head"), are composed of predominantly poorly sorted and poorly stratified angular debris (French, 1996). Gelifluction head deposits are regarded as indicative of Pleistocene solifluction and frost creep in particular (French, 1996). Their direct interpretation in terms of frost action is difficult; the problem lies in the inability to distinguish between solifluctional (implying seasonal frost) and gelifluctional (implying permafrost) induced head deposits (French 1996). Although gelifluction head deposits have been documented by Nicol (1973), there is too much uncertainty concerning the present-day as well as the palaeocryogenic environment to even consider gelifluction head deposits as an indicator of periglacial conditions.

4.3 Conclusion

The glossaries discussed in this chapter are seen as a means to standardise available cryogenic data as part of the development of the Cryogenic Processes and Landforms Spatial Database for Southern Africa (Appendix A). It was further recognised that the reliability of database information is dependent on more research and new data. Therefore several areas of concern were discussed as an attempt to focus attention on possible areas of research. The most important factor to consider is that, although the identification of distinct forms is essential in understanding the environment and the processes responsible for its evolution, form is only a means to an end and should not be the centre of inquiry. The only forms worthy of detailed attention should be those whose explanation adds something to existing knowledge of the landscape (Thorn, 1991). This is true for most environments of the world, and is applicable to the southern African cryogenic scene.

This concludes the developmental stage of the Cryogenic Processes and Landforms Spatial Database for Southern Africa. In the Chapter 5 the database will be implemented to evaluate certain issues in cryogenic research that have been discussed earlier.

CHAPTER 5

Preliminary data analysis through database manipulation

Chapter 5 focuses on preliminary data analyses (based on Schulze, 1998) through manipulation of the Cryogenic Processes and Landforms Spatial Database for Southern Africa (Appendix A) to evaluate database efficiency and feasibility. Key areas tested are (i) accessibility to data, (ii) data and database manipulation, and (iii) overall user friendliness in context of current debates in southern African cryogenic literature. The relevant requirements for an effective database were stipulated in Chapter 3:

- Quick access to data.
- Easy manipulation for overlaying, querying and map calculation.
- Reasonable generalisation of data.
- The possibility of entering new data and of upgrading, correcting and deleting existing data.

The purpose of this study is not to give a definitive analysis of southern African cryogenic data, but to provide a tool for future investigation and an objective data source to challenge specific research problems, thus adding to existing Quaternary knowledge. Ultimately the aim is to gain a better understanding of the intensity and spatial distribution of relict features and processes, and contribute towards reconstructing the southern African Quaternary environment.

5.1 Data analysis

The present situation of both relict and active cryogenic features and processes distribution can be constructed by projecting database attribute data onto spatial grid data. For this purpose a topographic map of southern Africa (Fig. 5.1) was used unto which glacial, relict periglacial and current periglacial phenomena were projected (Fig 5.2). Three focus areas for cryogenic features and processes manifested from the projection. The first are areas immediately adjacent to and in the near vicinity of the Lesotho/Kwa-Zulu Natal Drakensberg (above the Escarpment) (Region 1, Fig. 5.2; Fig. 1.2). The second are areas below the Escarpment comprising the Eastern Cape Drakensberg near the Lesotho border and a small extension towards the south-southwest (Region 2, Fig. 5.2). The third focus point is in the

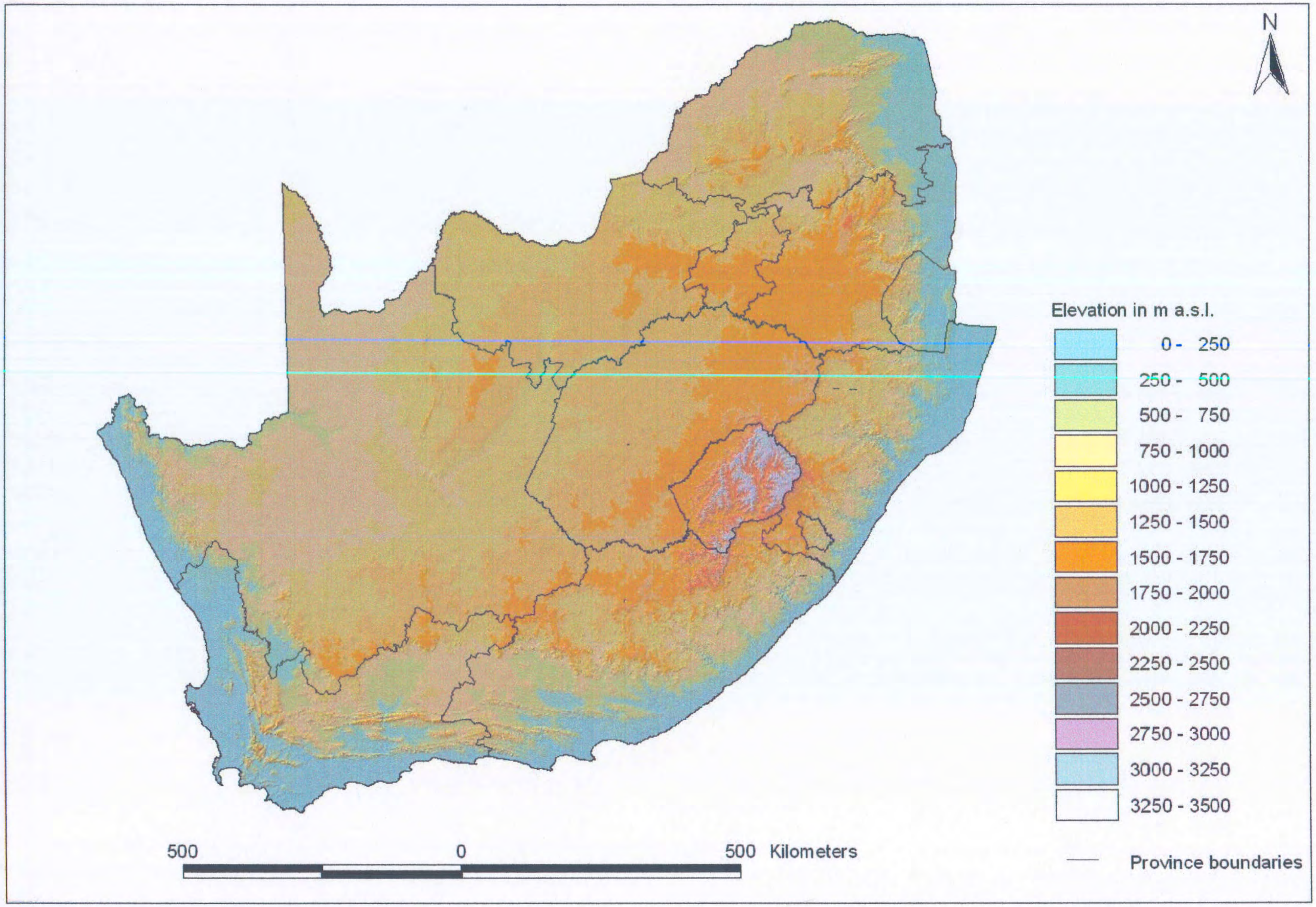


Figure 5.1: Topographic map of southern Africa.

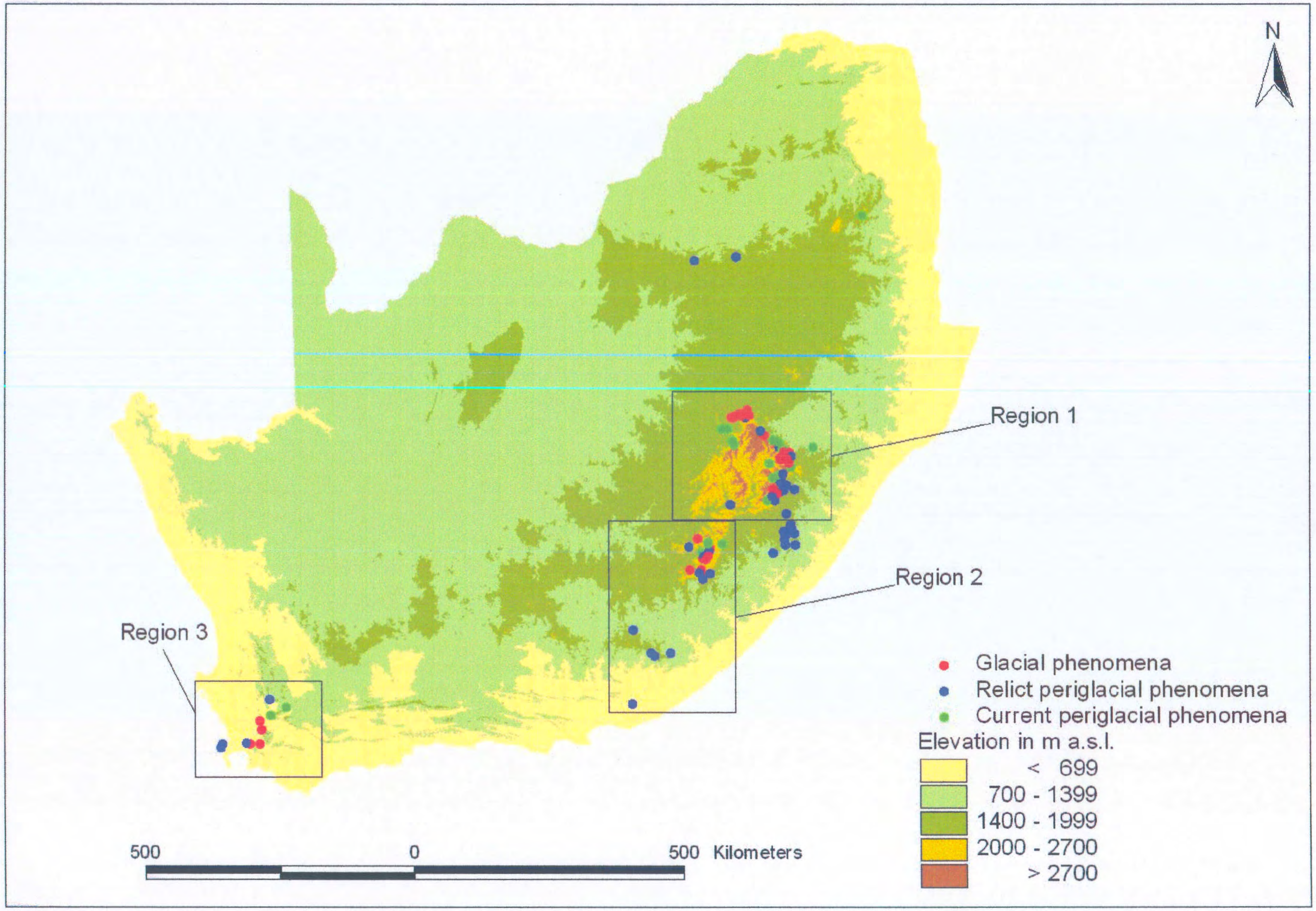


Figure 5.2: Proposed relict and current cryogenic phenomena and the main cryogenic regions.

Western Cape Mountains (Region 3, Fig. 5.2). Fig. 5.2 and Fig. 5.3 show that most features and processes occur at elevations above 1 200m a.s.l. along the major mountain ranges of southern Africa, especially at the Great Escarpment and Eastern Cape Drakensberg. With closer inspection, however, it appears that these areas are located primarily on basalts (Region 1), dolorites and sandstones (Region 2), and quartzites (Region 3; SACS, 1980; Dardis & Moon, 1988) and in regions that receive above 700mm annual precipitation (see later analysis). Clearly more in depth analysis is needed to comprehend the true nature of the distribution of cryogenic phenomena in southern Africa. Therefore the following themes will receive closer inspection:

- The current periglacial environment
- The periglacial palaeoenvironment
- The glacial environment

Each theme will be analysed by following a basic structure of inquiry:

- What are the general and specific conditions stipulated for a periglacial or glacial environment?
- What are the general and specific conditions of the southern African periglacial or glacial environment as documented by researchers?
- Which of those conditions will be examined in data analysis?

5.1.1 Current (sub-) periglacial environment

A periglacial environment is dominated by frost action features and processes and is not restricted to areas peripheral to glaciers, either in time or space (French, 1976, 1996). Periglacial regions display cold, non-glacial conditions and permafrost-related processes, although permafrost is not a necessary requirement for periglacial environments (French, 1976, 1996). Diagnostic criteria for all periglacial environments are freezing and thawing of the ground and/or the presence of perennially frozen ground (French, 1976, 1996). According to French (1976, 1996), the boundary conditions for periglacial domains are where mean annual air temperatures (MAAT) are less than +3°C, -2°C in areas where frost action dominates, or -2°C to +3°C in areas in which frost action processes occur, but do not dominate (Table 5.1).

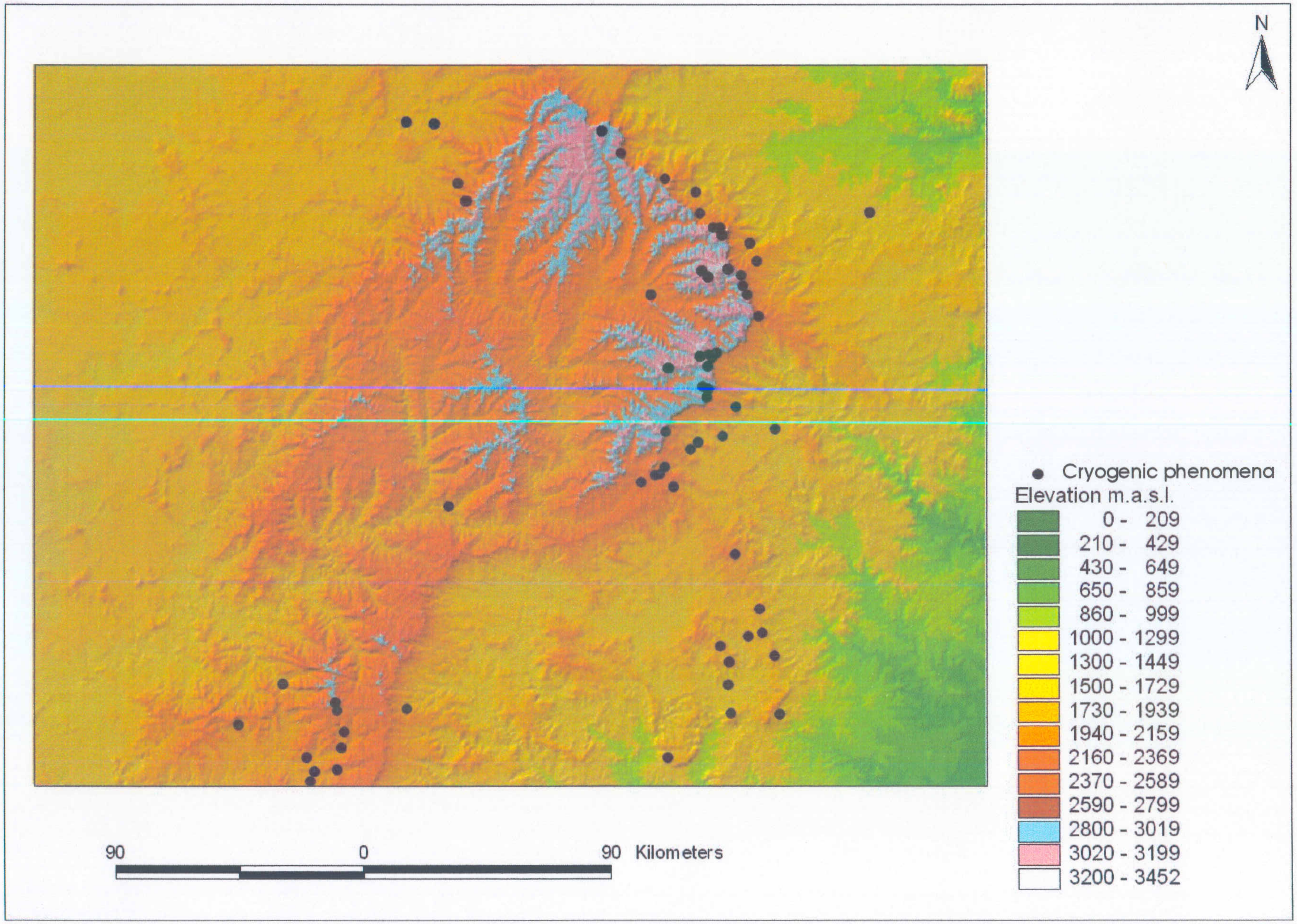


Figure 5.3: The main body of cryogenic features and processes are located at the Great Escarpment and Eastern Cape Drakensberg.

Periglacial climate	General	Description					Example
		Diurnal pattern	Seasonal pattern	Mean annual rainfall	MAAT		
					Range	°C	
High arctic	Polar latitudes	Weak	Strong	93 - 298mm	25 - 36	-8 to -14	Spitsbergen (78°N)
Continental	Subarctic latitudes	Weak	Strong	247 - 343mm	45 - 62	-5 to -10	Central Siberia (62°N)
Alpine	Middle latitudes Mountain environments	Well-developed	Well-developed	1 638 - 1 021mm	15 - 22	-3 to -7	Alps (47°N)
Qinghai-Xizang (Tibet) Plateau	High elevations (4 200 - 4 800m a.s.l.) Low latitude	Well-developed	Well-developed	345mm	23	-6	Fenghuo Shan (34°N)
Climates of low annual temperature range in azonal locations							
Island	Subarctic latitudes	-	-	365mm	8	0	Jan Mayen 71°N)
Mountain	Low latitudes	-	-	1 309mm	7	2	Andean summits (16°S)

Table 5.1: Classification of periglacial climates and environments based on elevation, insolation and temperature (after French, 1996).

5.1.1.1 Requirements for analysis

It was established that the following characteristics are distinctive of a present-day periglacial environment:

- Frost action and permafrost-related processes.
- Regular freezing and thawing of the ground.
- Perennially frozen ground.
- Not restricted to glaciated areas.
- MAAT between -2° and +3°C.

Compared to French's (1976, 1996) conditions for periglacial environments, the current southern African cryogenic environment display the following characteristics:

- Cryogenic phenomena occur at elevations above 1 200m a.s.l. (Marker, 1995a).
- Current cryogenic features and processes cluster along the main Escarpment of Lesotho, the Eastern Cape, and the Western Cape (Marker, 1995a).
- The current cryogenic environment displays a decline in altitude with lower latitude (Marker, 1995a).

- The current cryogenic environment extends from +1 700m a.s.l. in the Waaihoek Mountains, Western Cape, to +1 800m a.s.l. (southwestern Cape), +1 900m a.s.l. (north-eastern Cape) and +2 900m a.s.l. in northern Lesotho (Marker, 1995a).
- MAAT for the current cryogenic environment is between +4° and +7°C (Boelhouwers, 1991a; Hanvey & Marker, 1992).

Each characteristic is considered in the data analysis. Specific topics that need verification are the following:

- Whether the southern African environment is a marginal montane periglacial (Lewis, 1987; Boelhouwers, 1991a), borderline periglacial (Boelhouwers, 1991b; Hall, 1994), or a marginal frost action environment (Boelhouwers, 1994, 1995a; Grab, 1997a, 1997b).
- Whether cryogenic (sub-periglacial) features cluster along or adjacent to the Drakensberg Escarpment of Lesotho, Kwa-Zulu Natal, the Eastern Cape and the Western Cape (Marker, 1995a).
- The extent of the cryogenic (sub-periglacial) zone as proposed by Marker (1995a).
- Whether there is a decline in altitude with higher latitude (Marker, 1995a) for the present-day cryogenic (sub-periglacial) zone
- Whether the exact extent of the modern cryogenic (sub-periglacial) environment can be established (Lewis, 1987; Meiklejohn, 1992; Grab, 1997a).

The structure and procedure of the data analysis is reviewed in Table 5.2. Note that only processes, e.g. frost action, solifluction etc., are considered for analysis.

5.1.1.2 Discussion

After classifying current MAAT to fit French' (1976, 1996) requirements for a periglacial climate and projecting current frost action- and freeze-thaw related processes onto this, only a few areas along the Lesotho/Kwa-Zulu Natal Escarpment were identified as "periglacial" (Fig. 5.4). The regions below the Escarpment and the Western Cape-region (Region 2 and 3, Fig. 5.2) did not surface after calculation. Realising that most of these features and processes are probably seasonal rather than annual occurrences, a map was calculated to fit a seasonal cold pattern. The same periglacial requirements set by French (1976, 1996) were used to calculate seasonal "periglacial" regions for the subcontinent from mean annual minimum air temperatures (MAMAT). It was shown that larger areas that may be labelled as "seasonal periglacial" emerged from the calculation (Fig. 5.5). Parts of Region 2 (Fig. 5.2) are included

Analysis (A)		Map
A1	Current MAAT of southern Africa	
A2	Current frost action processes, permafrost-related processes, freezing and thawing of the ground in southern Africa.	
A3	Current MAAT and frost action processes, permafrost-related processes, freezing and thawing of the ground in southern Africa.	A1 + A2
A4	Current periglacial regions of southern Africa that meet the periglacial MAAT requirement of -2° to +3°C.	A3 + A4 = Fig 5.4
A5	Mean annual minimum air temperatures (MAMAT) of southern Africa.	
A6	Current periglacial regions of southern Africa that meet the periglacial MAMAT requirement of -2° to +3°C.	A2 + A5 + A6 = Fig. 5.5
A7	Mean annual precipitation (MAP) for southern Africa.	
A8	MAP for southern Africa and current periglacial regions that meet the periglacial MAAT requirement of -2° to +3°C.	A2 + A7 + A8 = Fig. 5.6

Table 5.2: Analysis structure for examining present sub-periglacial regions in southern Africa.

into this new definition and a few scattered areas to the south and south south-west surfaced (Fig. 5.5). Region 3 (Fig. 5.2) did not figure in this calculation.

Only air temperature was used in calculations. Another factor that needs consideration, especially where the Western Cape region (Region 3, Fig. 5.2) is concerned, is precipitation. The subcontinent receives its highest precipitation along the Western Cape Mountains, the Eastern Drakensberg, Mpumalanga and in the Northern Province along the Escarpment (Fig. 5.6). It is in these regions, except for those regions in the latter two provinces, that current cryogenic (sub-periglacial) phenomena cluster. MAAT calculations do not verify the existence of cryogenic (sub-periglacial) processes in the Western Cape Mountains.

From the findings it is suggested that the southern African environment is a cold environment where marginal frost action processes (Boelhouwers, 1994, 1995a; Grab, 1997a, 1997b) are prevalent. It is, however, not a periglacial environment (Fig. 5.4) in the strict sense of French's (1976, 1996) definition and it is not recommended that the term "sub-periglacial" be used to describe the environment unless defined according to recognised periglacial regions in

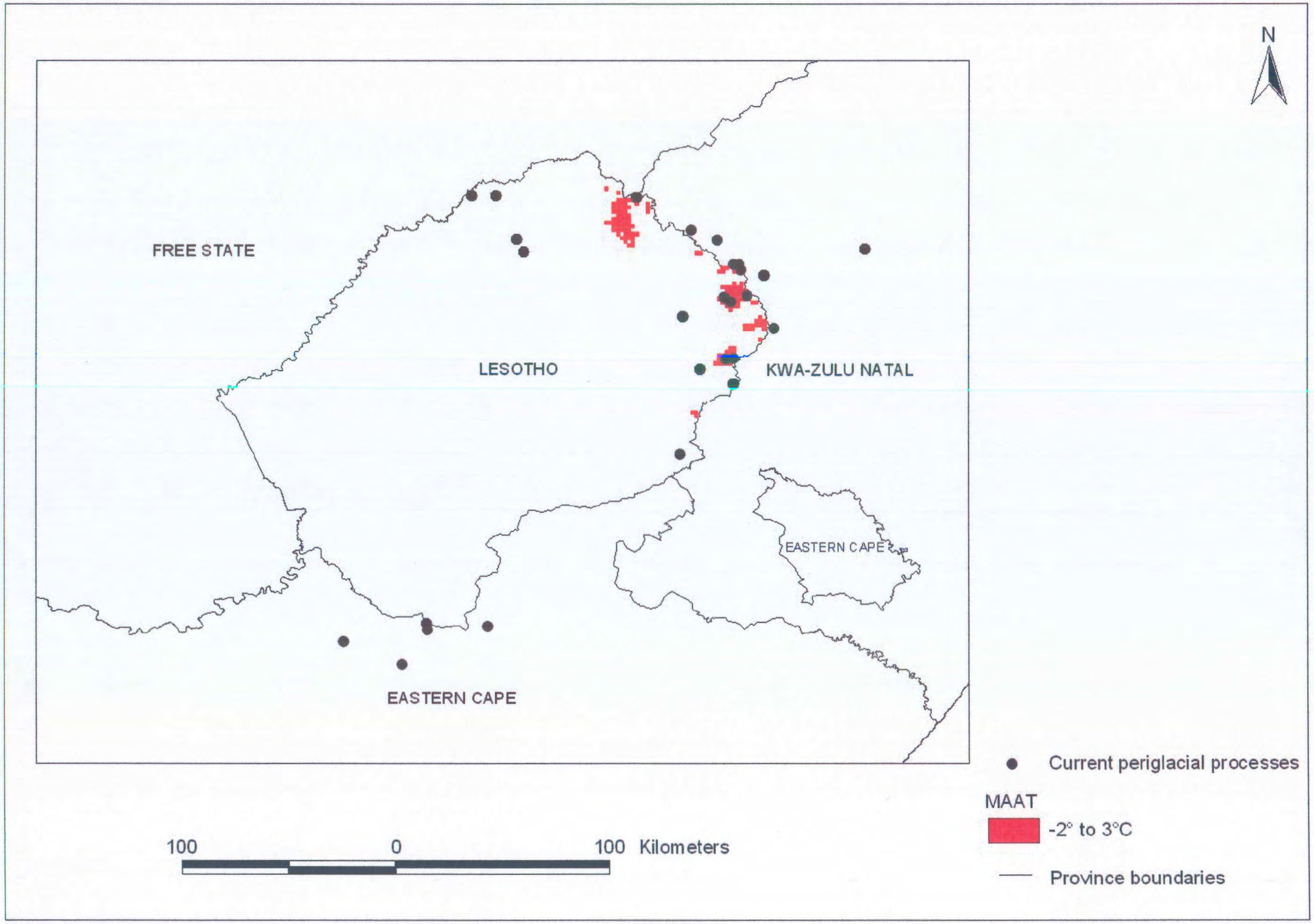


Figure 5.4: Regions that may be classified as current periglacial.

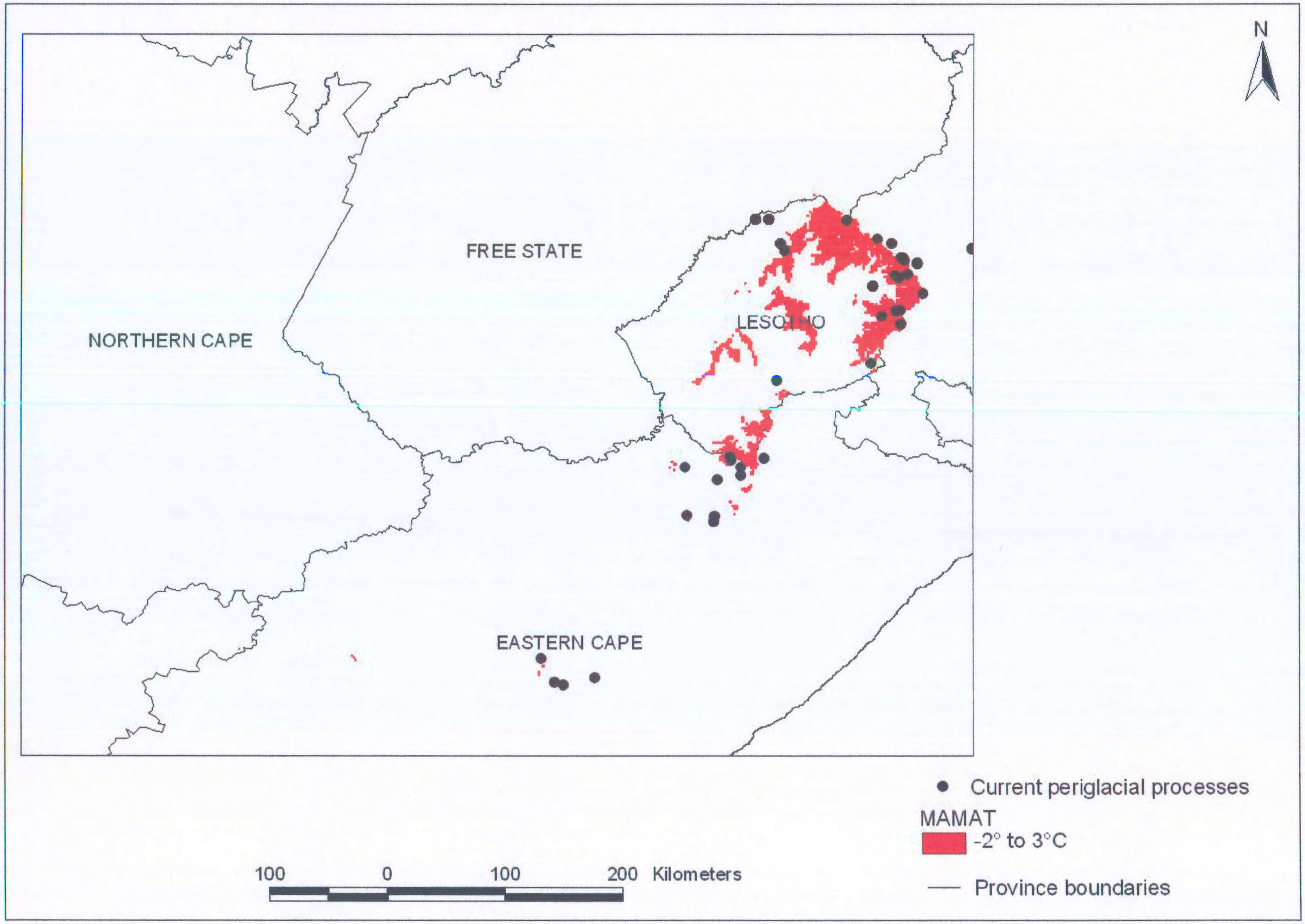


Figure 5.5: Current periglacial regions calculated on mean annual minimum air temperatures.

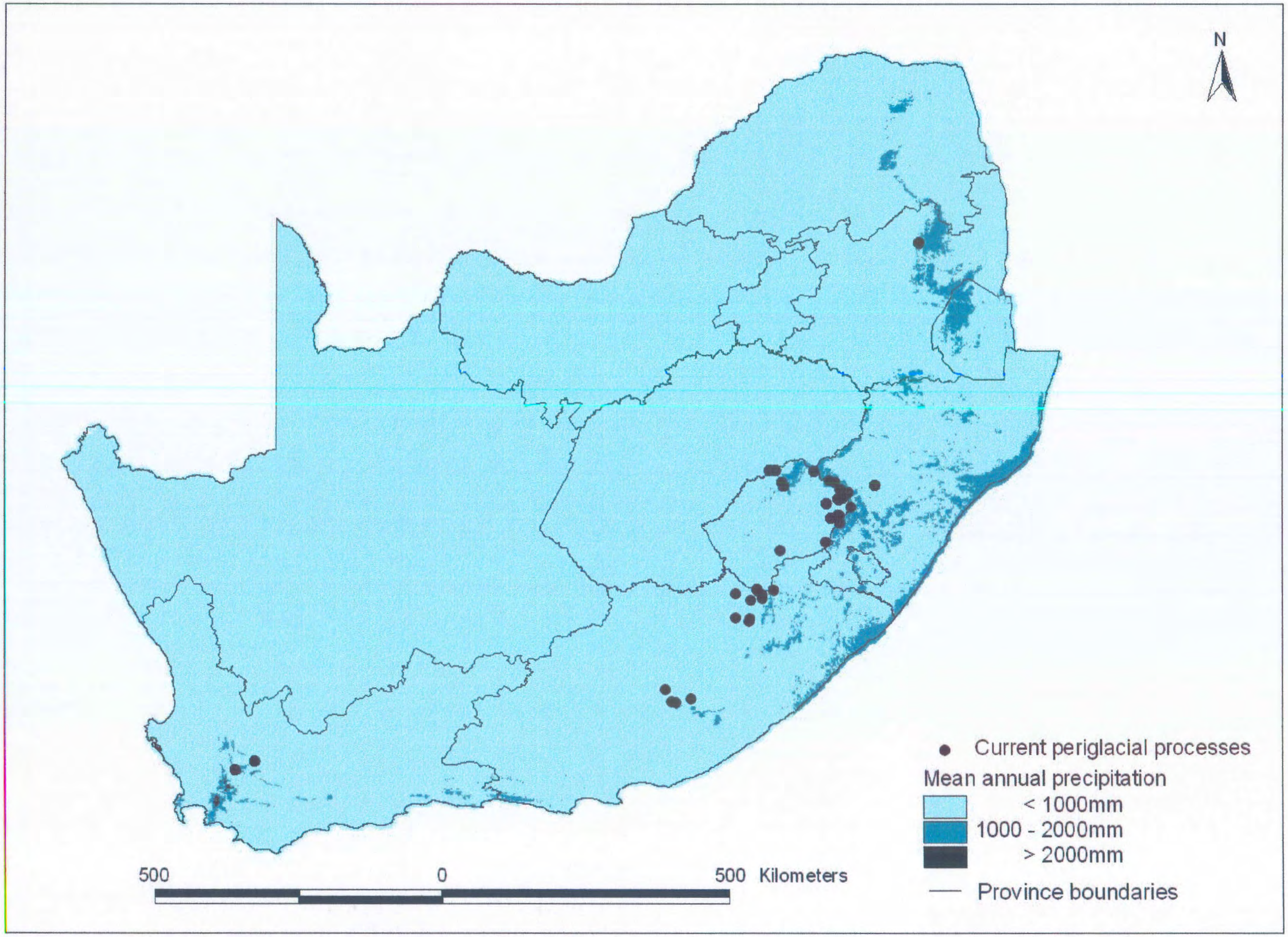


Figure 5.6: Current periglacial phenomena extrapolated on mean annual precipitation.

the rest of the world. The use of "marginal montane periglacial" (Lewis, 1987; Boelhouwers, 1991a) and "borderline periglacial" (Boelhouwers, 1991b; Hall, 1994) as terminology describing the southern African cryogenic situation, are not recommended, as it is not clear what the specific implications of these descriptions are. Calculations for Fig. 5.4, 5.5 and 5.6 did show that current cryogenic phenomena cluster along or adjacent to the Drakensberg Escarpment of Lesotho, Kwa-Zulu Natal, the Eastern Cape and the Western Cape as argued by Marker (1995a). It appears that phenomena occur in specific zones as suggested by Marker (1995a), namely above the Escarpment, directly below the Escarpment in the vicinity of the Eastern Cape at +1 900m a.s.l., and in the Western Cape at +1 700m a.s.l. (Fig. 5.2). The lower limit of the present-day cryogenic environment definitely shows a decline in altitude with higher latitude (Fig. 5.2) as proposed by Marker (1995a), although it is suggested that lithology play an important role in the spatial location and distribution of current (and relict) cryogenic features and processes.

There is little doubt that other factors other than precipitation and air temperatures, e.g. lithology, moisture factor for specific regions, vegetation patterns, and microclimate have to be considered to understand the full consequence of current cryogenic phenomena distribution in southern Africa as Fig. 5.4, 5.5 and 5.6 only give a general idea of the current periglacial situation from which only general conclusions can be drawn. It should also be considered that, given the occurrence of periglacial phenomena on the subcontinent (however marginal), the conditions stipulated for periglacial environments by French (1976, 1996) may be unsuitable for southern African. It may be more appropriate to find specific criteria that will be representative of the southern African cryogenic context.

5.1.2 Periglacial palaeoenvironment

When comparing periglacial palaeoenvironments with those of today, it must be kept in mind that there probably were differences in solar and snow cover conditions (French, 1976, 1996). French (1996) suggests that the contrast between summer and winter was less marked in both the Northern and Southern Hemispheres, that more freeze-thaw cycles occurred than at present, and that pronounced snow cover would have inhibited permafrost formation, but supported deep seasonal frost (French, 1976, 1996). Other factors may have played a greater role then than today, e.g. global atmospheric circulation patterns, wind action and greater fluvial activity (French, 1976, 1996).

Many features are used as evidence for periglacial processes in southern Africa. However, French (1996:235) cautions that the recognition of relict phenomena requires careful investigation because "... few provide unequivocal proof of periglacial conditions and only where several different features occur together or in association is one justified in assuming a frost-action environment." To gain a better understanding of the southern African relict cryogenic environment, the requirements as stipulated by French (1976, 1996) for current periglacial environments will be used in the next set of calculations.

5.1.2.1 Requirements for analysis

It was established that the following characteristics are distinctive of a periglacial palaeo-environment adjacent or not adjacent to glaciers:

- Palaeoperiglacial environments were most likely dominated by frost action processes like those of today.
- Permafrost-related processes were probably dominant.
- Freezing and thawing of the ground were probably regular occurrences.
- Palaeoperiglacial environments probably displayed perennially frozen ground.
- MAAT between -2° and +3°C where frost action occurred.

Compared to French's (1976, 1996) conditions for periglacial environments, the southern African cryogenic palaeoenvironment display the following characteristics:

- It is assumed that cryogenic features and processes were more widespread compared to those of today (Meiklejohn, 1992; Marker, 1995a).
- It is assumed that cryogenic phenomena occurred at lower altitudes (Lewis & Hanvey, 1993; Marker, 1995a).
- It is assumed that snow cover for the subcontinent was enhanced (e.g. Marker, 1990b, 1992, 1994b, 1998; Hanvey & Marker, 1992).
- Most phenomena are believed to have formed during the LGM (e.g. Lewis & Dardis, 1985; Lewis, 1996b; Marker, 1992, 1994b).
- A drop of between 5° and 10°C are suggested for the subcontinent during the LGM (e.g. Van Zinderen Bakker, 1963, 1964, 1986; Hastenrath, 1972; Talma *et al.*, 1974; Deacon *et al.*, 1984; Vogel, 1985; Talma, 1989; Partridge *et al.*, 1990; Marker, 1991b, 1995a, 1998; Meiklejohn, 1992; Hanvey & Marker, 1992; Grab, 1996a; Partridge, 1997).

Each characteristic is considered in the data analysis. More specific topics that need verification are as follows:

- Whether conditions on the subcontinent were suitably cold for widespread periglacial activity (Sparrow, 1971; Hanvey & Marker, 1992).
- Whether full periglacial conditions including permafrost (Fitzpatrick, 1978; Lewis & Dardis, 1985; Marker, 1989; Lewis & Hanvey, 1993; Lewis, 1994), or mild periglacial activity, excluding permafrost (Marker, 1995a), occurred.
- Whether ground freeze, nivation, and other freeze-thaw processes were active during the LGM (Marker, 1989).
- If relict landforms project into the two regions suggested by Marker (1995a).

The structure and procedure of the data analysis is reviewed in Table 5.3. Note that only processes, e.g. frost action, solifluction etc., are used for analysis. For the purpose of this analysis the 5° to 10°C drop in MAAT proposed for the LGM will be considered with a midway average point of 7°C as determined from the literature (Van Zinderen Bakker 1964, 1976; Harper, 1969; Sparrow, 1971; Talma *et al.* 1974; Vogel, 1983; Deacon *et al.*, 1984; Talma, 1989, Hanvey & Marker, 1992; Marker, 1992; Grab, 1996a, etc.).

Analysis (A)		**Map**
A1	Current MAAT of southern Africa minus 7°C for the LGM.	
A2	Relict frost action processes, permafrost-related processes, freezing and thawing of the ground in southern Africa during the Pleistocene.	
A3	Palaeoperiglacial regions of southern Africa that meet the periglacial MAAT requirement of -2° to +3°C.	A1 + A2 + A3 = Fig. 5.7
A4	Current MAMAT of southern Africa.	
A5	Palaeoperiglacial regions of southern Africa that meet the periglacial MAMAT requirement of -2° to +3°C.	A2 + A4 + A5 = Fig. 5.8

Table 5.3: Analysis structure for examining palaeoperiglacial regions in southern Africa.

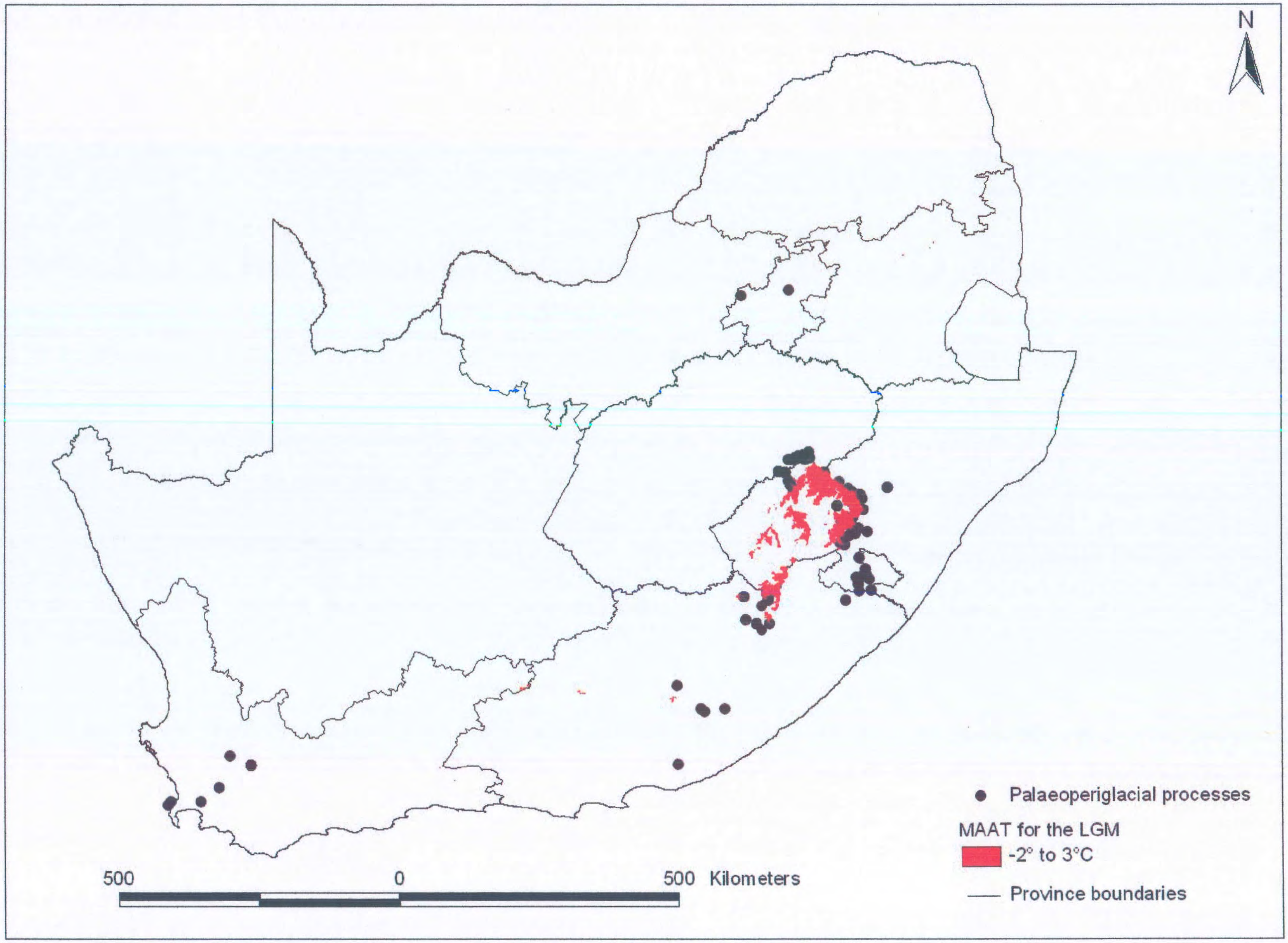


Figure 5.7: Possible periglacial regions for the Last Glacial Maximum based on 7°C drop in temperature.

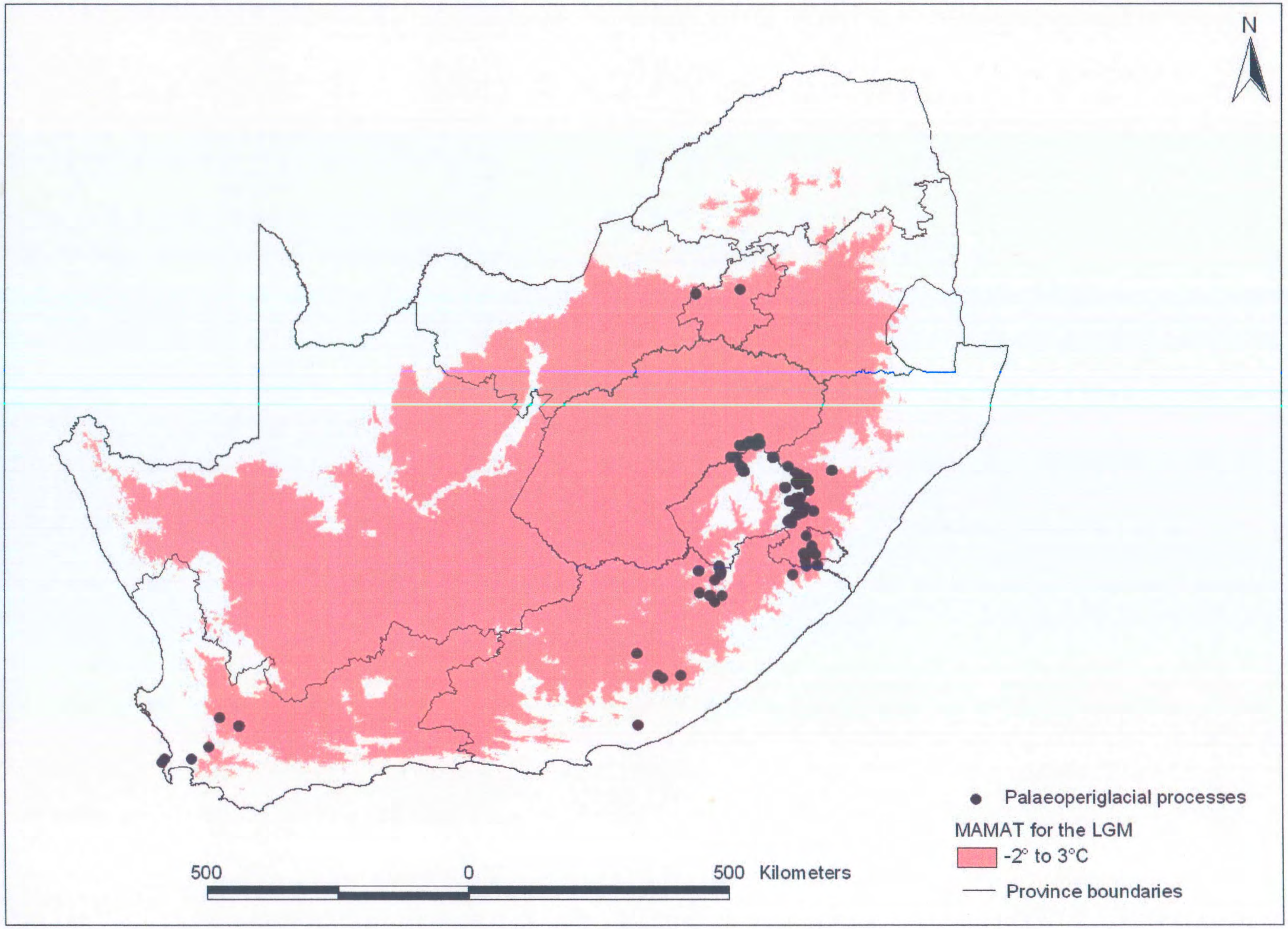


Figure 5.8: Possible periglacial regions for the LGM calculated on mean annual minimum air temperatures based on a 7°C drop in temperature.

5.1.2.2 Discussion

Fig. 5.7 revealed possible sites for periglacial activity during the LGM similar to those displayed in Fig. 5.5. Region 3 (Fig. 5.2) did not emerge from calculations. The seasonal palaeoperiglacial zone proved greatly enlarged after projecting MAMAT for the LGM (Fig. 5.8) and Region 3 (Fig. 5.2) finally surfaced. This suggest that temperature is not the only factor to consider in explaining the existence of relict forms in the Western Cape, and, like the current cryogenic environment, precipitation, lithology, vegetation cover, specific moisture factors, microclimatic differences etc. all may have had a significant impact yet unknown on the development and preservation of palaeocryogenic features and processes.

An environment with periglacial activity of mild intensity and relatively short duration, excluding permafrost as suggested by Marker (1995a), but more widespread than current cryogenic activity, is envisaged for southern Africa for the LGM. If MAAT values alone are considered, the LGM cryogenic environment is slightly enlarged, comparing with MAMAT calculations for the contemporary cryogenic environment (Fig. 5.5), but still excluding the Western Cape (Region 3, Fig. 5.2).

From Fig. 5.7 and 5.8 it is evident that conditions may have been suitable for widespread cryogenic (periglacial) activity on the subcontinent. Surviving landforms appear to project into the regions proposed by Marker (1995a), although a small extension of the Eastern Cape-region towards the Amatola Mountains is visible. The distribution and zonation for relict "periglacial" phenomena is comparable to that of contemporary phenomena (Fig. 5.2). This again implies that other factors such as precipitation and lithology need to be considered for a clearer understanding of relict cryogenic activity. Unlike the projections for the current cryogenic environment, precipitation values for the LGM could not be calculated since data are scarce and need intensive research and modelling beyond the scope of this study.

However, it cannot be said with absolute certainty from these map projections that a periglacial environment in the strict sense of French's (1976, 1996) classification existed. Although there are strong indications that frost action processes did take place (as displayed by the current cryogenic environment and the survival of various relict features that display a periglacial nature), more detailed analysis is needed incorporating other relevant factors as previously referred to. Again the possibility that periglacial conditions stipulated by French (1976, 1996) may be unsuitable for southern Africa should be considered and criteria should be revised to ensure a more representative presentation of the southern African cryogenic environment in future analyses.

5.1.3 Glacial palaeoenvironment

Many southern African features are attributed to glacial activity during the Quaternary cold periods (e.g. Borchert & Sänger, 1981; Lewis & Dardis, 1985; Sänger, 1988; Marker, 1989, 1990b; Hall, 1994; Grab, 1996a; Lewis, 1996b). Still, it is not certain if southern African palaeoclimates were favourable towards, or could support, glacial activity (e.g. Hall, 1994; Sumner 1995). To attempt glacial modelling, a closer look at the characteristics of glacial environments is necessary.

The most important factor in the formation of glacial ice is that more snow must fall in winter than melts in summer (Ahnart, 1998). Very cold winters are not necessary (Ahnart, 1998). Glaciers form in a matter of decades, and large ice sheets, e.g. the Greenland ice sheet, form within 200 years under favourable conditions (Sugden & John, 1976; Ahnart, 1998). Glacier formation is furthermore a function of precipitation, temperature, solar radiation, latitude, and distance from the ocean (Sugden & John, 1976). Thus, glaciation of continents or highland regions is controlled by the complex interaction of several variables (Fig. 5.9; Sugden & John, 1976).

Precipitation ⇨	Winter precipitation as snow is very important.
Temperature ⇨	Initially temperatures of -17,8° to -6,7°C were suggested as necessary for glacial ice to form and survive, but it has been found that MAAT need only to remain below 0°C. Below 0°C accumulation conditions are favourable, and above 0°C ablation takes place.
Solar radiation ⇨	Low solar radiation is more conductive towards glacier survival.
Latitude ⇨	High latitude regions receive lower radiation levels and are thus more conductive towards glacier development. Winters are also prolonged and temperatures often remain below 0°C.
Relief ⇨	Surface form is important for the maintenance of glaciers (it should be mentioned that glacial ice will accumulate if precipitation as snow is adequate, no matter the relief). Steep slopes tend to remain ice-free and highly dissected topography inhibits glacial development. Glacial development is dependent on topographical situations in combination with micro-climatic factors and adequate snowfall.
Aspect ⇨	Orientation of the ground surface with respect to incoming solar radiation is important at local scale.

Figure 5.9: Factors in glacial development (after Sugden & John, 1976).

Southern African mountain regions are mostly high enough to reach +2 100m a.s.l. limit for glacial development (Sugden & John, 1976) in most areas (Fig. 5.2), but the other factors summarised in Fig. 5.9 remain to be established for the subcontinent. At this stage only one aspect, namely air temperature, will be used in the following analysis.

5.1.3.1 Requirements for analysis

It was established that the following characteristics are distinctive of a glacial environment and the formation of glacial ice:

- Winter precipitation as snow.
- A surplus of snow surviving summer heat into the next year.
- Very cold winters are not necessary.
- Low solar radiation is more conductive towards glacier survival.
- Prolonged winters during which mean temperatures often remain below 0°C, are favourable conditions for glacier survival.
- Surface relief must be favourable towards glacial ice accumulation.
- The orientation of the ground surface with respect to incoming solar radiation is an important factor at local scale.

Compared to Sugden & John (1976) and Ahnert (1998)'s conditions for glacial environments, the southern African cryogenic palaeoenvironment display the following characteristics:

- Glacial ice is thought to have accumulated in the mountain areas of southern Africa at insolation-protected sites (Hall, 1991b; Marker, 1991b; Grab, 1996a).
- The glaciers would have enlarged pre-existing drainage lines, forming funnel-shaped hollows and cirques (Grab, 1996a).
- It is believed that snow precipitation was greater (Van Zinderen Bakker, 1975; Tyson, 1986; Marker, 1990b, 1992; Hanvey & Marker, 1992; Grab, 1996a etc.).
- A drop of between 5° and 10°C are suggested for the subcontinent during the LGM (e.g. Van Zinderen Bakker, 1963, 1964, 1986; Hastenrath, 1972; Talma *et al.*, 1974; Deacon *et al.*, 1984; Vogel, 1985; Talma, 1989; Partridge *et al.*, 1990; Marker, 1991b, 1995a, 1998; Meiklejohn, 1992; Hanvey & Marker, 1992; Grab, 1996a; Partridge, 1997).

Each characteristic is considered in the data analysis. More specific topics that need verification are the following:

- View 1: an *alpine glaciation* where ice masses in the form of plateau glaciers, feeding several shorter valley glaciers as suggested by Borchert & Sänger (1981), Maud & Partridge (1987), Sänger (1988), Hall (1994), and Lewis (1996b).
- View 2: an arid *marginal glaciation* in the form of a small ice cap restricted to the highest elevations and ice development marginal and ineffective (Dyer & Marker, 1979; Marker, 1992, 1994b).
- It is argued that the higher mountains experienced MAAT of between –1°C and –3°C (Grab, 1996a), which would have been favourable conditions for glaciation.
- Grab (1996a) argued that glacial ice development was localised.

The structure and procedure of the data analysis is reviewed in Table 5.4. For the purpose of this analysis the 5° to 10°C drop in MAAT for the LGM will be considered with a midway point of 7°C (see 5.1.2.1).

Analysis (A)		**Map**
A1	Current MAAT of southern Africa minus 7°C for the LGM.	
A2	Glacial features and processes.	A 1 + A 2
A3	Palaeoglacial regions of southern Africa that meet the glacial MAAT requirement of 0°C.	A 1 + A 2 + A 3 = Fig. 5.10
A4	Current MAAT of southern Africa minus 7°C for the LGM to show minimum temperatures values (5 classes) and also possible sites for glaciation.	A 1 + A 3 – A 2 = Fig. 5.11

Table 5.4: Analysis structure for examining palaeoglacial regions in southern Africa.

5.1.3.2 <u>Discussion</u>

Areas where glaciation could have taken place and that display MAAT of less than 0°C, were identified as the Great Escarpment of Lesotho/Kwa-Zulu Natal (Region 1, Fig. 5.2), the Eastern Cape below the Escarpment (Region 2, Fig. 5.2) and a smaller region on the border of the Free State and Lesotho at Golden Gate Highlands National Park (Fig. 5.10). Once again

Figure 5.10: Possible regions for a Last Glacial Maximum glaciation.

the Western Cape (Region 3, Fig. 5.2) did not figure as a glacial region. By projecting the various glacial features and processes onto Fig. 5.10, it became apparent that glacial phenomena also cluster into the three distinctive regions identified in Fig. 5.2. The Golden Gate-extension may be classified under Region 1 (Fig. 2.5).

The general view is that southern Africa was not glaciated during the LGM or the other glacials of the Pleistocene (e.g. Tyson, 1986; Deacon & Lancaster, 1988; Preston-Whyte & Tyson, 1988). It is difficult to speculate on the nature and intensity of glacial ice formation in the absence of supported evidence of glacial abrasion. The *alpine glaciation* claim of Borchert & Sänger (1981), Maud & Partridge (1987), Sänger (1988), Hall (1994) and Lewis (1996b), is therefore rejected. The arid *marginal glaciation* argument (Dyer & Marker, 1979; Marker, 1992, 1994b) will not be considered since more information and further testing is needed before a conclusion can be reached. From the findings, it is suggested here that there was a possibility of glacial ice development, but not glaciation on a large scale. If this assumption proves to be correct, then southern African did not experience a LGM-glaciation *per se* and cannot be classified as a glaciated environment. However, the need for further evidence, detailed analysis and research is stressed and viewed as important in understanding the true nature of the palaeoenvironment of South Africa and Lesotho.

For this analysis only temperature was used as a diagnostic indicator for a glacial environment. The other factors listed in Fig. 5.9 were not considered since these need more thorough research and modelling beyond the scope of this study. Calculations, nonetheless, support the opinion that the higher mountains probably experienced MAAT of between –1°C and –3°C (Fig. 5.11), that favourable conditions for glaciation possibly existed (Fig. 5.10 & 5.11), and glacial ice development was most likely localised as argued by Grab (1996a).

5.2 Conclusions

Chapter 5 focused on preliminary data analyses through database manipulation to evaluate database efficiency and feasibility. Key areas tested were data accessibility, data and database manipulation, and overall user friendliness. Further, the purpose of this section was not to give a definitive analysis of southern African cryogenic data, but to evaluate the database in terms of its usefulness in context of current debates in southern African cryogenic literature. The database was put to use successfully in the analyses and reconstruction of the southern African cryogenic environment and offers great potential for more intensive future investigation of cryogenic data.

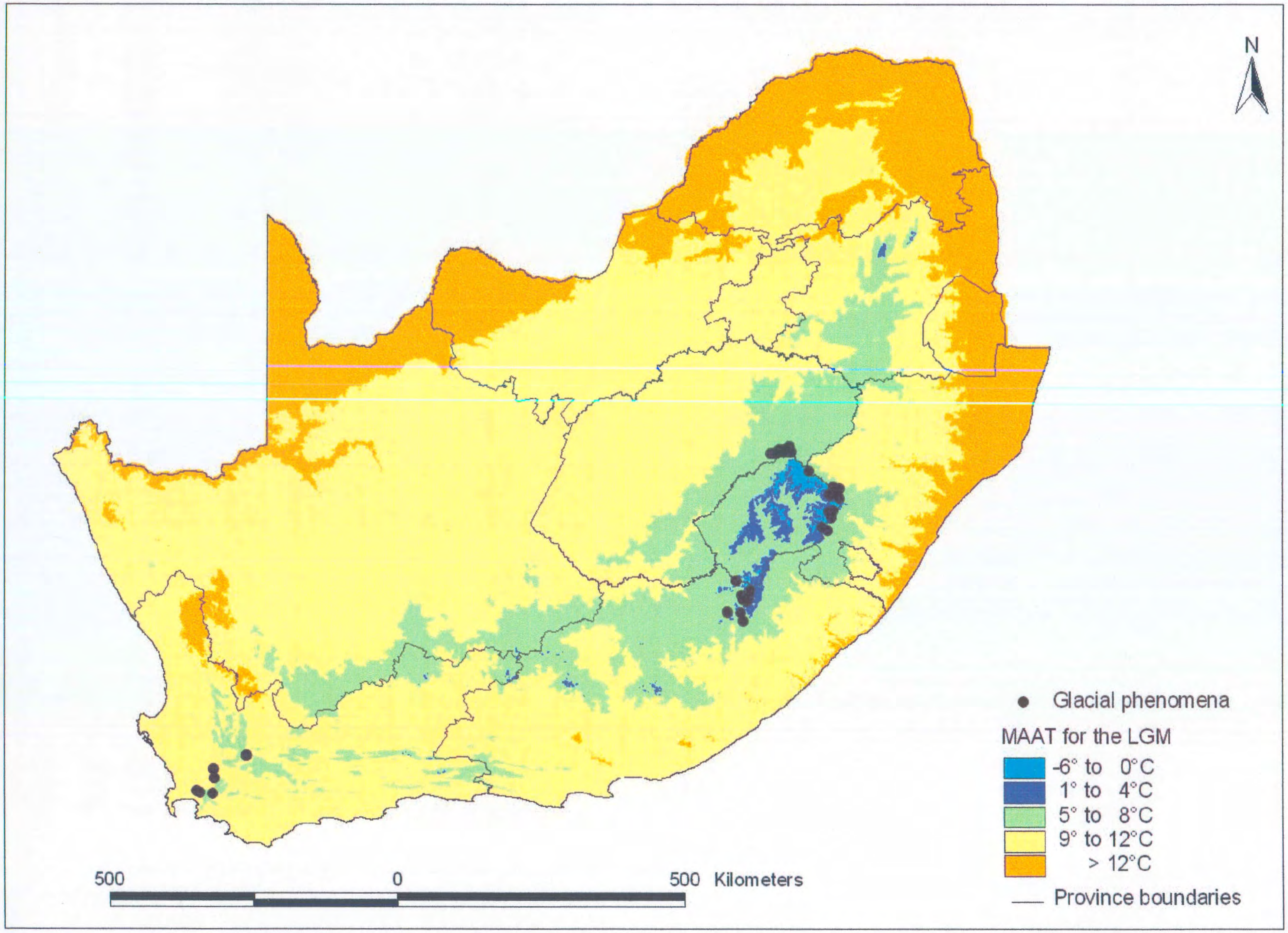


Figure 5.11: Possible temperature regime for the Last Glacial Maximum.

It must be pointed out that the database is a first attempt at assembling and classifying southern African data and is still in a preliminary stage. For example, at this stage the database will not adequately deal with geographical features with unique formative regimes or infer feature-process links unless, of course, broken up into several smaller units or expanded into a complex information centre. Nevertheless, it was shown that the database functions well and that the requirements stipulated in Chapter 3 for this study were met.

CHAPTER 6

Conclusions and recommendations

Cryogenic research is a growing field in southern African geomorphology. A diversity of features and processes have been identified and attributed to either glacial or periglacial origin. Most phenomena are believed to be products of the Last Glacial Maximum (LGM), thus indicating periods of climatic shifts during the Pleistocene. At present the subcontinent displays active cryogenic processes manifesting in a variety of features. It is believed that the contemporary cryogenic landscape is a remnant of a colder Pleistocene palaeoenvironment. However, there is uncertainty pertaining to the significance of relict cryogenic phenomena. This is because the intensity, dominance and spatial distribution of past processes are subject to considerable debate. Further, there is no conclusive data suggesting a Pleistocene glaciation, and evidence indicating periglacial activity is apparently not conclusive. Due to the absence of a modern snowline for the subcontinent, a palaeo-snowline can not be established and hence no clear interpretation of surviving features is possible along this line. Therefore, southern African cryogenic research is inconclusive.

It is evident that there is a need for a fresh approach to the problem. In addition, it is apparent that the origin of these cryogenic landforms should be explained within a larger, theoretical framework, incorporating other disciplines, e.g. biology, biogeography, zoology etc., and should aspire towards an interactive perspective (Chapter 2). This study represents an attempt to develop such an approach and to clarify some of the questions currently facing researchers. The research problem was established (Chapter 1) and investigated by

- determining the nature of cryogenic research and the problems facing it (Chapter 2);
- summarising data and compiling a database system that acts as (i) a data source, (ii) an aid in research, (iii) a basis for digital mapping, calculations and projections, and (iv) a possible medium for future modelling of climatic trends (Chapter 3);
- by compiling comprehensive glossaries as standardising measures for the database and as support in future research (Chapter 4).

Other objectives of this study was to expand on current cryogenic knowledge, to facilitate the reconstruction of the Pleistocene environment and, at the same time, provide a reliable data source. The aims and objectives (Chapter 1) were realised in the compilation and utilisation of the Cryogenic Processes and Landforms Spatial Database for Southern Africa (Appendix A). The database proved to be an excellent tool by which research issues can be challenged. As a data source, the database reduces the problem of poor spatial and temporal resolution of data. Through database manipulation, the spatial distribution of both past and present cryogenic phenomena was attempted. In this preliminary analyses it was possible to determine and map

- the extent of both relict and contemporary cryogenic activity, which demonstrated that the actual cryogenic palaeoenvironment probably did not differ much from the current one (Fig. 5.4 and 5.5);
- areas where mean annual air temperatures (MAAT) possible were sufficiently cold for periglacial activity (Fig. 5.7 and 5.8);
- and likely regions where glacial ice could have developed and survived (Fig. 5.10) during the Last Glacial Maximum.

In addition to the establishment of a cryogenic database, several glossaries and indices (Appendices C, D, E, F and G) were compiled as logical extensions of the project. The main glossary (Appendix C) is a first effort at explaining past terminology usage and providing a terminology basis for current research. The database, combined with the glossaries and indices, will be invaluable in future research and modelling. In short, the following results were obtained in this study:

- A better understanding of the spatial distribution of both relict and current cryogenic phenomena were achieved. It is believed that the dominance and intensity of especially relict processes will be possible through further specialised modelling.
- The database supplements current knowledge on the subject and will contribute towards the reconstruction of the southern African Quaternary environment.
- The database acts as a data source on which further research can be based. It is flexible, reliable and a very convenient tool in GIS-based problem solving.

It is clear from findings (Chapter 5) that the Cryogenic Processes and Landforms Spatial Database for Southern Africa can be applied in such a way as to successfully clarify complex problems, e.g. snowline elevation and possible Pleistocene glacial extent. For further enquiry into the possibilities of periglacial and glacial environments in southern Africa, it is recommended that the database be refined to create a more dynamic problem solving GIS-instrument.

In conclusion, a number of research opportunities were identified in the study. It was perceived that, to understand the full implication of the existence of the current cryogenic environment, factors other than MAAT should be considered in further database modelling, e.g. the role of lithology and geology, micro-climatic factors, precipitation, insolation, vegetation, etc. Future analyses and outcomes should be evaluated against other research findings, e.g. by Lewis (1987) and Marker (1995a). Furthermore, the database should be critically assessed and refined for a more representative picture of the southern African cryogenic environment through future GIS-modelling and analyses. Regarding the possibility of a periglacial palaeoenvironment, a number of issues should be addressed:

- Seasonal contrasts and global atmospheric circulation patterns during the LGM and how these affected the southern African climate.
- The moisture factor during the LGM. Many argue that the subcontinent experienced dry conditions (e.g. Van Zinderen Bakker, 1976; Partridge, 1990, 1997, etc.) due to changing weather patterns. This should be investigated more closely.
- The exact drop in temperature for the LGM.
- The Western Cape (Region 3, Fig. 5.2) should be considered as a unique and site-specific cryogenic environment and its significance relating to past and present climatic conditions should be studied. Other factors, e.g. precipitation, vegetation and lithology, are believed to be key elements in the formation of cryogenic phenomena observed there and need to be correlated with the MAAT values in this study (Chapter 5).

The possibility of a glacial palaeoenvironment needs more intensive research than was undertaken in this study (Chapter 5). The factors influencing glacial development as listed in Fig. 5.8 must be considered if a true picture of the LGM situation is to be gained.

This project is a first effort towards a better understanding of cryogenic phenomena by utilising GIS-based techniques. It is hoped that this study will contribute towards further research into the reconstruction of palaeoclimatic events and the construction of future climatic trends in southern Africa.

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