THE PRESENT-DAY FROST ACTION ENVIRONMENT AND ITS GEOMORPHOLOGICAL SIGNIFICANCE IN THE WESTERN CAPE MOUNTAINS, SOUTH AFRICA

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Cape Town, 1995

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Submitted in partial fulfillment of the requirements for
the degree of PhD in the Department of Earth Sciences,
University of the Western Cape, 1995.

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Cape Town, 1995

Opgedragen aan mijn vader
en ter nagedachtenis aan mijn moeder.

I declare that "The Present day Frost Action Environment and Its Geomorphological significance in the Western Cape Mountains, South Africa" is my own work and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references.

Abstract

Studies on periglacial features in the Western Cape mountains provide a fragmented picture on the existence of both active and relict frost action in the region. As anywhere else in the country quantitative analysis and identification of active frost action processes and landforms are noticably lacking. In response, this study aims to analyze and identify the cryogenic landforms and processes that result in the region and establish the environmental controls that govern them. The study thus provides a modern datum for the evaluation of past periglacial activity.

Climatic and soil movement monitoring sites were located in the Hex River range and its northward extension, at Waaihoek Peak (1900m a.s.l.) and Mount Superior (1860m a.s.l.), and were completed by a regional survey.

Cryogenic activity in the Western Cape mountains is restricted to three shale-exposed sites at altitudes of 1600m a.s.l. or higher. Here, the ground surface morphology is dominated by cryogenic landforms due to the stability of the surface in the dry summers. Frost processes are limited to needle-ice growth, resulting in frost creep down to 6cm, ejection and vertical tilting of clasts and patterned ground formation.

Results from the climatic record show the summit areas of the mediteranean mountains of the Western Cape to experience surficial, diurnal frost cycles only from May to September. No evidence in favour of frost-induced soil processes was found over most of the summit regions due to several environmental controls. First, irrespective of climatic controls, sandstone-derived sediments were found to be too coarse to allow for effective soil frost over most of the Western Cape mountains. Second, the frequency of effective soil frost days is extremely small due to insulation effects by snowcover and vegetation, the effectiveness of the zero-curtain effect and the high albedo values of sandy soils. Soil moisture forms no limiting factor to effective soil frost activity in the region.

A wide spectrum of weathering features were observed. Solution weathering features dominate in the field, while fires are considered the most important agent for mechanical fracturing at present.

Thermoclastic weathering was evaluated by means of rock temperature monitoring. Although summer conditions compare well with those recorded from hot desert environments, no direct evidence for the occurrence of thermal fatigue could be obtained. Potential for thermal shock at local rock surfaces is considered high, based on both the temperature record and field observations, while thermoclasty by fires is of widespread occurrence throughout the Western Cape region.

Morphological evidence for the occurrence of cryoclastic weathering remains inconclusive as it it not possible to differentiate its potential effects from other mechanical weathering mechanisms. Interpretation of the rock surface temperature record is limited as it is not known what constitutes an effective freeze-thaw cycle for the local lithologies.

Evaluation of past periglacial activity suggests that severe seasonal frost would have obtained during cold phases in the Pleistocene. Cryoclastic weathering is largely held responsible for the extensive debris mantles in the region. Complete meltout of snow accumulations in summer are suggested to be responsible for the extensive conglomeratic fans.

Acknowledgments

Throughout the course of this project I have received support from many different quarters, without which the study would not have been completed. First, and foremost, I would like to thank Prof. Kevin Hall under whose mentorship this project was conceived and put into practice. Much of the subject matter of the many stimulating discussions held over the years can be found back in this thesis. Many thanks also to Prof. Francisco Pérez under whose critical and thorough guidance the dissertation was completed. Prof. Jan van Bever Donker, internal promotor and departmental chair, is acknowledged for his perpetual willingness to provide the necessary logistical and administrative support and encouragement.

Financial and logistal support for this study was received from the University of the Western Cape and the Foundation for Research Development, while under their staff development programme. Both organisations are gratefully acknowledged for their support. Much valuable additional experience of periglacial environments to the benefit of this project, was gained under activities developed with Dr. Henk van Steijn of Utrecht University, as part of the UNITWIN-programme.

Field accommodation for this project was kindly made available in the Waaihoek area by the University of Cape Town Mountain and Ski Club. I am grateful to the Club and its members for allowing the use of Hoare Hut and the wonderfull company I have met over the years. I leave the place with fondest memories. The Ski Club of South Africa is thanked for allowing use of their hut at Matroosberg. The Chief Directorate of Cape Nature Conservation is acknowledged for allowing access into its conservation areas during the regional field survey.

No dissertation can be completed without considerable time to focus on the project. This necessitated passing on other responsibilities, both at work and home. I am most indebted to my colleagues in the Department of Earth Sciences for taking over much of my work load while absent on field trips and while writing the thesis. My gratitude not only goes to the staff but also to all students who have been part of this project over the years and who assisted in the field, particularly Messrs W.Rooy, T. Kanes, A. Samsodien, D.Williams and N.Rossouw. Your company has been most enjoyable. Messrs N.Rossouw and G.Engelbrecht assisted in the production of Figures 1 and 2.

A very special thanks goes to my wife Claire, who has kept things going in a most admirable way at home, when I so frequently left to visit the mountains. The knowledge that our children were in the best of hands while away always made things easier in the field. Your support over the months of writing has been formidable.

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CH. 1. INTRODUCTION

1.1. THE PERIGLACIAL RECORD OF THE WESTERN CAPE AND OBJECTIVES OF THIS STUDY

1.1.1. The periglacial record of the Western Cape

Literature on the (peri-)glacial record for the Western Cape has been summarized by Boelhouwers (1991) and recognizes observations on (i) Pleistocene debris deposits, (ii) indications for Pleistocene glaciation and (iii) recent cryogenic activity. Screes, block mantling and coarse colluvium covers are of widespread occurrence on slopes underlain by Table Mountain Group arenites (see Ch 2.). This angular blocky material extends down to sea level and is considered cryoclastic in origin (Butzer, 1973a,b, 1979; Lewis, 1988a,b). Less agreement exists on mode of transport and deposition of these rubble deposits. Linton (1969) described this cover on the coast near Cape Town as gelifluction mantling, an interpretation strongly rejected subsequently (Butzer and Helgren, 1972; Butzer, 1973a; Verhoef, 1970). Butzer and Helgren (1972, p.163) relate similar deposits near sea-level to 'sheetwash, creep and other gravitational mass movement with or without accessory frost generated motion'. Butzer (1979, p.160) does, however, interpret crudely stratified, subangular rubble at the west coast site of Elandsbay as a 'typical grèze litée' and thus does invoke a true periglacial origin. Butzer and Helgren (1972) further confirm the occurrence of solifluction deposits above 1500m a.s.l.. These have more recently been noted by Hagedorn (1984) at 2250m a.s.l.. However, in all cases the descriptions do not provide data on which interpretation can be based.

The occurrence of Pleistocene plateau, cirque and valley glaciers in the Western Cape mountains has been suggested by Borchert and Sänger (1981) and Sänger (1987, 1988a) based on identification of cirque and moraine morphologies from aerial photos. Glacial polishing and striae described for the summits are assigned by local geologists to the Pakhuis Formation (see Ch.2.) but are argued to be the result of a Late Quaternary glaciation by Sänger (1987, 1988a). With respect to recent morphodynamics Sänger (1988a,b) is the first to observe pipkrake and surficial frost heave resulting in the dislocation of stones. Present day frost shattering is said to occur at 1900m a.s.l., and Sänger regards nivation to be active.

1.1.2. Aims and objectives of this study

Regional periglacial studies exemplify several theoretical issues discussed under 1.2.. First, the description of cryogenic features for the Western Cape is fragmented and large areas are still unexplored. Particularly, the existence and extent of both fossil and active frost action in the Western Cape mountains remains virtually undocumented. Second, the periglacial studies to date are of a reconnaissance type, or form only a secondary focus within a study, and identify fossil periglacial landforms using superficial indicators such general morphological appearance (Hagedorn, 1984; Sänger, 1988a), angularity of clasts (Butzer and Helgren, 1972; Butzer, 1973b, 1979) and general sedimentological appearance (Linton, 1969; Butzer, 1979; Hagedorn, 1984). Yet far reaching paleoenvironmental interpretations are made, suggesting a 10°C mean annual air temperature lowering (Butzer and Helgren, 1972) and glaciation of the Western Cape mountains (Sänger, 1987, 1988a) for the Late Pleistocene. As argued above such genetic interpretations are conceptually unsound unless founded on quantitative, field-based analysis (see 1.2.). Third, as anywhere else in the country, quantitative analysis and identification of active frost action processes and landforms are noticeably lacking.

Based both on the conceptual debates concerning contemporary southern African periglacial geomorphology and the regional work to date the aims of this study have been identified as follows.

1) To identify and describe the morphology and sedimentary structures of active cryogenic landforms in the Western Cape mountains.
2) To establish the regional extent of these landforms in the Western Cape mountains.
3) To test the hypothesis that the surface forms and their regional extent are explained by the nature and intensity of local frost-induced processes. This can be achieved by soil movement monitoring on identified features and relating the results to the identified sedimentary structures and morphology of the forms.
4) To test the hypothesis that the nature and intensity of soil frost processes is, in turn, determined by prevailing local environmental conditions. This can be achieved by climate monitoring and sedimentary analysis.
5) To test the hypothesis that the nature and intensity of frost in local lithologies allows frost-induced processes to contribute to debris production in the Western Cape mountains. This is achieved by regional observations on weathering forms and climate monitoring.

1.1.3. The study area

It follows from the aims of this study that research has to be conducted at two scales. First, detailed environmental monitoring is site specific due to the logistical requirements. This means that a site has to be identified representative for a wider area. As micro-climatic parameters are known to be extremely variable even over very short distances, this representation can only possibly be valid for the general environmental trends. The site should be positioned on the dominant regional lithology, at the level of the highest summits, in a region with broadly uniform climatological trends. Further requirements for the selection of the monitoring site are that the site must be reasonably accessible and suitable for longer periods of stay. The availability of some type of accommodation/shelter is essential and the site must further be within reasonable travel distance. A suitable site was found at Waaihoek Peak (1900m a.s.l.) in the Zuurberg wilderness area, a property owned by the University of Cape Town (Fig. 1). The UCT Mountain and Ski Club offered free access and use of their hut. The Waaihoek range trends as a south-north extension from the Hexriver mountains near Worcester (Fig. 1). On the west altitude falls into the intermontane valley of the Bree River, while the easterly slopes descend onto the Ceres basin. Being an inland mountain range the lower coastal mountains of the Limiet Mountains form a first barrier between the Waaihoek range and the coastal lowland. The site is centrally positioned within the area included for the regional survey.

Second, criteria used for the demarcation of the area covered in the regional survey are i) broad climatic uniformity, i.e. position within the Cape winter rainfall region, and ii) practical feasibility to adequately cover the entire region of often poor accessibility within the duration of the study. Figure 1 presents the extent of the regional survey undertaken. The topography of the study area features a narrow coastal lowland bounded inland by the Cape Fold Mountains. Inland from the mountain ranges one encounters the semi-arid interior plateau (Fig. 1). A coastal mountain range is separated from the inland mountain chains by the intermontane basin of the Bree River. The Cape Fold Mountains trend roughly parallel to the Cape coast in an arcuate profile. The moderate height of the mountains can be appreciated from the topographic map (Fig. 1).

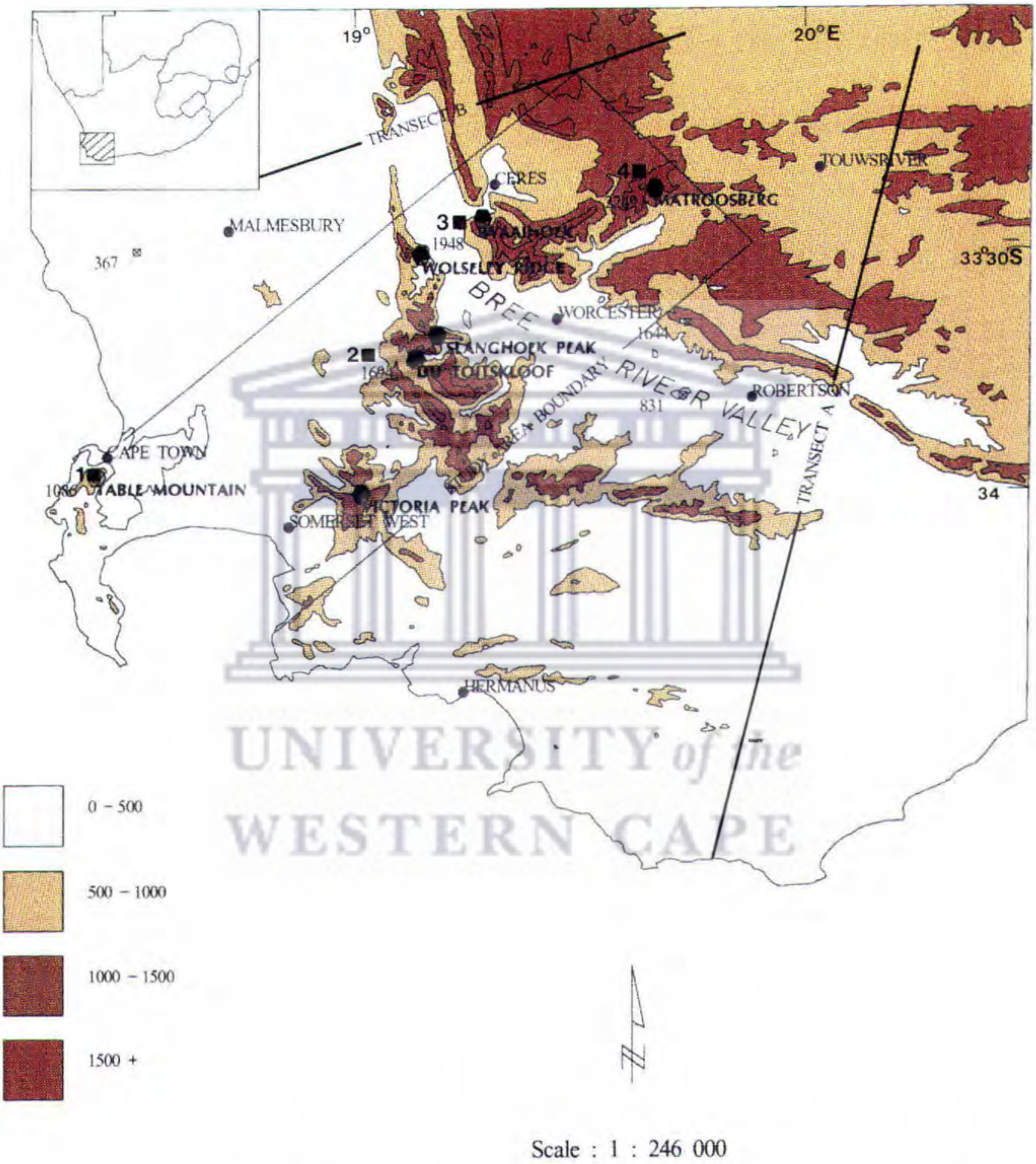


Figure 1. General topography of a part of the Western Cape and location of the study area. ■1 indicates the location of stations used in Figures 7 and 8. The transects refer to Figure 9.

1.2. PERIGLACIAL RESEARCH IN SOUTH AFRICA, CURRENT DEBATES AND QUESTIONS

South Africa is dominated by climates ranging from semi-arid to subtropical and it is no surprise that cryogenic features were only first noted in 1944 by Carl Troll. His observations were made in the Natal Drakensberg and Lesotho Highlands and most work has been concentrated on this highest mountain range in southern Africa ever since. Subsequent to this report fossil periglacial landforms have also been described for the Western Cape (Linton, 1969; Hagedorn, 1984) and eastern Cape mountains (Sparrow, 1967; Lewis and Dardis, 1985; Hanvey et al., 1986; Marker, 1986). Despite fifty years of work, international recognition of southern African mountains as a periglacial region has been slow. Two recent developments have contributed to wider recognition in the international community and a new impetus to southern African cryogenic research. First, active engagement in IGCP 297 resulted in a surge of activities and international participation in South Africa, the results of which were published internationally (Corte, 1991; Corte and Hall, 1991; Hanvey, 1990). A second development is the founding of the Southern African Permafrost Group in 1992. Through its association with the International Permafrost Association (IPA) this group will facilitate continued information exchange and academic debate with the international community.

It is no surprise that, coinciding with these recent developments, a dramatic increase in reviews and debates regarding the state of art of southern African periglacial geomorphology has occurred. Besides an attempt to arrive at a meaningful synthesis of existing studies by Lewis (1988a) some serious questions regarding the academic rigour of periglacial research are posed by Hall (1991, 1992) and in Hall et al. (1991). In the light of southern African periglacial geomorphology attempting to engage with current trends in periglacial geomorphology some pertinent questions do arise. These questions are:

- Do southern African periglacial geomorphologists work within the **objectives and theoretical framework** of the contemporary discipline?
- What can be the **contribution** of southern African periglacial studies to contemporary periglacial geomorphology?

1.2.1. Objectives of contemporary periglacial geomorphology

A paper by Thorn (1992) offers a stimulating discussion against which southern African researchers should measure themselves. Thorn's argument offers an in-depth analysis of the scientific framework within which periglacial geomorphology is currently operative and outlines "where theoretical ground appears firm and where attention needs to be directed" (p.1). It is against this argument by Thorn that I will continue to profile the state of art of southern African periglacial studies. Thorn describes five primary objectives of contemporary periglacial geomorphology, namely:

(1) to identify the chemistry, physics and/or mechanics of periglacial processes;
(2) to identify periglacial landforms where they occur;
(3) to identify the presence of permafrost wherever it occurs;
(4) to investigate the properties and behaviour of permafrost and active layer, and identify the associated processes;
(5) to reconstruct paleoenvironments (focus on either the past presence of periglacial regimes or, more narrowly, the past presence of permafrost) (Thorn,1992, p.3).

As permafrost conditions do not presently occur in southern Africa, objectives 3 and 4 do not apply to this region.

In the light of a recently published bibliography (Boelhouwers, 1993a), it is now possible to test the trends in southern African periglacial studies against these objectives. The content of the complete bibliography has been grouped under Descriptive Studies, Process Studies, and Reviews/Discussion Papers. These groups have been subdivided on the region of focus, that is, whether pertaining to southern Africa or elsewhere. Descriptive studies of the southern African region have further been subdivided into those focusing on fossil features, active features and those that include both. Table 1 lists 94 studies from 1944 to 1992.

TYPE	TOPIC	YEAR OF PUBLICATION					TOTAL
		40-59	60-69	70-79	80-89	90-92	
Descriptive studies	Fossil features in southern Africa	0	10	8	9	9	36
	Active features in southern Africa	1	0	2	2	4	9
	Fossil and active features in southern Africa	0	0	0	3	3	6
	Fossil and active features outside southern Africa	0	0	1	6	4	11
Process studies	Field processes in southern Africa	0	0	0	0	0	0
	Lab studies and/or field processes outside southern Africa	0	0	0	10	5	15
Reviews / Discussion Papers	Reviews / Discussions on southern Africa	0	0	1	3	6	10
	Reviews / Discussions general and non-southern Africa	0	0	1	1	5	7
TOTAL		1	10	13	34	36	94

Table 1. The focus of southern African periglacial studies per decade; based on Boelhouwers (1993a).

Table 1 indicates a steady increase in productivity over the record period. Moreover, in the last three years more publications have been produced than over the previous decade. Throughout the emphasis has been on past periglacial activity (35 papers) with very few studies exclusively describing active periglacial landforms (9).

Third, not one field study on frost action processes in southern Africa has yet been conducted! However, a great deal of engagement in laboratory and field process studies outside southern Africa has taken place since the early eighties (15). Fourth, as noted earlier, over the last three years southern African periglacial geomorphology has been subjected to an unprecedented review and discussion, indicating a state of self-reflection currently present under the southern African periglacial community.

Listing the regional studies on southern Africa only against the objectives forwarded by Thorn (1992) the following picture emerges (Table 2). While some papers have focused on identification of active periglacial landforms (20) most emphasis has been placed on the reconstruction of past periglacial environments (42). Again, this Table shows the complete absence of process identification in active periglacial landforms.

OBJECTIVE (after Thorn, 1992)	YEAR OF PUBLICATION					TOTAL
	40-59	60-69	70-79	80-89	90-92	
Process identification	0	0	0	0	0	0
Landform identification	1	1	4	7	7	20
Paleoenvironments	0	10	10	12	11	43

Table 2. The focus of regional studies on southern African periglacial geomorphology in terms of the objectives of contemporary periglacial geomorphology; based on Boelhouwers (1993a).

Points emerging from this table are, first that with the identification of both active and fossil periglacial landforms local researchers do have a positive contribution to make in international periglacial geomorphology. Second, given the absence of periglacial process studies in southern Africa one must conclude that identification of features is entirely based on morphology and sedimentology. Testing of these interpretations by process monitoring and identification of associated environmental controls should be undertaken. Only then can statements regarding origin and their use as climatic indicators be made. Thus, one may now ask whether the local studies have been undertaken strictly within the theoretical framework of periglacial geomorphology?

1.2.2. The theoretical framework of periglacial geomorphology

If the ultimate aim of geomorphology can be accepted to be the understanding of the origin of landforms then we have to consider in its analysis all aspects of relief namely morphology, process and age (Klimaszewski, 1982). In this respect Thorn (1992) argues that explanation in periglacial geomorphology as a science, should base itself "on theoretically and/or empirically derived, field verified processes" (P.2). Or, in the words of Haynes-Young and Petch (1983): "the origin of landforms ...cannot be defined except from evidence of how they have functioned or how they are functioning" (p.464). Morphology alone has no explanatory power (Haynes-Young and Petch, 1983; Hall, 1991, 1992; Thorn, 1992), yet, we have seen that southern African periglacial geomorphology has, to date, not produced a single field-based, process study. This means that the understanding of frost action processes and landforms is based on analogies in morphology and/or sedimentology with other parts of the world.

The dangers that this approach holds for paleoenvironmental reconstruction are clear and have been well formulated by Hall (1991, 1992). In addition, the interpretation of active periglacial landforms is flawed when it is based on analogy with high latitude environments. For example, Dardis and Granger (1986) linked the occurrence of stone banked lobes to Karte's (1983) environmental criteria from the Northern Hemisphere. Based on these criteria the authors estimate a present day mean annual air temperature between -5°C and -16°C, implying permafrost, at present on the Lesotho highlands! Microclimatic monitoring in the Western Cape on the other hand shows that stone-banked lobes can be active, when directly resting on bedrock, under diurnal frost cycles alone (Boelhouwers, 1995).

Without empirical evidence for the operation of certain processes the use of terminology with specific genetic implications should be avoided. The uncritical use of morphogenetic terminology is a main source of confusion in periglacial geomorphology (Thorn, 1988) as exemplified by reviews on rock glaciers (Martin and Whalley, 1987), frost weathering (Hall, 1991) and nivation (Thorn, 1988). Vague definitions, often resulting from incomplete understanding regarding origin of the landform, are open to misinterpretation by others. It is therefore imperative that morphological descriptions are not allocated genetic terminology without field verified evidence of process.

The uncritical allocation of morphogenetic terminology in southern African periglacial studies has been criticised on various occasions because of the qualitative, descriptive approach pursued by its practitioners (Butzer, 1973a; Hall, 1991, 1992). Unless a distinct re-orientation towards quantitative, field based process studies is developed in southern Africa one can have little hope that our understanding of frost action processes, past or present, will substantially improve.

It has been shown that process studies have been identified as one of the primary objectives of contemporary periglacial geomorphology. The absence of this research approach in southern Africa will probably be one of its major obstacles preventing engagement in international debates.

1.2.3. The southern African contribution to contemporary periglacial geomorphology.

In a brief assessment of international trends in periglacial geomorphology review articles over the last five years, i.e. 1988-1992, were consulted. From the reviews by Boardman (1989, 1990, 1991, 1992), Koster and French (1988), Pissart (1990) and Dixon and Abrahams (1992) it appears that some two dozen topics appear as active fields of research, including: mass wasting, weathering, patterned ground formation, frost wedging and cracking, ground ice, zonation, modelling, and paleoenvironmental reconstruction. Continued research on these topics within the framework outlined above should be the main objective of southern African endeavours.

Besides these 'traditional' topics two new areas of emphasis have recently emerged, namely environmental change and human impact assessment in periglacial environments (Pissart, 1990; Dixon and Abrahams, 1992).

First, Koster and French (1988), Pissart (1990), Hall and Walton (1992) and Dixon and Abrahams (1992) emphasize the important role of periglacial process studies in environmental change related to global warming. Arctic periglacial environments have been identified as one of the regions where such changes will undoubtedly have their greatest impact (Dixon and Abrahams, 1992). In contrast, environmental changes are expected to have little impact in the Antarctic (Hall and Walton, 1992). Evidence for anthropogenic environmental change from periglacial regions is now being reported from various parts of the world (Lachenbruch et al., 1988; Nyberg and Lindh, 1989; Kullman, 1989, 1992; and Burn, 1992). A further indication of the significance of this new emphasis is the recent establishment of the I.P.A. Working Group on Global Changes in Permafrost Zones.

It remains the task of southern African researchers to investigate the potential of using active periglacial features as indicators for climatic change in low latitude mountain environments. With only marginal soil frost action at present it can be expected that features like micro-patterned ground are very sensitive to even slight climatic change. A small general increase in soil temperature or drop in soil moisture may inhibit the frost action processes required for maintenance of the features concerned.

Second, Dixon and Abrahams (1992) observe that an understanding of periglacial processes is essential to assessing the impact of human activity in cold regions. Human impact takes place particularly due to increased pressure on natural resource development and extraction of natural resources. This can take place in mining and afforestation, recreational activities and expansion of human settlement with accompanying infrastructures. With increased pressure to develop southern African mountain environments impact assessments will become increasingly important. Data on the mechanisms and erosion rates by frost action processes will show to what extent soil frost processes should be considered. However, without process studies on non-periglacial processes in southern African mountain environments the relative significance of frost action processes cannot be assessed.

Lautridou et al. (1992) caution that there is a serious problem regarding the relative importance of fossil and present-day processes particularly in tropical and marginal periglacial mountain environments, like South Africa. In the words of Thorn (1992, p23.): "Are we perhaps devoting all our attention to the icing on the cake and not the cake itself?". Considering the broader dynamics of mountain environments may shed a new light on the interpretation of features interpreted as periglacial at present. For example, the dominance of mass wasting features documented in the lower sections of the Drakensberg (Boelhouwers, 1988, 1992) may necessitate a reinterpretation of the some of the slope morphology suggested to be nivation hollows in the Golden Gate National Park (Marker, 1990). Both the morphology of the erosion scar and the surface of some of the deposits, closely resemble the fossil landslides documented in Giant's Castle Game Reserve (Boelhouwers, 1988). In addition, debris deposits interpreted as remnants of rock glaciers (Lewis and Hanvey, 1993) may prove to be non-periglacial mass flow deposits that are of widespread occurrence in both the Western Cape (Boelhouwers and Rooy, 1993; Duiker and Van Duffelen, 1994) and Drakensberg (Boelhouwers, 1988). No evidence exists that excludes either a periglacial or non-periglacial origin in these examples. For that reason alone one should hesitate to argue for the extreme when similar features of non-periglacial origin proliferate in the landscape.

Emerging from this discussion is, again, the need for greater rigour in southern African periglacial studies as has been argued by Hall (1992). But there is also a need to widen the scope of geomorphological research on southern African mountain environments. There is a real danger that the narrow focus on periglacial studies leads to a failure to recognise the essentially non-periglacial components that are dominant in southern African mountain environments.

1.2.4. Summary

The positive identification of both active and fossil frost action features in southern Africa implies that local researchers have a contribution to make to the international community. However, this also calls for adopting a research approach following contemporary objectives and theoretical frameworks of the discipline. This requires that a more quantitative, process orientated approach be developed within the region.

Areas of continued focus for local periglacial studies are the identification of periglacial features and processes, and paleoenvironmental reconstruction. Areas where a need for new research exists are: field studies on mechanisms and rates of soil frost processes, weathering studies, the use of periglacial features as indicators for environmental change, and the role of non-periglacial processes in southern African mountain environments. This study addresses some of these imbalances by investigating the role of active frost-induced processes in the Western Cape mountains as set out in the objectives in section 1.1.2.

CH. 2 ENVIRONMENTAL SETTING

The environmental setting of the Western Cape mountains has been the focus of early activities of the Fynbos Biome Project, now the Fynbos Forum, which concerns itself with the ecology of fynbos, the vegetation characteristic for the Western Cape region (Deacon et al, 1983; Cowling, 1992; Van Wilgen et al, 1992). In providing the necessary background on environmental aspects relevant to this study much is owed to the published results of these efforts.

2.1. GEOLOGY

The various lithological units exposed in the Western Cape have a major influence on the general physiography of the region. Also, the micro-scale lithology and geological structure are of overriding importance on the geomorphological processes under consideration in this study.

2.1.1. Lithostratigraphy

The Western Cape region is composed of Late Precambrian and Paleozoic sedimentary sequences with occasional outcrops of Late Precambrian granitic intrusions (Fig. 2). Their classification and lithological characteristics are summarized in Table 3 and are briefly described below.

Pre-Cape succession

The various lithological units preceding deposition of the Cape Supergroup are classified under the Malmesbury Group, Cape Granite Suite and Klipheuwel Formation. The Malmesbury Group comprises a predominantly marine sedimentary sequence of a wide variety of argillites, limestones and greywackes as well as subordinate arenitic

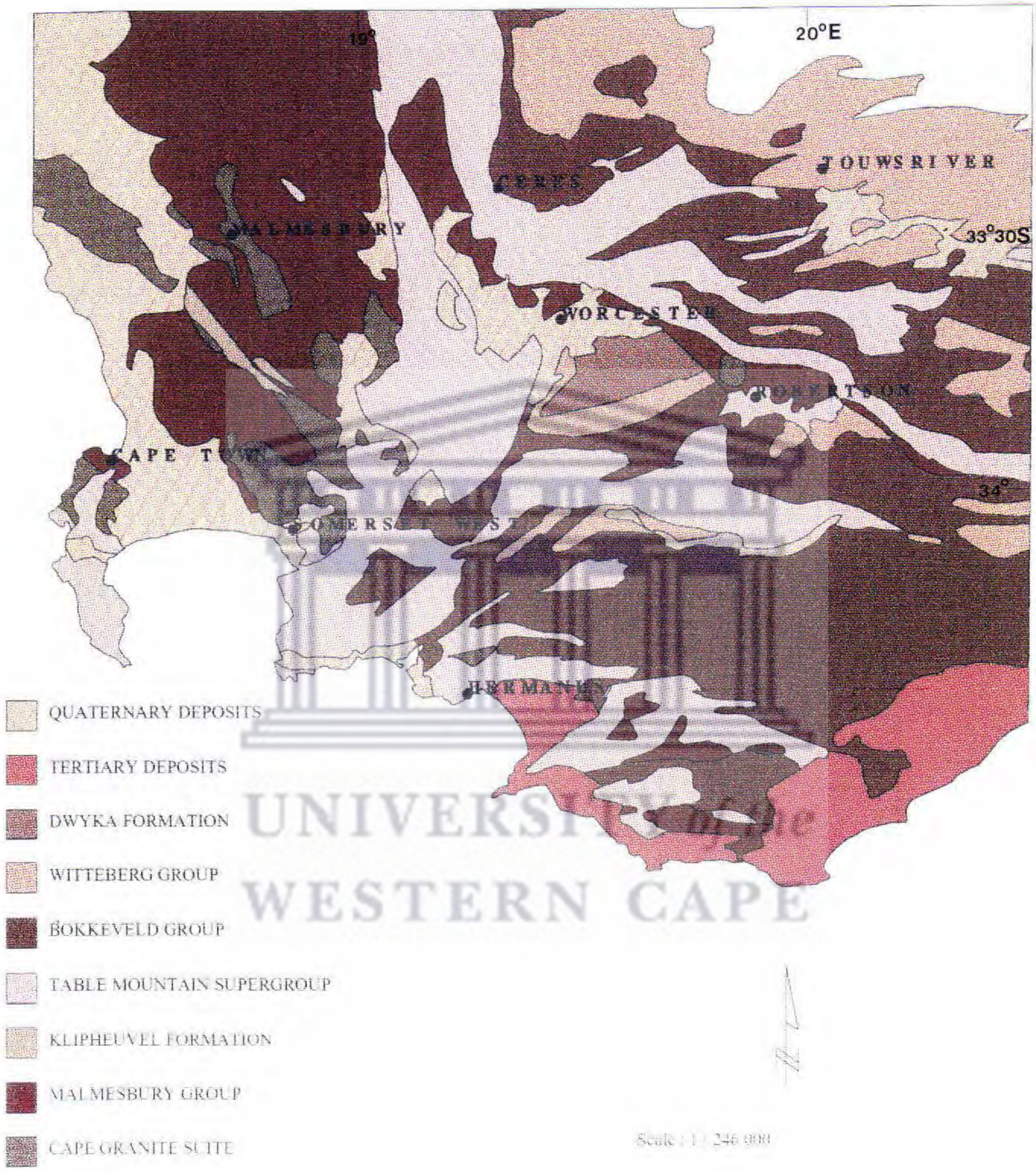


Figure 2. Geology of a part of the Western Cape, generalised from Department of Mineral and Energy Affairs (1984).

Table 3. Main lithological units and their age in the Western Cape; based on S.A.C.S. (1980).

Myr	AGE	STRATIGRAPHICAL UNIT	DOMINANT LITHOLOGY
300-	CARBONIFEROUS	Witteberg Group	Sandstone, shale
400-	DEVONIAN	Bokkeveld Group	Shale, sandstone
	SILURIAN	Table Mountain Group	Sandstone, conglomerate, shale
	ORDOVICIAN	Klipheuwel Formation	Sandstone, conglomerate, shale
500-	CAMBRIAN	Cape Granite Suite	Granite
	PRECAMBRIAN	Malmesbury Group	Argillites, greywacke, limestone

and conglomeratic strata (Theron, 1983).

Both before and during the Saldanian deformation intrusions of the Cape Granite Suite occurred which makes up the next major lithological unit. In total about ten granite plutons intrude the Precambrian rocks in the Western Cape, while the granite itself dates to 500-630 million years before present (Myr) (S.A.C.S., 1980).

Accompanying the culmination of the Saldanian orogeny was the deposition of terrestrial sediments belonging to the Klipheuwel Formation. They form a complex of fluvial sediments comprising conglomerates, feldspathic sandstones and shales and are said to be of Cambrian age (S.A.C.S., 1980; Theron, 1983).

The Pre-cape succession is predominantly found to underlie the coastal lowlands and intramontane basins in the Western Cape. In the case of the Cape Granite Suite prominant hills may form as in the case of Paarl mountain which reaches up to 729m a.s.l.. In the Waaihoek mountains only the Malmesbury Group is represented and occurs on the lower slopes of the Breerivier valley in the form of intensely folded phyllitic shale with sporadic quartzitic sandstone layers (Geological Survey, 1966; Van Zijl et al., 1981). The mountain ranges of the Western Cape are however closely associated with the occurrence of the more resistent lithologies of the Cape Supergroup.

Cape Supergroup

Renewed sedimentation followed upon subsidence in the Late Ordovician and continued into the Carboniferous in a near shore or terrestrial environment (Deacon et al., 1992). The sequence that accumulated in this Cape basin is characterised by a striking dominance of quartzitic sandstones (S.A.C.S., 1980). The lithostratigraphical subdivision of the Cape Supergroup is presented in Table 4. Three groups are identified, being the Table Mountain, Bokkeveld and Witteberg Group.

The Table Mountain Group attains a maximum thickness of 4000m and is virtually entirely comprised of medium- to coarse-grained, mostly supermature, quartzitic sandstone (Rust, 1967; Theron, 1983)(Table 4). In contrast to the predominantly arenaceous facies of the Table Mountain Group the Bokkeveld Group is characterised by alternating shale and sandstone sequences which make up the various formations and attains a maximum thickness of 3000m. In the south-western Cape the lithological characteristics of the basal formations of the Witteberg Group are similar again to those of the Table Mountain Group.

Sedimentation in the Cape basin ceased with upliftment as a result of crustal shortening and a new depositional centre developed further north in the Karoo basin (Deacon et al., 1992). Simultaneously, climate deteriorated with extensive ice sheets being formed. The associated diamictite and glacial outwash deposits of the Dwyka Formation attain a total thickness of 1000m which forms the basal formation of the **Karoo sequence**. Increased tectonic uplift of the Cape basin, known as the Cape orogeny, resulted in the formation of the Cape Fold Mountains during the Permian and

Table 4. Lithostratigraphy of the Cape Supergroup in the Western Cape; based on S.A.C.S. (1980).

GROUP	SUBGROUP	FORMATION	(m)	DOMINANT LITHOLOGY
WITTEBERG	LAKE MENTZ	Waaipoort	?	Shale (grey)
		Floriskraal	60	Shale, quartzitic sandstone
		Kweekvlei	130	Shale
		Witpoort	310	Sandstone
	WELTE-VREDEN	Swartruggens	450	Shale, sandstone
		Blinkberg	80	Sandstone (resistant white)
		Wagen Drift	70	Shale, sandstone
BOKKEVELD	BIDOUW	Karoopoort	50	Shale
		Osberg	55	Sandstone
		Klipbokkop	170	Shale
		Wuppertal	65	Sandstone
		Waboomberg	200	Shale
	CERES	Boplaas	30	Sandstone
		Tra-tra	85	Shale
		Hex River	100	Sandstone
		Voorstehoek	115	Shale
		Gamka	135	Sandstone
		Gydo	160	Shale
TABLE MOUNTAIN		Nardouw	500	Sandstone
		Cedarberg	120	Shale
		Pakhuis	40	Sandstone, conglomerate, diamictite
		Peninsula	1550	Sandstone (coarse, thick-bedded)
		Graafwater	440	Sandstone (thin bedded), shale (red)
		Piekenierskloof	800	Conglomerate, sandstone

Triassic (278-215Myr).

2.1.2. Structure of the Cape Fold Mountains and rock properties

The Cape Fold Mountains comprise of two major branches separated by a central area of syntaxis (Fig. 3). The western branch trends parallel to the west coast over a length of about 270km and shows open, upright megafolds, monoclines and

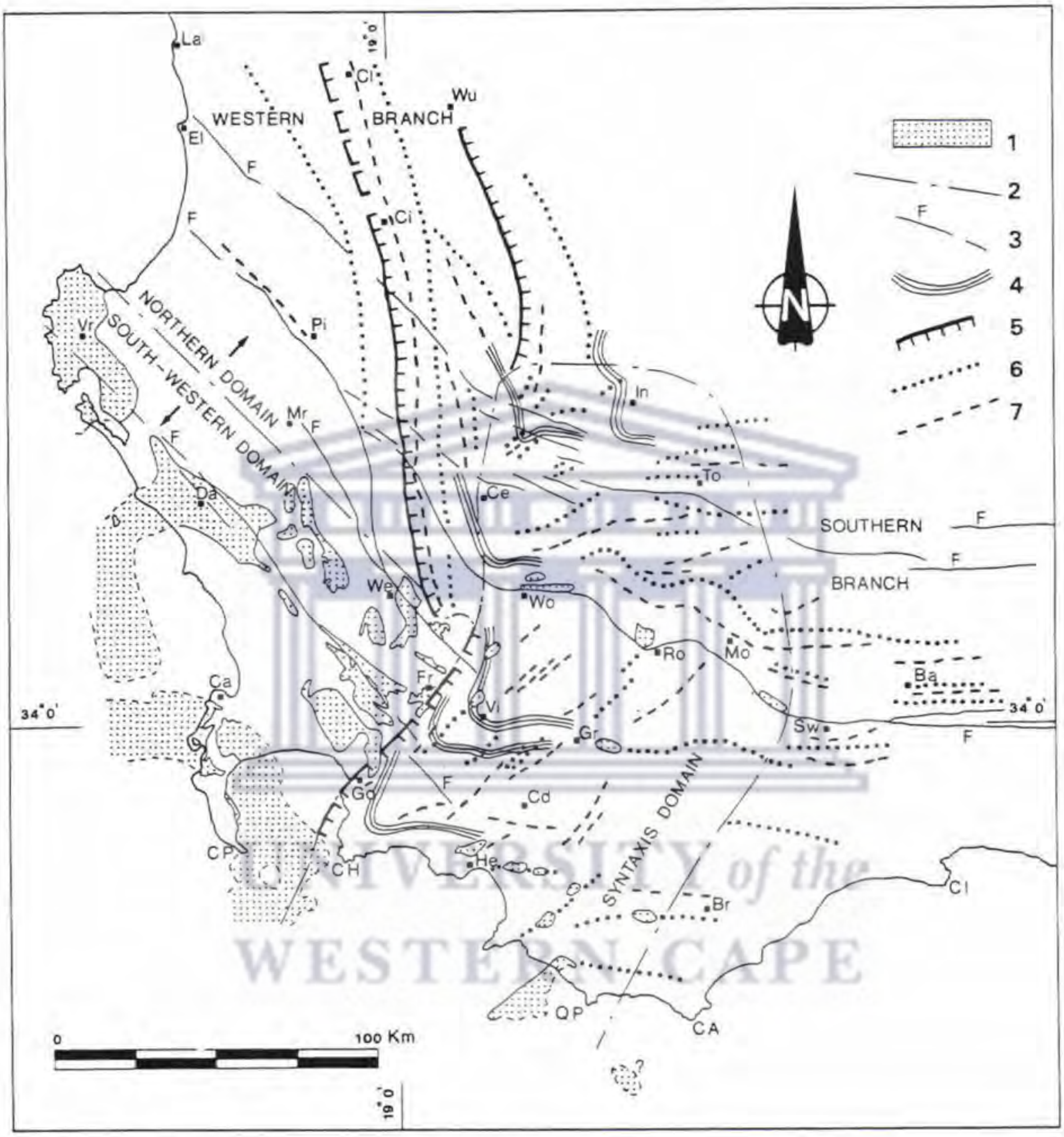


Figure 3. Main tectonic structures of the Cape Fold Belt in the Western Cape (from Söhnge, 1983).

Legend: 1. Cape Granite Suite; 2. Domain boundary; 3. Main fault zone; 4. Arcuate structure; 5. Monoclinal fold with facing direction; 6. Anticlinal axis; 7. Synclinal axis. Small faults omitted.
Localities: Ba - Barrydale; Br - Bredasdorp; CA - Cape Agulhas; Ca - Cape Town; Cd - Caledon; Ce - Ceres; Ci - Citrusdal; Cl - Clanwilliam; CH - Cape Hangklip; CP - Cape Point; Da - Darling; El - Elandsbaai; Fr - Franschhoek; Go - Gordons Bay; Gr - Greyton; He - Hermanus; In - Inverdoorn; La - Lamberts Bay; Mo - Montagu; Mr - Moorreesburg; Pi - Piketberg; QP Quoin Point; Ro - Robertson; Sw - Swellendam; To - Touwsrivier; Vi - Villiersdorp; Vr - Vredenburg; We - Wellington; Wo - Worcester; Wu - Wuppertal.

normal folds with a NNW strike. A southern branch stretches over 600km parallel to the Cape south coast. Here, northward verging folds are sliced by thrust and normal faults with a E-W strike. The intervening syntaxis area includes the Waaihoek mountains and displays a variety of upright folds and faults with a NE strike (Söhnge, 1983). On a smaller scale high density cleavage planes are found in the intensely folded shale and sandstone strata (De Swardt et al, 1974). Intense folding of the Table Mountain Group has thus resulted in high density joint and fault patterns throughout the Western Cape mountains both at a macro and micro scale (Figs 4 and 5). Due to the intense folding, residual stresses occur and stress fields within the rock are shown by microfractures which often split individual grains (Fig. 5). Furthermore, quartz grains in thin sections show undulose extinction under crossed polarized light which is indicative of stress fields within the grains (Deer et al., 1975).

The tectonic history of the mountains has important implications for the properties of the dominant lithologies, i.e. the Peninsula Formation sandstones. The quartzitic strata are mainly found where intense folding has resulted in metamorphosis of the sandstone. The grains are tightly packed with individual particles barely detectable. Secondary quartz overgrowth on quartz grains effectively reduces porosity (Thamm, 1988). On the other hand, medium to coarse grained sandstone with very low percentages of clays and feldspars dominates in the Peninsula Formation (Rust, 1967; Thamm, 1988). Bedding planes and sedimentary structures can easily be recognised. The grains are generally loosely packed and have secondary quartz overgrowths. Total porosity and permeability of intact sandstone is low but very low for the quartzite (Table 5). For weathered and micro-fractured sandstone total porosity increases to over 39% by enhanced intergranular and fracture pore volumes. Values for some physical rock properties of the Peninsula quartzite and sandstone strata are presented in Table 5.

Figure 4. High density bedding and joint planes in the Peninsula sandstone of the Waaihoek range.

Figure 5. Microphotograph showing fracturing across individual grains in the Peninsula sandstone of the Waaihoek range.

Table 5. Some physical properties of intact rock of the Peninsula Formation, based on analyses by the Centre de Geomorphologie, CNRS, Caen, France (Ozouf, pers. comm.).

	sandstone	quartzite
total porosity	2.87	1.89
total pore area (m^2/g)	0.358	0.645
average pore diameter (µm)	0.125	0.045
permeability (millidarcy)	0.17	0
capillary rise	88mm in 2h	0

The dense fracture patterns within the folded strata are primarily responsible for the effectiveness of rockfall activity in the Western Cape folded belt as these greatly facilitate most weathering processes noted for the area. Clast size of the debris produced from rockfalls can directly be related to the fracture widths of the bedrock from which it is derived. Further, sporadic seismic activity occurs in the region and has been noted to trigger rockfalls (Von Wiese, pers.comm.).

2.2. CENOZOIC ENVIRONMENTAL CHANGE

2.2.1. Tertiary environmental change

The Western Cape has been a passive continental margin ever since the breakup of Gondwana (140-100Myr). Continental breakup resulted in rapid denudation on the continent during the Late Jurassic and Cretaceous, as indicated by the 10km thick sediment off the Cape west coast (Dingle et al, 1983). Offshore sedimentation rates declined during the Tertiary, and virtually ceased by the Oligocene, as the long duration of stability resulted in a extensive planation of the continent's interior (Partridge and Maud, 1987). During the Miocene large parts of southern Africa experienced considerable uplift and triggered renewed denudation (Partridge and Maud, 1987).

Consensus exists that the southwestern Cape was not subjected to such uplift (Hendey, 1983, Partridge and Maud, 1987).

Throughout this period the Cape Fold Mountains extended well above this developing pediplain and have been subjected to subaerial weathering and erosion since at least the Cretaceous. The intermontane valleys separating the linear mountain ranges of resistant sandstone essentially attained their current shape in these times (Lambrechts, 1983; Partridge and Maud, 1987; Deacon et al, 1992).

Climatic conditions in the Western Cape, uniformly mild in the Mesozoic, deteriorated throughout the Tertiary to cooler, drier and more seasonal climates (Tyson, 1986). Early Cenozoic conditions were warm and humid and intense chemical weathering of various rocktypes is associated with this period (Lambrechts, 1983). Kaolinitic weathering of the Cape Granite, up to 50m deep, rapid ferrallitic chemical breakdown of primary silicates, and micas weathering to mica clay, kaolinite and (hydr-)oxides of iron and aluminium occurred in this period (Lambrechts, 1983). The ferricrete and silcrete, of widespread occurrence on the coastal lowlands, is also suggested to have formed during this period (Lambrechts, 1983).

The subtropical conditions of the Tertiary came to an end as a result of the growth of the Antarctic ice cap from about 14Myr to its maximum expansion at about 6,5Myr (Tyson, 1986). Accompanying the growth of the ice cap the westerlies moved equatorward and upwelling of the proto-Benguela cold current could establish itself off the Cape west coast. Consequently the present belt of sub-tropical high pressure cells was formed at about 5 Myr. Climates changed during this period from warm, humid (subtropical) to the distinctly seasonal mediterranean climate found in modern times. Vegetation changed from tropical to temperate forest and eventually to fynbos (Deacon et al, 1992).

2.2.2. Quaternary environmental change

The Pleistocene

The rhythmic alternation of glacial and interglacials forms a global feature of the Pleistocene. Glacial periods dominate with a time span of c. 90ky compared to the much shorter interglacial periods (c.10ky). Even under the coldest conditions of the Pleistocene the Cape Fold Mountains are considered to lay below the permanent snowline and no glaciation is suggested (Deacon and Lancaster, 1988; Tyson, 1986; Deacon et al, 1992). The Last Glacial Maximum at 18ky before present (BP) represents the coldest phase of the last 130ky with mean annual temperatures about 5°C lower than present (Deacon and Lancaster, 1988). The most reliable temperature record for the region covering the last 30ky is obtained from oxygen isotope data from a speleothem in the Cango Caves some 500km east of Cape Town (Fig. 6). The curve indicates a maximum temperature lowering of 7°C at 15.6ky BP (Talma and Vogel, 1992).

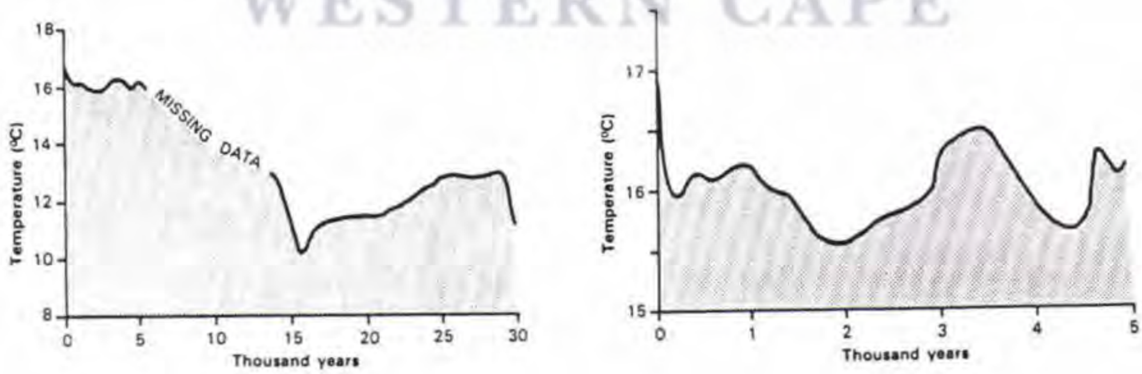


Figure 6. Paleotemperatures for the last 30ky from an oxygen isotope record at Cango Cave, Oudtshoorn, southern Cape. (after Talma and Vogel, 1992).

Precipitation trends with winter frontal activity and a dry summer period are thought to have prevailed throughout the Pleistocene (Deacon et al., 1992). Conditions during glacials are suggested to have been drier due to lower evaporation rates from cooler ocean surfaces and considerably lower sea levels (Deacon et al. 1992). Increased continentality of the Cape mountain climates may have been obtained by extension of the coastal lowland due to substantial sea surface lowering. The question however remains: how much cooler and how much drier (if at all) were the Western Cape mountains during the coldest phases of the Pleistocene (Deacon and Lancaster, 1988)?

Rapid warming and wetter conditions followed the Last Glacial Maximum throughout southern Africa from 14000 - 10000 BP. From 10000 - 7000 BP temperatures continued to rise but conditions became somewhat drier. The warming trend resulted in the period from 7000 - 4000 BP being warmer than at present. These were followed by a cooling trend for the last 4000 years (Fig 6) (Deacon and Lancaster, 1988).

2.3. CLIMATE

The Western Cape mountains are positioned in a Mediterranean climate with warm, dry summers and mild, wet winters. In summer the position of the South Atlantic anticyclone at 37°S west of the Cape provides for dry easterly winds, while in winter the northward migration of the pressure cell to 32°S allows for mid-latitudinal frontal systems to sweep the Western Cape from the west. The rapid succession of weather systems accompanying the westerlies in winter result in sharp day to day contrasts in wind, temperature and precipitation. The presence of the Western Cape mountains results in significant orographic rain and distinct rainshadow effects. Also, a distinct increase in continentality is experienced from the coast inland.

2.3.1. Temperature

Temperature records for the Western Cape mountains are virtually absent with most stations being positioned in the agriculturally important lowlands. Figure 7 summarises the characteristic monthly air temperatures for various stations near the monitoring sites in the Waaihoek range and near observation sites for the regional geomorphological survey. Air temperatures for the summit of Victoria Peak (1594m) near Stellenbosch have been recorded for 1984-1985 by the CSIR, while Sänger (1988a) measured air temperatures at Matroosberg (1800m) over short periods during 1979 and 1980. Frost frequency and intensity from the records of these two mountain stations are summarized in Table 6. The data indicate marginal frost in the winter months between April and October. The records, however, give no indication of the current soil frost regime and are thus of limited value to this study.

2.3.2. Precipitation

A pronounced winterrainfall regime exists in the region under study with as much as 80% of precipitation falling in the three winter months. The highest peaks in the Western Cape mountains receive over 2500mm/yr although most of the estimations are based on extrapolation. Summer moisture deficits are pronounced on the higher peaks but are less for the coastal ranges which experience greater cloudiness, lower pan evaporation and receive considerable moisture through mist.

Figure 8 depicts the monthly rainfall totals for several stations in the region. Snowfall occurs every winter on the highest peaks with an estimated frequency of 5.4 events per annum (Schultze and McGee, 1978).

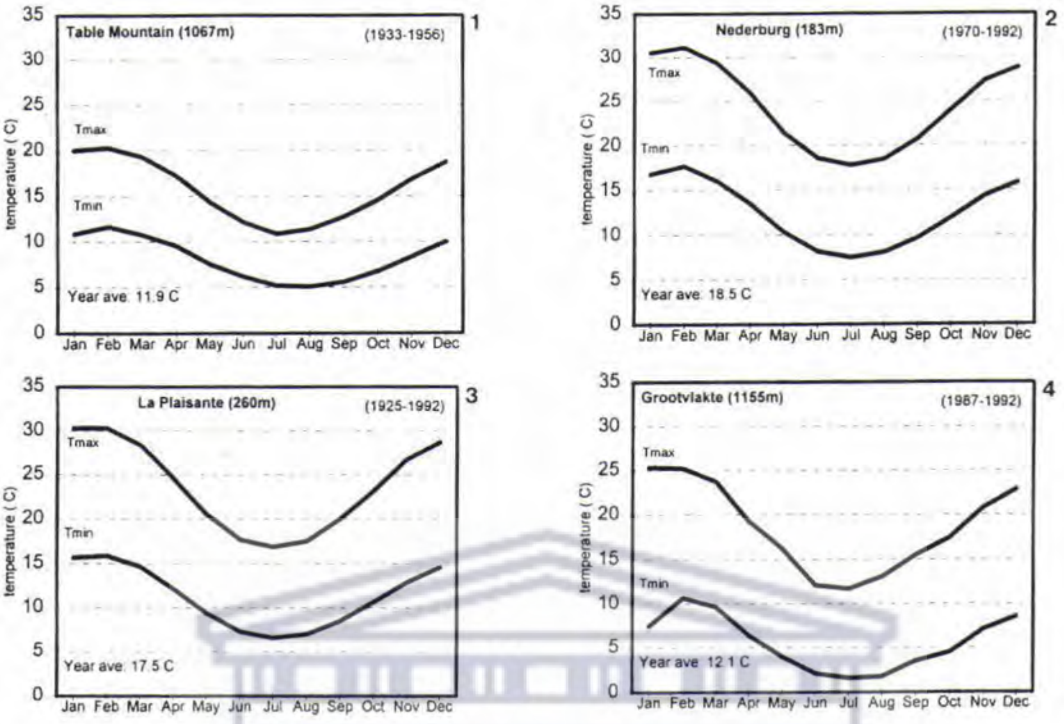


Figure 7. Annual temperature trends for some stations in the Western Cape, based on Weather Bureau (1986) and AGROMET (1993). For location of the stations, see Figure 1.

Victoria Peak (1584m a.s.l.)

1984	J	F	M	A	M	J	J	A	S	O	N	D	Yr
min < 0°C	0	0	3	4	4	3	6	6	6	6	0	0	32
min <-2°C	0	0	0	0	0	2	0	3	0	1	0	0	6
days no record	0	0	9	0	0	0	0	0	0	6	0	0	15
1985													
min < 0°C	0	0	0	1	0	2	7	8	7	0	0	0	25
min <-2°C	0	0	0	0	0	0	3	2	2	0	0	0	7
days no record	0	0	0	0	0	0	0	0	0	5	0	0	5

Matroosberg (1800m a.s.l.)

1979	J	F	M	A	M	J	J	A	S	O	N	D	Yr
min < 0°C	-	-	-	-	-	-	2	4	2	2	0	-	10
min <-2°C	-	-	-	-	-	-	5	1	8	0	0	-	14
days no record	-	-	-	-	-	-	15	15	1	20	18	-	69
1980													
min < 0°C	-	0	-	0	3	2	-	-	-	-	-	-	5
min <-2°C	-	0	-	1	5	2	-	-	-	-	-	-	8
days no record	-	20	-	23	6	12	-	-	-	-	-	-	61

Table 6. Diurnal frost frequency and intensity at Victoria Peak (CSIR, unpubl. data) and Matroosberg (Sänger, 1988a).

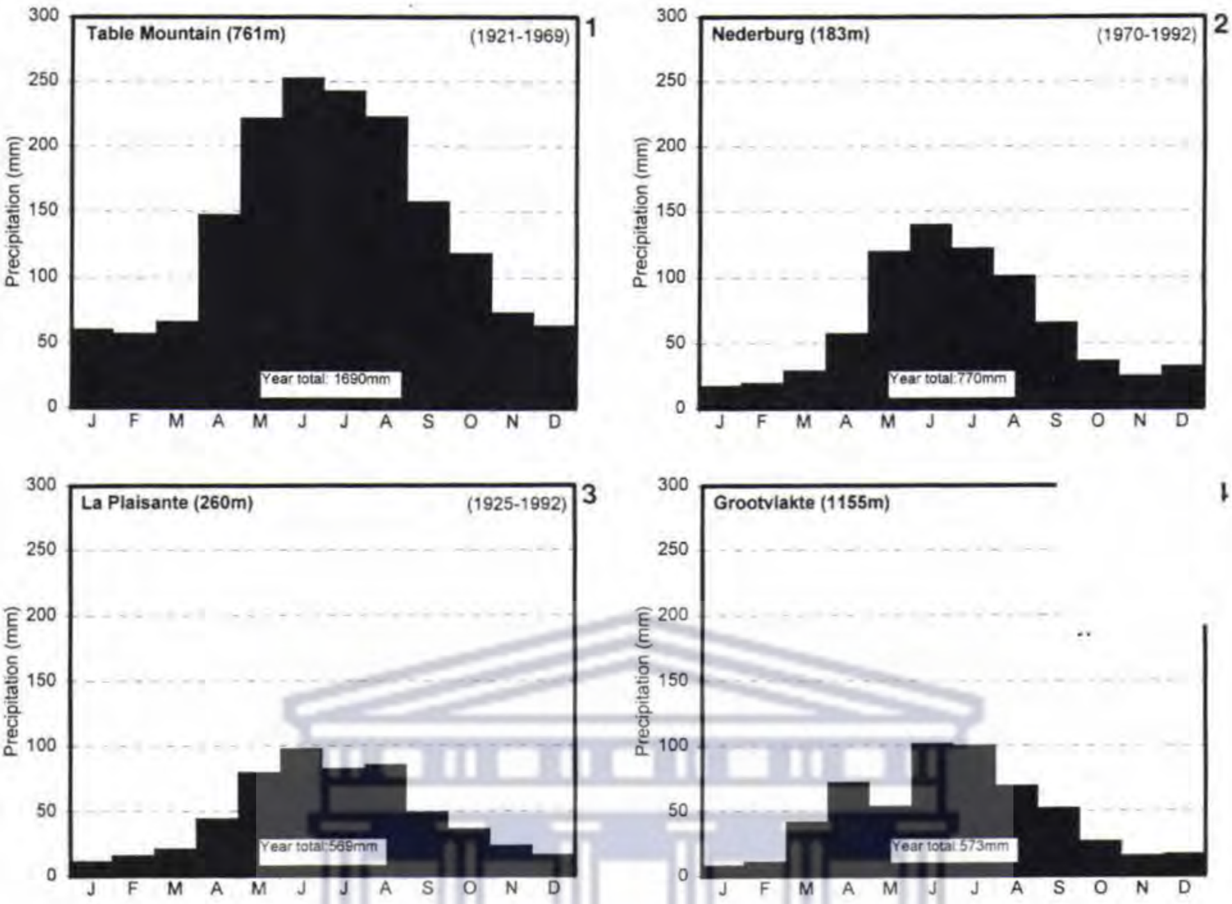


Figure 8. Annual rainfall trends for some stations in the Western Cape, based on Weather Bureau (1986) and AGROMET (1993). For location of the stations see Figure 1.

2.4. SOILS AND VEGETATION

2.4.1. Soils

The arenitic lithologies of the Table Mountain Group associated with the Western Cape mountains result in shallow, poorly developed soils (lithosols) with coarse soil texture (Lambrechts, 1983; Campbell, 1983). Soils associated with the Cedarberg Shale Formation have higher clay contents if not mixed with quartzitic colluvium. Campbell (1983) further associates coarse soil textures (low clay content) with rocky sites, northerly aspects, shallow soils and high altitudes. Leaching of the mountain soils results in extremely low levels of bases and phosphates (Stock and Allsopp, 1992). The pH of the acidic soils is below 5.5 and is conducive to the mobilization of iron, aluminium and organic matter (Campbell, 1983; Deacon et al., 1992). Table 7 summarizes various soil variables for different lithologies for the entire Cape Folded Mountains.

Table 7. Mean values of various soil variables in different geological units for the western and southern Cape mountains (from Campbell, 1983).

	Table Mtn quartzites $\bar{x}$	S.D.	Witteberg quartzites $\bar{x}$	S.D.	Non-quartzites $\bar{x}$	S.D.
S value (me/100g soil)	2.0	1.62	3.4	1.87	3.2	2.01
Total N (%)	0.07	0.038	0.08	0.049	0.09	0.043
Available P (ppm)	11.9	6.22	10.1	4.26	13.7	10.09
Oxidisable carbon (%)	3.2	1.69	3.5	2.09	3.3	1.81
pH	4.1	0.38	4.3	0.17	4.3	0.39
Coarse sand	13		6		13	
Medium sand	36		20		28	
Fine sand	36		52		32	
Silt	8		12		12	
Clay	7		10		15	
n	51		12		7	

2.4.2. Vegetation

Despite the low nutrient levels the mountain region is occupied by an extremely diversified vegetation, known as fynbos. This shrubby, fine leaved vegetation is characterised by the presence of restioids (wiry, evergreen reeds) with ericoids (shrubs with rolled leaves) and *Proteaceae* (tall shrubs with large leaves) being other important features (Campbell, 1985). Cowling and Holmes (1992) present a regional classification of the vegetation which is graphically summarised in Figure 9. Table 8 summarizes the characteristics of the fynbos communities identified in the mountain areas.

The monitoring sites used in this study are located on the inland mountain ranges and are charcterised by Restioid fynbos where underlain by sandstone and by

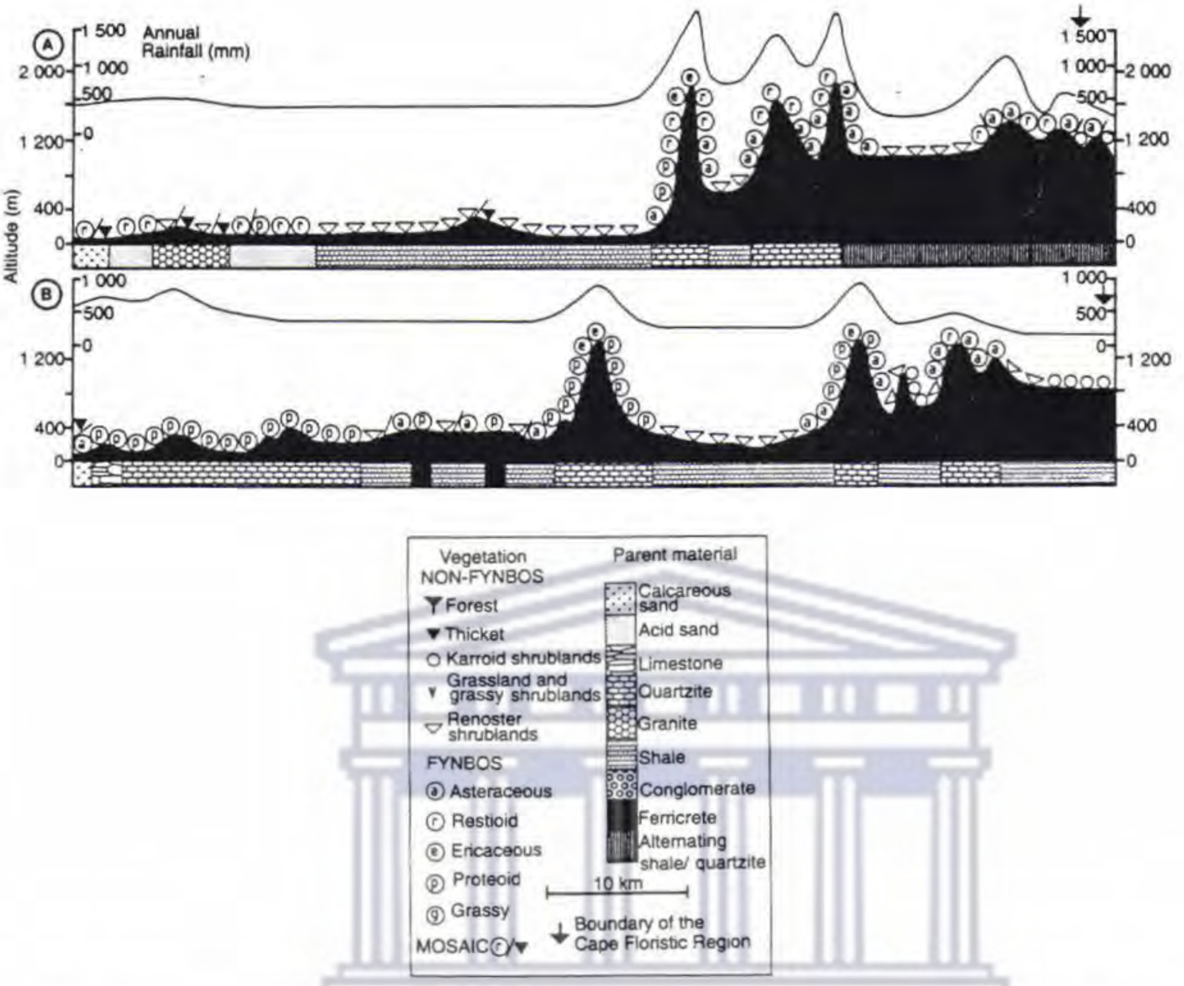


Figure 9. Distribution of vegetation in relation to rainfall, topography and geological substratum along two coast-to-interior transects in the Western Cape (after Campbell, 1985; Cowling and Holmes, 1992).

Asteraceous and Restioid fynbos at shale outcrops.

2.4.3. Fire

Natural fires have been an important component of fynbos ecology since pre-historic times. Many fynbos species develop fire resistant seeds or are even fire dependent for germination. The ecology of fynbos necessitates regular burning of the vegetation in order to maintain optimum species diversity. Natural fires are caused by lightning and rolling rocks while man has been using fire for at least the past 125.000 years (Deacon et al., 1983).

Table 8. Major plant communities of the western and southern Cape mountains based on Campbell (1985) and Cowling and Holmes (1992).

COMMUNITY	FORMATION	FEATURES	DISTRIBUTION	ENVIRONMENT
Grassy Fynbos	Low, mid-dense to closed grassy leptophyllous grassy shrubland	High grass cover and relatively high cover of non-proteoid nanophylls and forbs	Lower mountain slopes in east, southern interior	Fine textured soils, more fertile than other fynbos types
Asteraceous Fynbos	Low to mid-high open to mid-dense, leptophyllous shrubland	Low total cover, often high grass cover and high cover of non-ericaceous ericoids	Throughout the biome	Driest fynbos sites on a range of substrata, rainfall range from 450-960mm/yr, soils <0.4m depth
Restioid Fynbos	Dwarf to tall, mid-dense to closed restioland with sparse shrub stratum	High restioid cover low shrub cover (<30%), very low presence of tall shrubs	Throughout the biome	dry, north slopes in mountains or waterlogged sites
Ericaceous Fynbos	Low to mid-high, closed ericaceous shrubland	Leptophyllous shrubland, high cover of restioids, Ericaceous shrubs dominant	Southwestern Cape and southern coast	Confined to South-facing, wet slopes (>1500mm/yr) , soils have high carbon content , low pH, high fines percentage
Proteoid Fynbos	Low to tall, open to closed, proteoid shrubland	Distinguished by >10% tall proteoid shrubs	Throughout the biome	Confined to low altitudes on wide range of substrata, rainfall from 400-1100mm/yr

Van Wilgen (1987) summarises the main characteristics of fire regimes in the fynbos biome. For the dry and mesic mountain fynbos, which is most common in the Western Cape mountains, biomass, and thus fuel load, accumulates steadily with post-fire age. Biomass in mature fynbos, 12-20 years of age, can vary from 500 to 5000 g/m^2 (Kruger, 1977; Van Wilgen, 1982). Fires take place with frequencies between 4 and 40 years depending on available fuel, source of ignition and associated weather. The fynbos is however best adapted to fire intervals between 10 and 30 years. For optimum species diversity burning frequencies between 12 and 15 years are maintained, if possible, by nature conservation management. Most fires occur in the summer months when fire danger is highest (Van Wilgen, 1987). The average rate of spread of fires is 0.01-0.07m/s over large areas, with up to 35000 hectares burning at a time (Van Wilgen, 1985, 1987).

Few data are available on fire intensities but those which are available suggest values between 200 and 20.000 kW/m (Bands, 1977; Van Wilgen et al., 1985). Natural or uncontrolled fires normally burn the largest areas under dry summer conditions and also result in the highest fire intensities. Management fires are burnt under less extreme conditions, predominantly in autumn, and are therefore less intense (Van Wilgen, 1987). Prescribed burning also tends to decrease the size of the area burnt at one time to less than 1000ha.

An important geomorphological aspect of fires is its association with rock spalling. This form of thermoclasty is well known from several parts of the world including the forested slopes of the western Rocky Mountains (Blackwelder, 1926; Birkeland, 1984), southern France (Ballais and Bosc, 1992, 1994) and Australia (Ollier and Ash, 1983; Dragovitch, 1993). Its importance in mechanical fracturing of rock in the Western Cape mountains is further discussed in Chapter 6.

CH 3. FIELD EVIDENCE FOR SOIL FROST ACTIVITY

A geomorphological survey was conducted to investigate field evidence for soil frost activity in the Western Cape mountains. The study focused on the Waaihoek Peak and Mount Superior area where field observations were complemented by monitoring of sediment movement rates (ch.5). The location of these sites are presented in Figures 29 (p. 70) and 32 (p. 73) respectively. The selection of sites for the wider regional survey is based on field observations in these two areas, as well as the considerations on the frost-susceptibility of the sandstone sediment. Areas were visited where shale-derived soils are exposed at sufficient altitude to allow frost features to develop. Even at these sites however, Peninsula sandstone strata are always present and were also inspected. For the location of the sites discussed in this chapter see Figure 1 (p. 5).

3.1. WAAIHOEK PEAK

3.1.1. Ground and surface ice in sandstone-derived sediment

The summit area of the Waaihoek range (maximum altitude 1954m a.s.l.), like most of the Western Cape mountains, is underlain by Peninsula sandstone and is characterised by the presence of extensive, coarse debris mantles. No field evidence for segregation ice growth or needle-ice could be observed in these materials between January 1990 and December 1994. In contrast, saturation overland flow due to snowmelt and heavy rainfall is of common occurrence in winter. Freezing of this surface water can be observed to form an ice-crust at the soil surface. These ice-crusts formed under diurnal frost cycles resemble ground or seepage icings (c.f. Williams and Smith, 1989). Icings are, however, per definition features that persist for a considerable part of the year (Åkerman, 1980) and, thus, implied to be primarily a phenomena of permafrost regions (Pissart, 1987). Unlike in permafrost areas, no prolonged periods of groundwater seepage take place, but surface water is present due to saturation overlandflow. Water may continue to trickle downslope beneath this frozen water surface.

In other cases diurnal frost results in pore-ice at the soil surface. This may be with or without the presence of ice-crusts at the soil surface, depending on whether overland flow actually takes place. Pore-ice formation in saturated soils can readily be observed in winter on ridges, summit plateaus or other sites where shallow soils are in close vicinity to bedrock, or near streams and on terracette tread surfaces where throughflow arrives at the soil surface. In none of these cases is needle-ice growth or other forms of segregation ice observed. Pore ice forms in voids too large to allow soil moisture movement to the freezing plane (French, 1976). These observations thus further confirm the lack of frost susceptibility of the sandy soils in the Waaihoek Peak area.

The zero-curtain effect

The effect of latent heat maintaining temperatures near 0°C over extended periods in freezing or thawing soils has been referred to as the zero-curtain effect (Washburn, 1979; French, 1976). The effect has mainly been reported for permafrost environments (Williams and Smith, 1989), but has been shown by Outcalt et al. (1990, p.1514) to occur "when and where a thawed zone near the surface refreezes in moist to saturated medium-textured mineral or organic soils". Outcalt et al. (1990) further show that the zero-curtain effect is maintained not only by latent heat transfer but also by mass transfer in the surface layer due to localized condensation and evaporation as well as advection of soil moisture. The effect is terminated when most of the soil moisture is frozen (Williams and Smith, 1989) and is associated with a distinct drop in surface temperatures in the studies by Outcalt et al. (1990). Soil temperatures may fall rapidly after this desiccation phase.

The freezing of water at the surface of saturated soils and the formation of icings implies that, as elsewhere, significant amounts of latent heat are released when freezing temperatures are reached in the arenaceous sediments of the Waaihoek Peak area. Throughflow and overlandflow further increase sensible and latent heat supply near the soil surface. Rates of heat loss from the soil surface are limited, as indicated, by the high frequency of soil surface minimum temperatures around 0°C. On the other hand, air minimum temperatures at +0.1m reach significantly higher frequencies of values below -2°C. These are not readily explained by thermal insulation by snow cover as might be argued for the higher frequencies of temperatures below -2°C recorded at +1.5m (see chapter 4). Rather, this phenomenon is best explained by the effective compensation of sensible heat loss from the soil surface by latent heat release from the freezing of abundant soil moisture.

Conditions in the arenaceous sediment of the Waaihoek Peak area appear particularly favourable for the zero-curtain effect to be effective. High soil moisture levels prevail during most of winter and freezing rates are slow so do not overcome the latent heat release within a single diurnal frost cycle. This effect restricts frost penetration beyond the soil surface and maintains soil surface temperatures around the freezing point, while air temperatures may drop significantly lower. High moisture levels in winter may thus provide an important safeguard against frost damage of vegetation achieved on a similar principle as by local farmers spraying their crops and orchards. The zero-curtain effect may thus be an important ecological phenomenon in the summit regions of the Western Cape mountains.

3.1.2. Terracettes

A widespread surface feature on debris slopes in the Peninsula sandstones is the accumulation of clasts and sediment against either larger immobile blocks or other obstructions like vegetation tussocks. A general mobility of clasts at the surface of sandstone derived debris covers is conspicuous. Vegetated debris slopes with high clast abundance will display loose clasts resting against or on top of vegetation tussocks. Some of these may be moderately to well weathered. This, and the absence of rockwalls and slope angles of less than 20°, excludes an origin by rockfall in most of these cases. The same slopes also present widespread signs of surface erosion of the sandy matrix by splash and surface wash (Fig. 10). Removal of the matrix may result in surface armouring due to the presence of gravel lag deposits on the bare sediment surface.

Figure 10. Arenaceous debris slope with lag gravel accumulation on a pitted, sandy soil surface and small soil scarps indicating surface erosion by splash and surface wash. Slanghoek Peak, December 1994. Pencil for scale.

On debris slopes with a high clast abundance sediment mobility leads to an irregular but ubiquitously micro-stepped topography. The steps in the Waaihoek Peak area vary widely in size according to the nature and size of the obstruction. Characteristic dimensions are presented in Table 9. Differences in dimensions between the three populations, using one-way ANOVA testing, proved insignificant at a 95% significance level. The exception was formed by the height of the surface wash steps which differed significantly, at a 99% significance level, from the other two terracette types. Deposition of the sandy matrix behind obstructions like grass tussocks and blocks may lead to the development of terracettes with treads bare at the back and vegetated near the front. The riser is, however, bare and of erosional character, or may be formed by boulders exposed from the diamictons. Clasts may be found released from riser surfaces by removal of the surrounding matrix. In some cases, the accumulation of clasts and sediment behind larger immobile blocks at the Waaihoek site results in features of similar morphology to periglacial stone-banked steps, including a downslope coarsening trend towards the front of surface clasts.

In sandy soils with low clast abundance at the valleyheads southeast of Waaihoek Peak, terracettes are well developed at regular intervals. Typical dimensions are presented in Table 9. They deviate morphologically from turf-banked steps in that vegetation, present at the front of the tread surface, is absent from the riser. The back of the tread, near the next upslope riser, is frequently bare and covered with well-sorted, medium to coarse sand. Fine laminar layering of sand alternating with fine organic litter suggests deposition by surface run-off. The back of the tread surface may form a slight depression with shallow channels indicating concentrated surface run-off. Over the entire terracette profile fine hair roots are continuous down to 15cm. Higher vegetation density at the front of the tread is further reflected in the darker soil colour and higher organic matter content found here than in the A-horizon below the centre and back of the tread. No signs of slow soil displacement in the form of curving roots could be found at the riser front. Rather, the risers obtain an erosional, vertically concave profile with roots extruding from a bare surface. The outline of the steps is straight or concave rather than lobate. Boulders, where present, may act as barriers and form risers.

On near-horizontal slopes at the summit plateau of Waaihoek Peak, stepped micro-relief generated by surface wash was observed in soils less than 15cm thick, with low vegetation density. The features are somewhat smaller in dimension than the terracettes described above, but are mainly distinguished by their small riser height (Table 9). Tread surfaces are bare and composed of well-sorted sand deposited in a similar manner as found at the tread surface of terracettes. The tread front and riser is composed of organic debris and litter with twigs aligned parallel to the riser outline. The step is formed by the accumulation of the finely laminated sediment behind this barrier. These steps appear to be transient features that may appear and disappear after individual precipitation events.

		Length (m)	Width (m)	Height (m)	Slope gradient
Debris slope, high clast abundance (n =15)	$\bar{x}$	2.45	0.57	0.22	15°
	S.D.	1.27	0.16	0.1	2.3
Debris slope, low clast abundance (n =135)	$\bar{x}$	3.56	0.74	0.21	18°
	S.D.	1.93	0.31	0.09	9.4
Summit plateau (n =4)	$\bar{x}$	1.41	0.88	0.04	4°
		0.55	0.18	0.01	0

Table 9. Dimensions of terracettes in the Waaihoek Peak area.

3.2. MOUNT SUPERIOR

In the close vicinity of Mount Superior a geological window of Cedarberg shale forms a gentle summit dome at an elevation of 1850m a.s.l. which was first visited in December 1991. Active soil frost features observed here include micro-patterned ground and stone- and turf-banked steps and lobes.

3.2.1. Sorted micro-patterned ground

The near-horizontal surface of the summit area at Mt Superior is covered by a shallow soil, less than 15cm thick, and extensive bedrock outcrops. Vegetation is sparse in between many bare soil surfaces. On the bare soil surfaces upfreezing of clasts is very common. As a result, vertical sorting is well developed to a depth of 6cm. Vertical tilting of clasts occurs in well defined areas with sharply demarcated boundaries. As these boundaries develop in similar material on the same gradient adequate moisture supply appears to be the critical factor which allows this form of frost heave. Intricate surface patterns are formed by the alignment of the *a*-axis of rod-like clasts and the vertical position of the *a/b* plane of platy shaped shale material (Fig. 11). Regular patterns in the form of micro-polygons or circles can be distinguished in some cases but are generally not well developed, or are obscured by the high clast abundance at the surface. Expulsion of fines occurs in small pockets or in distinct linear patterns on sloping surfaces, between 3° and 6°.

The only form of well developed patterned ground are sorted stripes with lengths of several metres (Fig. 12). The stripes which comprise the fine grained fractions form domes and are slightly elevated above the coarse grained stripes. The extent of particle sorting at the surface between the coarse and fine stripes was established by measuring the a-axis of all surface clasts over a short, central section of two adjacent

Figure 11. Irregular, non-sorted surface patterns by vertical tilting and re-orientation of platy- and rod-shaped clasts near Mt. Superior (1850m), December 1992. Length of ruler is 47cm.

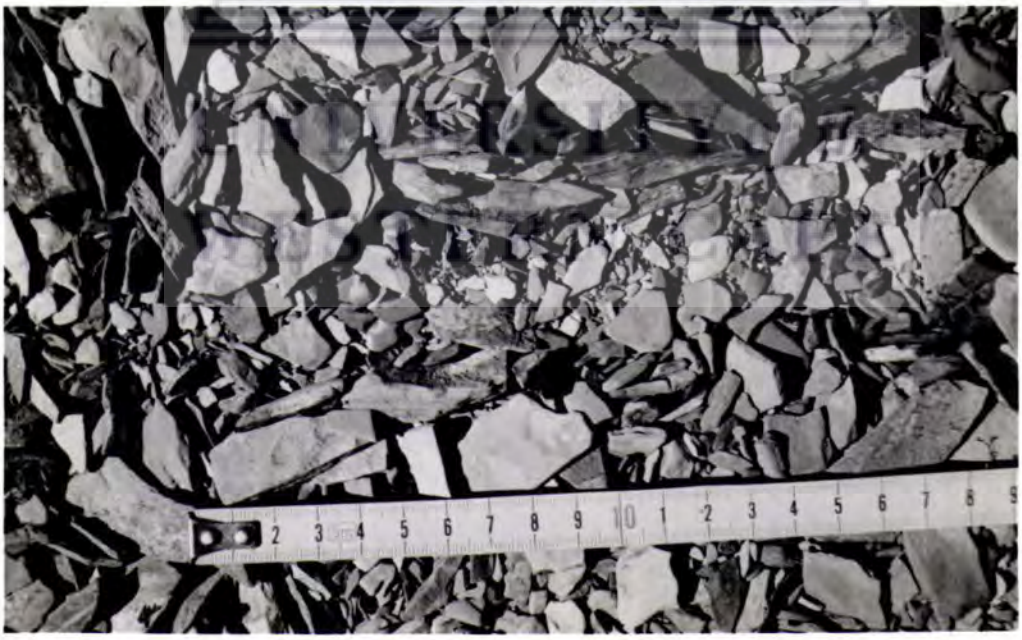


Figure 12. Detail of miniature sorted stripes at the Mt.Superior site (1850m). Note the vertical position of the *a/b*-plane of platy clasts and the orientation of the *a*-axis of large rod-shaped clasts parallel to the alignment of the coarse stripe. December 1992. Length of ruler is 20cm.

stripes. The results are illustrated in Figure 13. The coarse stripes have widths similar to the fine stripes (Fig. 14). A cross section was drawn from an undisturbed sample taken in the field by saturation with a polyester resin (Fig. 15). Clasts in the coarse stripes show distinct vertical tilting and a long-axis alignment parallel to the stripes (c.f. Pérez, 1992a). The general tendency of a coarsening upward sequence can be recognised down to 6cm. However, the clast alignment clearly indicates the updoming of unit 2 which is composed of granular material and forms the fine stripe, with the consequent sideways expulsion of unit 1, which is composed of small clasts and forms the coarse stripe. Subsurface movement is indicated by granule orientations in unit 3, composed of a high abundance of granular material in a loamy matrix. The orientations suggest a sideways and downward migration of the granule-rich material to form distinct wedge-shaped structures intruding in unit 4, a darkbrown loam with low granule abundance. Sediment of unit 4 appears domed upward beneath unit 2 from where unit 3 has been displaced (Fig. 15).

Origin of the micro-patterned ground

Micro-patterned ground has been reported from a wide variety of environments on the Southern Hemisphere, including alpine regions of east Africa (Troll, 1944; Jannsen, 1972; Hastenrath, 1973), southern Africa (Troll, 1944; Hastenrath and Wilkinson, 1973; Boelhouwers and Hall, 1990), the Peruvian Andes (Troll, 1944; Hastenrath, 1977; Francou, 1988), New Zealand (Soons and Price, 1990) and the sub-Antarctic islands (Chambers, 1967; Hall, 1979; 1983, 1984; Heilbronn and Walton, 1984; Wilson and Clark, 1991). A polygenetic origin is generally favoured in the formation of sorted stripes, with mechanisms comprehensively listed by Washburn (1956, 1970). In marginal frost-action environments, as found in southern Africa at

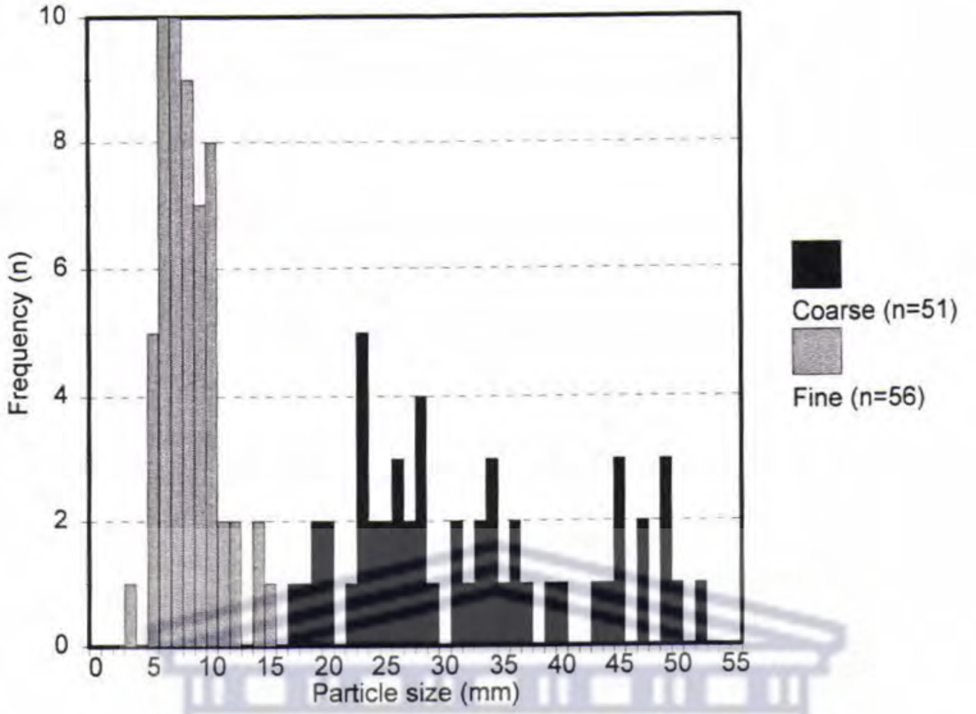


Figure 13. Sorting by particle size of surface clasts in coarse and fine stripes at Mt. Superior (1850m).

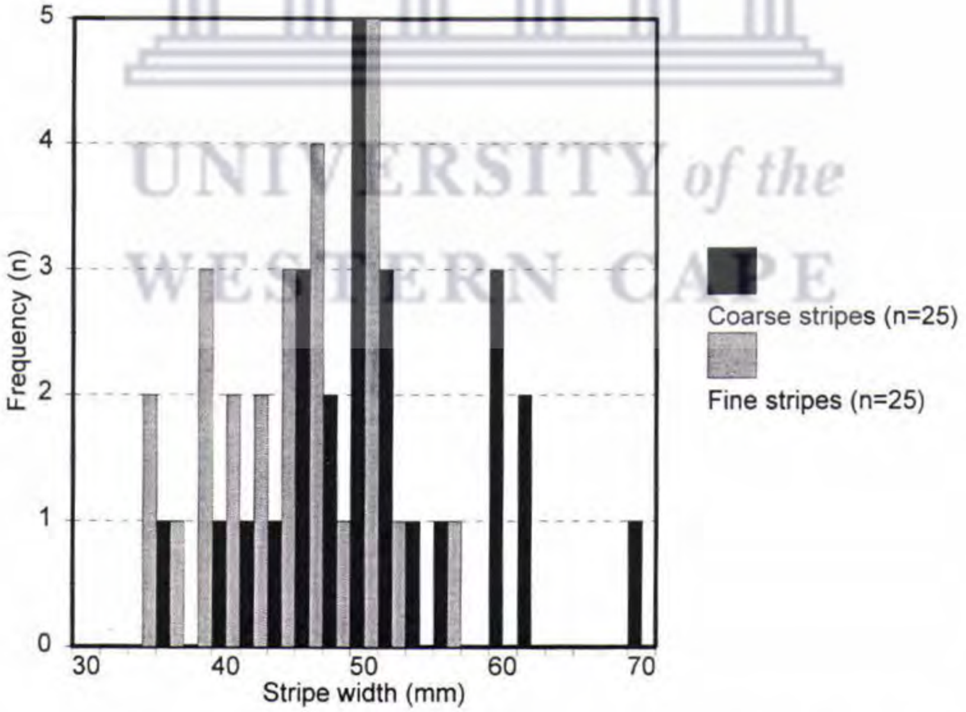


Figure 14. Plot of widths of coarse and fine stripes in micro-patterned ground at Mt. Superior.

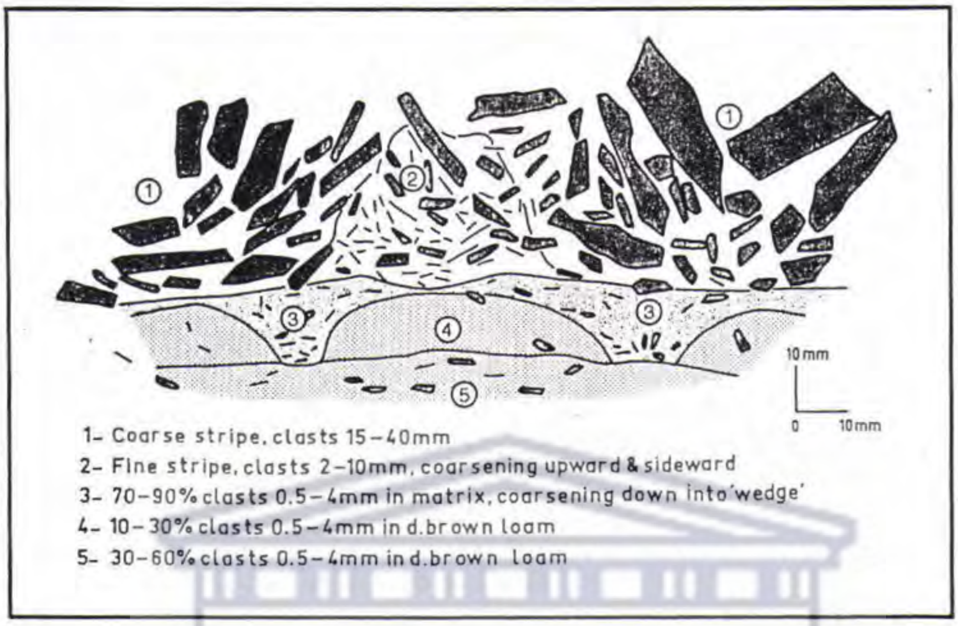


Figure 15. Cross section, aligned parallel to the contours, through a sorted stripe indicating sediment structures and clast orientations as found near Mt.Superior (1850m). Based on undisturbed sample taken by saturation with polyester resin, December 1992.

present, the models based on frost cracking under seasonal frost cycles cannot readily be applied, as also noted by Wilson (1992) for patterned ground development in southeast Ireland.

Sorted patterned ground development where no frost cracking is required involves processes such as cryostatic pressure, differential frost heave and frost sorting (Washburn, 1956, 1970). Needle-ice growth and ablation has been argued to be important in downslope movement of sorted stripes (Mackay and Mathews, 1974; Hall, 1983; Soons and Price, 1990; Pérez, 1984, 1992a) as well as their vertical and lateral sorting on slopes subjected to diurnal frost (Price, 1981; Pérez, 1992a). These mechanisms, however, fail to explain the regularity of the forms concerned. To account for this regularity of patterned ground formation models based on thermally induced convection in thawing of frozen soils (Ray et al., 1983; Krantz, 1990) and convection induced by density contrasts associated with drainage and thaw of oversaturated frozen ground (Hallet and Prestrud, 1986; Hallet, 1987). Ray et al. (1983) and Krantz (1990) deduce from their model width (W) to depth-of-sorting (D) ratios in the order of W=3.6D if width is measured from coarse to coarse border. Ratios measured at Mount Superior are in the order of 2.7, considerably below the predicted value. The subsurface structures in the sorted stripes described above, however, do indicate the upward movement of the finer fractions and a descending of the coarser fractions of the sediment.

Although the structures described here do not readily fit the free convection models, it is evident that the sorted patterns reflect the result of freeze/thaw processes under diurnal frost cycles operative in the upper 6cm of the soil. This depth closely corresponds with the soil thickness in which soil disturbance by needle-ice growth is observed (Price, 1981; Pérez, 1992a).

3.2.2. Turf-banked steps

On the south-facing slopes of the shale outcrop at Mt. Superior (1850m) a well developed tall grass cover is present. Soil thickness increases from 30cm near the summit to 70cm near the base of the slope. Turf-banked steps have formed here over the entire slope with characteristic bare tread surface and vegetated riser. Slope angles vary between 7° and 16°. Characteristic dimensions of the turf-banked steps on various slope sections are presented in Table 10 but fail to show a statistically significant relationship between size and slope position. Using one-way ANOVA testing only between the upper middle and lower middle slope could a significant increase in step length be shown at a 95% confidence level. The wide variation in size is indicated by the large standard deviations. With increase in slope angle individual steps are more difficult to identify as the sediment from one tread surface connects with that of a lower surface. Active sediment movement is evidenced by the bending of roots of the vegetation in an upslope direction at the risers (Fig. 16).

3.2.3. Stone-banked lobes and steps

The upper section of the north-facing slope of Mt. Superior exhibits bare, shallow soil directly on bedrock in which stone banked lobes have formed. Dimensions of these features are summarised in Table 10. A cross section shows that these forms rest directly on bedrock (Fig. 17). A downward fining sequence occurs in the upper 6cm presumably due to the upfreezing of stones. Below this surface layer a distinct coarsening occurs down to bedrock. Lateral sorting is very distinct at the surface from the upper section of the lobe to the lobe front. Fabrics show a dominant alignment of clasts in the downslope direction. Where movement is retarded clasts show imbrication and are re-orientated to dip into the lobe.

3.3. VICTORIA PEAK

The summit of Victoria Peak ($34^0$01'S, $19^0$02'E, 1594m a.s.l.) is comprised of Cedarberg shale and forms a gentle dome a few hundred metres across, bordered by an erosional rock surface at the contact with the Pakhuis Formation. This erosional surface shows widening of joints and reversed relief by case hardening from iron-oxide precipitation along the joint surfaces. Surface roughness caused by this pseudo-karst diminishes towards the smooth, densely grassed shale slope. The gradients increase from 2° to 12° towards the summit over a distance of 50 to 150 m. Bare debris with

		Length (m)	Width (m)	Height (m)	Slope gradient	Tread angle
North-facing slope						
Stone-banked steps						
(n =4)	x̄	1.02	0.63	0.93	7°	6°
	S.D.	0.33	0.16	0.04	0	0.8
Stone-banked lobes						
(n =19)	x̄	1.49	1.93	0.20	16°	8°
	S.D.	0.74	0.85	0.07	2.0	4.7
South-facing slope						
Turf-banked steps (upper)						
(n =12)	x̄	2.73	0.90	0.17	8°	
	S.D.	2.71	0.31	0.05	0.8	
Turf-banked steps (upper middle)						
(n = 11)	x̄	1.82	1.01	0.23	16°	
	S.D.	1.04	0.20	0.06	0.8	
Turf-banked steps (lower middle)						
(n = 11)	x̄	2.74	1.21	0.22	10°	
	S.D.	1.91	0.66	0.04	0.8	
Turf-banked steps (lower)						
(n = 10)	x̄	2.67	1.02	0.18	12°	
	S.D.	1.88	0.17	0.04	0.8	
Turf-banked steps (all)						
(n =54)	x̄	2.53	1.01	0.19		
	S.D.	2.36	0.45	0.06		

Table 10. Dimensions of turf- and stone-banked steps and lobes found near Mt.Superior (1800-1850m).

Figure 16. Upslope orientation of grass roots parallel to tread surface at the front of a turf-banked step near Mt. Superior (1820m).

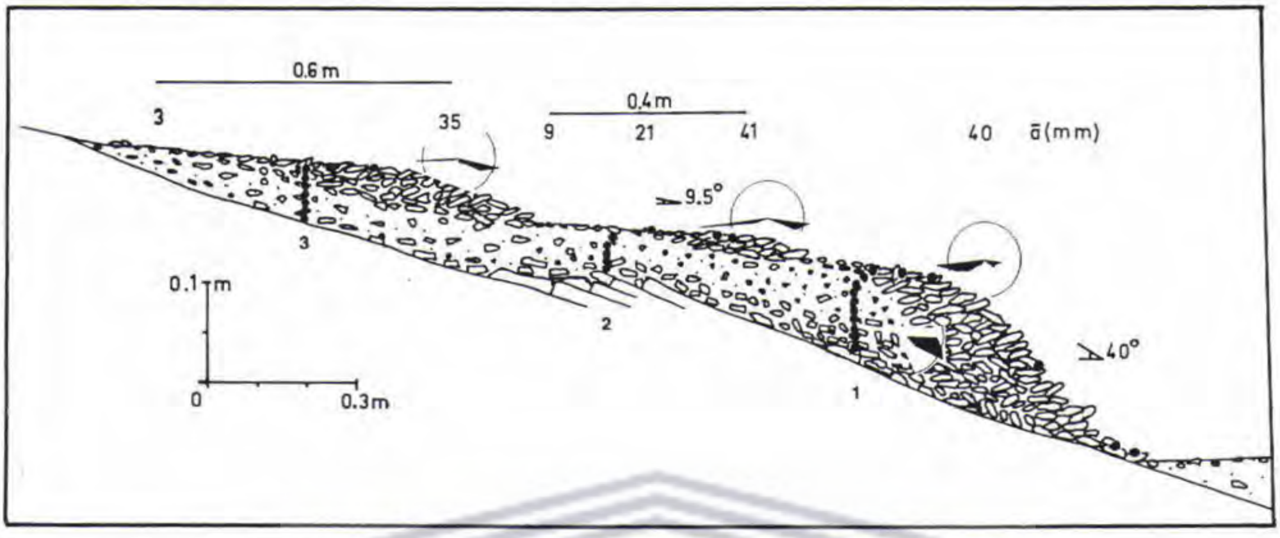


Fig. 17. Cross section through a stone-banked lobe indicating sediment structures, as well as clast size and clast dip at various points. Diameter of the circle indicates a frequency of 24%. Position and deformation of pebble columns used to monitor sediment are given; see p.108 for further discussion.

shale clasts at the surface form regular patches in between the grass at the foot of the slope in a 30/70 (Bare/Grass) ratio. These bare sediment surfaces become larger and more dominant towards the summit where bare bedrock and sediment dominate over the grass cover in a 75/25 ratio. Sediment thickness also reduces from 30cm at the base to 5cm at the summit. Limited evidence for soil frost activity was found at the summit in the form of needle-ice striped ground and stone- and turf-banked steps.

3.3.1. Needle-ice striped ground

Evidence for needle-ice activity was found in the form of expulsion of fines between clasts on bare sediment surfaces and disruption of grass tussocks. Furrows and ridges, forming non-sorted stripes, are found in bare soil and areas of disrupted grass cover. In the latter case, remnants of grass tussocks are present on the ridges of the patterns. This striated soil is found at the summit area on slopes with an aspect between northeast and south. The orientation of the stripes is however consistently in a northwest-southeast direction. The furrows are positioned only 1.0 - 2.5 cm below the ridge but both have similar widths of about 2.0 cm. Length of the features varies from 5 to 40 cm. Vegetation disruption can be caused by a variety of mechanisms particularly by raindrop impact (c.f. Krüger, 1994), runoff and biological activity. In this case the alignment and regularity of the patterns is very suggestive of needle-ice activity.

The alignment of needle-ice sorted stripes has been associated with both the early sun (Hastenrath, 1973, 1977; Hastenrath and Wilkinson, 1973; Mackay and Mathews, 1974; Pérez, 1984) and predominant wind direction during needle ice growth (Troll, 1944; Schubert, 1973; Beaty, 1974; Hall, 1979; 1983). At Victoria Peak the northwest-southeast alignment corresponds with both the early sun and the common wind directions. Northwesterly winds dominate in winter in association with approaching frontal depressions. Weather conditions linked to these systems, including high wind speeds, are not conducive to calm, clear sky conditions normally associated with needle-ice growth. However, Hall (1979) reports on needle-ice striped ground parallel to the wind on Marion island where overcast and windy conditions are very common. Stripe formation under the influence of wind may thus not be entirely excluded here. A second observation is that the striated soils occur exclusively on northeasterly to southerly exposed slopes. These are the slopes that receive early morning sun while other slope sections are still in shade. It may be suggested that by the time the shaded slopes receive direct radiation the needle-ice will already have ablated, or that the angle of the sun with the surface is too high for striations to develop. Non-sorted stripe formation thus appears to be more favourably associated with the early morning sun rather than with wind.

The absence of sorted patterned ground at this site is worth noting. This may partly be due to the very shallow frost penetration. However, the extremely high precipitation totals for this site of over 2500 mm/yr (Weather Bureau, 1986) strongly suggest surface runoff to be of very common occurrence. This may readily destroy soil frost features at the soil surface outside, or even during, the active frost season.

3.3.2. Turf- and stone-banked steps

Turf-banked steps are also found on the grassy shale slopes of the summit dome of Victoria Peak (1540m) (Fig. 18, Table 11). The steps show bare treads with densely grassed risers and have developed in soils with thicknesses between 10 and 30cm. Tread surfaces show expulsion of fines and vertical stacking of clasts, indicative of surficial frost action. Clasts of 20-30mm diameter are found to form a single clast layer

Figure 18. Turf-banked steps on shallow soil at Victoria Peak (1580m), October 1994. Length of tape is 50cm.

		Length (m)	Width (m)	Height (m)	Slope gradient
Stone-banked steps (n =12)	$\bar{x}$	0.67	0.62	0.06	8°
	S.D.	0.20	0.23	0.02	2.6
Turf-banked steps (n =5)	$\bar{x}$	4.14	1.01	0.13	7°
	S.D.	1.36	0.09	0.06	0.75

Table 11. Dimensions of turf- and stone banked steps at Victoria Peak (1570-1594m a.s.l.).

beneath which smaller granular material 2-5mm is found resting on a dark loam. Down to a depth of 25-30mm clast abundance is very low (<5%), but these are abundant below this level (40-50%). Overturning of tussocks and bending of roots further indicates active, superficial soil movement.

Stone-banked features are found on bare, shallow soils where gradients steepen downslope from the near-horizontal summit (Fig. 19). Dimensions of the features are summarised in Table 11. A typical association of individual lobes is shown in Fig.20. Depth of soil in which the steps have formed ranges from 5 to 15 cm. Particle sorting is best developed at the surface showing distinct downslope and lateral coarsening from granule size on the most upslope tread surface to clasts of 20 cm at the riser. Clast imbrication and *a*-axis alignment parallel to the riser is common at the lobe front, while vertically stacked clasts and signs of needle-ice activity can be found at the tread surface.

3.4. MATROOSBERG

Matroosberg forms the highest peak in the Western Cape mountains (33°22'S, 19°40'E, 2248m a.s.l.) and was studied by Sänger (1988a). Sänger (1988a) describes the presence of needle ice and garlands for the slopes above the ski hut at altitudes between 1900 and 1940m but does not mention lithological control for this area. A survey in December 1994 found indicators for needle-ice growth, stepped micro-relief and sorted micro-patterned ground. Some relict deposits are also described

3.4.1. Stepped micro-relief

Forms of stepped micro-relief were found on the slopes immediately above the ski hut, beneath Conical Peak. The colluvial material is mainly derived from the Cedarberg shale with a subordinate component derived from the sandstone.

Terracettes

Cedarberg shale derived debris slopes below Conical Peak show terracettes on a rectilinear northeast-facing slope of 23°. Dimensions are summarised in Table 12. The steps are characterised by a high clast abundance at the tread surface and a *Restio* spp. cover near the front of the tread. The bare riser forms an erosional soil scarp with roots protruding from its surface. Sänger (1988a) reports observations of needle ice growth at these soil scarps in winter. Surface wash, drop impact and water surfacing at the scarp by throughflow are further considered important agents in the scarp retreat of these features as well as in the transport and deposition of the clasts. The clasts found on the tread surface may to a large extent be derived from release due to soil scarp retreat, but form a lag deposit due to surface erosion of the fines.

Turf-banked steps

At the convex crest of the slope where terracettes are observed, turf-banked steps occur. Here the vegetation cover is reduced from 60% to 20% and soil thickness from over 50 cm to between 15 and 30 cm with bedrock surfaces exposed in places.

Figure 19. Stone-banked step at Victoria Peak (1590m), October 1994. Note steep tilting and imbrication of platy clasts and downslope coarsening. Length of tape is 30cm.

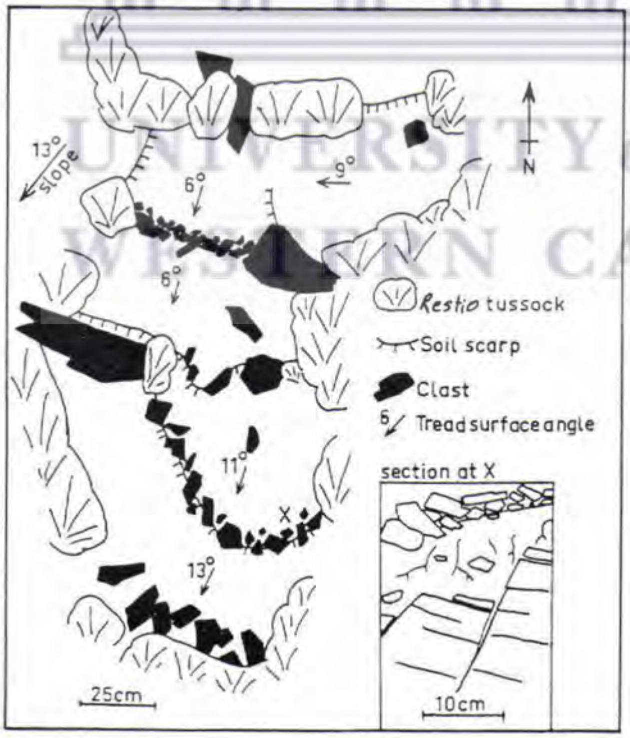


Figure 20. Sketch of turf- and stone-banked steps at Victoria Peak (1580m), based on slide and field measurements. October 1994.

		Length (m)	Width (m)	Height (m)	Slope gradient
Terracettes					
(n =12)	x̄	1.55	0.55	0.12	17°
	S.D.	0.52	0.12	0.03	
Turf-banked steps					
(n =5)	x̄	3.19	0.91	0.19	12°
	S.D.	1.02	0.31	0.07	

Table 12. Dimensions of stepped micro-relief at Matroosberg (1700-2100m a.s.l.).

Vegetation is only present at the front of tread surfaces. The slope gradient decreases from 17° to 12° in upslope direction. The turf-banked steps are more continuous laterally than the terracettes (significant at 95% level using ANOVA) and are referred to by Sänger (1988a, p. 173) as garlands. A cross section is presented in Figure 21. The steps rest directly on bedrock and show distinct coarsening of the surface material in downslope direction. Elongated and platy surface clasts of up to 4.0 cm show vertical orientation at the tread surface. An upward coarsening trend occurs in the upper 3.5 cm

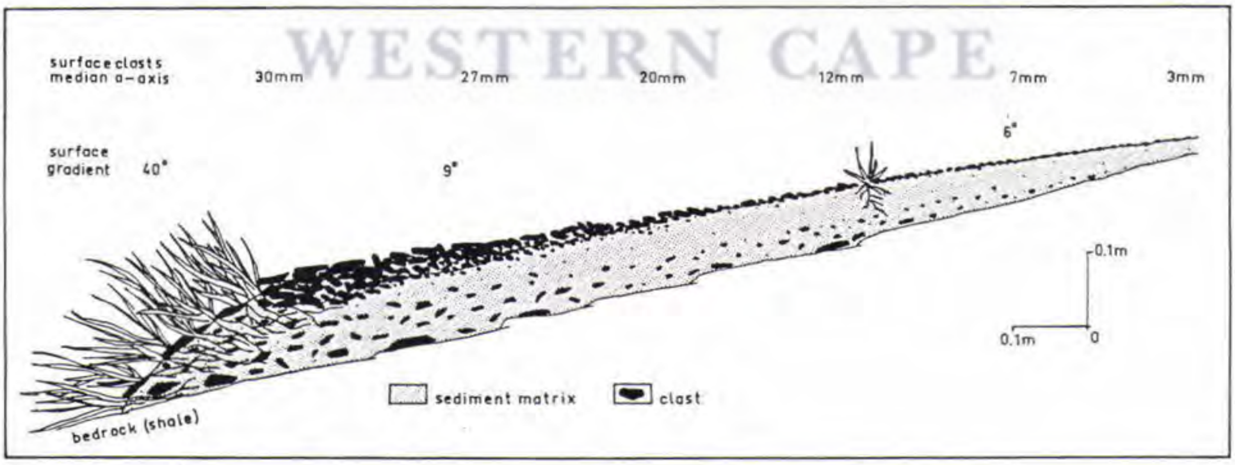


Figure 21. Cross section through a turf-banked step on a shale debris slope above the ski hut at Matroosberg, 1840m.

indicating the depth of active frost penetration, unless covered by a thicker openwork clast layer such as at the tread front. Sediment movement is further evident by clast accumulation at the tread front, which forces over the *Restio* spp. tussocks at the riser. Platy clasts, dipping steeply in upslope direction at the tread surface are found imbricated against the vegetation. Beneath the zone of active frost penetration the steps are comprised of a matrix supported diamicton. No distinct orientation of clasts could be noticed in this material.

3.4.2. Sorted micro-patterned ground

At the saddle between Conical Peak and Matroosberg at 1900m a.s.l. micro-patterned ground could be found on tread surfaces of turf-banked steps of 1° inclination, on a slope of 4°. Sediment here is also derived from the Cedarberg shale. Both polygons and sorted stripes occur, the latter only having lengths of up to 30 cm (Fig. 22). Fig. 23 shows a cross section through a set of sorted stripes. The wedge-shaped coarse stripes are composed of material up to 3.0 cm (*a*-axis). The fine material forms elongated ridges composed of a loose, friable and highly porous material of granular texture. The granules are comprised of nodular-shaped aggregates of fines with diameters of 3-4mm. Roots of vegetation are completely absent in this layer which has a thickness of 30mm. Beneath this band a more compact structureless sediment with moderate clast abundance is present. Clasts and soil are not separated as in the layer above. Fine roots are abundant, some growing horizontally at the contact between the two layers. The depth of soil disturbance and associated features is very similar to those found at Mount Superior at similar elevations. As for the micro-patterned ground at Mount Superior needle-ice growth is suggested as the primary agent of sorting and soil movement responsible for the soil frost features.

3.4.3. Needle-ice growth in sandstone debris

At the end of the Spekrivierkloof a gully has deeply incised into a coarse sandstone debris cover. At one section in the upper part of the gully the matrix of the diamict shows signs of recent needle-ice growth (Fig. 24). Although the occurrence of needle-ice is not exceptional it forms the only observation of recent soil frost activity in sandstone-derived debris. This points to the fact that frost susceptibility is not determined by lithology but by the granulometry of the sediment concerned. However, granulometric differences may result from lithological variations in the Table Mountain Group arenites.

3.4.4. Relict slope deposits: openwork boulder accumulations and scree

Non-sorted, colluvial, debris covers are of widespread occurrence throughout the Waaihoek range as everywhere in the Western Cape mountains where the Peninsula Formation is exposed. The material forms a matrix- or clast-supported diamict with isolated, but occasionally extensive, areas of openwork boulder material. The latter may be the result of rockfall or rock avalanching and form distinct screes. However in many cases the openwork material occurs at considerable distance from a rockwall on slopes well below 30° and is normally completely surrounded by vegetation. As opposed to scree accumulations these openwork deposits are positioned in slight depressions compared to the surrounding debris slope (Fig. 25). At a few sites in the Hexriver Mountains distinct sedimentary structures are found in the openwork block accumulations. Further description of the openwork slope materials is presented for the Matroosberg area where all are found in close proximity of each other.

Openwork boulder accumulations are widespread on the southwest exposed valley-side of the Spekrivierkloof, its valleyhead, near the summit of Matroosberg and

Figure 22. Micro-patterned ground on the tread surface of a turf-banked step at the saddle between Matroosberg and Conical Peak (1900m), December 1994. Length of tape is 20cm.

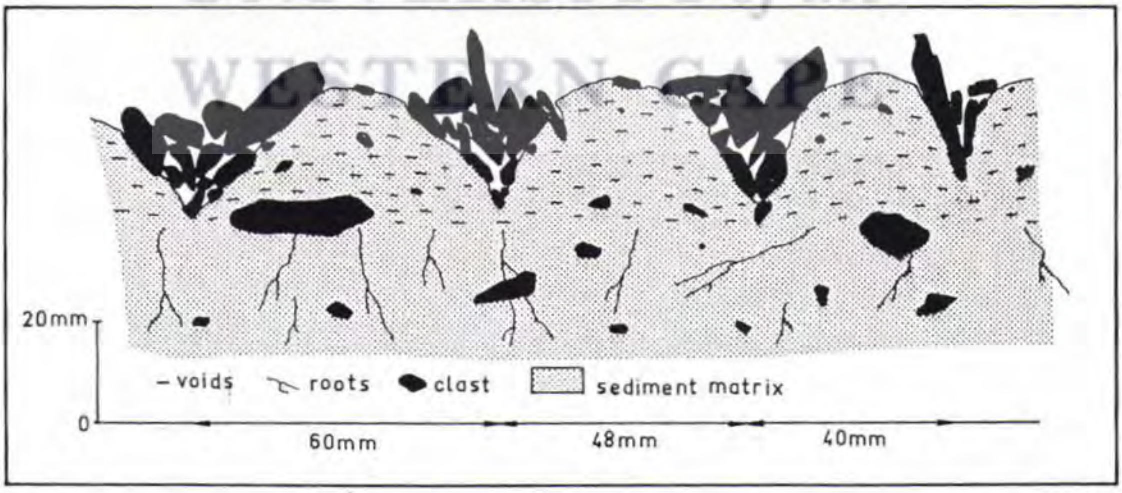


Figure 23. Cross section through the sorted stripes shown in Figure 22. See text for further details.

Figure 24. Friable, heaved matrix at the surface of a sandstone-derived diamict exposure near the ski-plateau at Matroosberg, 1980m a.s.l., December 1994.

Figure 25. Linear openwork boulder accumulation in a lowered position relative to surrounding debris slope, thought to have developed due to matrix removal by concentrated subsurface flow, Victoria Peak (1360m a.s.l.), October 1994.

other rockfaces in the summit region. Notable differences in the deposits occur between these sites.

Screes

Rectilinear debris slopes of over 30° occur beneath large rockwalls halfway in the Spekrivierkloof at altitudes above 1300m elevation. The blocky cover of these slopes is of rockfall origin. A recent slab failure has contributed a large volume of boulder material to these slopes. Besides this low frequency, large magnitude event both the rockwall and debris slope appear stable and are fully lichen covered with moderately weathered surfaces. These boulder accumulations may be referred to as true scree or talus. Large sections of these slopes are now composed of clast supported diamicts as voids are filled with matrix and support substantial vegetation covers.

Openwork material by matrix removal

Further upvalley the southwest-facing slopes are essentialy debris veneered bedrock slopes with regular exposure of bedrock surfaces. An irregular, but in places extensive patchwork of openwork boulder covers is present on these slopes. Most of these patches are positioned level, or even somewhat recessed into the surrounding debris slope. Lower end fronts may, however, be raised between 0.5 and 1m above the surrounding slope. The position of the openwork covers is not related to any rock outcrop that could supply the clasts, but completely surrounded by a vegetated matrix or clast supported diamict and occurs on slopes well below that required for accumulation by rockfall. The position of the block material in slight depressions, near breaks of slope or bedrock outcrops suggests that the material is a residual deposit by removal of matrix by throughflow. This phenomenon is of widespread occurrence in the Western Cape mountains and occurs over a wide range of altitudes (Table 13).

Blockstreams

A third category of openwork boulder accumulations is found in places on the same southwest-facing slope near the valleyhead, at the valleyhead itself and the slopes leading to Matroosberg summit. At Matroosberg summit one lobate accumulation rises up to 3m above the surrounding debris surface (Fig. 26). Here elongated blocks up to 2m have been heaved from the surface and dip steeply in upslope direction. At the boulderstream front tabular boulders are found imbricated at steep angles with dips in upslope direction, while elongated blocks lie in transverse position parallel to the

Location	Altitude a.s.l. (m)	Slope aspect	Location	Altitude a.s.l. (m)	Slope aspect
Scree - rockfall deposits					
Table Mountain	300	ESE	Bailey's Peak	1100	E
Table Mountain	400	W	Wellington Sneeukop	1600	SW-SE
Du Toitskloof	800	SW	Matroosberg	1300	SW-W
Openwork boulder deposits by matrix removal from diamictons					
Table Mountain	400	W	Matroosberg	1700	SW-W
Du Toitskloof pass	350	NE	Somerset Sneeukop	1300	N-E-S
Du Toitskloof	600	S	Sybasberg	1740	E
Dwarsberg	1350	NW-NE	Waaihoek Peak	1750	SW
Victoria Peak	1450	SW			
Openwork boulder deposits with sedimentary structures					
Waaihoek Peak	1800	SW	Matroosberg	1800	SW-W-N
Sentinel Peak	1600	W			

Table 13. Occurrence of some openwork boulder deposits in the Western Cape mountains. Altitudes are minimum values for each location.

Figure 26. Block stream front, here 8m high, near the summit of Matroosberg (2200m a.s.l.). Note the steep dip of the large rock slabs in upslope direction as well as their imbrication.

raised front. Upslope from the accumulation a vegetated matrix to clast supported diamict is found. The boulder accumulation is stable at present. No distinct variation in degree of weathering could be found within a single accumulation. The angularity of the boulder covers at Matroosberg summit are however significantly higher than for those found at the Spekrivierkloof valleyhead. The latter are a few tens of metres wide and several tens of metres long in downslope direction. They also show vertical positioning of elongated blocks, imbrication and a general downslope orientation of elongated blocks at the surface. Gully incision through a large accumulation shows an upward coarsening in openwork material up to 1.5m thick in places. Beneath this a clast supported diamict over 4m thick is present grading in upslope direction to a matrix supported diamict.

Soil formation in the form of well developed podzolisation indicates this deposit to be a relict feature, stable for at least most of the Holocene. Iron precipitation in the C-horizon covers the surface of clasts. On screes, blockfields and debris slopes solution processes appear to alter the angular shape of clasts to rounded, pitted surfaces. The shape of the scree and debris material beneath rockwalls also appears modified rather than generated by chemical processes. This points at the dominance of physical release mechanisms in the debris production.

Concerning the origin of these accumulations a cryoclastic debris production best explains the presence of the extensive volumes of angular blocks (see section 5.3.). Subsequent transport of these blocks, some over 3m diameter, took place over slope gradients under 15°. This, as well as the sedimentary structures described, strongly suggest a cryogenic origin for the origin of the deposits. Sänger (1988a) refers to these deposits as "blockmeere" (blockfields) transported by postglacial solifluction. Hagedorn (1984) also refers to the boulder accumulations at Matroosberg as solifluction deposits. By analogy with the explanation for similar deposits in the Natal Drakensberg (Boelhouwers, 1994) an origin by gelifluction under severe seasonal frost is suggested here.

3.5. WOLSELEY RIDGE

3.5.1. Sorted micro-patterned ground by desiccation cracking

Sorted patterned ground formation outside permafrost regions has frequently been associated with desiccation cracking of the soil and clasts filling such cracks (Washburn, 1956; Chambers, 1967; Pissart, 1973, 1974; Warburton, 1990). Contraction cracks may form either by water drainage and evaporation from the soil (Ballantyne and Matthews, 1983) or result from seasonal frost (Krüger, 1994). Ballantyne and Matthews

(1983) show that filling of the cracks starts before the entire crack network has fully developed. Processes that may be involved in material accumulation in the cracks include frost heaving (Chambers, 1967), needle ice activity (Pissart, 1972), surface wash, rain splash and wind (Chambers, 1967; Krüger, 1994).

Sorted micro-polygons by desiccation cracking were first observed on Table Mountain, Cape Town (950m a.s.l.) in summer 1990. Similar forms are described here from observations at Wolseley Ridge (33°31'S, 19°09'E, 870m a.s.l.) in early spring 1994. On flat bedrock surfaces thin sediment layers less than 7cm thick may fill shallow depressions in bedrock. Dense moss covers occupy these sediment surfaces. Desiccation of the moss cover results in polygonal, wedge-shaped, cracking at the surface down to a depth of ±1.5 cm (Fig. 27). The centres are comprised of dense moss that is very resistant to further break-up. Granule- size gravel with a median *b*-axis of 5mm, can be found to occupy the open wedges at the surface. Finer material is found lower down in the cracks. The origin of the contraction cracks cannot be related to soil frost cycles due to the altitudes at which they are found. Rather, they are considered features developed from seasonal wetting and drying. Due to their shallow depth the soils are rapidly saturated in winter and desiccate after winter rainfall in late spring. Mechanisms involved in material sorting in the cracks are also considered to be of a non-cryogenic origin. It is suggested that the granular material filling the cracks is washed in by surface runoff during rainfall events which gives rise to sorted polygonal micro-patterned ground. It is unclear whether these are seasonal features or whether they develop progressively over time.

It is worth noting that no turf-banked steps are observed at Wolseley Ridge, a site at 870m a.s.l.. Here only steps by surface wash, as observed for the sandstone debris slopes, are present. It thus appears that, besides soil texture, altitude is a factor

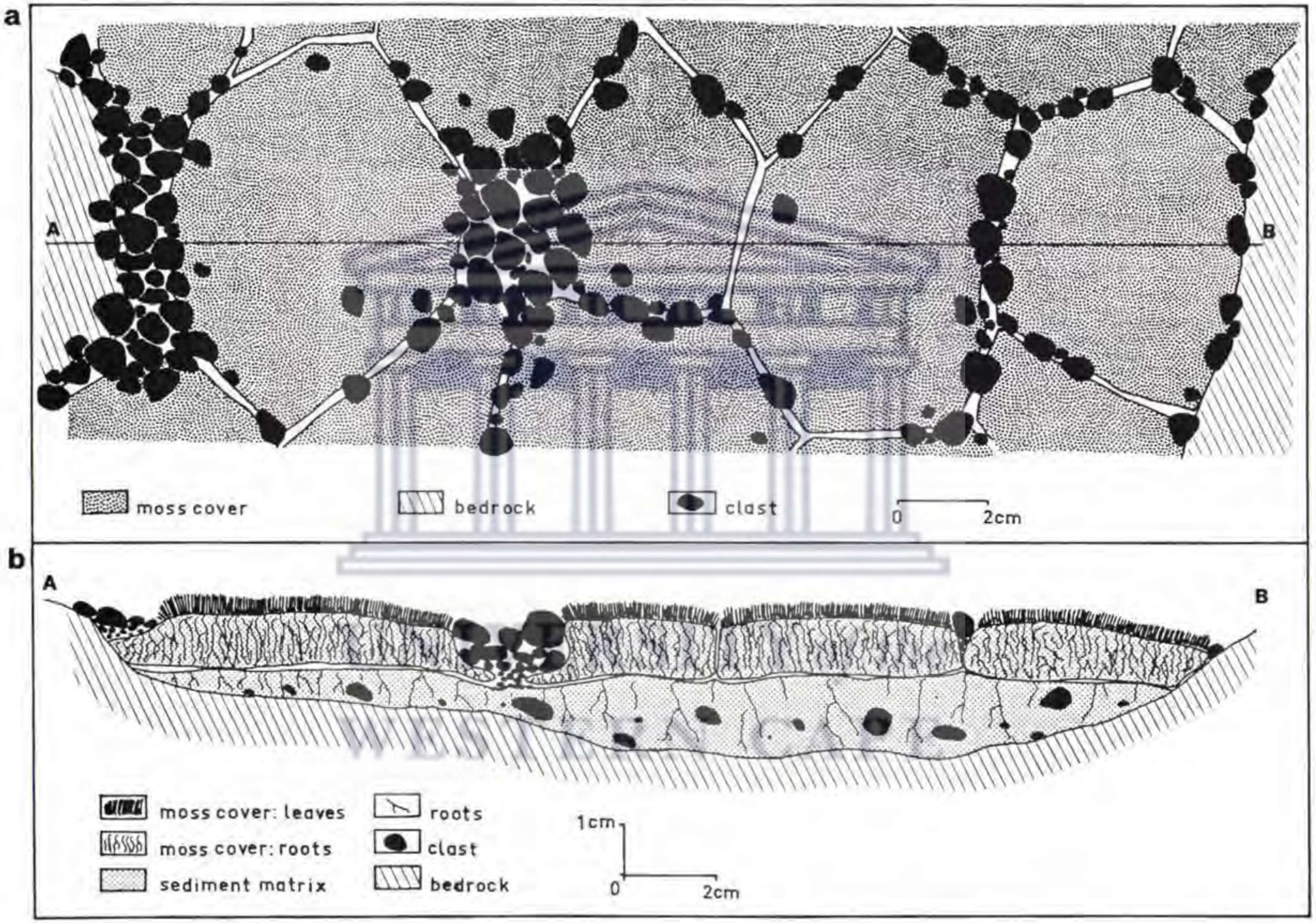


Figure 27. Sorted micro-patterned ground of a desiccation origin at Wolseley Ridge, a) in plan view, and b) in cross section; 870m a.s.l., October 1994.

related to the spatial distribution of turf-banked steps. This further points to the role of soil frost in their development.

3.6. SLANGHOEK PEAK

In the Slanghoek Peak area (33°41'S, 19°11'E, maximum altitude 1697m a.s.l.) the Cedarberg shale forms a band overlain by the quartzites of the Nardouw Formation, which closely resemble the lithologies found in the Peninsula Formation. The presence of overlying quartzites, however, results in coarse colluvial debris mantles covering the Cedarberg shale sediment. As a consequence geomorphological features found at the surface closely resemble those described for the sandstone debris slopes in the Waaihoek peak area (see 3.1.). No evidence for soil frost activity was found in this area. during the survey in October 1994.

An extensive sandstone erosion surface is found immediately north of Slanghoek Peak at the contact with the Cedarberg shale (Fig. 28). Here, mostly well-rounded sandstone clasts weathered to a varying degree are found as residuals on the exhumed rock platform. Most are concentrated in the linear depressions formed by the widened joint patterns suggesting water-aided transport. Median size of the clasts is about 0.2m with maxima up to 0.5m (*b*-axis) and have been transported on a 5° slope. New clasts are being released from sediment by soil scarp retreat at the margins of the rock platform. Soil scarp retreat takes place through matrix removal by continuous throughflow extruding from the soil scarp as well as direct drop impact and overland flow. Sänger (1988a) observed needle ice growth at a similar soil scarp developed at the contact with the shale at Matroosberg. The extent of colluvial addition of coarse sandstone debris will however determine from site to site whether the soil texture allows for needle ice growth or not.

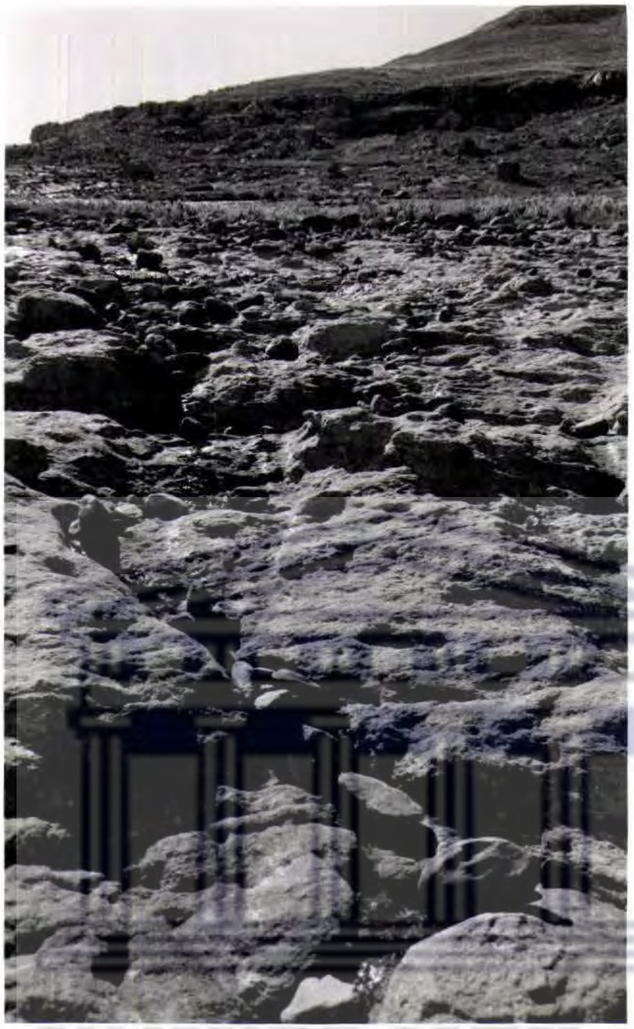


Figure 28. Erosion surface at the contact of the Cedarberg shale with underlying resistant sandstones north of Slanghoek Peak (1000m a.s.l.). Note clast deposition along linear joint patterns. Surface roughness and joint width and depth increases with distance away from the contact with the shale. October 1994.

CH 4. ENVIRONMENTAL CONTROLS ON SOIL FROST ACTIVITY

4.1. INTRODUCTION

In assessing the controls on the contemporary soil frost processes two groups of factors must be considered, namely climatic factors and material properties (Washburn, 1979; Williams and Smith, 1989; Krantz, 1990). Material properties relate particularly to the frost susceptibility of the sediment and are further considered under section 4.4. Main attention will be given to climatic factors controlling the effectiveness of formation of ground frost features, including intensity, frequency and duration of freeze/thaw cycles and soil moisture availability during these cycles (Washburn, 1979; Williams and Smith, 1989; Krantz, 1990).

Air temperature records at Victoria Peak (CSIR, unpubl. data) and Matroosberg (Sänger, 1988a) indicate the presence of limited diurnal frost for the summit regions of the western Cape mountains (Table 6). However, air temperatures are also known to bear no precise relationship to ground temperature (Chambers, 1966; Fahey, 1973; Williams and Smith, 1989). Further, data on frequency and depth of soil frost penetration as well as soil moisture conditions are not available for these mountains. A description of the climatic controls on soil frost potential therefore required the direct measurement of these parameters. To this effect two data logger stations were established in the summit region of the Waaihoek mountains. The general criteria for the location of the monitoring sites were outlined in section 1.1.3. Two sites were established at Waaihoek Peak and Mount Superior, respectively. The general characteristics of these two sites and their instrumentation are described here.

4.1.1. Waaihoek Peak

The Waaihoek Peak monitoring site is positioned on the southeast extension of a small summit plateau at 1900m elevation where it changes into a southeast trending ridge flanked by two small valleys (Fig. 29). The station stands on a 4-5° slope with an aspect of 140° and is underlain by steeply dipping quartzitic sandstone of the Peninsula Formation. A shallow sandy soil here reaches a thickness of 0.35m and supports a sparse vegetation cover of *Restio* (Cape reeds) species up to 0.2m high with a total cover of around 30% (Fig. 30).

Locally manufactured MCS data loggers were used for this project. The first data logger was installed on 7-1-1990. This logger stored data on tape and used batteries which supplied power for up to 8 weeks. The system proved highly unreliable, producing the broken data record for 1990 and 1991. Acquisition of an updated model, using data storage on IC modules and power supply from a solar panel, improved continuity in records since 29-11-1991. A gap in the 1992 record occurred due to the physical collapse of the solar panel as a result of high windspeeds, while in 1993 one memory module was damaged resulting in a loss of data. The system still proved sensitive to moisture under cold conditions and has resulted in a less than optimal record. Further technical details regarding the instrumentation is provided in Appendix 1.

The physical structure of the stations and the type and position of sensors maintained between 1990 and 1994 are described in Figure 31. Soil and air temperature sensors produce an output voltage proportional to temperature between -20°C and +70 °C with an accuracy of ±0.2°C. All sensors were calibrated according to manufacturers instructions (Mike Cotton Systems, Cape Town). Soil moisture was monitored by nylon resistance blocks consisting of an inner mesh electrode wrapped in nylon material, and an outer mesh electrode enclosing the sensor (Bouyoucos, 1949). This sensor is calibrated by setting the sensor value at 0 when it is air dry. A

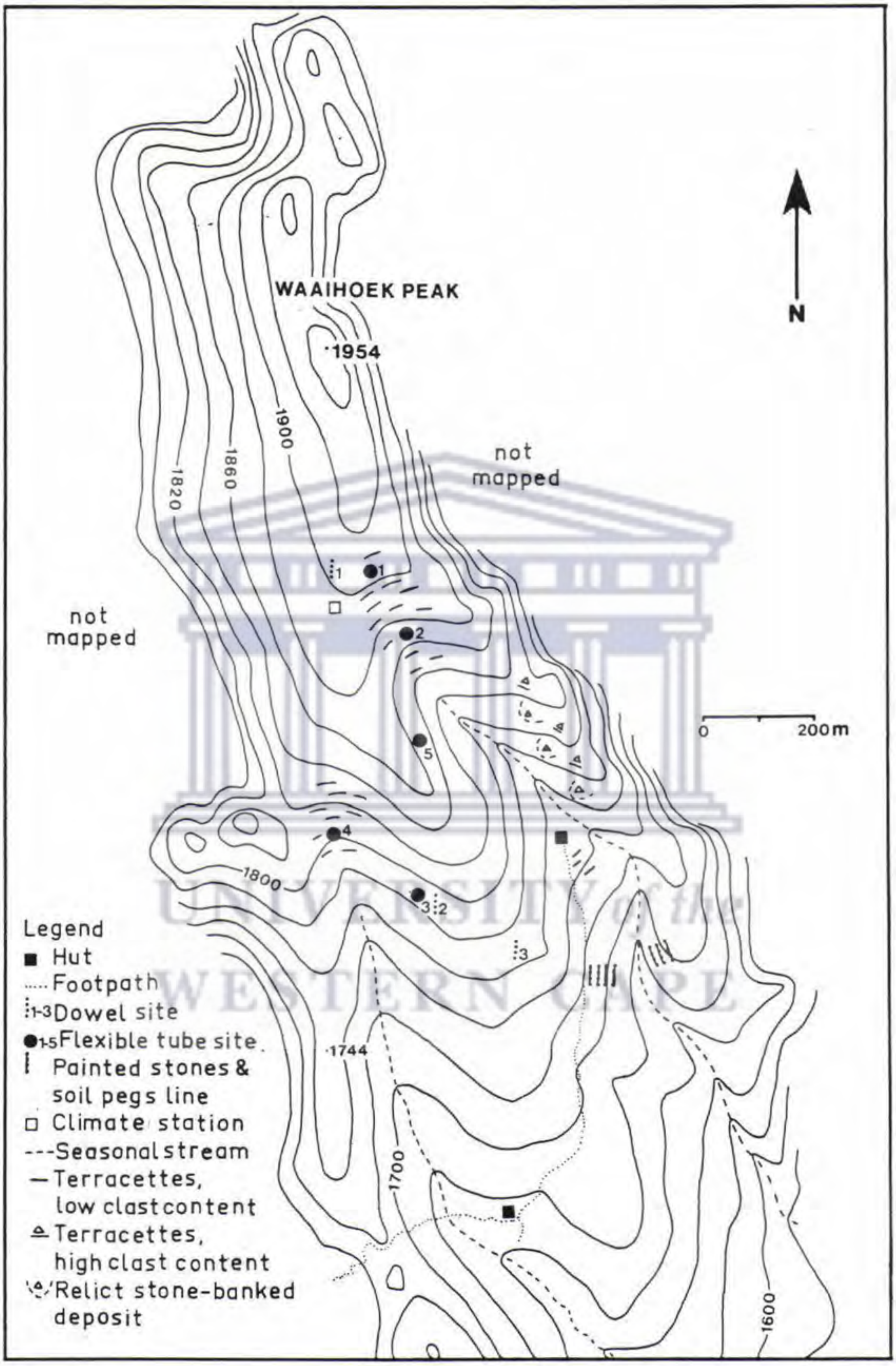


Figure 29. Topography, some geomorphological features and field monitoring sites of the Waaihoek Peak area. Altitudes in metres.

Figure 30. The climatic monitoring station at Waaihoek Peak (1900m a.s.l.).

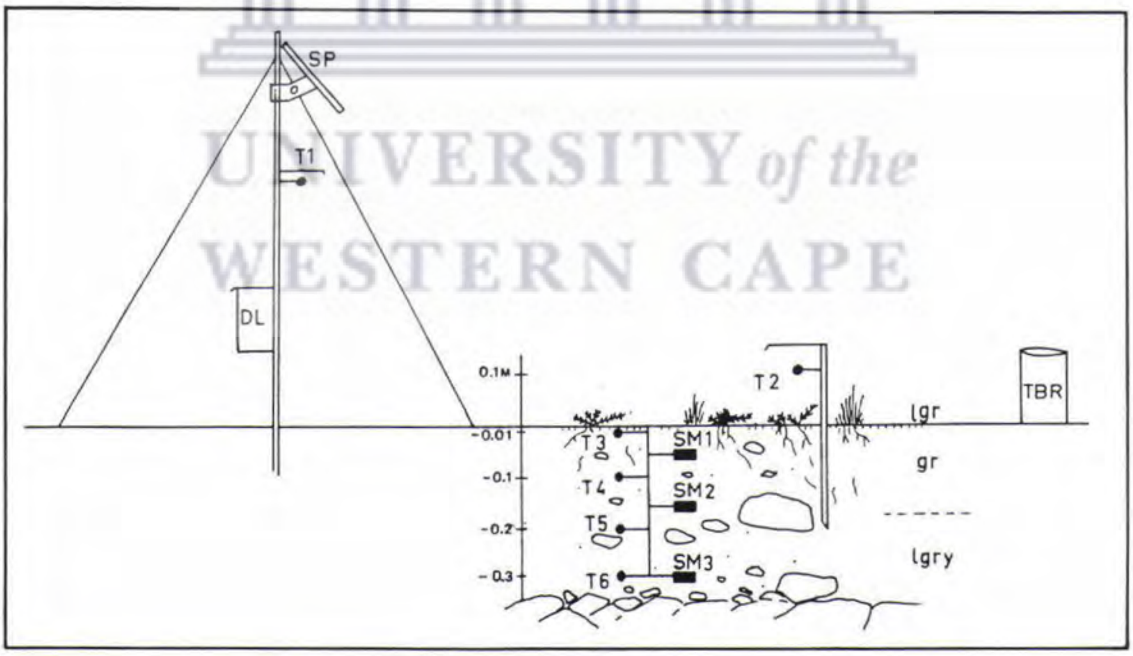


Figure 31. Site characteristics and position of sensors at the Waaihoek Peak climatic monitoring station. Legend: SP - solar panel; DL - data logger; T1-6 - temperature sensor; SM1-3 - soil moisture sensor; TBR - tipping bucket raingauge. Soil colour codings: lgr - lightgrey; gr- grey.

value of 100 is assigned to a sensor in fully saturated condition. The sensors thus record relative soil moisture levels on a linear scale between air dry soil and complete saturation. Tipping bucket raingauges with a bucket capacity of 0.2mm were used to record precipitation.

Initially both daily and hourly records were kept which necessitated frequent visits to replace the data storage tapes. As from 29-11-1992 only daily records were kept, including maximum and minimum temperature and 24hr precipitation totals. Average daily soil moisture levels were recorded only as the range between daily maximum and minium values proved to be minimal.

4.1.2. Mount Superior

Field observations established the presence of active soil frost features near Mount Superior during December 1991. A second data logger site was consequently established by 1-5-1993 to provide microclimatic data from a site with a different substrate and currently active soil-frost processes. The Mount Superior station is positioned 5km SSE of the Waaihoek Peak site on a flat summit plateau of Cedarberg shale at 1860m elevation (Fig. 32). The surface cover is comprised of fractured bedrock and bare shallow soil with tussocks of *Restio* spp. up to 0.5m high (Fig. 33). The instrumentation set-up is described in Figure 34 and was similar as used for the Waaihoek Peak site. The soil temperature and moisture sensors were placed in a bare sediment of 0.15m depth. Daily maximum and minimum temperature were recorded for each sensor as well as daily average relative soil moisture levels and daily precipitation totals.

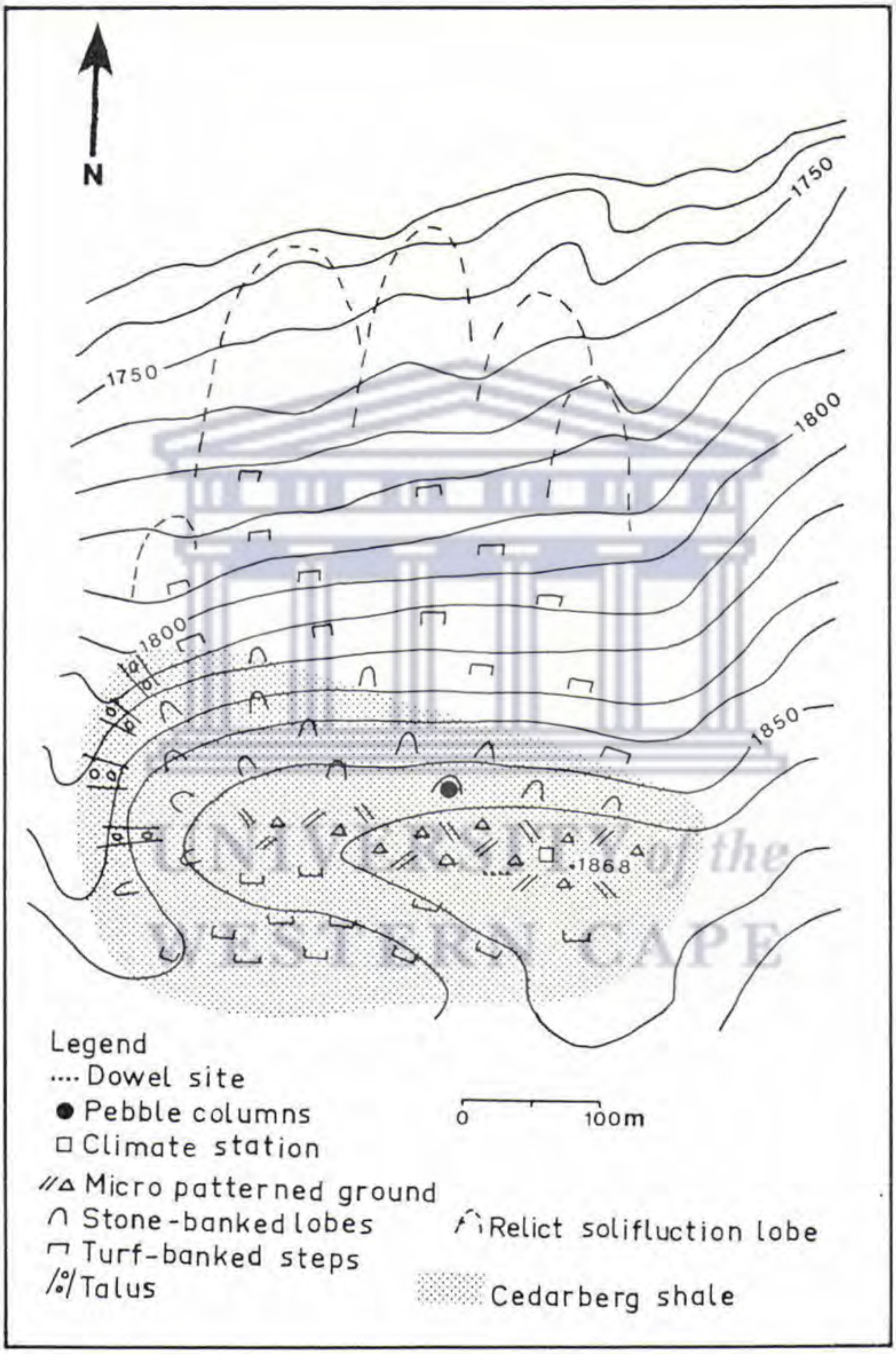


Figure 32. Topography, some geomorphological features and field monitoring sites at the Cedarberg Shale outcrop near Mt. Superior. Altitudes in metres.

Figure 33. The climatic monitoring station at Mount Superior (1850m a.s.l.).

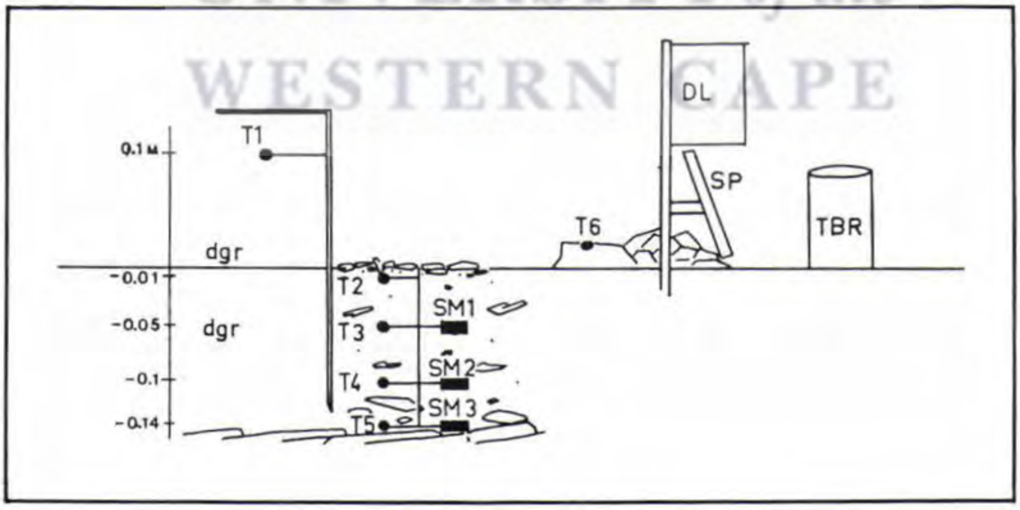


Figure 34. Site characteristics and position of sensors at the Mount Superior climatic monitoring station. Legend: see Figure 31. Soil colour coding: dgr - dark grey.

4.2. THE TEMPERATURE RECORD

4.2.1. General temperature characteristics

Average monthly and yearly temperatures present a first general characterisation of the thermal regimes at the two micro-climatic stations. Monthly averages were complete record of monthly values that could be calculated for the two stations is given in Appendix 2 and includes a record on missing days. Averaged monthly and yearly values for the period 1990-1994 at Waaihoek Peak and 1993-1994 at Mt. Superior, were calculated from this record (Table 14). The short period of record, particularly at Mt. Superior, implies that the values cannot be taken as long term averages and that single values may significantly influence the calculated mean. Although a great interannual variation exists between monthly values for some sensors, this method is the only way in which annual trends in the discontinuous record can be presented.

Yearly average temperatures at Waaihoek Peak increase somewhat from the +1.5m level (9.8°C) to the soil surface (11.5℃) in response to higher summer maximum temperatures at the soil surface, but remain at about 10.6°C in the upper 0.2m of the soil (Table14). Average temperatures at Mount Superior appear to be somewhat higher than at Waaihoek Peak throughout the year. Monthly average temperatures remain well above 0°C for all sensors at both sites (Table 14). An absolute lowest value of 1.2°C is recorded at -0.2m at the Waaihoek Peak site for July. At this level daily temperature ranges are minimal thus indicating that seasonal cooling is responsible for temperatures approaching freezing point.

Monthly minimum temperatures are plotted for both sites in Figure 35. At Waaihoek Peak these monthly values increase from the +0.1m level to -0.2m for most of the year but all approach 0°C in the coldest month. It is worth noting that minimum

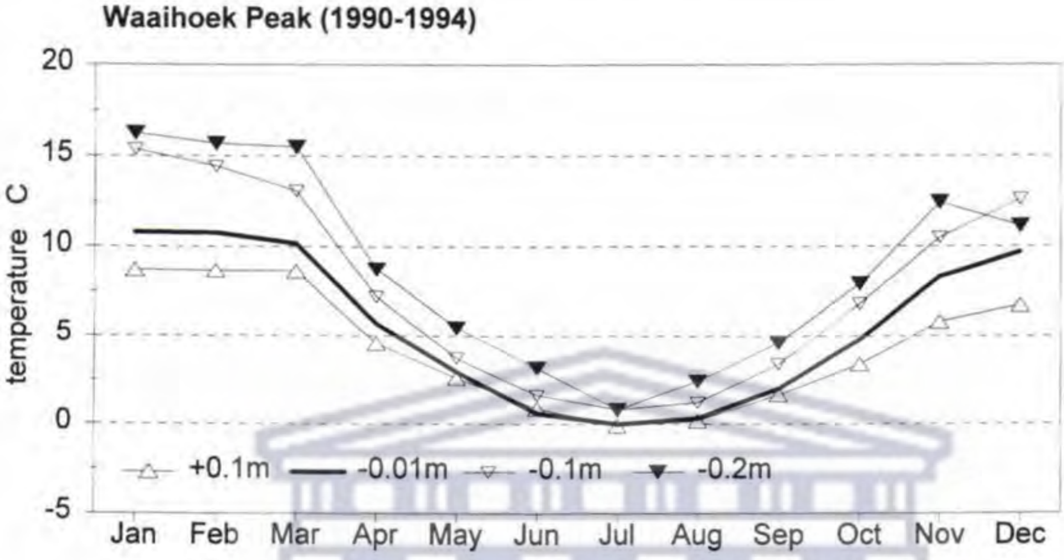
Average monthly temperatures at Waaihoek Peak (1900m a.s.l.)

Month	AVE+1.5	MAX+1.5	MIN+1.5	AVE+0.1	MAX+0.1	MIN+0.1	AVE-0.01	MAX-0.01	MIN-0.01	AVE-0.1	MAX-0.1	MIN-0.1	AVE-0.2	MAX-0.2	MIN-0.2	AVE-0.3	MAX-0.3	MIN-0.3
Jan	15.8	23.4	10.2	17.5	30.5	8.7	22.1	42.1	10.8	19.7	25.3	15.4	19.2	23.1	16.2	18.2	19.2	16.3
Feb	14.6	22.0	9.8	16.0	28.7	8.6	20.5	38.8	10.8	18.1	23.3	14.4	19.2	24.2	15.7	17.5	19.1	16.7
Mar	14.9	21.9	10.4	15.1	27.2	8.6	18.1	34.1	10.1	16.4	20.9	13.0	17.1	20.7	15.5	15.2	16.6	14.4
Apr	10.3	15.4	6.4	9.6	18.3	4.6	10.0	17.7	5.7	9.5	12.7	7.2	9.9	13.9	8.7	9.8	10.6	9.4
May	7.5	11.6	4.3	6.8	14.0	2.6	6.2	11.5	2.9	5.6	8.2	3.7	6.2	8.2	5.5	6.3	7.0	5.9
Jun	3.8	7.3	0.8	3.7	8.0	0.8	2.9	6.3	0.6	2.9	4.7	1.6	3.5	4.7	3.2	4.0	4.4	3.7
Jul	4.1	7.6	1.1	3.4	8.2	-0.1	2.1	5.0	-0.0	2.1	3.7	0.8	1.2	2.3	0.8			
Aug	4.6	8.8	0.7	4.7	11.9	0.2	3.4	8.4	0.3	2.7	4.5	1.2	3.1	4.8	2.4	2.5	3.1	2.0
Sep	6.5	11.8	2.0	7.5	16.9	1.6	6.2	13.6	2.0	5.7	9.2	3.4	5.7	8.4	4.6	5.3	6.4	4.5
Oct	9.4	15.7	4.7	10.9	23.4	3.4	11.9	24.4	4.8	10.5	15.3	6.8	10.0	14.2	7.9			
Nov	12.7	19.4	7.3	14.6	28.6	5.8	16.4	31.2	8.3	15.8	22.2	10.5	15.0	18.0	12.4			
Dec	13.6	21.0	8.2	15.6	29.9	6.7	18.1	31.7	9.7	17.1	22.5	12.6	16.6	21.9	11.1			
Year	9.8	15.5	5.5	10.4	20.5	4.3	11.5	22.1	5.5	10.5	14.4	7.6	10.6	13.7	8.7			

Average monthly temperatures at Mt. Superior (1860m a.s.l.)

Month	AVE+0.1	MAX+0.1	MIN+0.1	AVG-0.01	MAX-0.01	MIN-0.01	AVE-0.05	MAX-0.05	MIN-0.05	AVE-0.1	MAX-0.1	MIN-0.1	AVE-.14	MAX-0.14	MIN-0.14
Jan	18.4	33.7	8.6	25.9	58.4	8.5	21.5	32.5	14.2	20.3	25.3	16.9	19.8	23.1	17.8
Feb	18.1	32.7	9.1	22.5	52.5	7.7	20.9	32.1	14.1	19.9	24.5	16.9	19.3	22.0	17.7
Mar	15.7	28.7	8.4	17.9	43.6	7.0	17.4	26.9	12.1	17.7	22.0	15.0	17.5	20.2	16.0
Apr	12.2	21.9	6.3	13.7	32.5	5.5	12.6	18.7	9.2	13.1	16.0	11.4	13.2	15.1	12.1
May	7.7	15.9	3.3	7.4	20.2	1.9	6.5	10.9	4.0	6.9	9.2	5.5	7.1	8.6	6.1
Jun	4.6	10.2	1.2	4.2	11.7	0.6	3.0	5.5	1.6	3.3	4.7	2.4	3.4	4.4	2.8
Jul	3.5	8.8	-0.1	3.9	10.2	0.7	2.6	4.9	1.3	2.7	4.0	1.9	2.8	3.7	2.2
Aug	5.4	13.4	0.3	6.7	20.0	-0.2	4.2	8.5	1.7	4.4	6.7	2.9	4.0	5.5	2.9
Sep	8.2	17.2	2.0	8.7	22.4	1.7	6.8	12.6	3.3	7.9	10.9	5.9	6.7	8.6	5.3
Oct	12.2	24.6	4.0	15.8	38.9	3.5	12.3	21.0	6.6	14.0	18.6	10.7	11.1	14.1	9.1
Nov	13.1	25.9	4.2	17.9	42.3	3.6	15.1	24.3	8.9	18.5	23.4	15.1	14.1	17.1	12.1
Dec	15.0	29.0	6.4	26.2	55.3	10.2	16.9	26.0	10.5	20.2	25.3	16.5	15.9	19.1	13.6
Year	11.2	21.8	4.5	14.2	34.0	9.2	11.6	18.7	7.3	12.4	15.9	10.1	11.3	13.5	9.8

Table 14. Average monthly and yearly temperatures at Waaihoek Peak and Mt. Superior.



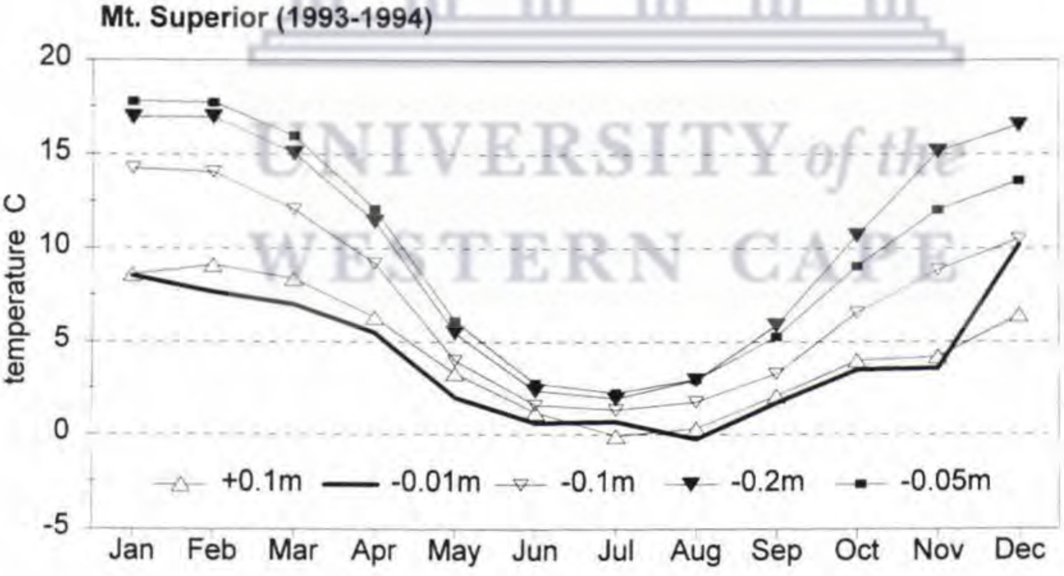


Figure 35. Average monthly minimum temperatures at Waaihoek Peak and Mt. Superior.

temperature values for July at +0.1m, -0.01m and -0.1m all level off at 0°C. At Mt. Superior subsurface temperatures show a similar increase with depth in the period from summer to winter but during spring temperatures at -0.1m exceed those at -0.14m. Further, soil minima in winter also appear to be slightly higher than at Waaihoek Peak. The monthly minima at the surface of the shale soil in July (generally the coldest month) are slightly higher than expected in both 1993 and 1994, suggesting this slight jump to be more than 'just an exceptional event'.

The average monthly maximum recorded for December 1993 at the Waaihoek Peak station (33.2°C) is significantly lower than the 63.7° C recorded at the bare and darker soil surface at Mt. Superior. Diurnal temperature fluctuations in soils generally decrease with depth (e.g. Oke, 1987) and is also observed in this study (Table 14). Highest monthly temperature ranges are encountered at the soil surface but are much higher at the Mt. Superior site due to the much higher maxima recorded in the shale loam (Table 14). It is interesting to note, however, that temperature ranges decrease much more rapidly with depth in the shale soil, compared with the sandy soil at Waaihoek Peak. These two observations point at sensible heat concentration at the shale soil surface suggesting a lower thermal conductivity in this loam relative to the sandy soil. This is in agreement with thermal conductivity values listed for dry loamy and sandy soils in Clark (1966) and Oke (1987). Thermal conductivity for both soils will, however, significantly increase with an increase in soil moisture content (Clark, 1966; Oke, 1987). Less cloud cover, lower precipitation, as well as the significantly thinner soil all contribute to lower soil moisture values at the Mt. Superior site, and are all factors that can be expected to contribute to the high soil surface temperature range and its rapid decrease with depth at this site.

Vertical temperature profiles, constructed from the averaged monthly and yearly values, illustrate the commonly observed trend of highest temperature ranges close to or at the soil surface (Fig. 36)(c.f. Oke, 1987). At Mt. Superior the level of predominant heat exchange corresponds with the soil surface. An important deviation is found at the Waaihoek Peak site. In summer greatest heating is experienced at the soil surface, but nocturnal heat exchange throughout the year is greatest at 0.1m above the soil surface. This radiation buffering is commonly found to be a result of vegetation or snow cover (Oke, 1987). The occurrence of this effect in the summer temperature profile suggests that the radiation shading is a function of the sparse vegetation cover at the monitoring site. Both vegetation and snowcover may moderate soil surface maxima and minima in winter. The occurrence of the greatest heat exchange somewhat above and not at the soil surface may significantly reduce the soil frost frequency and intensity experienced at the Waaihoek site.

4.2.2. Frequency and intensity of freeze/thaw cycles

The daily temperature record for the two logger stations is graphically presented in Appendix 3. Monthly and annual totals of frost frequencies were calculated from this record for each year, the results of which are tabled in Appendix 4. Averaged monthly and annual totals are derived from this record (Table 15). It must be noted that the averaged values are influenced by the variable length of record per sensor and month. As in the case of the averaged monthly temperatures this is the only manner in which annual trends can be presented from the discontinuous record at Waaihoek Peak.

Waaihoek Peak

The frequency of freeze/thaw cycles at Waaihoek Peak, as measured by diurnal values below 0°C, is presented in Table 15. Occasional daily average values remain

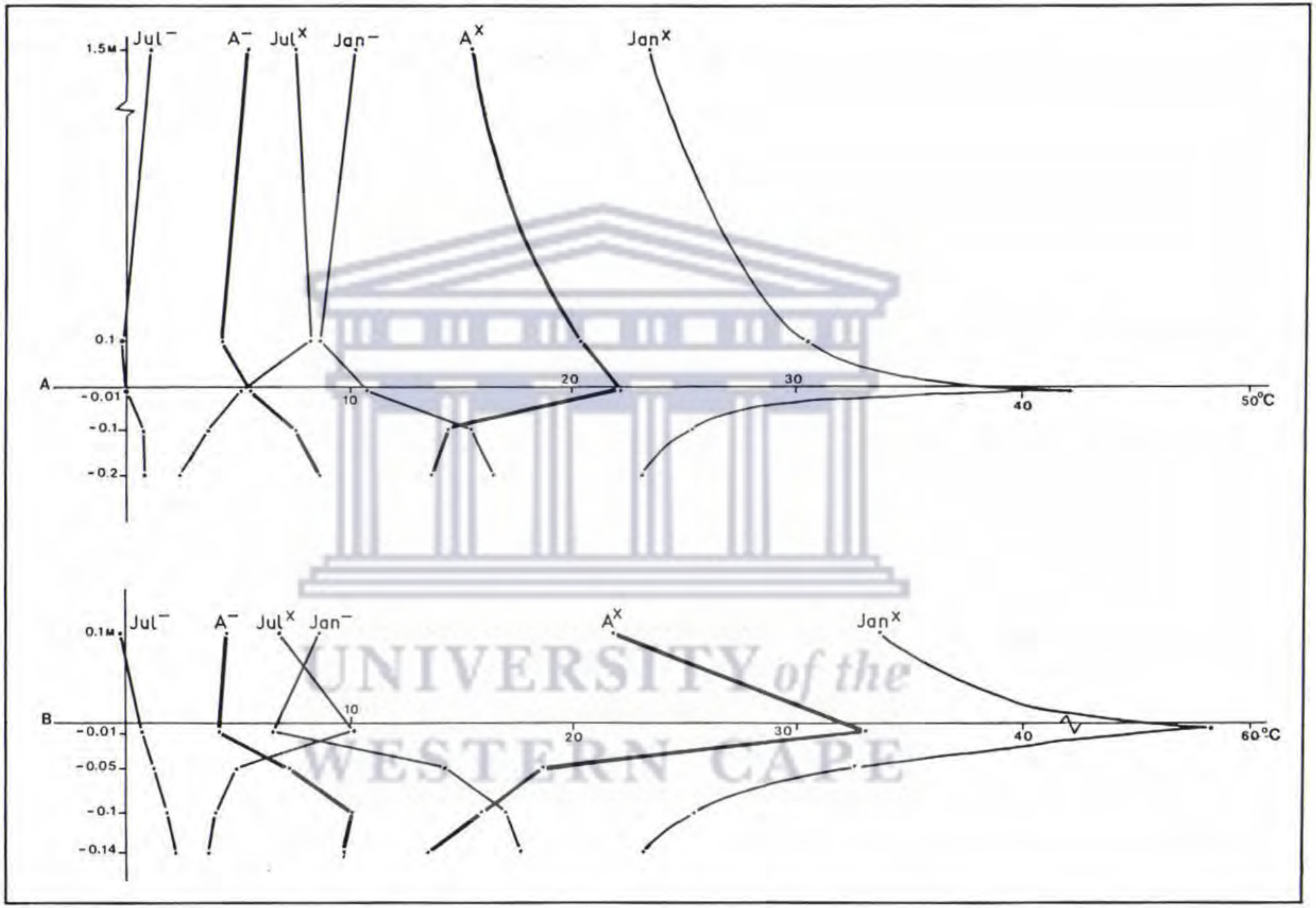


Figure 36. Vertical temperature profiles for a) Waaihoek Peak and b) Mt. Superior. Key to symbols: Jul - July; Jan - January; A - Annual; $^-$ - minimum temperature; ^{x} - Maximum temperature.

Waaihoek Peak (1990-1994)

	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0
APR	0	0	2.8	0	0	4.4	0	0	0	0	0	0	0	0	0.7
MAY	1.3	0	5.8	1.8	0	8.9	0	0	5	0	0	0	0	0	0
JUN	5.3	1.4	15.4	5	1.3	12.3	0.5	0	15.6	0	0	8.3	0	0	0
JUL	4.1	0.8	10.9	4.6	0	17.6	1.5	0	24.6	0	0	12.6	0	0	0
AUG	5.4	1.5	12.6	4.8	0.8	15.4	1.3	0	18.1	0	0	10.3	0	0	0
SEP	2.3	0.5	7.9	3	0	9.3	0.8	0	9.8	0	0	3	0	0	0.5
OCT	0.3	0	4.7	0	0	6	0	0	1	0	0	1.3	0	0	0
NOV	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
DEC	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
YEAR	18.7	4.2	62.1	19.2	2.1	76.1	4.1	0	74.1	0	0	35.5	0	0	1.2

Mt. Superior (1993 - 1994)

	+0.1m			-0.01m			-0.05m			-0.1m			-0.14m		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0
MAY	1.5	0	6.5	0	0	9	0	0	0	0	0	0	0	0	0
JUN	7	2	14	3	1.5	10.5	0	0	0	0	0	0	0	0	0
JUL	7.5	2	18	0	0	3.5	0	0	0	0	0	0	0	0	0
AUG	3	0	15.5	1	0	16	0	0	0	0	0	0	0	0	0
SEP	1.5	0	10.5	0	0	8	0	0	0	0	0	0	0	0	0
OCT	0	0	4	0	0	4.5	0	0	0	0	0	0	0	0	0
NOV	0	0	4.5	0.5	0	6	0	0	0	0	0	0	0	0	0
DEC	0	0	1	0	0	0.5	0	0	0	0	0	0	0	0	0
YEAR	20.5	4	77	4.5	1.5	61	0	0	0	0	0	0	0	0	0

Table 15. Average number of days with temperatures below 0°C at Waaihoek Peak (1990-1994) and Mt. Superior (1993-1994).

below 0°C in the air, but this does not mean that continuous freezing occurred on these days. Only diurnal freeze/thaw cycles occur in the soil. Frost penetration appears restricted to the upper 0.1m of the soil, in agreement with studies in other environments of diurnal frost action (Gradwell, 1954; Fahey, 1973; Pérez, 1984). A high interannual variability in number of frost days is apparent from the five year record in winter, ranging between 0 and 27, 14 and 31, and 9 and 19 for June, July and August respectively (App. 4). The duration of the frost season varies at different monitoring levels. Air temperatures reach below 0°C from April to October, with slightly higher frequencies in each of these months at the +0.1m level, relative to those at +1.5m. The period with freeze/thaw cycles at the soil surface (-0.01m) runs from May to September. The frost season shortens in length and decreases in intensity with depth below the surface and is insignificant at 0.2m depth.

Frost intensity, as measured by monthly frequency totals of minimum temperatures reached, is tabled in App. 4 and summarised in Table 16. The average yearly totals for the 1990-1994 period were calculated from the averages of the individual months and are thus influenced by the variable length of record (see App.2). From Table 16 it is evident that the lowest temperatures, down to between -6 and -8°C, are recorded in the air, but are limited to values between 0 and -2°C at, and below, the soil surface. The limited frost intensity at the soil surface relative to that obtained in the air is important to note.

Mount Superior

Diurnal freeze/thaw cycles were recorded at Mt. Superior from April to November, both at 10cm above the ground and at the soil surface (Table 15). No frost cycles were recorded beneath the soil surface. The total number of frost days in 1993 and 1994 at +0.1m compare well with those at Waaihoek Peak (App. 4). However, the monthly frost frequency records for the soil surface are not easily compared. A high interannual variability in number of freeze/thaw cycles for individual months is also noted for the Mt. Superior site.

Although depth of frost penetration at Mt. Superior appears to be less, frost intensity at the soil surface is higher than that recorded at Waaihoek Peak. Temperatures between -2°C and -6°C make up an important percentage of the total number of frost days (Table 16, App. 4).

Based on the temperature record presented the character of the diurnal

Waaihoek Peak (1900m a.s.l.)

	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
YEAR	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
1990	(n=170)														
< -8				0	0	0	0	0	0	0	0	0	0	0	0
-8 - -6				0	0	0	0	0	0	0	0	0	0	0	0
-6 - -4				0	0	2	0	0	0	0	0	0	0	0	0
-4 - -2				0	0	9	0	0	0	0	0	0	0	0	0
-2 - 0				9	1	20	0	0	15	0	0	0	0	0	0
TOTAL:				9	1	31	0	0	15	0	0	0	0	0	0
1991	(n=157)														
< -8	0	0	0				0	0	0						
-8 - -6	0	0	1				0	0	0						
-6 - -4	1	0	12				0	0	3						
-4 - -2	3	1	20				0	0	12						
-2 - 0	17	2	28				15	0	80						
TOTAL:	21	3	61				15	0	95						
1992	(n=301)														
< -8	0	0	0	0	0	0	0	0	0	0	0	0			
-8 - -6	0	0	6	0	0	2	0	0	0	0	0	0			
-6 - -4	2	0	12	0	0	7	0	0	0	0	0	0			
-4 - -2	9	1	17	4	0	26	0	0	0	0	0	0			
-2 - 0	10	7	33	26	6	54	0	0	79	0	0	2			
TOTAL:	21	8	68	30	6	89	0	0	79	0	0	2			
1993	(n=323)														
< -8	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
-8 - -6	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0
-6 - -4	0	0	5	0	0	6	0	0	0	0	0	0	0	0	0
-4 - -2	2	0	8	1	0	11	0	0	0	0	0	0	0	0	0
-2 - 0	5	1	22	5	0	40	0	0	36	0	0	19	0	0	2
TOTAL:	7	1	37	6	0	59	0	0	36	0	0	19	0	0	2
1994	(n=344)														
< -8	0	0	0	0	0	0	0	0	0	0	0		0	0	0
-8 - -6	0	0	3	0	0	0	0	0	0	0	0		0	0	0
-6 - -4	1	0	6	0	0	8	0	0	0	0	0		0	0	0
-4 - -2	4	1	23	0	0	30	0	0	0	0	0		0	0	0
-2 - 0	14	2	27	19	0	52	1	0	77	0	0		0	0	1
TOTAL:	19	3	59	19	0	90	1	0	77	0	0		0	0	1

Mt. Superior (1860m a.s.l.)

1993	+0.1			-0.01			-0.05			-0.1			-0.14		
YEAR	AVG	MAX	MIN	AVG	MAX	MIN	AVG	MAX	MIN	AVG	MAX	MIN	AVG	MAX	MIN
-8	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
-6	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0
-4	0	0	3	0	0	7	0	0	0	0	0	0	0	0	0
-2	1	0	16	0	0	8	0	0	0	0	0	0	0	0	0
0	13	3	37	9	4	66	0	0	0	0	0	0	0	0	0
TOTAL:	14	3	60	9	4	82	0	0	0	0	0	0	0	0	0
-8	0	0	0		0	0	0	0	0	0	0	0	0	0	0
-6	0	0	0		0	1	0	0	0	0	0	0	0	0	0
-4	0	0	6		0	10	0	0	0	0	0	0	0	0	0
-2	0	0	30		0	13	0	0	0	0	0	0	0	0	0
0	27	5	55		0	27	0	0	0	0	0	0	0	0	0
TOTAL:	27	5	91		0	51	0	0	0	0	0	0	0	0	0

Table 16. Annual frost frequency and intensity at Waaihoek Peak and Mt. Superior.

freeze/thaw cycles at the two monitoring sites may be summarised as follows (Table 17). At Waaihoek Peak soil frost occurs down to -0.1m but temperatures do not reach below -2°C. On the other hand, freeze/thaw cycles occur only at the soil surface at Mount Superior but temperatures reach down to -6°C on a regular basis. The temperature record now allows for the assessment of this environmental control on potential soil frost activity.

Table 17. Summary of freeze/thaw cycle characteristics at the soil surface for Waaihoek Peak and Mt. Superior.

Parameter	Recording level	Waaihoek Pk	Mt. Superior
Duration	+0.1m	April - October	April - November
	-0.01m	May - September	April - November
	-0.1m	June - August	no frost
	-0.2m	no frost	no frost
Annual frequency (min. temp. <0°C) (1994 data only)	+0.1m	90	91
	-0.01m	77	51
	-0.1m	7	0
	-0.2m	1	0
Maximum intensity (1994 data only)	+0.1m	-6°C	-4°C
	-0.01m	-2°C	-6°C
	-0.1m	no data	no frost
	-0.2m	-2°C	no frost

4.2.3. Implications for soil frost activity

It is a well established fact that the 0°C boundary does not necessarily correspond with the freezing point of soil water (e.g. French, 1988). As frost intensity at the monitoring sites is limited, particularly at Waaihoek Peak, any depression of the freezing may greatly affect local soil frost potential. Consideration should be given to the depression of the freezing point in soils by dissolved salts, adsorption and capillary action as well as observations on temperatures at which ice segregation may occur (Williams and Smith, 1989).

The dissolution of salts in soil water may result in soil water freezing at temperatures somewhat below 0°C. Natural salt concentrations in soil water are however considered so weak that this normally lowers the freezing point only by 0.1°C (Williams and Smith, 1989). More importantly, Williams and Smith (1989) indicate that soil moisture adsorption and capillary suction in soil pores may result in considerable amounts of unfrozen water in soils at temperatures below 0°C. Although in sand 100% of the soil moisture may freeze at a temperature of -0.2°C, in clay the unfrozen water content may still make up over 10% of the dry weight of the soil at -2°C (Fig.37). Implications of these considerations are that a difference in the freezing point of water can be expected between the two sites. Although it was not possible to establish the freezing point for the two local soils even a depression in the freezing point of only 0.1°C does reduce the number of effective frost days by about 10% at both sites (Table 18).

Environments subjected to diurnal frost cycles only are characterised by ice segregation in the form of ice needles at the soil surface (e.g. Gradwell, 1954; Mackay and Mathews, 1974; Pérez, 1984). Unlike for ice segregation at depth in seasonal frost and permafrost regions, mechanisms and conditions required for needle ice growth are relatively well understood (Soons and Greenland, 1970; Outcalt, 1971; Lawler, 1988). Outcalt (1971) observed that temperatures of at least -2°C are required to start ice nucleation, a value which appears to be considered generally applicable (Lawler, 1988). Once the process of needle-ice growth has started temperatures below 0°C are sufficient to maintain growth until limited by moisture supply or an imbalance between the rate of heat loss from the freezing plane and the rate of heat of fusion released by

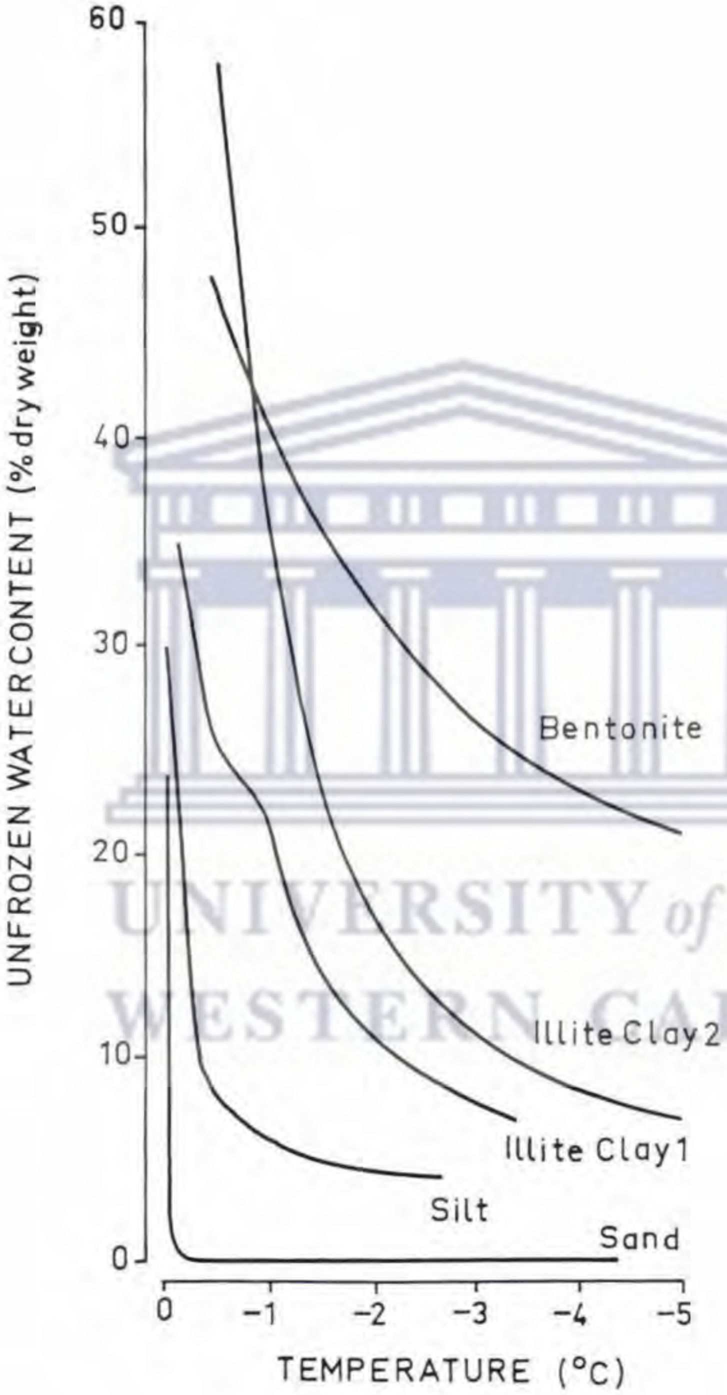


Figure 37. The unfrozen water content in different textured soils at temperatures below 0°C (from Williams and Smith, 1989).

freezing soil water (Outcalt, 1971). As no laboratory facilities were available to establish temperature limits for needle-ice formation in local soils, the value of -2°C was taken as the minimum temperature required for effective freeze/thaw cycles.

The soil temperature record from Waaihoek Peak registered 15 days with temperatures below -2°C during 1991 out of the four winter records (Fig. 38, App. 4.). Potential for effective freeze/thaw cycles thus appears to be very limited for the Waaihoek Peak site even for needle-ice growth. On the other hand, nocturnal temperatures at Mt. Superior reached between -2°C and -6°C on 16 days during 1993

Table 18. Frequency of daily minimum temperatures below 0°C at Waaihoek Peak and Mt. Superior.

	Waaihoek Peak						**Mt. Superior**		
TEMP. (°C)	1990	1991	1992	1993	1994	% of sum total	1993	1994	% of sum total
< -8.0	0	0	0	0	0	0	0	0	0
-8.0≤ t<-6.0	0	0	0	0	0	0	1	1	2
-6.0≤ t<-4.0	0	3	0	0	0	1	7	10	13
-4.0≤ t<-2.0	0	12	0	0	0	4	8	13	16
-2.0≤ t<-1.9	0	8	0	0	0	3	3	2	4
-1.9≤ t<-1.8	0	3	0	0	0	1	2	2	3
-1.8≤ t<-1.7	0	5	0	0	0	2	2	2	3
-1.7≤ t<-1.6	0	1	0	0	0	0	1	0	1
-1.6≤ t<-1.5	0	1	0	0	1	1	1	1	2
-1.5≤ t<-1.4	0	2	0	0	0	1	1	0	1
-1.4≤ t<-1.3	0	1	0	0	6	2	0	0	0
-1.3≤ t<-1.2	0	3	0	0	11	5	1	2	2
-1.2≤ t<-1.1	0	4	0	0	1	2	1	2	2
-1.1≤ t<-1.0	0	3	1	0	7	4	0	1	1
-1.0≤ t<-0.9	0	1	4	0	4	3	4	0	3
-0.9≤ t<-0.8	0	2	7	1	4	5	2	3	4
-0.8≤ t<-0.7	0	5	8	6	5	8	2	2	3
-0.7≤ t<-0.6	4	3	11	0	8	9	4	1	4
-0.6≤ t<-0.5	1	3	6	3	7	7	3	2	4
-0.5≤ t<-0.4	2	4	9	8	9	10	2	1	2
-0.4≤ t<-0.3	2	8	13	5	7	11	4	4	6
-0.3≤ t<-0.2	2	9	7	2	0	7	11	0	8
-0.2≤ t<-0.1	3	7	6	3	4	8	9	1	8
-0.1≤ t< 0.0	1	7	10	8	3	10	13	1	11

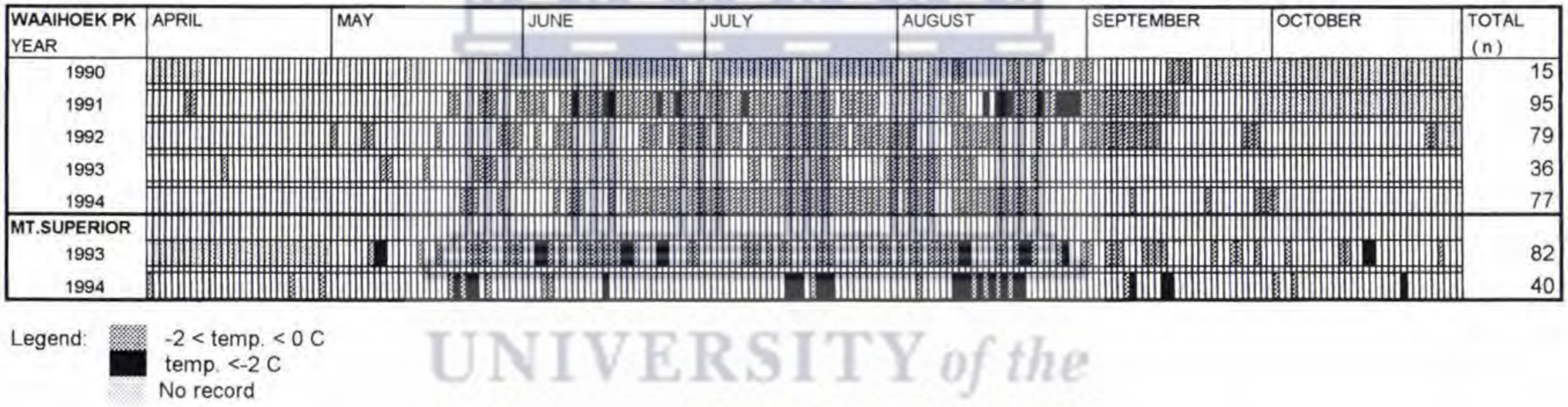


Figure 38. Occurrence and intensity of diurnal freeze/thaw cycles at the soil surface at Waaihoek Peak (1990 - 1994) and Mt. Superior (1993 - 1994).

and 24 days in 1994 (Table 16). This suggests that the potential exists for a limited number of days with needle-ice growth at this site, annually.

4.3. PRECIPITATION AND SOIL MOISTURE

4.3.1. Precipitation

Daily precipitation totals were monitored at Waaihoek Peak from 1991 to 1994 and at Mt. Superior from 1993 to 1994 (App. 5). The record is based on unshielded precipitation gauges standing 0.4m above the ground surface. The position of the gauges and the difficulty of snowfall estimation with the use of tipping bucket raingauges may influence the outcome of the record. Annual totals reach over 2000mm at Waaihoek Peak, 77% of which fell during the freeze/thaw season from May to September in 1994 (Table 19). Annual precipitation at Mt. Superior amounts to 841mm for 1994 but the seasonal distribution is similar to Waaihoek Peak with 72% of the annual total falling in the same period. The monthly number of precipitation days at both sites is very similar (Table 20). The difference in precipitation received between the two

MONTH	**Waaihoek Peak**				**Mt. Superior**	
	1991	1992	1993	1994	1993	1994
January	-	0.8	9.6	65.0	-	8.4
February	-	198.4	78.8	7.6	-	8.2
March	-	12.4	16.0	34.6	-	21.6
April	69.0	361.8	337.2	225.8	-	78.0
May	359.0	154.2	341.4	104.0	-	64.2
June	628.2	800.2	-	875.8	-	236.4
July	421.2	452.0	883.0	326.2	-	120.8
August	204.8	121.4	83.4	76.2	-	44.2
September	252.6	198.8	49.6	181.2	4.8	144.2
October	-	392.4	5.6	91.2	4.4	56.2
November	-	-	55.8	3.2	69.2	11.6
December	14.0	-	100.6	38.0	78.2	47.4
Year total	-	2692.4	1961.0	2028.8	-	841.2

Table 19. Monthly and annual precipitation totals for Waaihoek Peak and Mt. Superior. Hyphen indicates missing data.

MONTH	Waaihoek Peak				Mt. Superior	
	1991	1992	1993	1994	1993	1994
January	-	1	5	6	-	4
February	-	5	7	7	-	8
March	-	7	6	9	-	9
April	8	13	15	12	-	12
May	9	13	19	11	-	10
June	21	18	-	15	-	15
July	17	16	20	19	-	14
August	12	16	14	13	-	7
September	9	14	8	15	-	13
October	-	17	5	7	5	7
November	-	-	6	3	8	5
December	3	-	8	6	8	8
Year total	80	120	113	123	-	112

Table 20. Monthly and annual number of precipitation days for Waaihoek Peak and Mt. Superior.

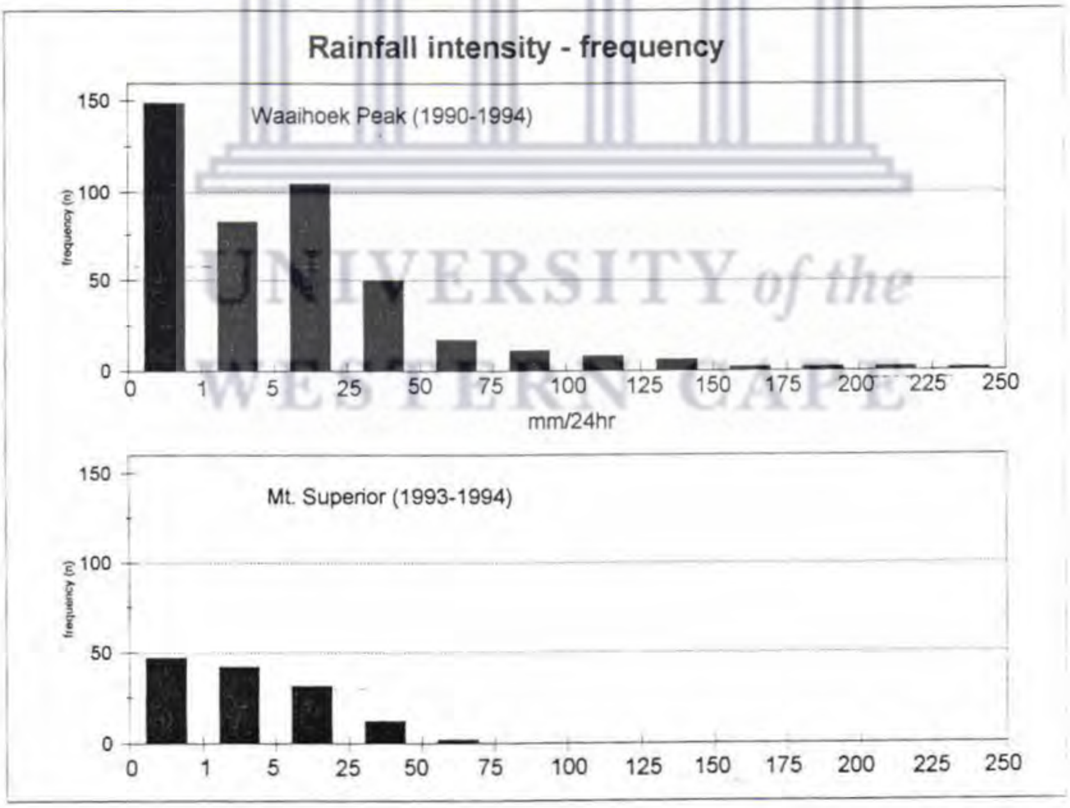


Figure 39. Precipitation intensity-frequency distributions for Waaihoek Peak and Mt. Superior.

sites can, however, be attributed to its greater intensity at Waaihoek Peak, with totals over 150mm/24hr occurring here in every year of observation (Fig. 39, App. 5).

Snow

No direct observations on snow cover could be made over the winter season, except during occasional visits for data logger maintenance. Two sources of data do, however, allow for estimation of snowfall frequencies and duration of snow cover. First, logbook entries at Hoare Hut were checked for the period 1972-1994 for reports on snowfall and the presence of a snow cover in the Waaihoek Peak area. These present direct, but subjective observations and impressions pertaining to snow conditions on the wider Waaihoek range. As the hut is only occupied during most, but not nearly all,. weekends and holiday periods an underestimation of the number of snowdays (days with snowfall and/or snow cover) can be expected from this record.

A second method to estimate the duration of snow cover at both Waaihoek Peak and Mt. Superior is based on interpretation of the impact of snow cover on soil surface temperatures. Field investigations on freeze/thaw weathering at snowpatch sites show that the insulating effect of seasonal snow greatly reduces diurnal temperature ranges beneath a snow cover (Thorn, 1979; Hall, 1980). Both Thorn (1979) and Hall (1980) observed diurnal temperatures to range between -1.0 and +1.0°C at rock surfaces beneath a seasonal snow cover until meltout.

The soil surface temperature records obtained from the two logger sites in this study also reveal distinct periods with much reduced diurnal amplitudes and values consistently immediately above or below 0°C (App. 3). However, due to ineffective insulation by thin snow and relatively high air and ground temperatures diurnal temperature variations associated with the presence of snow were found to be higher than in the studies of Thorn (1979) and Hall (1980). Consequently, dates with diurnal temperature ranges below 4°C were plotted as a second estimate for snow cover duration. Results were further checked against absolute temperature recorded, which were found to be comparable with those found by Thorn (1979) and Hall (1980). This method provides an indirect estimation at a single, very localised, observation site. It is also limited by the fact that small diurnal temperature ranges may be caused by heavily overcast days with rainfall, and may thus provide an over-estimate. Further, as both sites are positioned on level ground at a summit ridge snow cover thickness may be reduced here by snowdrift. The latter has been observed to cause highly variable snow thickness in the Waaihoek Peak area. Estimations of snow cover duration remain difficult when the snow distribution is highly variable in the terrain.

Results from the logbook entries at Waaihoek Peak present a long term record indicating high interannual variation on snow cover duration (Fig. 40). On average 31.4 days/yr with snow cover are reported for this site. Estimates from the temperature record shows some, but not particularly good, agreement with the logbook records (Fig. 41). Keeping in mind the limitations discussed above the combined record provides the most accurate available record.

Estimation of snow cover duration based on the temperature record at Mt. Superior shows the presence of snow in essentially the same periods as at Waaihoek Peak, although there is poor correspondence in daily patterns (Fig. 41). The total number of snow cover days obtained from the temperature records are very similar for the two stations. From the records it appears that snow is a common feature from mid-May to the end of September with occasional falls in April and October. First snow tends to melt within one or two days but may remain for up to three weeks in the period from July to September.

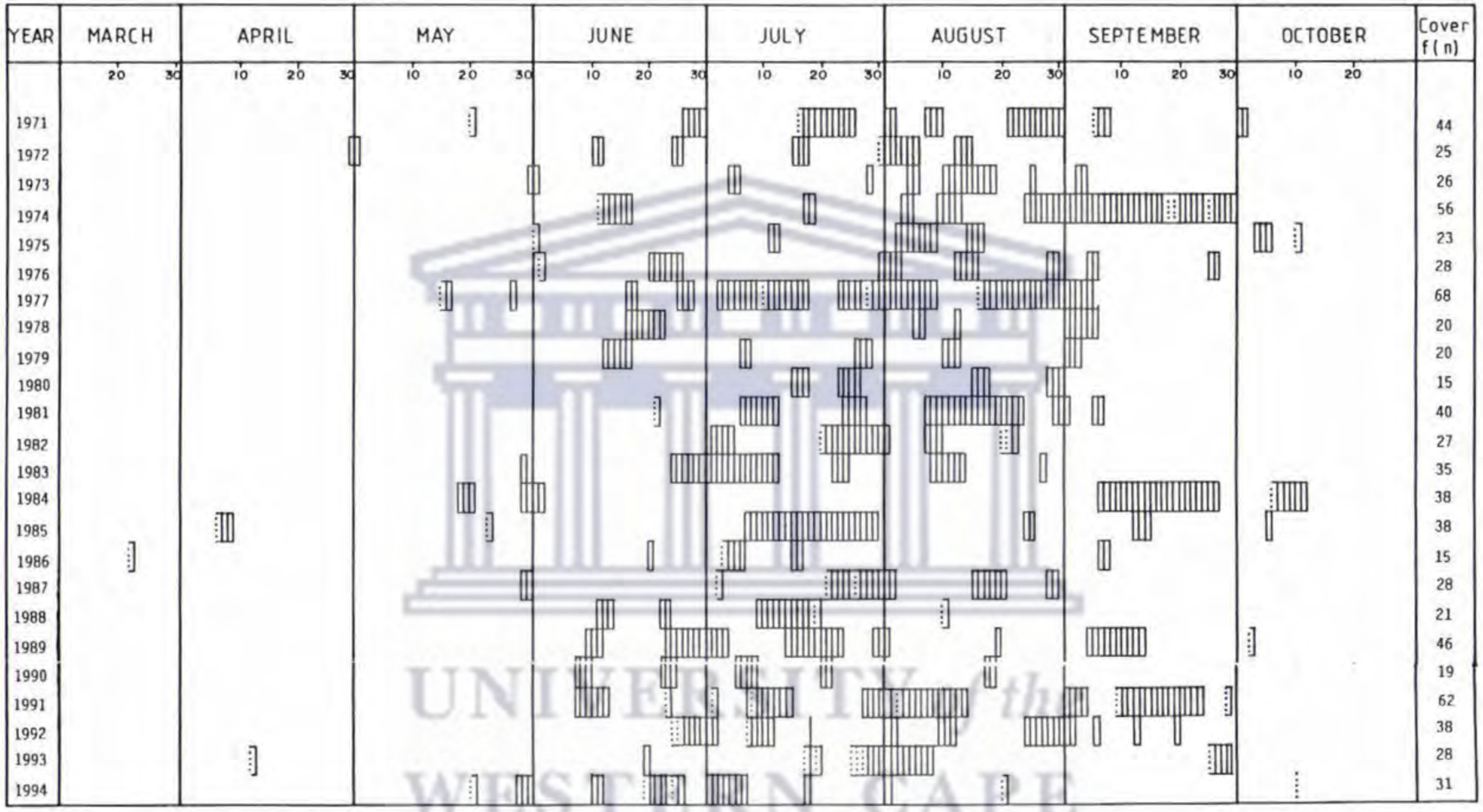
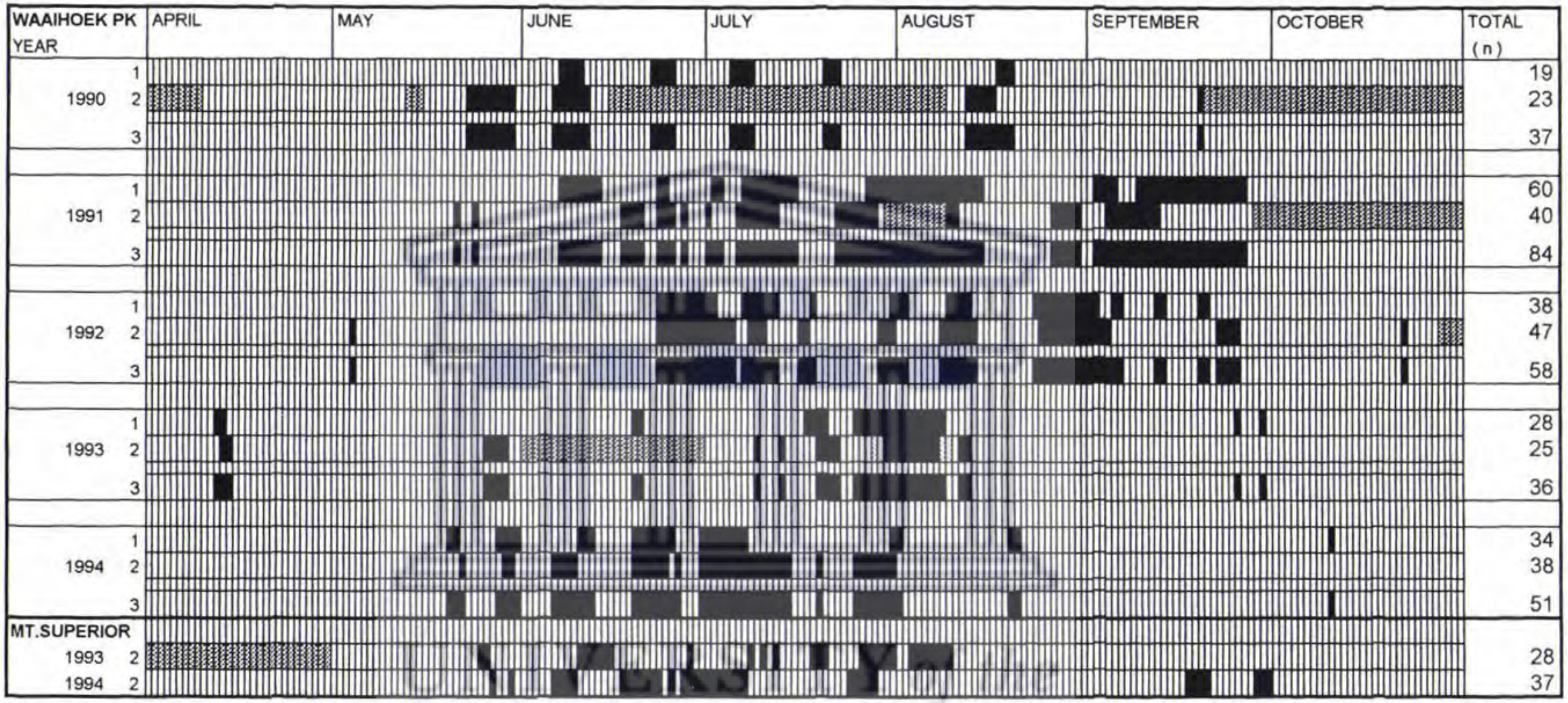


Figure 40. Snowfall and snow cover duration estimation from logbook entries at Hoare Hut, Waaihoek Peak (1800m a.s.l.).



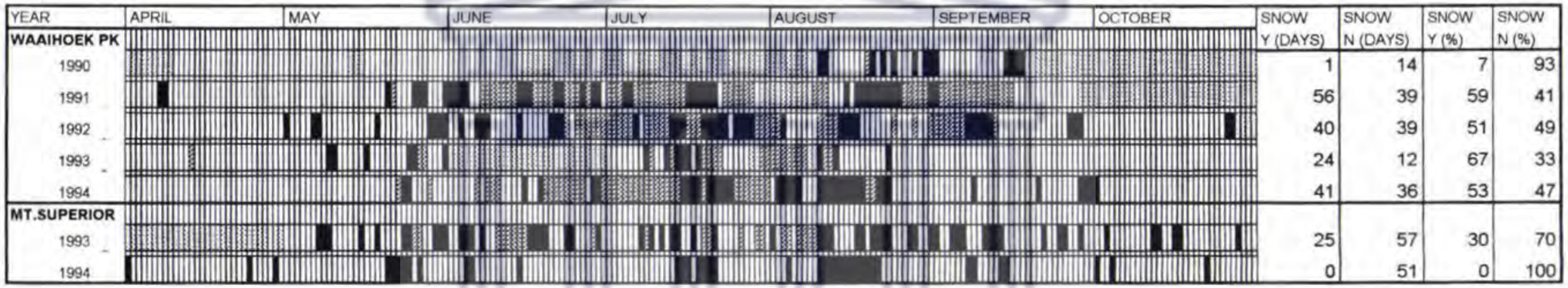
Source:
1 Logbook record, Hoare Hut
2 Temperature record, diurnal range <4 C
3 Combined record from 1 and 2
▨ No record

Figure 41. Snow cover duration estimations at Waaihoek Peak and Mt. Superior, based on 1) logbook entries at Hoare Hut, 2) soil surface temperature ranges, and 3) the combined record from 1) and 2).

The relation between snow cover and freeze/thaw at the soil surface is illustrated by means of Fig. 42. Periods of several days, up to three weeks, characterise the distribution of frost days at Waaihoek Peak, while at Mt. Superior frost days at the soil surface are scattered throughout the season. Based on the combined record of days with snow cover for 1991-1994, it is estimated that 57% of frost days at Waaihoek Peak are associated with snow (Fig. 42). During these days diurnal temperatures range between +4 and -1°C. For short periods this temperature effect is also present at the +0.1m level, while reduced diurnal temperature amplitudes at -0.1m are maintained a few degrees above 0°C (App. 2). At Mt. Superior the percentage of frost days associated with the presence of snow is much lower (Fig. 42). Rather, as can be expected, soil frost is typically associated with periods during which snow is absent. During periods with snow soil surface temperatures range between +4 and -1°C in 1993, but between +4 and +1°C in 1994 at this site. From the Waaihoek Peak record it may be suggested that the presence of a snow cover maintains soil surface temperatures near 0°C and inhibits temperature amplitudes sufficient for effective soil frost activity over 57% of the number of soil frost days. At Mt. Superior soil frost activity is reduced in a similar manner, but effective freeze/thaw cycles occur from May to October when snow is absent.

4.3.2 Soil Moisture

Results of the direct measurement of relative soil moisture levels in percent by volume, i.e. percent saturation, at the two logger sites are presented in Appendix 5. Due to the limitations posed by the Bouyoucous resistivity blocks the reliability of these data should be viewed with caution (see Appendix 1). This discussion is based on the assumed linear response of the blocks and an identical response function between



YEAR	SNOW Y (DAYS)	SNOW N (DAYS)	SNOW Y (%)	SNOW N (%)
WAAIHOEK PK				
1990	1	14	7	93
1991	56	39	59	41
1992	40	39	51	49
1993	24	12	67	33
1994	41	36	53	47
MT.SUPERIOR				
1993	25	57	30	70
1994	0	51	0	100

Legend:
▩ Frost days with snowcover
■ Frost days without snowcover
░ No record

Figure 42. Frost days with/without snow cover at Waaihoek Peak and Mt. Superior.

them. In situ testing of the validity of this assumption was not possible (App. 1). During the summer months relative soil moisture levels drop to less than 10% at 5cm depth at Waaihoek Peak and approach 0% at the same level in the 0.14m-thick sediment at Mt. Superior. Late summer and autumn rainfall of 50mm/day produces rapid near-saturation of soils at Waaihoek Peak. The significantly lower diurnal totals at Mt. Superior are insufficient to raise the water content above 10% until the onset of the autumn and winter rains.

Both the Waaihoek Peak and Mt. Superior record indicate soil moisture levels generally over 80% throughout the rainy season from April to November (Fig. 43; App. 5). The shallow sediment at Mt. Superior shows rapid desiccation throughout its profile when precipitation becomes more sporadic, while moisture is lost more gradually from the 0.35m soil profile at Waaihoek Peak. Moisture levels remain highest at -0.15m at the onset of the summer dry period (1993 record, App. 5). This may possibly be related to downward percolation at -0.3m into macropores of the underlying fractured bedrock, while evaporation losses are highest at the soil surface. On the other hand, water concentration at the soil-bedrock interface may explain higher soil moisture levels at -0.3m in response to first autumn rainfalls in 1991 (App. 5).

The soils at both sites are suggested to maintain high saturation levels as a result of the high number of precipitation days (Table 20), the high absolute amounts received, particularly at Waaihoek Peak (Table 19) and the frequent snow cover (Fig. 41). Field observations and the air temperature record indicate that during periods with snow cover snowmelt occurs during the day. This ensures continuous moisture supply to underlying soils.

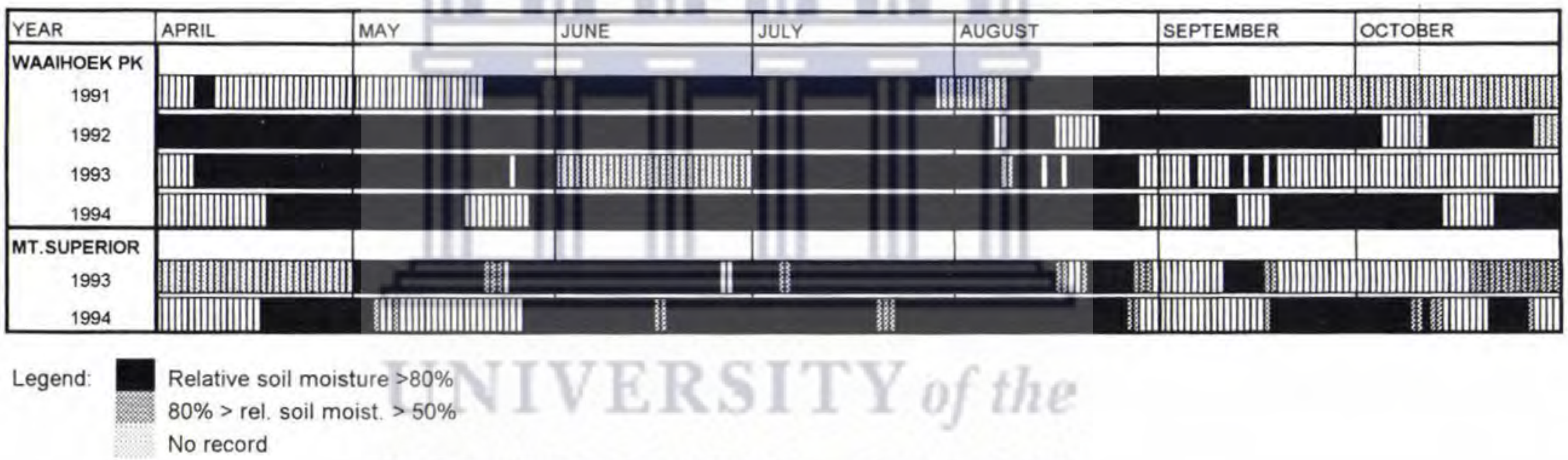


Figure 43. Relative soil moisture levels during the frost season at Waaihoek Peak (1991-1994) and Mt. Superior (1993-1994).

4.4. FROST-SUSCEPTIBILITY OF THE SOIL MATERIALS

4.4.1. Soil texture

The potential for a sediment to facilitate soil moisture migration to a freezing plane and the consequent growth of segregation ice is generally known as the frost susceptibility of the sediment (French, 1976; Williams and Smith, 1988). Taber (1929, 1930) tried to establish the texture controls on segregation ice formation and concluded that a minimum of 30% clay is required for ice lens development. Meentemeyer and Zippin (1981) point out that natural frost heaving occurs in soils coarser than this. They summarise the conclusions of various other workers by stating:

> "Soil texture must be neither too fine to retard flow of water to the freezing plane nor too coarse to impede capillarity. The actual movement of water to the freezing plane is controlled by the interaction of moisture availability and texture" (Meentemeyer and Zippin, 1981, p. 114).

From their analysis Meentemeyer and Zippin (1981) conclude that a minimum of 8% of fines (i.e. the fraction <63µm) is required for needle ice growth in water-saturated soils.

In this study a distinction needs to be made between soils derived from the quartzitic sandstone strata of the Peninsula Formation and those derived from the Cedarberg shale. Soil samples were collected from the A-horizon at a depth between 5 and 10cm below the surface at a variety of sites near Mt. Superior (n=6) and Waaihoek Peak (n=25) (App. 6). Results of particle size analysis of the fraction smaller than 2mm are presented in Figure 44. The particle size is presented in phi units. The median value for the sandy soils is 1.55 phi (350µm), while the median particle size for the shale-derived soils is considerably smaller, at 2.85 phi (140µm). More important for this study is the combined percentage of silt and clay, which constitutes the fine

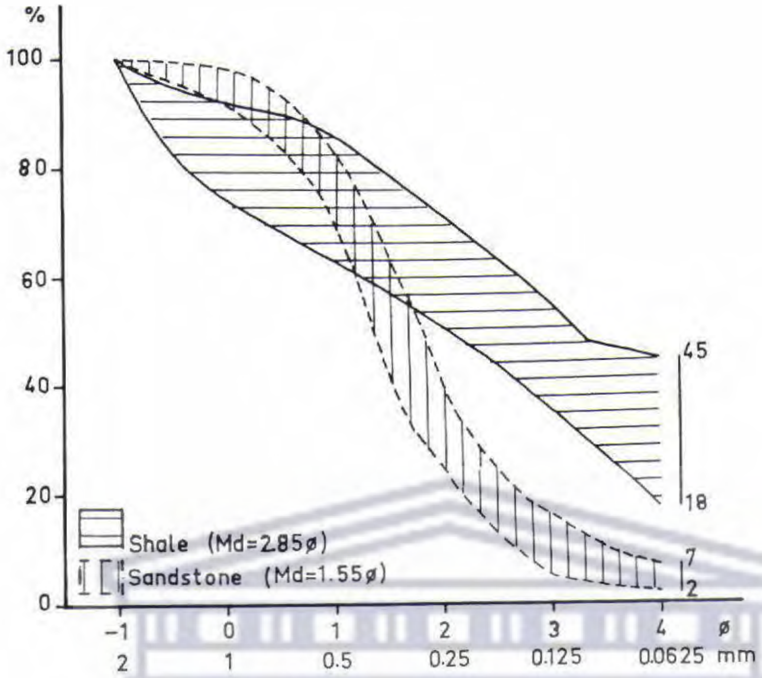


Figure 44. Envelopes for particle size distributions for soils at Waaihoek Peak and Mt. Superior.

fraction. For sandstone-derived soils the fines fraction ranges between 2 and 7 percent, and between 18 and 45 percent for the shales. The spatial distribution of the sandstone derived values for fines is presented in App. 6. This shows that no broad trends exist as to where highest values of fine material may be found in the terrain.

4.4.2. Soil moisture and texture implications for needle-ice growth

High soil moisture contents are required for needle-ice growth (Lawler, 1988) but vary with soil texture (Meentemeyer and Zippin, 1981). The influence of soil texture on minimum soil moisture levels required for needle-ice growth were experimentally established by Meentemeyer and Zippin (1981), (Fig. 45).

The sandy soil at the Waaihoek logger site contains 4-5% fines and 21.5% (dry weight) moisture at saturation. When tested against the relationships found by

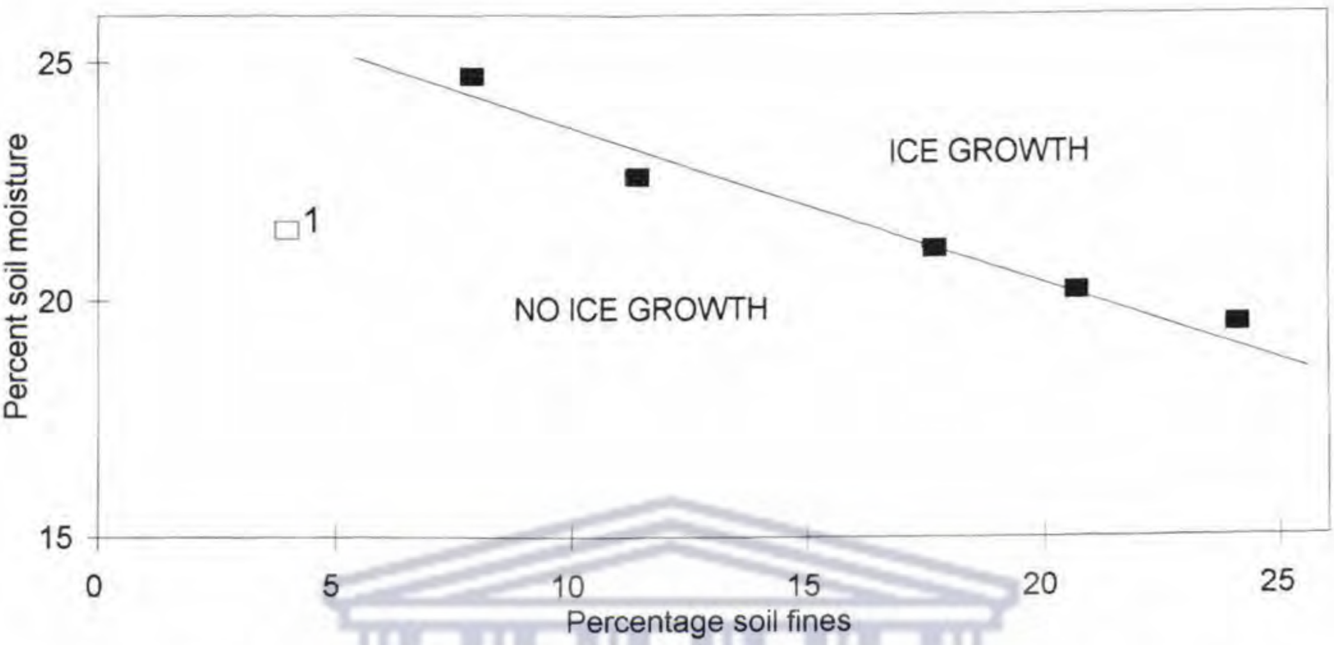


Figure 45. Soil moisture and texture control on needle-ice growth (from Meentemeyer and Zippin, 1981). ■ indicate data derived from Meentemeyer and Zippin (1981). □1 indicates the position of a saturated sample from the Waaihoek Peak logger site. See text for further explanation.

Meentemeyer and Zippin (1981) (Fig. 45) the sediment is found too coarse, even under saturation, to develop ice needles. On the other hand, the high percentage of fines in the shaley soils make this material highly frost susceptible. The sediment at the Mt. Superior logger site contains 24% fines and attained water saturation at 44% (dry weight). Meentemeyer and Zippin (1981) achieved needle ice growth in a soil with 24.1% fines at a minimum soil water content of 19.5%. Similar critical soil moisture values for comparably textured soils were obtained by Outcalt (1971) and Pérez (1984). For the Mt. Superior site this converts to a relative soil moisture content of 45-50%. Relative soil moisture levels at Mt. Superior are predominantly above 50% during the freeze/thaw season from April to November (App. 5).

The data logger record from Mt. Superior suggests that the soil water content in the sandy loam at this site is favourable for needle-ice formation during most of the freeze/thaw season. In contrast, even under saturation the sandy soils at Waaihoek Peak are non frost-susceptible. When one considers that sandstone from the Peninsula Formation underlies large sections of the western Cape mountains, it appears that material properties may exert an important control on the spatial distribution of soil frost features, irrespective of climatic conditions.

4.5. Assessment of effective soil frost cycles

Climatic control on the soil frost potential may be summarised, based on the record presented above. Several limiting conditions controlling ice segregation have been identified from the literature. A requirement for a minimum nocturnal temperature of -2°C for needle ice growth is based on the general acceptance of the findings by Outcalt (1971) and Lawler (1988). Evaluation of the freezing point depression of soil water suggest that this will not be lowered beyond the value of -2°C, but this could not be validated by experimental studies.

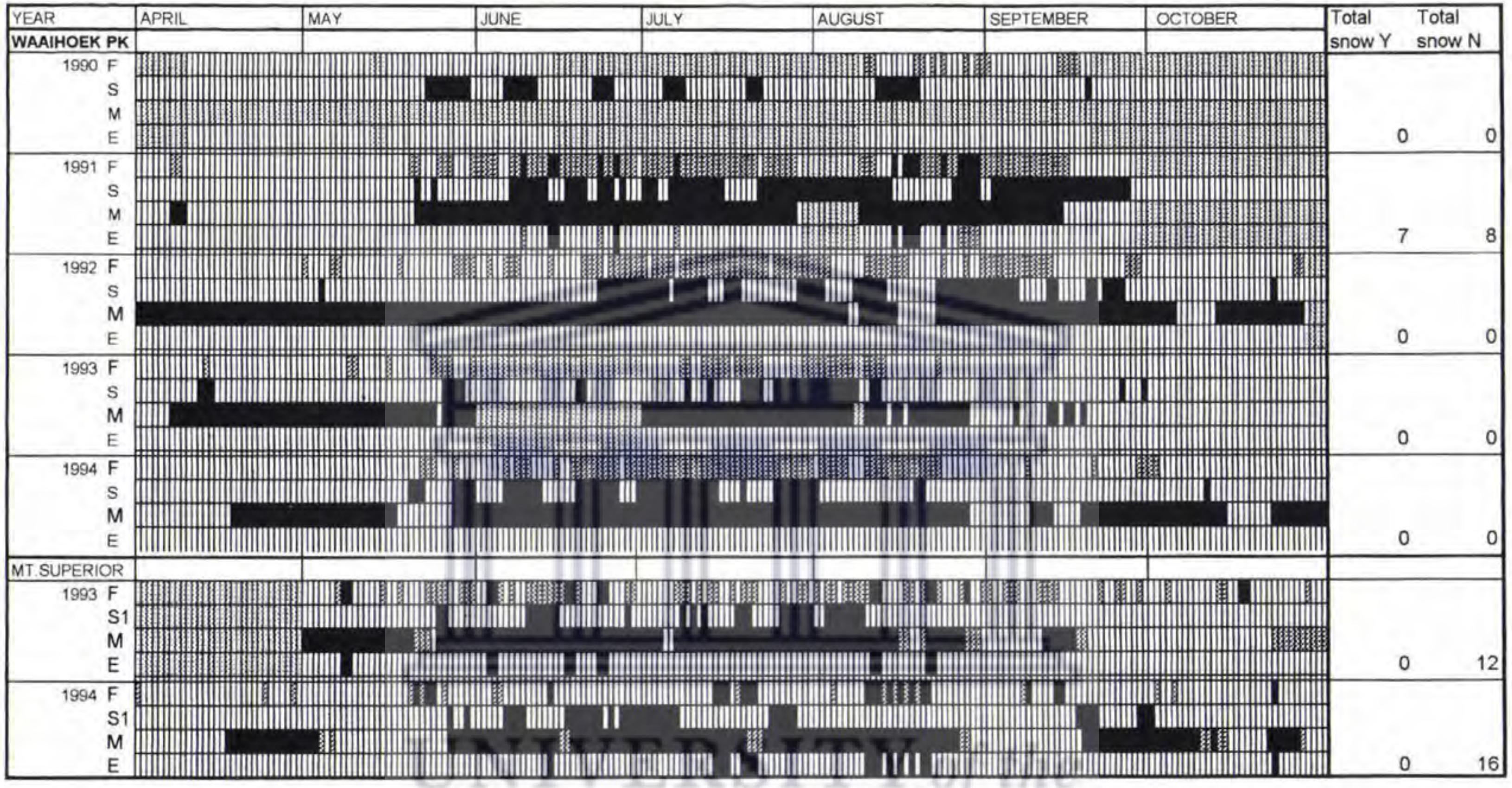
The lack of laboratory facilities to determine soil moisture requirements for needle-ice growth in local soils also limits the assessment of moisture availability during freeze/thaw cycles. However, the sediments at Waaihoek Peak appear to be too coarse to allow sufficient water migration for needle ice growth, even under saturated conditions (Meentemeyer and Zippin, 1981). For the coarsest sediment at Mt. Superior a minimum soil moisture content of about 21% (weight) would be required, based on Meentemeyer and Zippin (1981) (Fig. 45). This converts to a relative soil moisture content of 50% (volume) for the soil at the data logger site. This value has been taken as a guideline for the minimum soil moisture required for needle-ice growth at Mt. Superior.

These limiting conditions may be applied to assess the occurrence of effective soil frost at the two monitoring sites (Fig. 46). At Waaihoek Peak effective frost days were only registered during 1991 out of a four-year record. Seven of these occurred on days with, and eight on days without, snow cover. This low frequency of effective frost days is caused by the low number of days with temperatures ≤-2°C. This has been related to the insulating effect of snow for 57% of frost day occurrences (Fig. 42).

Effective freeze/thaw cycles at Mt. Superior occurred with a frequency of 14 and 16 days during snow free periods in 1993 and 1994 respectively (Fig. 46). As the total number of days with snow is very similar at both sites, differences in snow cover cannot explain the higher intensity of freeze/thaw cycles at Mt. Superior. Factors limiting frost amplitudes at Waaihoek Peak may include radiation shielding by vegetation, latent heat release when soil water reaches freezing point (Outcalt et al., 1990) and soil thermal properties.

Higher soil frost intensity has been recorded in drier soil by Lliboutry (1955) and Pérez (1984) but similar soil moisture characteristics have been recorded in this study for the two sites in 1993 and 1994. Precipitation totals at Waaihoek Peak are, however, twice those at Mt. Superior during 1994. Further, the sandy soils at Waaihoek require about half the absolute amount of soil water to achieve saturation than the sandy loams at Mt. Superior. Despite greater permeability and soil thickness on the sandstone slopes surface runoff has been observed to be common during winter (see Ch 3.1). The presence of overland flow may be an important factor inhibiting soil frost activity as it will be this water that will freeze first. Associated latent heat release may effectively compensate for the radiational heat loss from the surface and inhibit further cooling of the soil. This has been further discussed in Ch 3.1.

The effects of vegetation on minimum temperatures is best illustrated in Figure



Legend: F Frost days: ▨ -2 < temp. < 0 C
■ temp. <-2 C
S Snowcover, combined from 1 and 2 in Table
S1 Snowcover, based on diurnal soil surface temperature range < 4 C
M Relative soil moisture levels: ■ >80%
▨ 80% > soil moist. > 50%
E Effective soil frost days, based on temp. < -2 C and a relative soil moisture > 50%.
■ snow absent
▨ snow present
░ No record

Figure 46. Frequency of effective soil frost days at Waaihoek Peak (1990-1994) and Mt. Superior (1993-1994).

36 and shows the soil surface to be the level of greatest heat exchange at Mt. Superior, that is, the level with greatest diurnal temperature ranges and absolute extremes. Elevation of this 'active surface' (c.f. Oke, 1987) to 0.1m above the soil surface reduces the diurnal temperature extremes experienced at the soil surface at Waaihoek Peak. The darker soil surface at Mt. Superior can further be suggested to enhance the temperature differences experienced at the two sites.

Irrespective of the limitations posed by current climatic conditions the coarse textures of soils derived from the Peninsula Formation preclude any ice segregation in the Waaihoek Peak area. In contrast the sandy loams at Mt. Superior appear highly frost susceptible. The Peninsula Formation underlies over 90% of the western Cape slopes over 1000m elevation. This strongly suggests material properties exert a major control on the spatial distribution of soil frost processes and landforms at present and possibly during the colder phases in the recent geological past.

CH. 5. SOIL MOVEMENT IN RESPONSE TO FROST

Soil movement monitoring sites were established to i) monitor rates of differential frost heave, i.e. the upheaving of clasts, ii) to establish vertical movement profiles, and iii) to measure downslope movement rates of surface materials. Sites were set up on the sandstone slopes at Waaihoek Peak and the shale outcrop near Mount Superior (Figs. 29, p.70 and 32, p.73).

5.1. DIFFERENTIAL FROST HEAVE

The effectiveness of differential heave by segregation ice formation has been monitored in patterned ground using dowels of various sizes (Washburn, 1979, 1989; Hallet and Prestrud, 1986), and painted lines across stones (Benedict, 1970, 1992). First assessment of frost heave activity was made in this study by creating dowel sites for short term monitoring in both the Waaihoek Peak area and on the shales near Mount Superior. Round wooden dowels of 5mm diameter and lengths varying between 5, 10 and 15cm were inserted on bare soils on relatively level surfaces. Three sites were established in the Waaihoek Peak area (Fig. 29) between 5 and 8 January 1990. Site 1 was terminated on 21/9/91, while sites 2 and 3 were last measured on 13/11/1994. No lateral movement had taken place and all dowels proved very stable with no indications of displacement of the dowels themselves. At all three sites, however, slight variations in dowel height above the ground surface were noted which could readily be linked to surface erosion or sand deposition by overland flow. The dowel sites thus show frost heave to be of no importance in the sandstone soils at Waaihoek Peak. This result appears due to both limited soil frost penetration as shown by the temperature record from Waaihoek Peak, and the lack of frost susceptibility of the sandstone soils in this area. The analysis of surface erosion rates by changes in marker elevation above the surface is presented under section 4.4.3.

Dowel sites were established on a near-horizontal surface in the shale sediment at Mount Superior at 1850m a.s.l. The shallow soil allowed only for 5cm long dowels to be inserted. Two 0.5m x 0.5m sites were established, one with 25 wooden dowels spaced 10cm apart and the second with 25 concrete dowels of 5cm length and 10mm diameter also spaced 10 cm apart. Dowels were inserted vertically and level with the ground surface on 28 March 1992. Inspection of the site on 5 June 1992 revealed all dowels, both wooden and cement, to be completely heaved out of the soil. This result clearly illustrates soil frost activity to be highly effective in this material and stands in contrast to the sandstone slopes. Unfortunately, no temperature record is available for the period of measurement which makes it impossible to relate the results to frequency and depth of diurnal frost cycles at the site.

5.2. VERTICAL MOVEMENT PROFILES

A variety of techniques have been developed to monitor vertical movement rates of downslope mass wasting by creep and solifluction, including flexible tubes (Williams, 1966; Mackay and Mathews, 1974; Smith, 1987, 1988; Price 1991), dowel columns of various materials (Benedict, 1970; Mackay and Mathews, 1974; Smith, 1988; Coutard et al., 1988; Harris, 1993) and other similar strategies. More complex designs allowing continuous monitoring are described by Williams (1957, 1966) and Lewkowicz (1992). In all cases markers or probes are inserted in the soil which requires physical disturbance of the site. This disturbance may result in deformation of the probes during settling after closure of the pit (Anderson and Finlayson, 1975). Smith (1993) suggests that the higher magnitude of movement rates observed over the short term (<5yrs) relative to long term averages (>10yrs) may be attributed to this site disturbance.

5.2.1. Flexible tubes

In the Waaihoek area flexible tubes were used as they are inexpensive, theoretically easy to install and allow for repeated measurement (Anderson and Finlayson, 1975). A disadvantage is that any lateral shearing of the soil will not be detectable. Installation of the tube required digging a pit as augering was not possible due to the presence of large stones in the soils. The tubes were placed vertically in the pit. The plastic tubes had a 40mm outer diameter and although they bent readily do not fold. The bottom end was sealed with polyester resin and the top with a rubber stop to prevent water penetrating and standing in the tube. An aluminium rod that fitted neatly in the tube was used to keep the pipe straight while filling the pit. The tubes were left reaching a few centimetres above the surface. Subsequent reading of the tube profile was achieved by lowering a small perspex vessel, minimally narrower than the tube inner diameter, and filled with warm jelly, down the tube. After setting of the jelly the vessel is lifted out and from the angle of the jelly surface with the vessel wall the inclination of the tube at that depth can be reconstructed. Readings were taken every 10 cm. Location of the five tubes inserted in the Waaihoek Peak area is presented in Figure 29. Sites 1, 2 and 4 are located on terracetted slopes while 3 and 5 are positioned on NW and NE-facing debris slopes respectively. From the profile descriptions in Figure 47 it is evident that in all cases tubes are inserted in matrix supported diamict. The presence of large clasts caused great difficulty to placement of the tubes and is the reason for the low number of sites created and their relatively low depth of insertion for some of them.

The tubes were installed on 5-8/1/1990 and final readings were made on 12/11/1994. In all cases no deformation of the tubes was detected over this period of 4 years and 10 months. In fact the aluminium rod used for the tube installation could still

Parameter	Site 1	Site 2	Site 3	Site 4	Site 5
Location	valleyhead	valleyhead	debris slope	valleyhead	debris slope
Altitude	1900m	1870m	1780m	1800m	1850m
Site aspect	170°	175°	230°	140°	40°
Site gradient	9°	18°	14°	20°	25°
Micro-topography	terracettes	terracettes		terracettes	
Soil thickness	0.8m	0.55m	?	0.51m	?
Depth of tube	0.8m	0.55m	0.51m	0.51m	0.46m
Date installed	5/1/1990	5/1/1990	7/1/1990	8/1/1990	8/1/1990
Date final reading	12/11/1994	12/11/1994	12/11/1994	12/11/1994	12/11/1994
Soil profile					

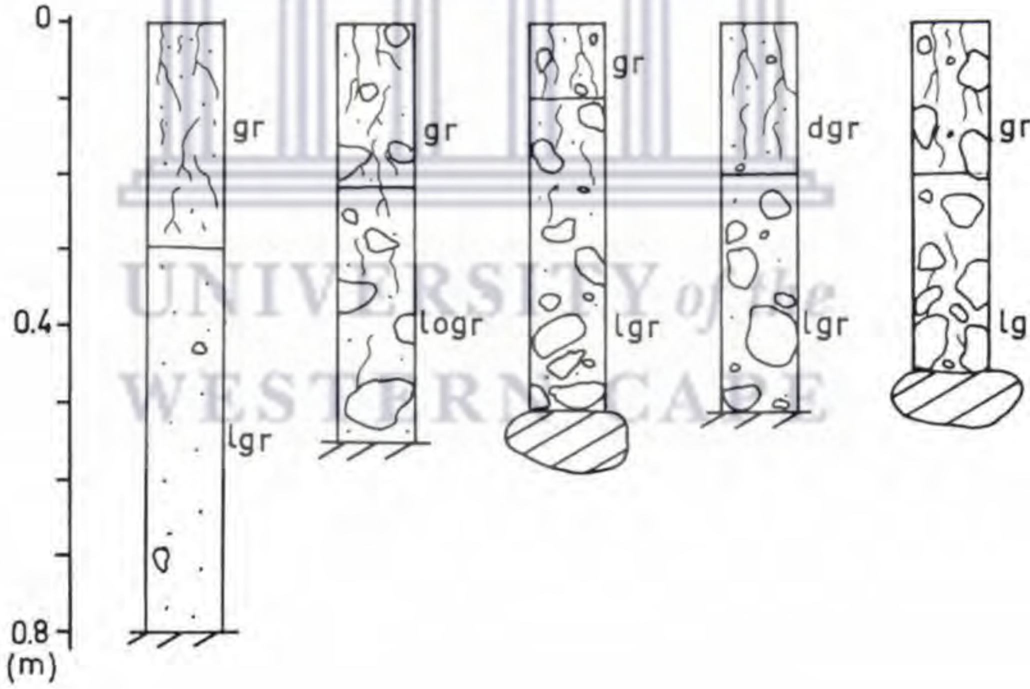


Figure 47. Site characteristics and soil profiles for the tube sites in the Waaihoek Peak area. For the site locations see Fig. 29, p.70. Soil colour codes: gr - grey, lgr - light grey, dgr - dark grey, logr - light orange-grey.

be inserted over the full length of the tube at all sites. Smith (1993) evaluated long term monitoring of slow mass wasting using flexible tubes and concluded that initial disturbance of the site results in high initial movement rates (<5yrs) which fall to more consistent level over the long term (>10yrs). However, the tubes inserted here in matrix supported debris show no deformation whatsoever after a period of nearly 5 years. The absence of deformation by disturbance of the pit may be attributed to minimal compaction of the sandy matrix and clasts compared with a sediment of higher clay content. Although the possiblity of some sediment movement past the tubes, or block movement of the entire soil profile must be recognised, the results clearly point at a high stability of the debris mantle under present environmental conditions. It can safely be assumed that no frost generated creep or solifluction takes place at present on these slopes. Furthermore, the terracettes observed at the surface also do not appear to be caused by creep or solifluction in the upper soil layer. Judging from these results they are not the result from shearing in the upper soil profile.

5.2.2. Pebble columns

Vertical movement profiles in the shale sediment were established in a stone-banked lobe (Fig. 17, p. 49). In this case quartz pebble columns were used as the sediment was too thin to install flexible tubes. Three pebble columns were installed on 24/11/92 and excavated on 13/1/95, providing a 25 month record. After excavation pebble positions were mapped directly on transparent film. The results are shown in Figure 48.

Particles embedded in the openwork surface layer moved the furthest in all three columns. Rates of displacement decreased rapidly with depth and became undetectable at a depth of 5cm. The column near the front of the lobe (Site 1) shows

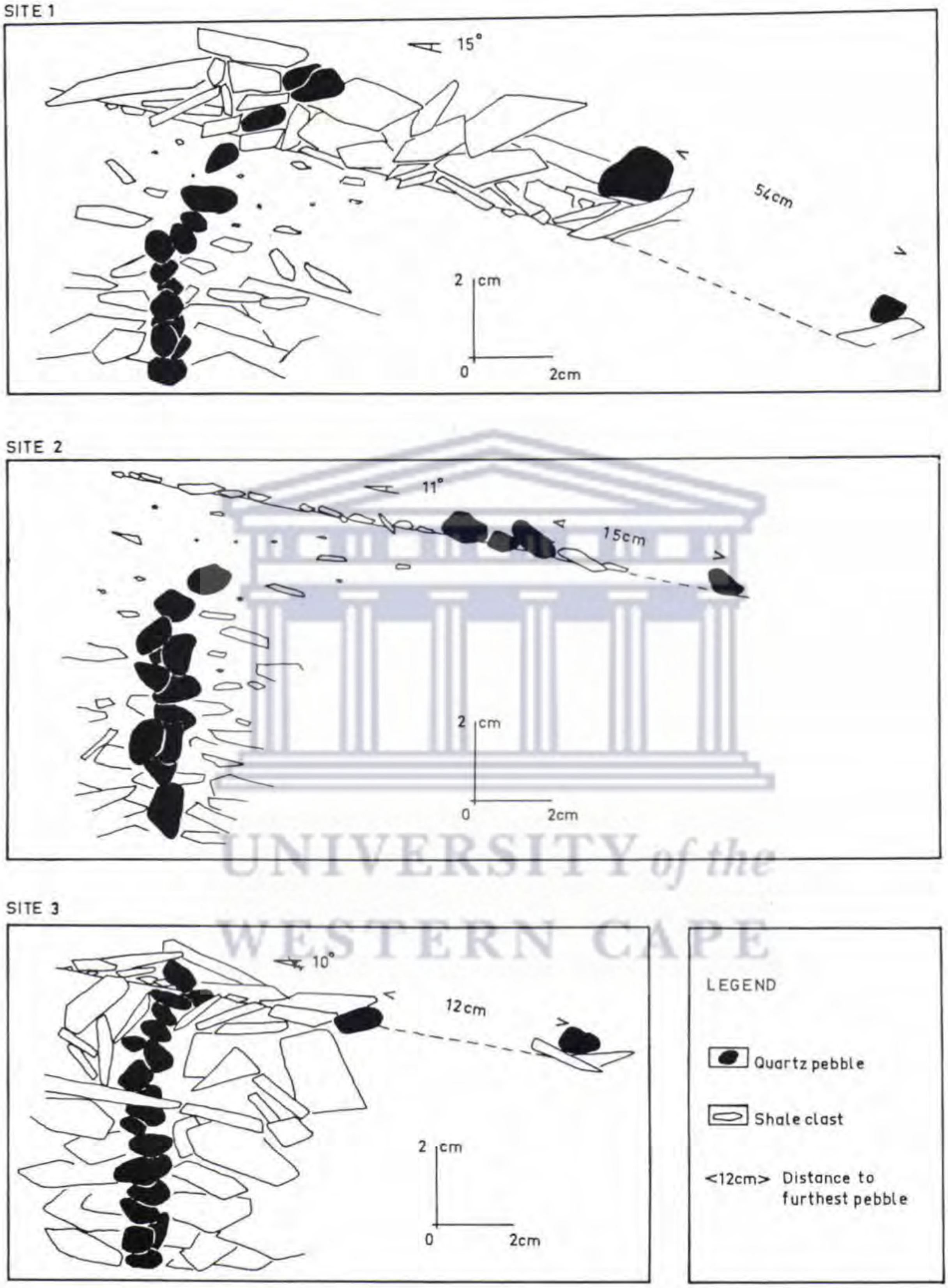


Figure 48. Deformation of pebble columns installed on a stone-banked lobe near Mt. Superior (1850m a.s.l.). For location of the sites see Figure 35, p.85.

the highest surface transport rates with a maximum pebble displacement of 87cm. Maximum movement in the columns upslope was significantly less, possibly under the influence of a lower slope gradient. The vertically concave movement profile and the maximum depth of displacement agrees well with the field measurements by Benedict (1970) and Mackay and Mathews (1974) and those obtained in laboratory studies by Coutard et al. (1988), Harris et al. (1993) and Harris (1993). In these studies the sediment movement is related to surficial frost creep by needle-ice growth under diurnal frost cycles. The high surface movement rates can also be explained by needle-ice induced frost creep (Harris et al., 1993). The results obtained here thus further suggest needle-ice activity to be important in the generation of the soil frost features observed.

5.3. SOIL SURFACE SEDIMENT TRANSPORT

Surface transport of fine sediment by wash became evident after initial observations at the dowel sites and from field observations of terracettes. Dowels at three monitoring sites, unaffected by frost heave, showed signs of sediment loss or gain around the pillars by surface wash. Site details and summary data are provided in Table 21. Plots of change in dowel height relative to the soil surface are presented in Fig. 49. All three sites show a net loss of soil surface sediment but the standard deviations indicate a very high variability at sites 1 and 3. Site 2, however, shows relatively high surface erosion rates. This may be attributed to close proximity of the dowels to a location where surface runoff concentrates between two terracette treads. Results from site 3 best illustrate the high variability of surface erosion rates due to micro-relief variations on the sandstone debris slopes (Fig. 49).

From the dowel sites results as well as field observations, the question arose to what extent rates of frost-induced sediment transport compare with erosion by surface runoff. Although not a primary focus of this study, transects of erosion pins were installed on two debris slopes to obtain indications of surface erosion rates by overland flow. Between fifteen and thirty nails, 10cm long and 5mm diameter, were placed parallel to the contour over a length of approximately 10m. Four such transects were created on an east-facing slope and three on a west-facing slope (Figs. 50, 51). Details of the transects and summary statistics are provided in Table 22. Initial elevation of each nail above the soil surface was measured. Where possible the nails were placed to reach 5mm above the surface, but this height fluctuated due to the stoniness of the debris mantle. The sites were installed on 23/11/92 and final readings taken on 13/11/94, providing a 2 year record. The shortest distance between the soil suface and

Site characteristic	Dowel site 1	Dowel site 2	Dowel site 3
Location	summit plateau	debris slope	water divide
Altitude	1910m	1780m	1760m
Site aspect	215°	230°	160°
Site gradient	1-2°	14°	10°
Surface cover	40% dwarf Restio spp. & grasses 30% gravel, clasts 30% bare soil	60% Restio spp. & grasses 15% clasts 25% bare soil	40% Restio spp. tussocks 30% clasts 30% bare soil
Micro-topography	Terracettes by surface wash	Terracettes, signs of surface run-off	Irregular steps, signs of surface run-off
Soil thickness	0.15m	>0.5m	0.25m
N° dowels per length			
5cm	3	5	16
10cm	3	2	0
15cm	1	0	0
N° dowels lost	0	1 (10cm)	1 (5cm)
Date installation	5/1/1990	8/1/1990	8/1/1990
Date final reading	21/9/1991	13/11/1994	13/11/1994
Period of record	20 months	58 months	58 months
Average erosion rate	3.4 mm/year	5.0 mm/year	1.6 mm/year
Standard deviation	3.4 mm/year	0.9 mm/year	2.1 mm/year

Table 21. Site characteristics and summary statistics for the dowel sites in the Waaihoek Peak area. See also Figure 49.

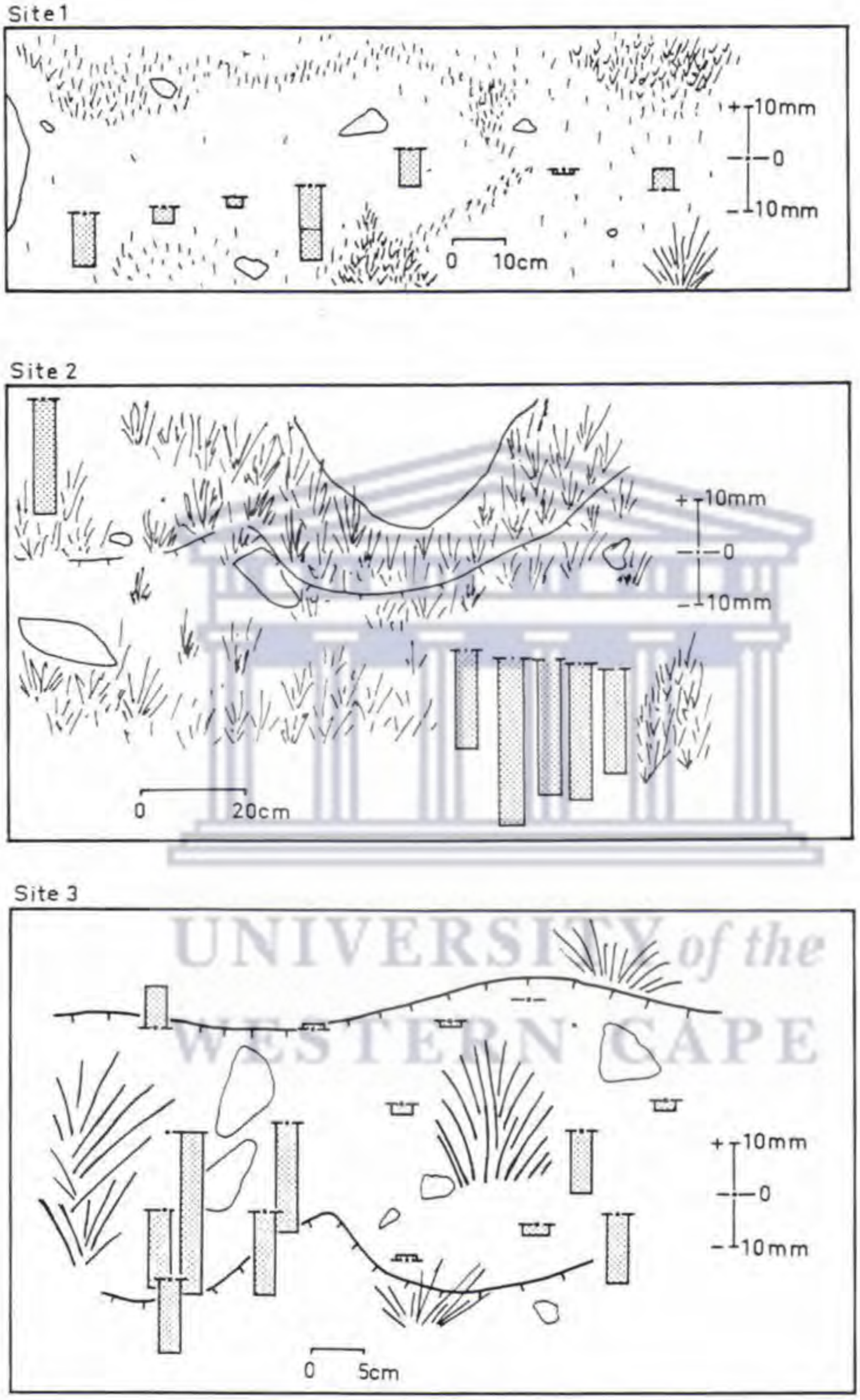


Figure 49. Plots of net sediment movement at dowel sites 1-3. Bars with negative values indicate mm of surface erosion. Bars with positive values indicate mm of surface accumulation. For location of the sites see Fig. 10, p. 37.

Figure 50. View on the east-facing slope used for the soil pin and painted stone line transects, Waaihoek Peak (1800m a.s.l.). Photograph taken in November 1994. For location of the sites see also Fig. 29.

Figure 51. View on the west-facing slope used for the soil pin and painted stone transects, Waaihoek Peak (1800m a.s.l.). Photograph taken in November 1994. For location of the sites see also Fig. 29.

Table 22. Details and summary statistics for the soil peg transects at Waaihoek Peak.

	Line 1	Line 2	Line 3	Line 4
East-facing slope				
Position	Upper slope	Upper middle	Lower middle	Lower slope
Slope gradient	27°	23°	20°	20°
Slope aspect	78°	78°	78°	78°
N° pegs installed	9	11	18	22
N° pegs lost	2	8	2	3
Period of record	24 months	24 months	24 months	24 months
Average total erosion	1.2 mm	5.1 mm	7.6 mm	5.7 mm
Annual erosion rate	0.6 mm/yr	2.6 mm/yr	3.8 mm/yr	2.8 mm/yr
Standard deviation	1.6 mm/yr	3.5 mm/yr	3.1 mm/yr	3.4 mm/yr
Average erosion for slope	2.7 mm/yr			
West-facing slope				
Position	Upper slope	Middle slope	Lower slope	
Slope gradient	24°	22°	24°	
Slope aspect	240°	240°	240°	
N° pegs installed	25	25	15	
N° pegs lost	7	0	8	
Period of record	24 months	24 months	24 months	
Average total erosion	9.2 mm	6.8 mm	9.1 mm	
Annual erosion rate	4.6 mm/yr	3.4 mm/yr	4.5 mm/yr	
Standard deviation	3.8 mm/yr	3.5 mm/yr	3.0 mm/yr	
Average erosion for slope	4.1 mm/yr			

the top of the nail were measured with a ruler. Repeated measurement at one site suggests that this achieved a precision of ±2mm.

A considerable number of nails could not be recovered (Table 22). This may partly be due to the fact that they were inserted too deeply and may have been buried by sediment. This implies that rates of sediment accumulation must be considered an under-estimation. Vegetation overgrowth and the rust colour of the nails were further causes of problems with marker retrieval. In three cases were nails found covered by clasts, the largest of which had a 24.0 cm *a*-axis. Results of measurements from nails that were recovered are provided in Figures 52, 53 and Table 22. At all transects the average values indicate that surface erosion does take place. However, this is to be expected due to the bias in results against areas of sediment accumulation. Values are

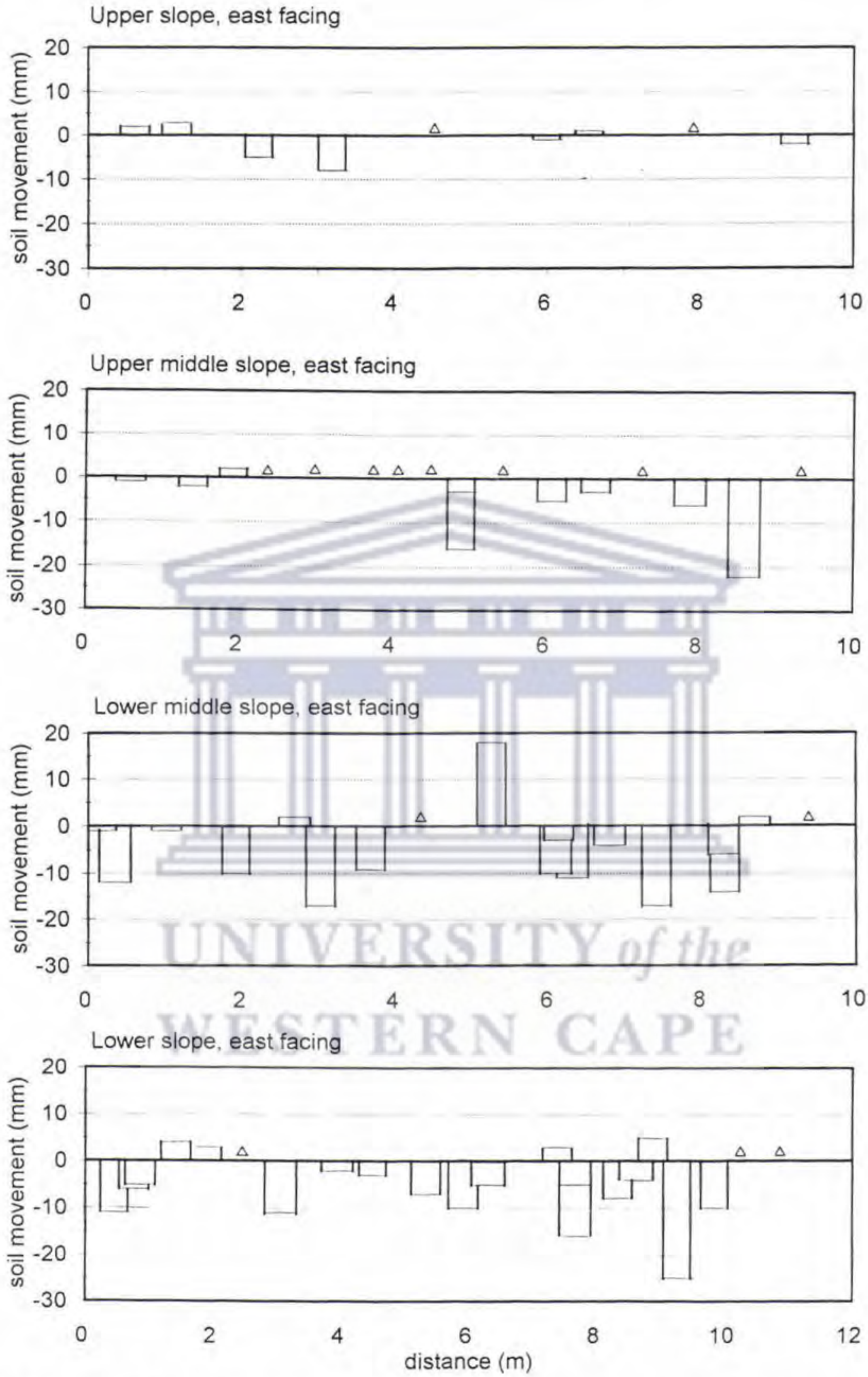


Figure 52. Plots of soil erosion rates at the soil peg transects on an east-facing slope at Waaihoek Peak (1800m a.s.l.). Negative values indicate soil removal; positive values indicate soil accumulation. Missing pegs are indicated by a triangle.

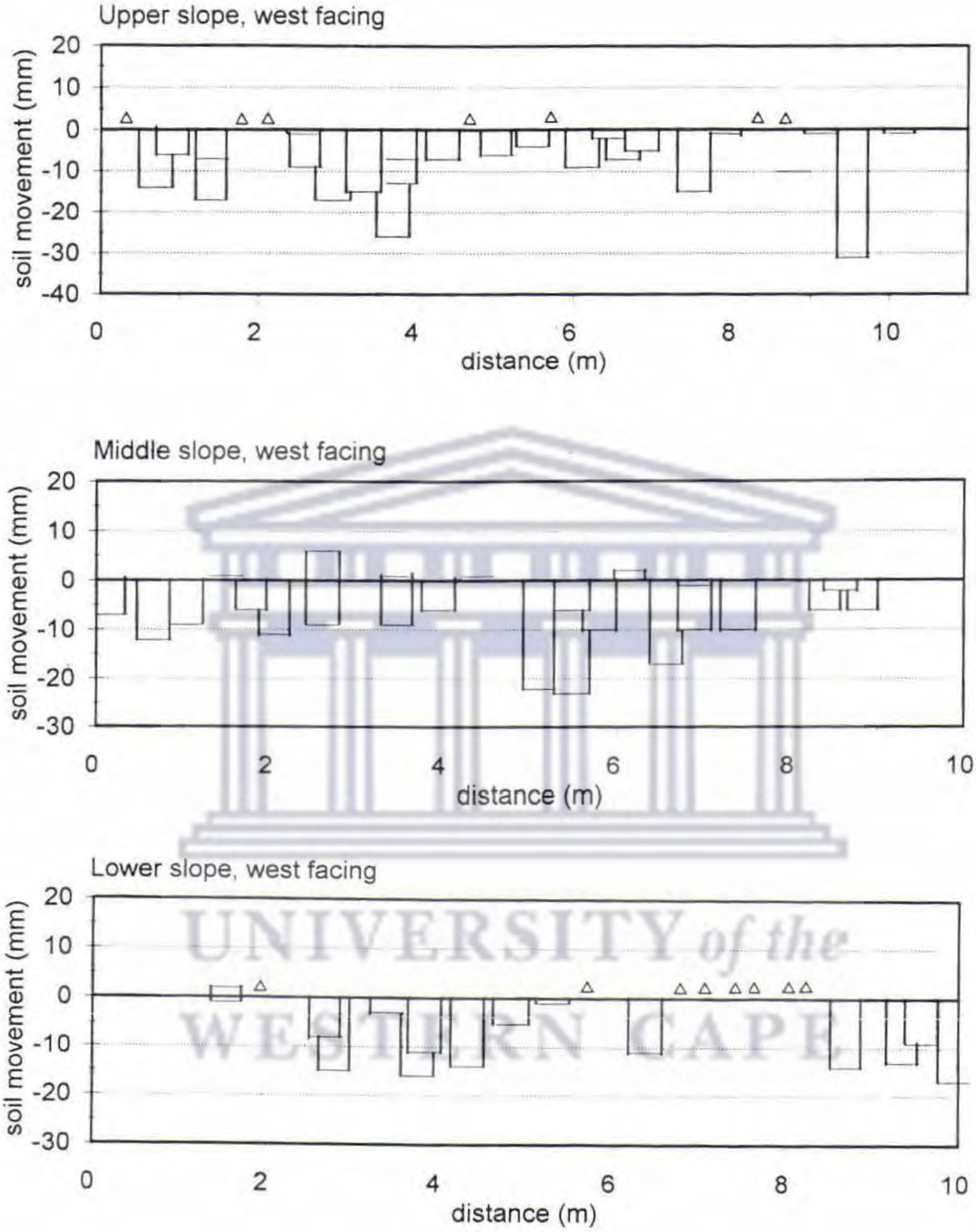


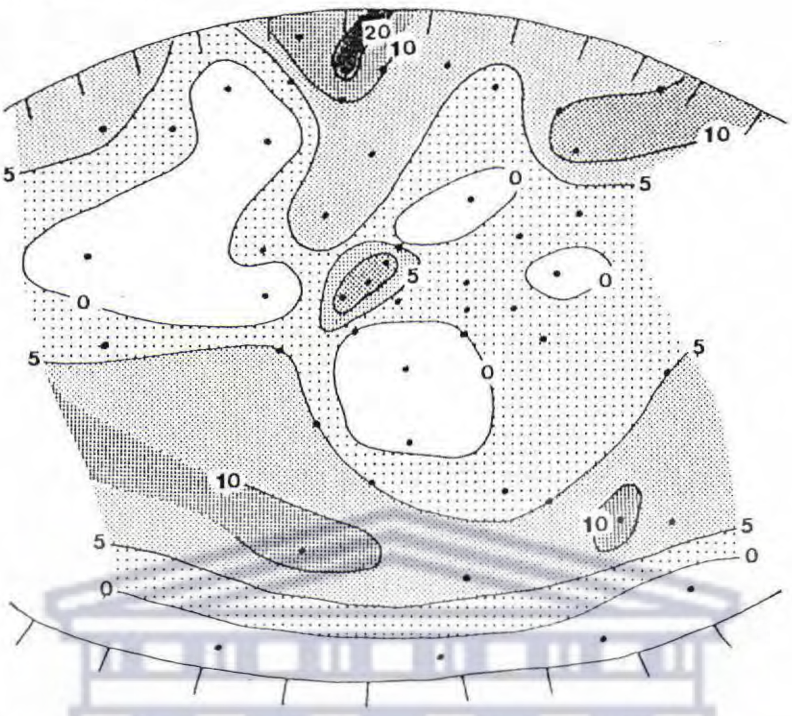
Figure 53. Plots of soil erosion rates at the soil peg transects on a west-facing slope at Waaihoek Peak (1800m a.s.l.). Negative values indicate soil removal; positive values indicate soil accumulation. Missing pegs are indicated by a triangle.

highly variable between markers, which is clearly reflected in the high standard deviations obtained. Results are thus very similar to those obtained from the dowel sites. Trends in average erosion rates on both slopes are insignificant or absent due to the high standard deviation in values obtained. Values obtained from the east-facing slope may however be lower than those from the west-facing slope, although this trend is also statistically insignificant (Table 22). Higher vegetation cover on the east-facing slope, which increases infiltration and lowers erodibility of the soil may, however, play a role. The east-facing slope is further positioned on the lee-side of the winds that bring precipitation. This may result in lower totals being obtained on this slope than on the west-facing valley-side, thus reducing overlandflow.

In an attempt to demonstrate the role of micro-topography on surface erosion rates, values from nails placed on stepped surfaces were plotted according to their position on the stepped micro-relief. Results from both slopes are presented in Fig. 54. Highest erosion values are measured at the foot of a riser on both slopes with lower values on the tread surface. However, standard deviations remain very high.

Results from the soil pins suggest mean surface erosion rates between 0.6 and 4.6 mm/yr. It must be considered, however, that the values are over-estimates as soil accumulation could not be measured where pins were inserted too deeply in the soil. Field observations do in fact indicate that surface accumulation of sediment is widespread. It is felt that much of the sediment measured to have been removed is transported over only short distances to be deposited again behind nearby obstructions on the same slope. The values obtained here are therefore not suggested to relate to erosion rates on a slope or catchment scale. Secondly, the physical presence of a soil pin will interfere with the course of overlandflow and may enhance surface erosion

A. East-facing slope (n= 52)



B. West-facing slope (n= 33)

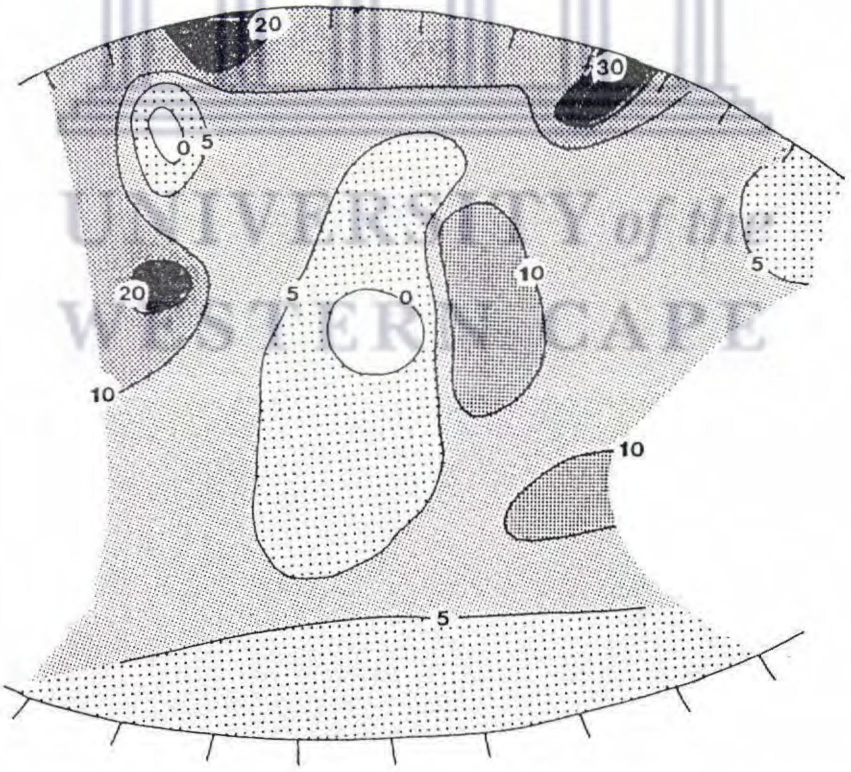


Figure 54. Isopleth map of soil erosion rates, in mm, recorded over 24 months on terracette surfaces using soil pins, on a) an east-facing slope, and b) a west-facing slope near Waaihoek Peak (1800m a.s.l.). Steps measure approximately 0.3m to 0.5m across.

around the pin. This phenomenon could be recognised in cases and has been compensated for by measuring the ground level slightly away from the peg.Third, the margin of error for the measurements is estimated at 2mm. Precision of the readings is not considered a significant factor affecting the values obtained here. Fourthly, surface erosion rates do not only vary widely on a micro-scale but can be expected to vary greatly in space and time depending on factors such as vegetation type and density, time after fire, slope aspect relative to winds associated with rain-producing systems, orographic effects, slope material composition and thickness and related variation in hydrological properties.

In conclusion, surface erosion by overland flow does take place but rates are highly variable both on a micro- and macro-scale. Where stepped micro-relief is present, soil removal rates appear highest at the foot of the riser. Field observations indicate that soil accumulation by surface wash occurs but was not adequately monitored here.

5.4. SURFACE TRANSPORT OF CLASTS

A common technique to monitor surface transport of clasts is the use of painted stones, as introduced by Michaud (1950) and used in studies by Rapp (1960), Smith (1988) and Pérez (1987, 1988). This method was applied here marking clasts with *a*-axes between 45 and 118mm long on the same transects as used for the soil pins. Details of the transects are provided in Table 23. The sites were established on 23/11/1992 and clast positions were re-measured on 13/11/1994 providing a two year record. A transect was established by stretching a tight line between two benchmarks. Clast positions were measured by the shortest distance between the line and the centre of the clast. Due to the presence of vegetation and boulders it was difficult to reestablish the exact position of the datum line two years later and a precision of no better than 30mm could be achieved for the readings. Results are presented in Table 23 and Figures 55 and 56.

Movement of the clasts is highly variable and even upslope in several cases. Few of these measurements are however significant as they fall within the expected margin of error and these values are not further considered here (Figs. 55, 56). Between 8 and 33% of the painted stones did move over distances that averaged between 26 and 73mm/yr per transect (Table 23). No trends in number of mobile clasts or distance moved occur on the east-facing slope but are present on the west-facing slope. For the latter, both the number of mobile clasts and their average movement

Table 23. Site details and summary data for the painted stone transects at Waaihoek Peak.

	Line 1	Line 2	Line 3	Line 4
East-facing slope				
Position	Upper slope	Upper middle	Lower middle	Lower slope
Slope gradient	27°	23°	20°	20°
Slope aspect	78°	78°	78°	78°
Period of record	24 months	24 months	24 months	24 months
N° clasts installed	25	30	25	29
N° clasts lost	0	1	0	2
N° clasts mobile	2	6	4	4
% clasts mobile	8	21	16	15
Average movement of mobileclasts	37 mm/yr	26 mm/yr	50 mm/yr	43 mm/yr
Average movement of all clasts	2.3 mm/yr	2.3 mm/yr	10.9 mm/yr	10.9 mm/yr
Standard deviation on annual movement of all clasts	11.0 mm	14.7 mm	21.8 mm	20.1 mm
West-facing slope				
Position	Upper slope	Middle slope	Lower slope	
Slope gradient	24°	22°	24°	
Slope aspect	240°	240°		
Period of record	24 months	24 months	24 months	
N° clasts installed	25	20	24	
N° clasts lost	0	1	0	
N° clasts mobile	3	5	8	
% clasts mobile	12	26	33	
Average movement mobile clasts	27 mm/yr	48 mm/yr	73 mm/yr	
Average movement all clasts	2.1 mm/yr	10.8 mm/yr	22.6 mm/yr	
Standard deviation on annual movement of all clasts	10.7 mm	26.7 mm	46.0 mm	

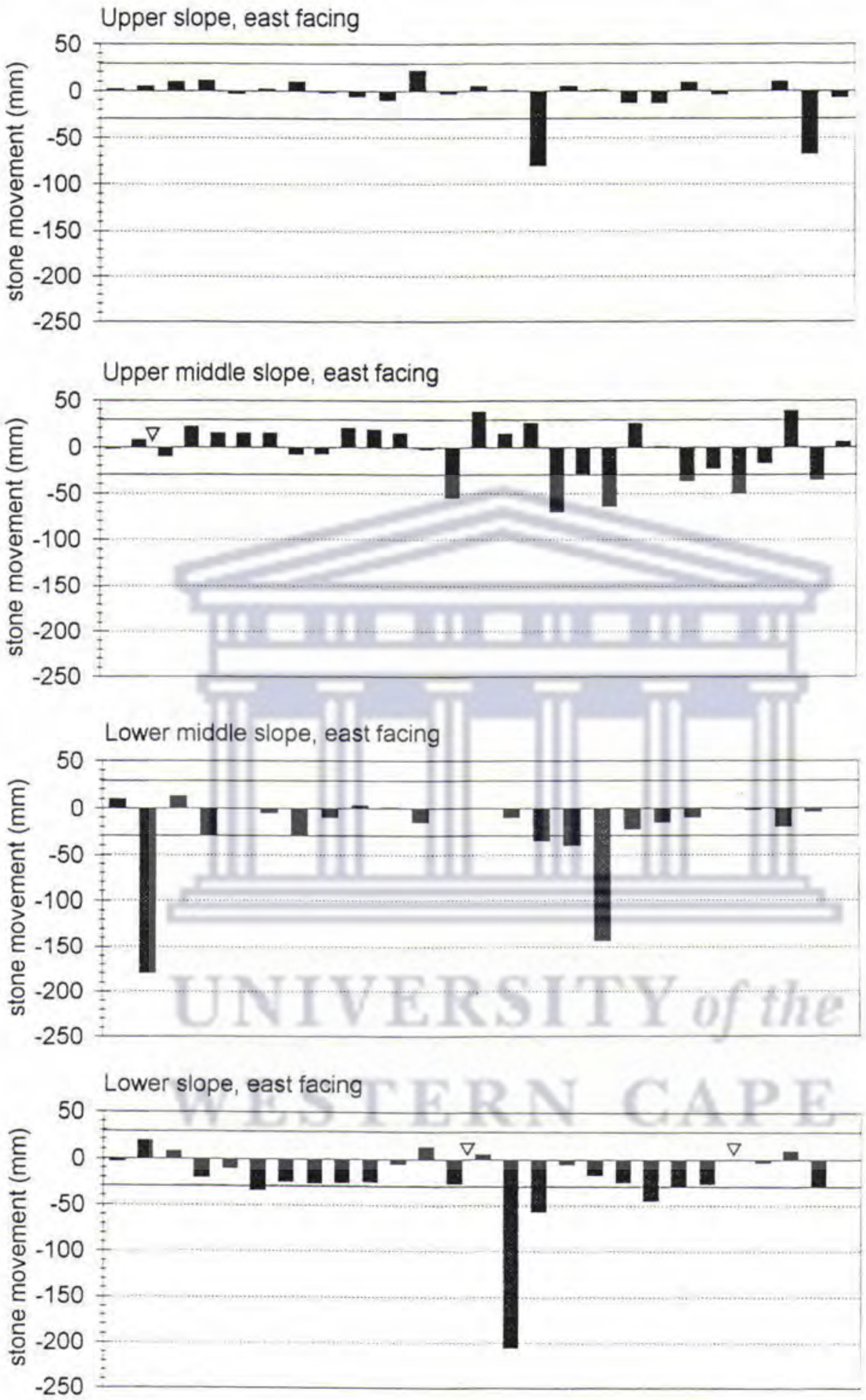


Figure 55. Plots of painted stone movement at four transects on a east-facing slope at Waaihoek Peak (1800m a.s.l.). Negative values indicate downslope movement. Positive values indicate upslope movement. Missing stones are indicated by an asterix. The margin of error is shown by a solid horizontal line.

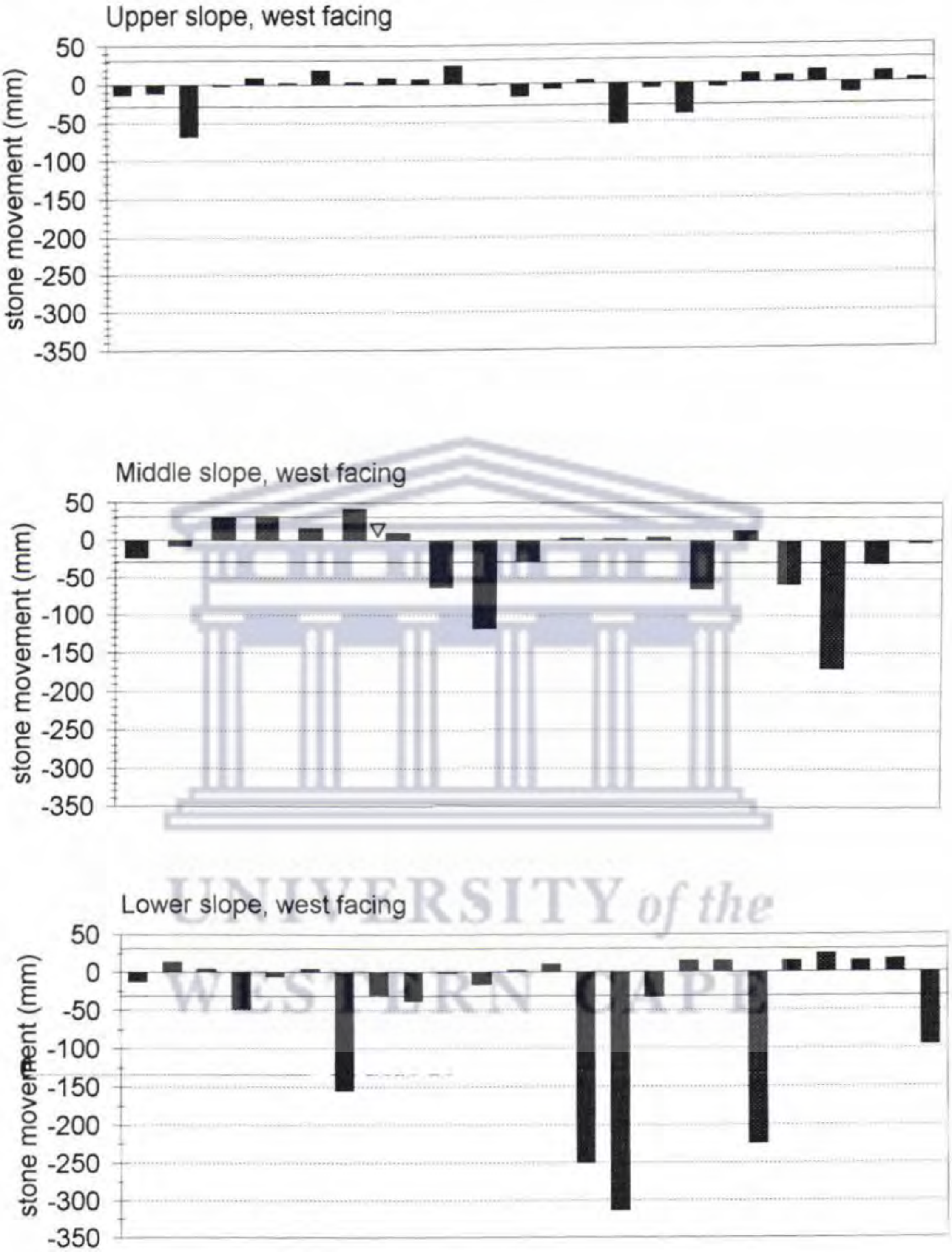


Figure 56. Plots of painted stone movement at three transects on a west-facing slope at Waaihoek Peak (1800m a.s.l.). Negative values indicate downslope movement. Positive values indicate upslope movement. Missing stones are indicated by an asterix. The margin of error is shown by a solid horizontal line.

increases in a downslope direction. Comparison of these values and trends with the rates of surface erosion obtained from soil pins are limited due to the high variability in all rates measured. The upper transect on the east-facing slope obtained low values for both fine sediment and clast mobility but high values are recorded for both on the west-facing slope. There is thus some, although statistically insignificant, support for the suggestion that clast mobility is enhanced by surface erosion of the fine debris matrix.

Clast mobility, measured by number of moved clasts and their annual movement rates, are low in this study compared with values obtained by Pérez (1987, 1988). Pérez (1987) measured clast mobility in a high tropical mountain environment using clasts of similar size and on similar slope gradients as used here. Following a two year period of measurement, spatial variability of movement rates were found to be high but all clasts had moved downslope with average annual rates of movement rates between 18.9 and 25.2 cm/yr. The transport of clasts in the studies by Pérez (1987, 1988) is primarily related to needle ice activity. As found in other environments where slow mass movement occurs surface markers are displaced in these cases over a wide front, although certainly not necessarily at uniform rates (Benedict, 1970; Furrer, 1972; Smith, 1988; Bennett and French, 1991). The low percentage of mobile clasts and the high spatial variability of movement rates strongly suggests that no creep or solifluction processes are involved in their transport.

5.5. CLASSIFICATION AND ORIGIN OF STEPPED MICRO-RELIEF IN THE WESTERN CAPE MOUNTAINS

5.5.1. Classification of stepped micro-relief in the Western Cape mountains

The observations on stepped micro-relief may be summarized by means of a classification of forms found during the field survey. Variability in the morphology of the stepped micro-relief forms encountered is summarized in Fig. 57. Classification of these forms is based on the nature of the step surfaces, dimensions and sediment composition. Based on the nature of the tread surface (bare or vegetated) and the riser (bare soil, vegetated or stony) forms are readily classified into commonly accepted categories. The non-genetic classification used here uses criteria and terminology derived from Washburn (1956, 1970) and Benedict (1970) for periglacial forms of stepped micro-relief, i.e. stone- and turf-banked steps and lobes. These have been distinguished from non-periglacial steps for which the term terracette is used, although a wide variety of terms has been applied in various studies (Vincent and Clarke, 1976).

Stone- and turf-banked steps and lobes are distinguished from terracettes by the bare tread surface of the former and the bare riser of the latter. Of these two criteria the bare riser of the terracette is most diagnostic as vegetation on a terracette tread surface may only be present near the front. Distinction between terracettes on slopes with high clast abundance and stone-banked steps/lobes is primarily by the unvegetated tread surface and the distinct sedimentological features of stone-banked steps/lobes. Further, stony terracette risers are mainly limited to a single or very few large clasts or boulders and generally, but not always, lack the downslope coarsening of surface clasts on the tread surface.

In order to summarize the dimensional characteristics of the various stepped micro-relief populations, scatterplots of step width against length and riser height to width were made. Length is here defined as the dimension along the contour, while width is measured along the fall-line. The width against length plot in Figure 58 identifies clusters of the various step populations. All clusters overlap to a greater or lesser extent but trends separating the various categories identified above are present. Terracettes stand out by their great lateral length relative to their width in contrast to

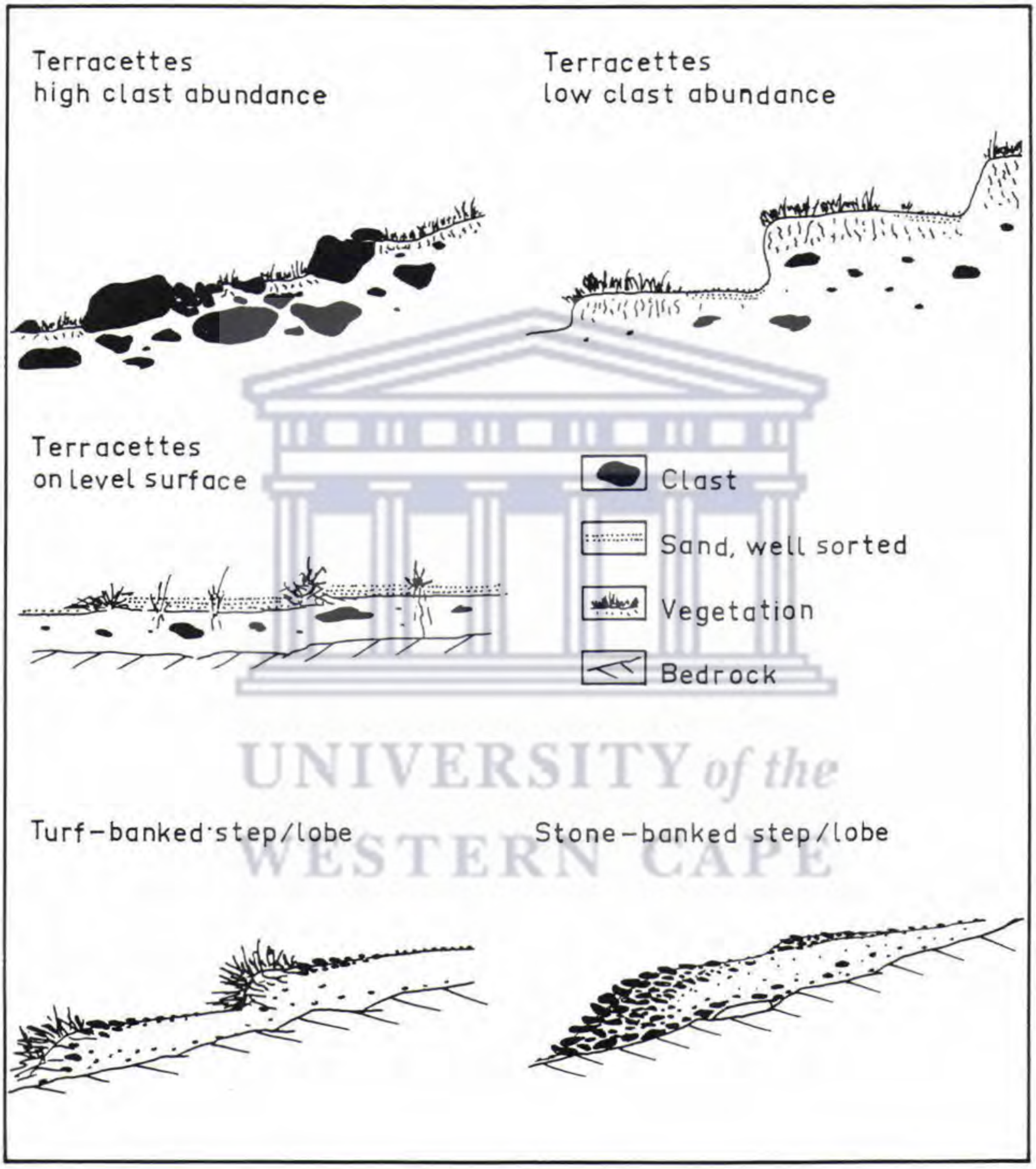


Figure 57. Schematic representation of the morphological variation in stepped micro-relief forms encountered in the Western Cape mountains.

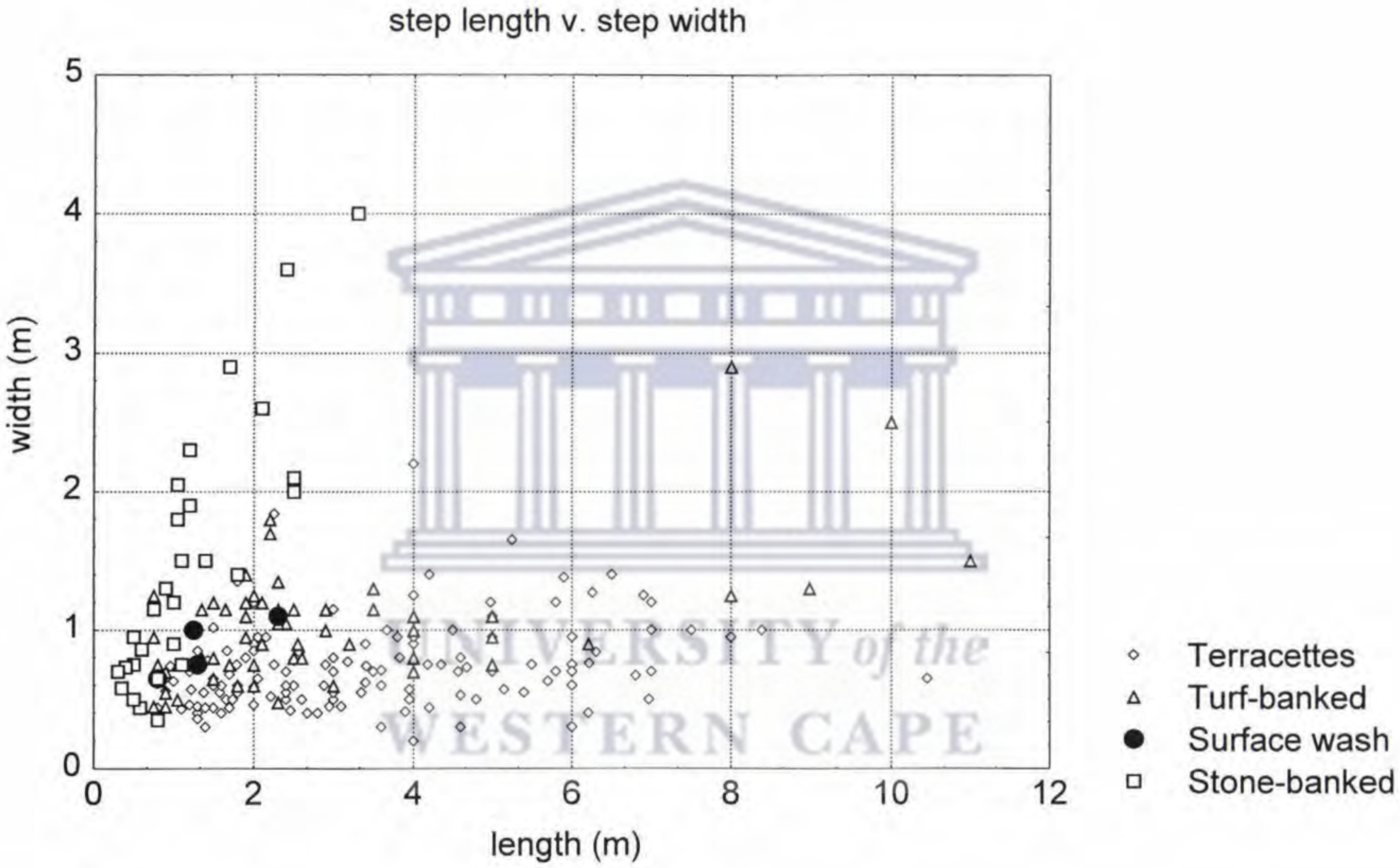


Figure 58. Scatterplot of step width against step length for the various groups of stepped micro-relief measured during the field survey.

stone-banked lobes which possess a predominant downslope dimension. Turf-banked steps at Mount Superior take an intermediate position. Widths and lengths of turf-and stone-banked micro-relief at Victoria Peak are more characteristic for terracettes. If step morphology is a manifestation of their forming processes, this may indicate that the forms at this site of very high precipitation and less evident frost action than at Mount Superior are of a more polygenetic origin, combining both processes of runoff and frost creep.

A conspicuous feature of the different terracette clusters is that lengths over 2m are only obtained on slopes with low clast abundance. Tread width appears independent of length for this last mentioned population. Two virtually identical terracette clusters formed on clast-rich debris slopes, one in sandstone diamict, the other in a shale debris containing small clasts. Both debris thickness and slope angle are comparable at these two sites. The smaller lengths obtained in both groups suggest that terracettes on slopes with abundant clasts are more discontinuous than those developed in finer material. This may be interpreted to indicate that the terracettes developed in coarse materials are not formed by uniform slow mass movement of the slope, but rather by particulate sediment transport influenced by obstructions on the slope, such as by surface wash. The steps developed by surface wash on near-level slopes form a distinct cluster characterised by their small dimensions and high width-to-length ratio, compared with the other terracette groups.

The scatterplot of height against width produces trends less supportive of the morphological classification of the stepped micro-relief forms (Fig. 59.). All clusters, with the exception of the 'surface wash steps' overlap to a great extent. A distinction between terracettes and stone-banked lobes is lost, while the similarity between the turf-banked steps and terracettes with low clast abundance populations is worth noting.

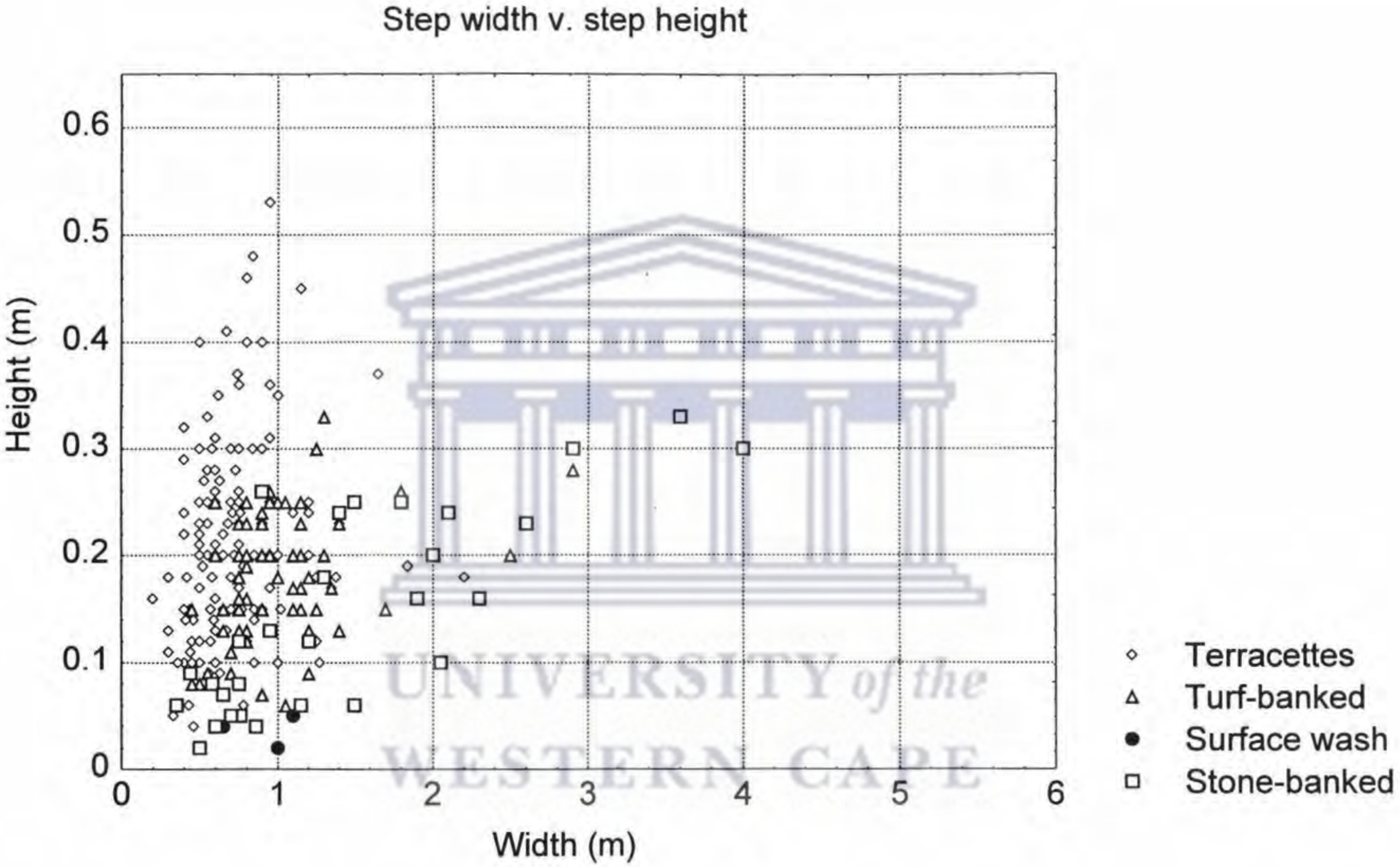


Figure 59. Scatterplot of step height against step width for the various groups of stepped micro-relief measured during the field survey.

The difference in clast size found on shale and sandstone debris slopes may well be related to the greater height-to-width ratio of the terracettes at Waaihoek relative to those at Matroosberg.

5.5.2. Origin of the stepped micro-relief forms

Terracettes

Terracettes have been studied in many parts of the world and various processes have been forwarded to explain their origin. Vincent and Clarke (1976) distinguish between processes of initial terracette formation and mechanisms by which their morphology, once created, is maintained. Initial formation of the steps is suggested to result from soil slippage, soil flow and soil creep, depending on topography, soil and vegetation characteristics. Animal disturbance may further be important in terracette formation and/or their maintenance of form (e.g. Higgins, 1982). Studies on terracettes in southern Africa have concentrated on the slopes of the main Escarpment in the eastern Transvaal and Natal Drakensberg (Troll, 1944; King, 1944, 1982; Verster et al., 1985; Verster and Van Rooyen, 1988; Garland, 1987; Watson, 1988; Day, 1993). Garland (1987), reviewing studies to that date, concludes that terracettes in the Drakensberg are of polygenetic origin including shear failure and sheetwash erosion as important initiating processes. Watson (1988) and Verster and Van Rooyen (1988) favour slow soil movement as initiating processes in terracette formation. Maintenance of form in the Drakensberg is achieved by soil scarp retreat due to rain splash, runoff and needle-ice growth (Garland, 1987).

Observations on terracette forms and measurement of soil movement rates in the sandstone debris mantles allow for discussion on terracette formation in the western Cape mountains. Indicators for terracette formation by slow mass movement were obtained from the flexible tubes sites and analysis of soil frost activity in the Waaihoek area. These data argue against soil creep or solifluction as significant mechanisms of terracette formation at present. The coarse nature of the sandstone debris, for which Atterberg limits could not be established, further argues against the occurrence of sporadic creep or soil slippage. The role of animal disturbance in terracette initiation or maintenance can also safely be discarded as domestic grazing animals are absent. Small antelope species are relativelyfew in number and do not follow each other in herds as required for cattle step formation (Higgins, 1982).

Both field observations and soil movement monitoring results suggest that runoff and splash are important agents for sediment movement on sandstone slopes. Detachment and transport of the sediment matrix occurs during the wet winter season when precipitation totals are high and continuity of moisture supply is maintained by snowmelt. The lack of cohesion due to sandy soils and low organic matter content further aids the mobility of the sediment. Surface features suggest that erosion and re-deposition of medium to coarse sand occurs over short distances. On a micro-scale, surface erosion appears to dominate on steeper slope sections with bare soil or where runoff is concentrated. Re-deposition will occur wherever runoff is retarded. The patterns of surface erosion and re-deposition are thus closely related to the roughness, clast abundance and vegetation density of the slope surface. This also reflects in the terracette morphology. Slopes with high clast abundance and small vegetation tussocks develop terracettes that are laterally more discontinuous than those on slopes with low clast abundance and more continuous, higher density, vegetation. The transient terracette features observed on near-horizontal slopes and entirely built of slope wash sediment are considered features formed at the end of a continuum of terracette forms developed essentially by surface wash processes.

A further factor in soil scarp maintenance could be the surfacing of throughflow at the riser. This was observed to take place on terracettes at the valleyhead above Hoare Hut, Waaihoek Peak, 25 November 1992. Small strips of aluminium were inserted 3.0cm into the profile at various heights collecting the discharge in beakers that were emptied every minute until the rate had stabilised (Fig. 60). By placement of traps immediately above each other the discharge was collected only from the cut section between the two traps. As expected, the discharge rates increased towards the base table. No sediment was trapped during this brief experiment but it is envisaged that continuous water seepage may aid particle removal from the riser surface, particularly at the foot of the riser. Needle ice growth would be very effective if this type of seepage would take place in frost-susceptible soils.

An important mechanism of terracette form maintenance by needle ice growth, also known as turf exfoliation or 'Rasenabschälung' (Troll ,1973; Pérez, 1992b), has been shown by field observations at Matroosberg above 1800m a.s.l. in this study and by Sänger (1988a). Pérez (1992b) shows this form of erosion by needle ice to be the dominant mechanism in terracette form maintenance in the Venezuelan Andes. High

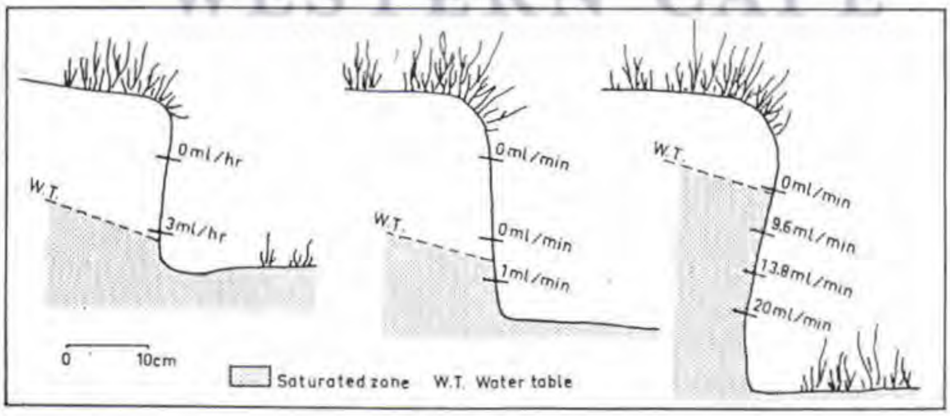


Figure 60. Rates of throughflow discharge at three terracettes risers near the summit of Waaihoek Peak (1910m a.s.l.), 25 November 1992.

winter precipitation in the western Cape mountains, however, results in runoff playing of the riser, which can readily be explained by the increase in head below the water an important role in terracette development. Observations at Wolseley ridge show that terracettes are also of widespread occurrence on shale slopes at altitudes where frost processes play no role. Needle ice growth is thus considered only a secondary process in terracette maintenance in the mountains of the western Cape.

Turf- and stone-banked steps and lobes

Both frost creep and solifluction are generally considered responsible for turf- and stone-banked stepped micro-relief (Benedict, 1970, 1976; Hansen-Bristow and Price, 1985; Butler and Malanson, 1989). Bending of grass roots in the turf-banked steps and surficial sorting in stone-banked features indicate that surficial frost creep is active in the upper 6 cm, primarily by needle ice growth.

Slow mass flow, or solifluction, is further considered active in the formation of both forms of stepped relief. High pore water pressures responsible for solifluction may result from thawing segregation ice in the surface layer, snow melt and high rainfall events (see Ch. 4).

5.6. DISCUSSION AND SUMMARY

The micro-climatic record as presented in chapter 4 has shown climatic conditions to be favourable for diurnal soil frost processes, primarily needle ice activity. Several factors however limit effective soil frost activity to occur. First, the quartzitic sandstones and quartzites of the Table Mountain Group make up over 90% of the higher parts of the western Cape mountains. The textural analyses discussed in chapter

4 and the regional field survey strongly indicate that the coarse textured sediments derived from these lithologies are non-frost susceptible at present throughout the region. A single site showing needle-ice activity in a sandstone-derived diamicton at Matroosberg forms the exception. On the other hand, sites at similar elevation on loamy soils from the Cedarberg formation show widespread evidence of cryogenic activity. The general absence of soil frost features in the summit regions of the western Cape mountains thus appears not to be due to unfavourable temperature or moisture conditions but is primarily a result of the coarse texture of the sandstone-derived sediment.

Sediments associated with the Cedarberg Formation are exposed at limited sites in the summit regions of the mountains. Where overlain by quartzite or sandstone strata the loam-rich sediment is frequently covered by coarse textured colluvial debris. Also, the arenitic strata overlying the shale band act as caprocks resulting in a high slope angle of the debris mantles covering the Cedarberg Formation. Location of the shale outcrops thus forms a second factor limiting conditions favourable for soil frost landforms to develop. A third control is exerted by altitude. Only at Victoria Peak (1590m), Mount Superior (1850m) and Matroosberg (1900m) was the frost-susceptible material found at a favourable location and sufficient altitude to develop.

Soil frost activity at all three sites is characterised by widespread evidence for needle-ice growth, resulting in frost creep at the soil surface, ejection and vertical tilting of clasts and patterned ground formation. Frost penetration by diurnal frost cycles develops only to depths of 30mm at Victoria Peak, 60mm at Mount Superior and 35mm at Matroosberg. Lowest frost penetration values are obtained at the site of lowest altitude (Victoria Peak, 1590m a.s.l.). This site is also positioned in the coastal mountain range which receives significantly higher precipitation in both summer and winter than the inland mountain ranges where Mount Superior and Matroosberg are positioned. This implies that soil frost landforms may be more readily destroyed at Victoria Peak by runoff than at the other two sites. Dimensions of the stepped micro-relief forms at Victoria Peak are more similar to terracettes at Waaihoek than the cryogenic steps and lobes at Mount Superior. One may speculate that this indicates runoff to play a role in their formation, despite the distinct cryogenic features found at their surface. The regional survey does, however, not provide any substantial information to make more hard statements on a possible gradient in current frost-process activity from the coast inland.

The results presented point out that runoff processes may be very important in sediment transport in the summit regions of the western Cape mountains, taking note that considerable sediment transfer by rapid mass wasting processes is not being considered in this study. Removal and re-deposition of arenaceous sediment and sporadic mobility of surface clasts are of widespread occurrence throughout the region. Slow mass movement by creep or solifluction could not be shown to occur for the sandstone-derived debris mantles and appear stable under present day climatic conditions. Isolated islands of cryogenic activity are found in loamy soils of the Cedarberg Formation at favourable sites above 1600m a.s.l.

CH 6. WEATHERING: PRESENT-DAY DEBRIS PRODUCTION MECHANISMS

6.1. INTRODUCTION

Weathering studies in southern Africa are said to be "limited in number and of a generalised and unquantified nature" (Hall, 1988a). This appears particularly valid for statements regarding weathering in the Western Cape region. Regional observations have focused on the origin of the extensive Pleistocene debris accumulations in the Table Mountain Series which extend down to sea level at the Cape south coast. These debris accumulations are generally argued to be cryoclastic in origin based on the angularity of the clasts (Butzer and Helgren, 1972; Butzer, 1973a,b; Lewis, 1988a). Based on this interpretation, a Pleistocene drop in temperature of 10°C is considered for this region (Butzer and Helgren, 1972; Butzer, 1973a,b; Deacon and Lancaster, 1988). Further, frost shattering has been claimed to occur at present at1900m elevation in the Western Cape mountains, based upon unspecified observations on the occurrence of angular clasts at Matroosberg (Sänger, 1988a).

It is evident that the understanding of the origin of the angular debris has major implications for the interpretation of Pleistocene landform development in the region. However, no evidence substantiating the occurrence of freeze/thaw weathering in the Western Cape region has yet been presented. In fact, Hall (1991) cautioned against the use of angularity of clasts as an indicator for frost weathering, as this clast characteristic can be produced by a variety of mechanical weathering processes, including salt crystallisation pressure, hydration of salts or clay minerals, thermally induced stresses on rock and salt minerals, as well as dilatation (Ollier, 1984; Yatsu, 1988; Hall, 1988b, 1991). Further, freeze/thaw frequently operates in close association with these processes (McGreevy, 1981; Fahey, 1985; Hall, 1988b, 1991) and so it seems impossible to discern the role of any individual process. To date, field evidence for recent frost action from the southern African subcontinent in the form of rock temperature and moisture monitoring is all but non-existent. Thus, the occurrence of recent, significant cryoclastic weathering in the region remains an open question.

In order to provide data on debris production in the Western Cape mountains, reconnaissance field observations of weathering features were made in the Waaihoek and Hex River mountains and in the areas visited during the regional field survey (Fig. 1). These are complemented by microclimatic monitoring to evaluate the potential for present day frost action and thermoclasty. Thus it is attempted to evaluate the range of weathering mechanisms potentially operating at present.

6.2. FIELD OBSERVATIONS

6.2.1. Chemical weathering features

A variety of weathering features associated with chemical alterations in the Peninsula sandstone and quartzites are noted and described individually.

Solution features

The release of mineral ions in either free pore water or a thin water film enveloping the mineral is considered one of the first chemical alteration processes to which rock is exposed (Ollier, 1984). The effectiveness of the process is largely determined by the solubility of the mineral and the mobility of the water passing through the rock (Winkler, 1973).

Solution features in the Table Mountain sandstones are of widespread occurrence and are clearly visible in microphotographs (Fig. 61). The thin section shows increased intergranular pore space and disaggregation of quartz grains at the rock surface. With depth the effects of dissolution of the secondary quartz overgrowth diminishes. Zones with highest permeability are most readily attacked, i.e. (micro)fractures, bedding planes and coarse grained sandstones. At a macro scale solution is visible by a rounding of rock surfaces and etching along joint patterns which form pseudo-karst rock formations (Fig. 62). This chemical action along the joint patterns has been suggested to render individual blocks unstable at rock exposures and to lower the threshold for rockfall (Rapp, 1960; Douglas et al, 1991).

The extent of chemical weathering, as reflected in fracture widening, rounding of edges and surface etching can positively be linked to the duration of subaerial exposure of the rock surface in cases where the Cedarberg Formation makes contact with the underlying thin band of tillite and/or Peninsula sandstone. Throughout the Western Cape mountains higher denudation rates in the shales have resulted in an erosion surface of a few ten or, in exceptional cases, some hundreds of metres wide (Fig. 28, p.67). With increasing distance from the contact of the shale-derived debris mantle pseudo-karst features become more pronounced on the bare sandstone surface. The fact that smooth rock surfaces exist at the contact with the soil strongly suggests that the solution features develop only after removal of the overlying shales and not due to subsurface weathering.

Surface induration and secondary iron precipitation

Despite the generally supermature nature of the Peninsula sandstone, iron oxide stained strata are not uncommon in the study area. It is generally considered that ferrous iron (Fe2+) released from primary minerals in an aerated environment is

Figure 61. Microphotograph showing dissolution of secondary quartz overgrowth which increases intergranular porosity in Peninsula sandstone at Waaihoek Peak. Exploitation by lichen thalli aids granular disaggregation at the rock surface.

Figure 62. High density joint and fracture planes are exploited by solution to result in pseudo-karst landforms in Peninsula sandstone at Waaihoek Peak.

oxidized to ferric (Fe3+) iron (Curtis, 1976). Because ferric compounds are insoluble in oxygenated water, precipitation takes place close to the site of weathering, or close to the change from reducing to oxidising conditions. The presence of organic molecules, however, may enhance its solubility (Curtis, 1976; Birkeland, 1984). On the other hand, under reducing (waterlogged) conditions Fe2+ is considered mobile over the normal pH range for soils (Birkeland, 1984).

The occurrence of iron staining throughout the rock in the Peninsula sandstone indicates low mobility of the iron and the occurrence of oxidation under aerated conditions. However, surface induration and secondary iron precipitation at the aerially exposed rock surfaces and along joint planes is also observed (Fig. 63). The induration is associated with enrichment of iron (hydr-)oxides, and secondary manganese oxides forming black coatings and dendritic patterns also occur. No evidence was found for enrichment by secondary silica which is considered common for soft porous sandstone in temperate environments (Robinson and Williams, 1987).

The mechanisms of surface induration are highly complex and understanding remains incomplete (e.g. Birkeland, 1984). From the above considerations, however, the development of iron-rich coatings indicates iron mobility under water-saturated conditions and/or over very long periods of time. This suggests that the induration could have developed at the sub-surface, and has consequently been exposed at the surface by denudation of the regolith.

6.2.2. Mechanical weathering features

Various forms of mechanical rock breakdown have been observed in the study area and result in a variety of forms decribed here.

Figure 63. Secondary iron (hydr-)oxide precipitation along joint surfaces results in relief inversion.

Unloading features

Denudation, subsequent upon Mesozoic folding in the Western Cape mountains, has resulted in steeply angled dip slopes and cliffs along which slab failure and rockfall occur. Residual stresses in the folded strata, as discussed in section 2.1.2, undoubtedly play a role in the generation of unloading features. Ample locations exhibit scree beneath sites of slab failures in support of this notion.

Thermal stress release induced forms

Throughout the Western Cape mountains intact quartzite and sandstone show active shattering features resulting in multi-faceted blocks; clasts with up to 14 facets are not uncommon. The fractures are conchoidal and are particularly present at the corners of the blocks, giving the clasts a rounded appearance (Fig. 64). That the

Figure 64. Multi-facetted boulder with conchoidally-shaped spalls at the summit of Slanghoek Peak (1694m a.s.l.) thought to be a result of fire-induced thermal stress release.

rounding is due to weathering rather than transport is indicated by the fracturing of bedrock, the occurrence of *in situ* fragments on the rock surface, and the recognition of fracture planes on *in situ* blocks. The fracturing occurs in clasts from 0.1m up to bedrock-attached blocks of 3m diameter.

The occurrence of conchoidal fracturing is restricted to intact quartzite and massive sandstone, with no similar active shattering of weathered sandstone being observed. Fracture planes deviating from this shape occur where stresses have been released along bedding and/or joint planes. The location of the fracture planes at the corners of blocks indicates the zones of highest stress which are thought to be thermally induced. The following arguments can be forwarded in favour of thermal stress release rather than frost action or other mechanical weathering mechanisms.

i) Conchoidal fracturing has only been observed on intact, massive sandstone and quartzite. Experimental studies have shown this material to be non-frost susceptible (see section 6.4.3.) and if it were operative then frost action would be expected to first exploit existing micro-fissures in the rock, rather than form new fractures in massive rock. The possibility of active frost shattering in these low porosity, non-frost susceptible rocks can safely be rejected. The absence of sorption-sensitive minerals (Dunn and Hudec, 1966) further precludes hydration as a potential shattering mechanism in these pure arenites.

ii) The geometry of the fractures at the corners and the flaking at the rock surface argues in favour of thermally induced stress by fires causing the rock breakdown and are very similar to those described by Blackwelder (1926), Emery (1944), Ollier and Ash (1983), Ollier (1984), Dragovitch (1993) and Ballais and Bosc (1992, 1994).

iii) Spalled fragments, blackened by smoke, were found beneath quartzitic sandstone boulders up to 1m above the surface where a fire had swept through dense fynbos two days before (Steenboksberg, 13/2/1995).

iv)Fires are of common occurrence throughout the region as discussed under 2.4.3.

Besides these arguments for fire accelerated mechanical weathering it is interesting to note the absence of conchoidally shaped debris on screes, which lack vegetation. This further points to the role of fires in inducing this type of conchoidal fracturing. Fires are common throughout the western Cape and may significantly contribute to the mechanically shattered debris found in the region.

During visits in the field frequent loud sharp sounds, like pistol shots, have been heard during the late morning and afternoon. Although they seemed to come from not far away in some cases, they were very difficult to locate. Early workers like Streeruwitz (1892) report on similar loud noises, which they relate to thermal stress release under diurnal temperature cycles.

Figure 65. Polygonal fracture patterns in sandstone similar to those described in Brown (1924) and Hall and Hall (1991) and suggested to be related to thermal stress release.

A further indication of thermoclasty is found in the almost polygonal fracture patterns on quartzitic sandstone and quartzite clasts (Fig. 65). These features show similarity with the fracture patterns illustrated by Brown (1924) and Hall and Hall (1991), for a Peruvian desert and the Argentinean Andes respectively. Superficial flaking of quartzitic sandstone and quartzites may further exemplify thermally induced spalling. Rock temperature records obtained and described below provide further data to evaluate the potential for thermoclasty by insolation.

Hydration shattering features

Shattering, as opposed to wedging, of sandstone bedrock occurs in the few sandstone strata containing clays and feldspar (Fig. 66). Cubic shaped angular blocks distinguish this type of shattering from the conchoidal fracturing described above. Rust-

Figure 66. Cubic fracturing in clay-rich sandstone may be related to hydration of clays or volume changes upon chemical alterations.

brown weathering rinds have thicknesses of 3-10mm. Clay mineral analysis by Thamm (1988) indicates kaolinite and illite as the main components in the Table Mountain Series. Hydration pressures from water adsorption and consequent swelling have been considered as an important mechanism for shattering of clay-rich sedimentary rock (White, 1976; Hall, 1991). Chemical alteration of impurities by hydration and other reactions may further result in volume changes which have been argued to play a role in rock breakdown (Brunsden, 1979; Trenhaile, 1987) Again, the allocation of the hydration mechanism for shattering in these sandstones remains unproven and can safely be excluded as a potential weathering mechanism in the Peninsula sandstones due to the low clay content in this rock type. However, hydration may be potentially highly effective in the clay containing sedimentary rocks (e.g. of the Graafwater and Cedarberg Formations).

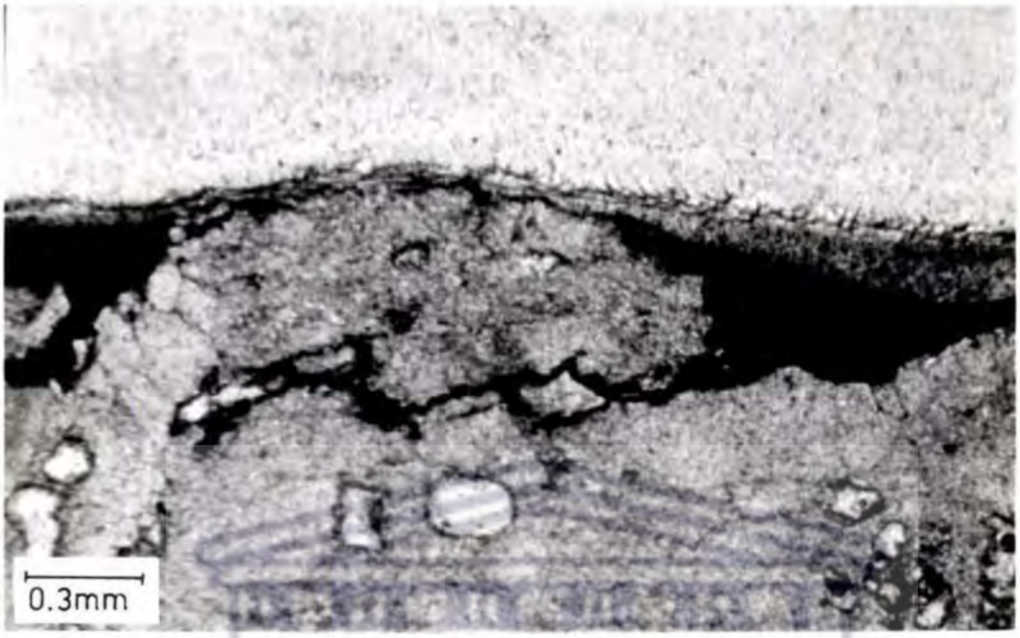


Figure 67. Lichen thalli penetration in a surficial microfracture responsible for flaking by both biochemical and biomechanical action.

1990; Cooks and Otto, 1990).

Microphotographs demonstrate the role of lichens in disaggregation and flaking at the rock surface of the Peninsula sandstone (Figs. 61, 67). Figure 67 illustrates thalli penetration by epilithic lichen in an existing surficial microfissure. Active widening of the fracture by the lichen has occurred and thus shows the potential for flaking. This type of action has been attributed to both biomechanical action in the form of hyphae penetration and thalli expansion, as well as biochemical action in the form of dissolution, organic acid production and chelation (e.g. Viles, 1984; Cooks and Otto, 1990). Colonisation by lichen of intergranular pore spaces is illustrated in Fig. 67. Primary weathering has taken place by solution, as described above, thus creating a habitat suitable for hyphae penetration. The lichen growth enhances rates of granular disaggregation by the complex interaction of the factors listed above (Viles, 1984;

Cooks and Otto, 1990).

6.2.4. Weathering of the Cedarberg Shale

Mechanical shattering dominates, and is very active at present, at the Cedarberg shale outcrops near Mt. Superior (1850m a.s.l.). Screes of up to 20m long, built of very angular shale fragments, underlie small rock faces up to 1.5m high (Fig. 68). The exposed shales are extensively fractured and easily loosened by hand. Cedarberg shale outcrops at Victoria Peak (1594m a.s.l.) are found in a similar topographic position as at Mt. Superior. Bedrock surfaces here show superficial cracking only and extensive breakup of the material is absent. The shale debris is moderately rounded with only bedrock attached flakes showing high angularity (Fig. 69). Observations at other sites in the region failed to find Cedarberg shale exposed (Matroosberg, Slanghoek Peak, Wolseley Ridge). From the amount of debris present at both sites mechanical weathering rates at Mt. Superior appear significantly higher than at Victoria Peak. The higher degree of roundness of shale fragments at Victoria Peak is considered a result of longer subaerial exposure of the fragments and/or higher chemical weathering rates due to somewhat higher temperatures and the significantly higher precipitation at this site (CSIR, unpubl. data).

Weathering mechanisms responsible for the effective shattering of the shale at Mt. Superior may be attributed to both hydration and frost action. Insolation weathering may contribute to fracturing at the rock surface, such as shown to occur at Victoria Peak in Fig. 69. Hydration shattering, on the other hand, may play an important role in fragmentation of the shale as this lithology is considered highly sorption sensitive (Dunn and Hudec, 1965; 1972). Expansion and contraction in response to wetting and drying may occur well beneath the surface and result in extensive fracturing of the rock, such as experienced at the site. If, however, the shale is indeed sensitive to hydration

Figure 68. Bedrock shattering and scree in Cedarberg shale near Mt. Superior (1820m a.s.l.). Note the fresh nature and high angularity of the fragments at this site. For location of the screes see also Figure 32, p.73.

Figure 69. Shale outcrop at the summit of Victoria Peak (1594m a.s.l.). Note the subrounded edges of the fragments and lesser amount of debris compared with the site in Figure 68.

shattering the question arises why the shale exposures at Victoria Peak appear relatively unaffected by this weathering mechanism? Three possibilities may be suggested here. First, Victoria Peak receives higher amounts of moisture in summer from cloud cover and coastal rain that does not reach the inland mountains of which Mt. Superior is part. This may result in fewer wetting and drying cycles at Victoria Peak if rock moisture levels were maintained throughout summer in this manner. Field observations suggest, however, that rocks do dry between precipitation events and that, rather, a higher frequency of wetting and drying cycles in summer is experienced at this site than at Mt. Superior. Second, intense folding at Mt.Superior has rendered the Cedarberg shale highly stressed, as indicated by the high density cleavage planes in the rock (c.f. De Swardt et al, 1974). This could not be noted for the shales at Victoria Peak. The importance of microcrack patterns in facilitating bedrock fracturing are emphasized by Douglas et al (1991, p. 316) who state that:"...cliff disintegration is as much controlled by the rock properties as by the climate". Third, hydration shattering may operate synergistically with other weathering mechanisms at Mt. Superior, notably frost action, for which conditions are unfavourable at Victoria Peak.

No rock temperature measurements are available from Victoria Peak. Observations on soil frost activity do indicate freeze-thaw cycles to be more effective at Mt. Superior (see Ch.4). As this difference is largely attributed to altitudinal control on temperature, freeze-thaw cycles at the rock surface may also be considered to be less frequent and less intense at the Victoria Peak site. Rock surface temperatures were measured to evaluate the frequency and intensity of freeze-thaw cycles at Mt.Superior. The results are presented and discussed in section 6.4.

6.2.5. Tors

Throughout the region slopes underlain by sandstones of the Cape Supergroup feature tors and rocky buttresses varying in size from a few stacked boulders to those the size of castle kopjes (Figs. 70, 71). They are of widespread occurrence irrespective of altitude. In most areas the surfaces of the sandstone blocks are typically rounded and show micro weathering features such as weathering pits and pans, grooved surfaces, etching along bedding planes, relief inversion by case hardening and generally sustain an extensive lichen cover. In the summit regions of the Hexriver and Waaihoek Mountains qualitative observations suggest a significantly higher degree of mechanically shattered sandstone blocks that make up the tors (Fig. 71). Micro-weathering features such as found on the tor surfaces at lower altitudes are here found to be less pronounced or completely absent and superimposed on the angular blocks.

As tors occur in a wide range of environments several explanations of their formation have been proposed (Embleton and King, 1975; Ollier, 1984). In essence all refer to differential rates of subsurface weathering and erosion of its products. For non-periglacial environments the origin of the tors has been related to two phases of development. During the first stage deep subsurface weathering under warm, humid conditions preceeds the second stage during which stripping of the regolith exhumes the resistant bedrock and corestones (Linton ,1955; Ackermann,1962; McCraw,1965). Demek (1964) favours this hypothesis for tor development in Bohemia with the specification that the stripping took place under periglacial conditions in the Pleistocene. The tors were subsequently subjected to frost action and periglacial mass wasting. Single stage development under periglacial conditions has been proposed by Demek (1964) and Czudek (1964) for the Bohemian and Moravian mountains respectively, whereby cliff retreat by frost action results in tors surrounded by cryoplanation terraces.

Figure 70. Small tors protruding through dense fynbos near Wolseley Ridge (540m a.s.l.). Note the generally pitted and rounded nature of the rock surfaces.

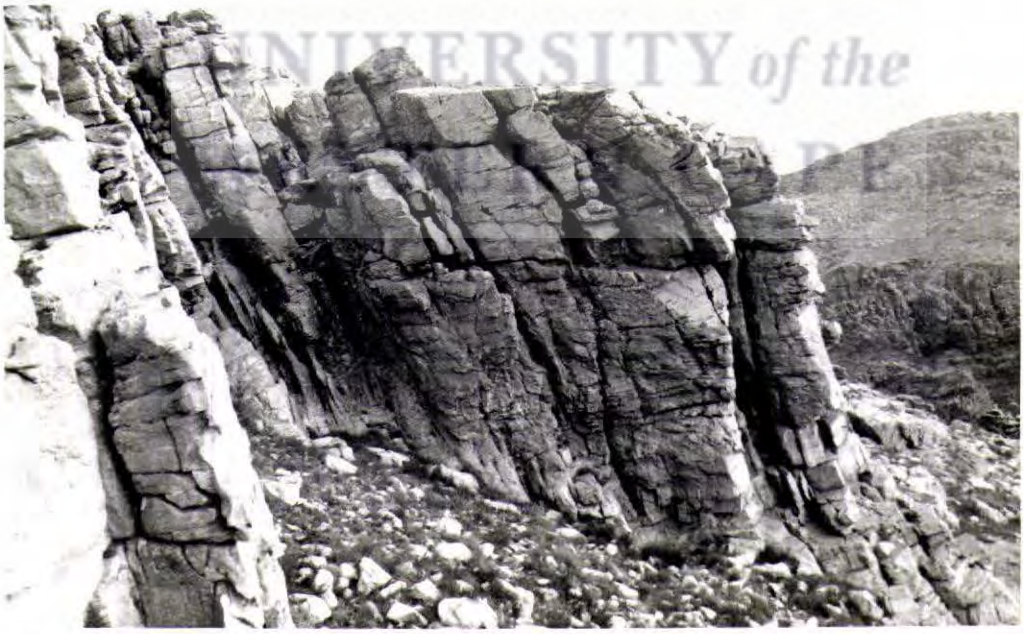


Figure 71. Tor near Mt.Sentinel at 1740m a.s.l.. Note the high density of both horizontal and vertical joint planes and the generally angular nature of the rock.

The suggestion by Linton (1955) that a phase of deep chemical weathering is a necessity for development of the Dartmoor tors seems largely based on the rounded appearance of the corestones. Both Selby (1972) and Derbyshire (1972) however observed tors with both rounded and angular rock surfaces in Antarctica. Chemical weathering has since been well established to be an important process in periglacial environments. The necessity to invoke a two stage development to account for the rounded appearance of the blocks that make up tors thus seems unwarranted. In a similar vein the dangers involved in linking angularity with frost action have been pointed out earlier. Frost action should not be uncritically assumed if based solely on the angular shape of tor material.

Tor development in the Western Cape is suggested to be the result of ongoing differential weathering between zones of higher and lower fracture density and surface removal of the regolith, the relative rates of which will fluctuate under varying climatic environments. Warm humid conditions during the Tertiary resulted in deep kaolinitic weathering of granite in the region (Lambrechts, 1983) and may have been favourable for differential subsurface weathering in the quartzitic sandstones. Field observations, however, suggest that chemical action on sandstone surfaces dominates under present day subaerial conditions. This point is most strongly supported by observations on the pseudo-karst formation on bedrock surfaces exposed by the relatively rapid lateral slope retreat of the Cedarberg shale. There is no reason to suggest that the rounded appearance of blocks on a 20 meter high rock buttres is the result of subsurface weathering. Similarly, the extent of mechanical fracturing on the rocky butresses in the summit regions and their subsequent modification by chemical processes indicates that a significant amount of subaerial weathering has taken place since exhumation. The tors can thus be considered to be of considerable age and the shape of their surfaces a result mainly of subaerial weathering subsequent to exposure. Ongoing differential denudation rates between zones of higher and lower weathering resistance will determine the size and extent of the tors.

Summary

Although none have been studied in any detail it appears that a wide spectrum of chemical, mechanical and biological processes are contributing to debris production in the western Cape mountains often in close association with each other. Results for the arenaceous lithologies, ordered by size of the debris produced, are summarised in Table 24. Chemical weathering features dominate in the field at present and result in the release of fine grained debris. Solution along planes of weakness further aids rockfall both directly, and by facilitating the operation of other weathering mechanisms. Fires may be considered an important agent for mechanical weathering at present.

Process	Mode	Debris type	Lithology
Solution	granular disaggregation	grains / solutes	sandstone
Oxidation	case hardening	solutes / precipitates	Fe-rich sandstone
Lichen growth	flaking / granular disaggregation	grains / flakes	sandstone / quartzite
Thermal stress	flaking / shattering	flakes /angular blocks	quartzite
Hydration	shattering	angular blocks	clay-rich sandstone
Frost action	wedging	angular blocks	sandstone / quartzite
Dilatation	slab failure / rockfall	angular blocks	sandstone / quartzite
Solution (along joints)	rockfall / toppling	(sub-)rounded blocks	sandstone / quartzite

Table 24: Summary of observations on present-day weathering phenomena and their products in the Western Cape mountains.

6.3. THE ROCK TEMPERATURE RECORD AND THERMOCLASTIC WEATHERING

6.3.1. Introduction

Mechanical rock breakdown under the influence of thermally induced stresses is known as thermoclasty (Brunsden, 1979; White et al, 1984). Thermal stress may be effected due to variations in receipt of solar radiation at the rock surface (insolation) and with favourable rock properties, and is commonly referred to as insolation weathering (Brunsden, 1979; Ollier, 1984; Goudie, 1989; Cooke et al.,1993). The poor thermal conductivity of rock may result in steep internal temperature gradients when subjected to radiational heating or cooling of the surface. Also, fluctuations in the radiative heat exchange with the surrounding air may cause expansion upon heating and contraction upon cooling of the rock surface and thus induce mechanical stress. As different minerals possess different thermal properties this may further result in differential expansion/contraction rates within polymineral rocks. Fires are also a well known heat source to induce thermal stress capable of mechanically fracturing rock surfaces, a process referred to as "ignifraction" by Ballais and Bosc (1992,1994).

Early field observations reported spalling under the influence of diurnal temperature ranges (Streeruwitz, 1892), but the experiments of Blackwelder (1925) and Griggs (1936) appeared to disprove the operation of such a mechanism. Gray (1965) and Rice (1976) however re-opened debate by pointing out that the laboratory experiments by Blackwelder (1925) and Griggs (1936) were not representative of field conditions by using small, polished, rock samples and subjecting these to unnatural temperature conditions. Under confined conditions the small thermal expansion rates induced by diurnal temperature fluctuations are argued to possibly result in breakdown with time (thermal fatigue), particularly for large rocks (Rice, 1976).

On the other hand, permanent strain by fracturing may be sustained by sudden temperature changes, also referred to as thermal shock (Yatsu, 1988). Richter and Simmons (1974) found that sudden temperature changes induce sufficient thermal stress to cause rock breakdown if the rate of change is >2°C/min in igneous rock cylinders of 1cm diameter and 5cm length. As thermal properties vary between different rock types this value has no direct relevance to this study, but the results point to the potential of sudden temperature fluctuations inducing *effective* thermal stress in a wide variety of natural environments. Measurement of temperature gradients in the field over short time intervals are much needed to verify how commonly such values are obtained. Assessment of thermal shock can, however, only take place if temperature values from the field can be related to the known thermal properties of the rock types concerned.

Spalling by thermal stress, on its own or in association with salt weathering, is traditionally associated with hot desert environments. Including their own data, Kerr et al. (1984) list ten studies that provide field data on rock surface temperatures in hot deserts. Maximum values recorded vary between 42 and 79.3°C. The importance of absolute maximum temperatures in relation to thermal stress may however be questioned, as it is the temperature variation in time and with depth that determines the extent of thermal stress generated in a particular rock. They do however provide data on the natural thermal regime of rocks in which thermal fatigue is considered potentially operative.

Researchers of the mechanisms of frost weathering have a long standing pre-occupation with rock temperature. This focus does not only relate to temperature conditions required for the freezing of moisture in rock (McGreevy and Whalley, 1982), but thermal stress, particularly thermal shock, has also been considered as a potential mechanism of rock breakdown in cold environments (Eichler, 1981; Hall and Hall, 1991). In the simulation experiments by Hall and Hall (1991) rock surfaces, of unspecified lithology, are heated by infra-red lamps when at an air temperature of -19°C. Heating rates of 8.3°C/min were recorded immediately upon switching on of the lamps. This value is however of limited use in relation to field conditions where air temperatures of -19°C, during the day, are seldom attained. Also, heating rates may have been exaggerated by the use of an artificial heat source.

In contrast to the much debated contribution of insolation to thermoclasty, spalling by fires is a well accepted mechanism of rock breakdown (Blackwelder 1926; Emery, 1944). Birkeland (1984) considers fire an important weathering agent for the forested mountain slopes in western Colorado, while Ballais and Bosc (1992, 1994) report on ignifraction (spalling by fire) in scrubland in southern France. Dragovitch (1993) describes spalling and fracturing aided by fire in semi-arid shrubland of the Pilbara, Western Australia. In all these studies a specific clast shape is associated with spalled rock fragments. Birkeland (1984) describes thin sheets of spalled fragments breaking off boulders with more rounded corners. Ballais and Bosc (1994, p.220) describe the ignifracts in detail using statistical parameters and conclude: "...ignifraction provides specific material which can easily be identified from its flattening index". This result appears to be independent from lithology (limestone and limestone breccia). Dragovitch (1994, p.298) recognised fire-induced spalling by "...sharp-edged small fragments... detached from a large boulder that then became more rounded; vertical fracturing...irregular linear and curvilinear fractures...). Spalled fragments were noted to be further broken down by later fires.

The evaluation of thermoclasty in the study area needs to consider rock temperatures under both summer and winter conditions, while further attention needs to be given to the role of fires, supported by field observations. Thermal stress must be considered in terms of temperature fluctuations with time and in terms of internal rock temperature gradients, both on a daily basis (thermal fatigue) and on the short term (thermal shock). Available data include (1) diurnal maximum-minimum temperatures in a sun-exposed and shaded crack of a quartzitic sandstone rock surface as well as a sun-exposed crack in Cedarberg shale; (2) surface and internal temperatures at ten minute intervals from a quartzitic sandstone and shale clast; (3) surface and internal temperatures at one minute intervals from a quartzitic and shale clast. Results are presented in the following sections.

6.3.2. Diurnal rock temperature regimes

Daily maximum and minimum temperatures provide first field data to characterise daily rock thermal regimes with respect to thermal fatigue potential. Rock surface temperature was measured in Peninsula quartzitic sandstone (further referred to as sandstone) over three summers (1991/2-1993/4) and three winters (1992-4). Two temperature sensors were placed in cracks at the rock surface. The first sensor was placed on a large boulder with a length of 1.4m, width of 0.6m and height of 0.45m. The sensor was placed on its west-facing surface (aspect 260°) which dips at 26°, in a surficial crack at a height of 22cm above the ground. The crack has a width of 7mm and maximum depth of 17mm with the sensor inserted to a depth of 9mm. This rock surface receives direct insolation from late morning onward and care was taken that the sensor itself was not directly exposed. The second sensor was placed in a crack of a bedrock attached block of 1.9m long, 0.75m high and 0.5m wide. The sensor was positioned on a near-vertical surface with an aspect of 100° (ESE) in a crack at 12.2cm above the ground. The crack had a width of 13mm and a maximum depth of 29mm which is the depth at which the tip of the sensor was placed. The sensor was always in shade but the rock surface received early morning sun for a brief period of time, depending on the season. The sensor tips were wedged in the crack thus measuring the air temperature at the rock surface in the crack. No compounds were applied to improve contact between the sensors and the rock surface. The data from the east-facing rock surface thus present values for a shaded site while the data from the west-facing rock surface represent a sun-exposed site. The sites will further be referred to in this way. A third sensor recorded rock surface temperatures on sun-exposed Cedarberg shale during the winter of 1993 and the summer of 1993/4. This sensor was positioned in a rock crack of 4mm width at 15mm depth.

Daily rock surface maximum temperatures

Daily maximum temperatures obtained during summer (December, January, February) and winter (June, July, August) are described in frequency histograms (Fig. 72). As the histograms for each individual year closely corresponded with each other, seasonal data of all three years were lumped together for the compilation of the histograms. Variations in sample size necessitate presentation of frequency in percentages, to allow comparison between sites and/or seasons. Table 25 presents summary statistics comparing winter and summer maximum temperatures of all three years for shaded and sun-exposed sandstone.

Winter maximum temperatures on shaded sandstone range from 0 to 19°C, and from 0 to 29°C for the sun-exposed sandstone. The frequency distributions for both sites show a positive skewness and negative kurtosis but the latter is more pronounced for the sun-exposed sandstone. These trends are however influenced by the somewhat bimodal distributions. Both curves peak at maxima in the range 0-2°C which are related

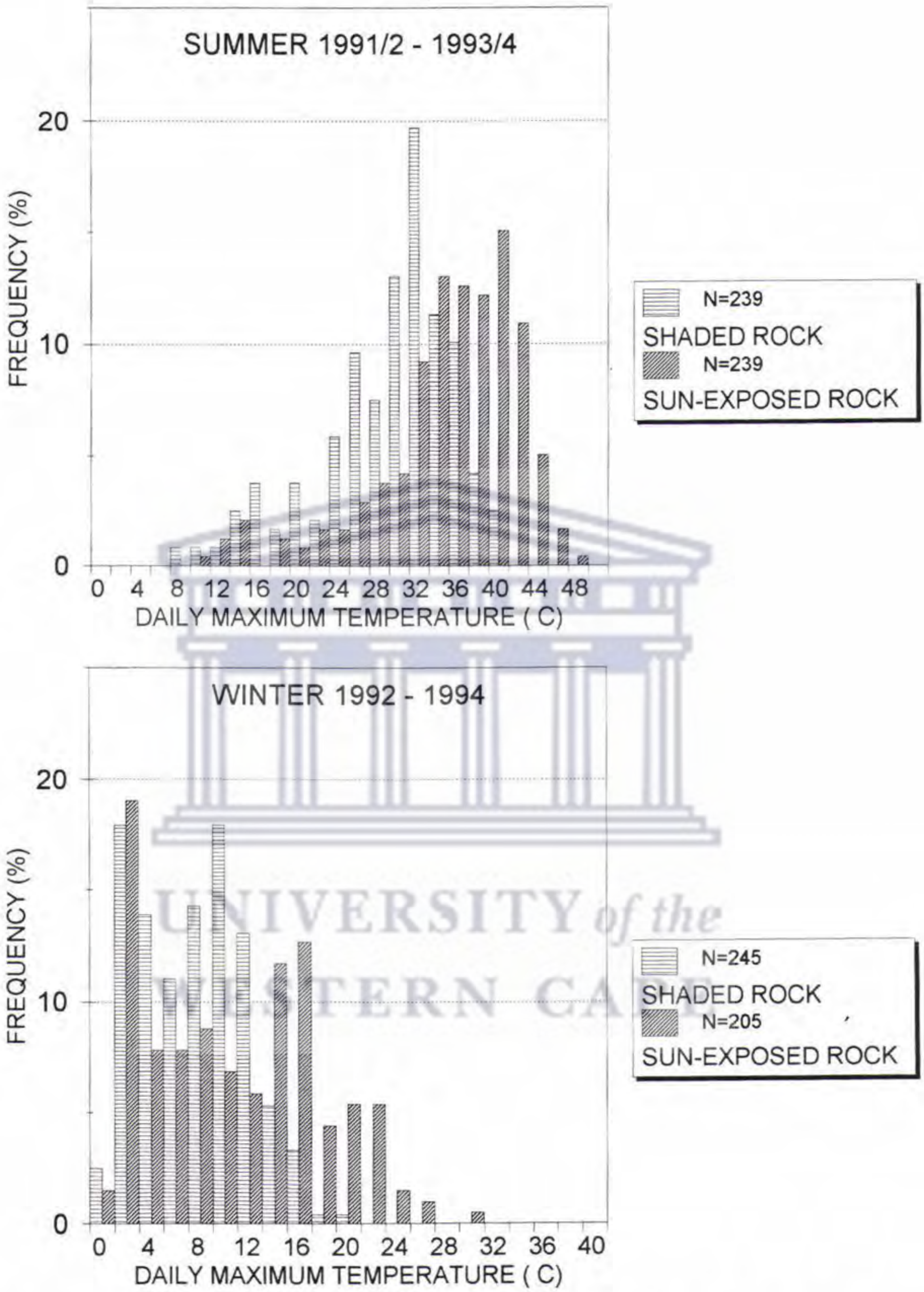


Figure 72. Frequency histograms of daily maximum temperatures in summer and winter on a shaded and sun-exposed sandstone surface at Waaihoek Peak.

Statistic	Summer 1991/2 - 1993/4		Winter 1992 - 1994	
	Shaded	Sun-exposed	Shaded	Sun-exposed
Sample size	239	239	245	205
Minimum	6.3	8.8	-0.7	-0.4
Maximum	39.9	46.6	19	28.5
Lower quartile	24.8	31.2	2.8	3.3
Median	29.6	35.1	6.5	9.6
Upper quartile	32.3	38.9	9.5	12
Skewness	-0.95	-1.27	0.24	0.2
Kurtosis	0.57	1.85	-0.75	-0.99

Table 25. Summary statistics for frequency distributions of daily maximum temperatures in summer and winter at a shaded and sun-exposed sandstone surface at Waaihoek Peak.

to periods of snowcover, which is present over about 20% of the time in winter. The second peak is obtained at temperatures around 6-12°C (shaded site) and 12-16°C (sun-exposed site), with the latter obtaining a 3°C median value. This difference can be attributed to variation in insolation between the two surfaces. The absolute values obtained for both sites are only moderate. This is not only due to low solar radiation levels, but also due to the high incidence of cloud cover that characterises the winter season.

Daily maximum temperatures on the sandstone in summer range from 6 to 40°C in the shade and from 9 to 47°C on the sun-exposed sandstone surface (Fig. 72, Table 25). Median and quartile values for the sun-exposed site are about 6.5°C higher than for the shaded site due to additional daily heat influx. Both distribution curves show a negative skewness due to outliers found on the lower end of the value range. These values are related to low frequencies of overcast days, associated with weak atmospheric disturbances in summer. Rock surface maxima are relatively low for the sun-exposed site compared to those reported in the literature (c.f. Brunsden, 1979; Kerr et al., 1984). It must be remembered, however, that the sensors measure temperatures at the air/rock contact at the bottom of cracks and not directly at the rock surface itself. This aspect is further discussed under 6.4.6.

Lithological control on daily maxima

The influence of lithology on daily maximum temperatures can be described by comparing the data obtained from sun-exposed Cedarberg shale with the Peninsula sandstone rock surfaces. Data are available from only a single winter (1993) and summer season (1993/4). The frequency histogram and summary statistics for both winter and summer data are presented in Table 26 and Figure 73, respectively. Winter maxima for 1993 on sandstone range between 0 and 21°C and for shale between 0 and 35°C. The median for the values obtained from the sandstone surface is 9.4° C and 14.5°C for the shale. The distribution curves for both sites are almost symmetrical with values for the sandstone being more evenly distributed than for the shale surface. The peak in maximum values between 2-4°C in the sandstone record can again be related to snowcover in winter. This peak is absent in the shale record. A main difference in the frequency distributions between the two records is the wider range in rock surface temperatures for the shale.

Explanation of this difference needs to consider both variations in lithological and site characteristics. Lithological characteristics include albedo and rock thermal properties, while relevant site characteristics are cloudiness, snowcover, rock surface orientation and inclination, height of the sensor above the ground (in relation to snow cover). As it is impossible to separate the influence of all these variables no definite conclusions can be drawn. It is felt, however, that the lower albedo of the dark coloured

Statistic	Summer 1993/4		Winter 1993	
	Shale	Sandstone	Shale	Sandstone
Sample size	90	89	92	61
Minimum	7.8	8.8	-0.3	-0.42
Maximum	52.1	45.2	35.3	21.2
Lower quartile	34.8	31.5	6.4	3.5
Median	39.6	37.7	14.5	9.4
Upper quartile	43.2	40.6	21.2	14.8
Skewness	-1.59	-1.58	0.08	0.1
Kurtosis	3.11	2.52	-0.66	-1.2

Table 26. Summary statistics for the frequency distribution of daily maximum temperatures in winter and summer on a sun-exposed shale and sandstone surface, at Mt.Superior and Waaihoek Peak, respectively.

shale as compared with the light coloured sandstone plays a role in explaining the high shale maxima. Further, comparing the precipitation record at both stations it is evident that the sandstone site at Waaihoek Peak received significantly higher precipitation amounts than the shale site at Mt. Superior (Table 19, p.89). These records and field experience suggest higher cloudiness and snowcover frequency and thickness at Waaihoek Peak. These site factors may to a large extent be responsible for the higher peakedness of the sandstone frequency curve. The difference in sample size between the two data populations does not influence the nature of the two curves, as shown by the distribution curves produced when only the months July and August 1993 are considered (Fig. 73c).

The frequency distribution curves for the shale and sandstone surface maximum temperatures in the summer of 1993/4 show very similar trends (Fig.73a). However, maximum temperatures for the shale range up to 52°C, slightly higher than for the sandstone (45°C). Median values are very similar at 38°C (sandstone) and 40°C (shale)(Table 26). Both curves show distinct negative skewness and positive kurtosis, of which the latter is most pronounced for the shale. The clear sky conditions

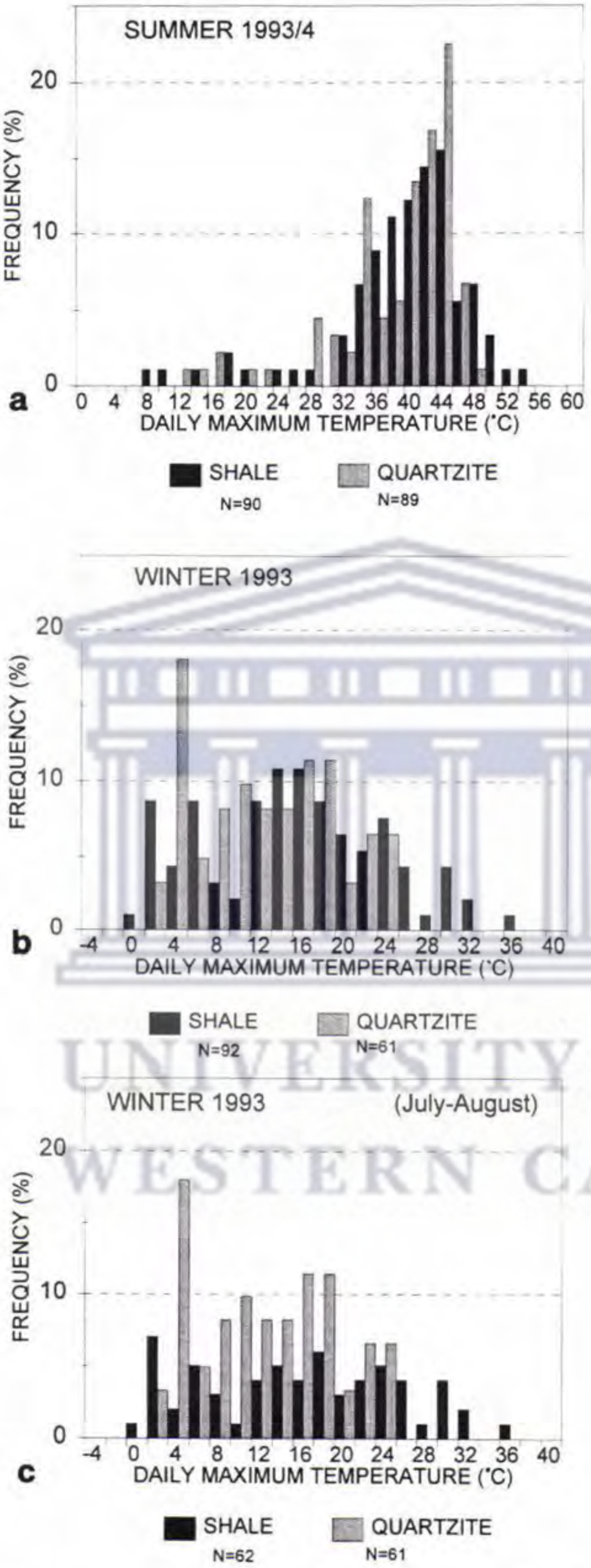


Figure 73. Frequency histogram of daily maximum temperatures in a) summer and b) winter, on a sun-exposed shale and sandstone surface. Figure c) presents a frequency histogram for winter temperatures in July and August 1993 only. See text for further explanation.

characteristic for summer are responsible for the high peakedness of the curve as this results in little day-to-day variation in radiation inputs and rock moisture conditions. Lower maxima obtained under cloudy conditions result in the distinct skewness of the curves. The lower and upper quartile values indicate that summer temperatures characteristically vary between 31.5 and 40.6°C for sandstone and 34.8 and 43.2°C for shale. These values also show this record is not able to show differences in maximum temperatures due to lithological variations under clear radiation conditions. This may however be, to a large extent, due to the positioning of the sensors in rock cracks and not directly at the rock surface.

Daily rock surface temperature range

The daily rock surface temperature range was analysed using the same data sets and methods as applied for the maximum rock surface temperatures described above. Frequency histograms of daily temperature ranges of shaded and sun-exposed sandstone are presented for winter and summer (Fig. 74). Summary statistics are given in Table 27. Daily temperature ranges in winter for the shaded site produce a virtual normal distribution around a median value of 6°C. The sun-exposed site shows a bimodal distribution. The peak in the lower range values (2-6°C) is attributed to low diurnal temperature ranges as a result of snow cover. The second, and much more pronounced, peak at 10-14°C is considered representative for snow-free conditions in winter. Typical winter conditions with high cloud cover and low direct radiation values explain the moderate values for the daily temperature ranges of both surfaces. Higher daily temperature ranges are caused by direct solar radiation during the day resulting in higher maximum values for sun-exposed rock surfaces (Fig. 74). Higher temperature ranges for the sun-exposed surfaces relative to the shaded site can thus be seen as a

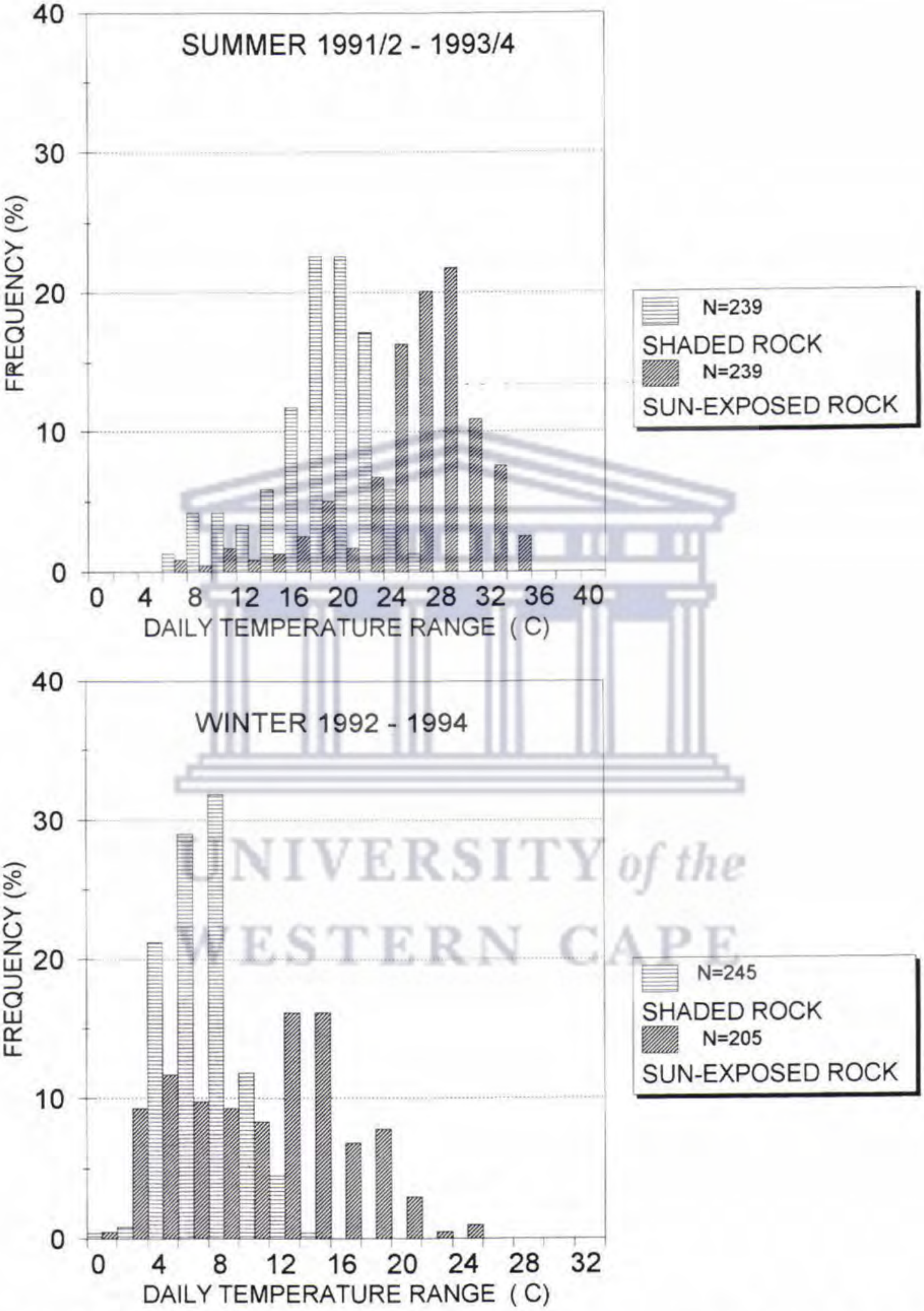


Figure 74. Frequency histograms of daily temperature ranges in summer and winter on a shaded and sun-exposed sandstone surface at Waaihoek Peak.

Statistic	Summer 1991/2 - 1993/4		Winter 1992 - 1994	
	Shaded	Sun-exposed	Shaded	Sun-exposed
Sample size	239	239	245	205
Minimum	5.0	5.0	-0.3	-0.0
Maximum	24.7	33.4	12.5	18.9
Lower quartile	15.3	22.6	4.4	4.2
Median	17.6	25.2	6.0	9.3
Upper quartile	20.0	27.8	7.1	12.4
Skewness	-0.9	-1.26	0.29	0.02
Kurtosis	0.49	2.03	0.03	-1.12

Table 27. Summary statistics for frequency distributions of daily temperature ranges in summer and winter at a shaded and sun-exposed sandstone surface at Waaihoek Peak.

result of day-time warming by direct solar radiation.

Characteristic daily temperature ranges in summer as indicated by the interquartile range vary between 15.3 and 20°C for the shaded rock and between 22.6 and 27.8°C for the sun-exposed rock surface. The quartile values are about 7.5°C higher at the sun-exposed site. Both frequency distributions are negatively skewed due to a relatively low number of cloudy days, while the platykurtic distribution of values for the sun-exposed site is caused by a higher range in values obtained at this site.

Lithological control on diurnal temperature range

Daily temperature range values of sun-exposed sandstone and shale rock surfaces are compared in Table 28 and Figure 75. Winter values for the shale surface range widely, between 1 and 34°C, while the sandstone surface obtained temperature ranges between 0 and 18°C. The median of the sandstone data (8.8°C) is somewhat lower than the median for the shale values (12.5°C). Differences in the distribution curve are mainly attributable to variations in site characteristics. Lower cloud cover and precipitation totals at Mt. Superior best explain the higher temperature range values at the shale surface.

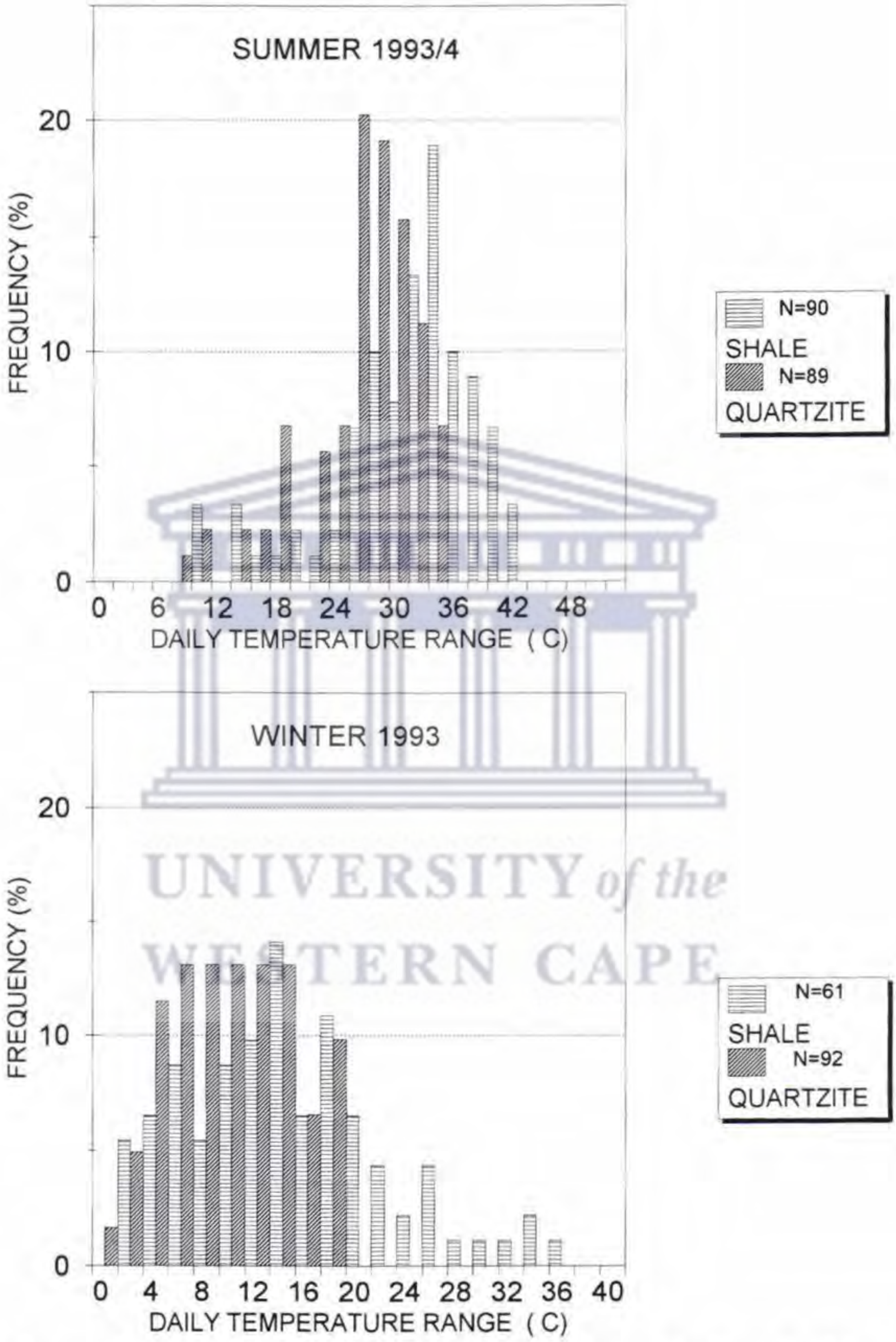


Figure 75. Frequency histograms of daily temperature ranges in summer and winter at a shale and sandstone surface, at Mt.Superior and Waaihoek Peak, respectively.

Statistic	Winter 1993		Summer 1993/4	
	Shale	Sandstone	Shale	Sandstone
Sample size	92	61	90	89
Minimum	0.8	0.0	8.3	6.9
Maximum	34.3	17.8	41.1	33.4
Lower quartile	7.4	4.7	26.7	23.8
Median	12.5	8.8	31.7	26.3
Upper quartile	17.7	12.5	34.4	29.2
Skewness	0.57	0.07	-1.21	-1.23
Kurtosis	0.02	-0.98	1.30	1.38

Table 28. Summary statistics for frequency distributions of daily temperature ranges in summer and winter at a shale and sandstone surface, at Mt. Superior and Waaihoek Peak, respectively.

Summer values for the shale surface vary between 8 and 41°C and for the sandstone between 7 and 33°C (Table 28, Fig. 75). The distinct negative skewness and positive kurtosis is attributable to predominantly clear sky conditions in summer, associated with high diurnal temperature ranges. The low frequency of overcast days results in the lower end outliers. The median value of the shale is about 5.5°C higher than for the sandstone and points at an influence of lithology on diurnal temperature range, with higher values being obtained at the shale surface under clear sky conditions.

6.3.3. Short term rock temperature variations (10minute interval)

Mechanical fracturing, apparently due to thermal stress, has not only been observed on large rock surfaces but also in quartzitic sandstone clasts down to 15cm (Fig. 65, p.145). Shattering of shale occurs in clasts smaller than 10cm. Secondly, the data presented above provide information on diurnal temperature fluctuations in rock cracks but do not indicate potential for sudden temperature changes to induce thermal shock effects directly at the rock surface. Further, by monitoring at separate sites micro-climatic factors cannot be separated from lithological variations. In order to obtain indicators of short-term thermal stress induced in clasts, temperatures were measured in shale and quartzite at the Waaihoek logger station at intervals of ten minutes over the period 28/12/1992-15/01/1993 and are described here. A monitoring experiment at one minute interval was also conducted and is described in section 6.3.4. Dimensions and positions of the clasts and sensors are given in Fig. 76. Both clasts were placed in a horizontal position on the soil surface without insulation. Heat fluxes were thus received from all sides and not only by the top surface as has been done in other experimental studies (Kerr et al. 1984). Motivation for this is that it is the only way in which representative thermal regimes can be measured in clasts that show active shattering in the field.

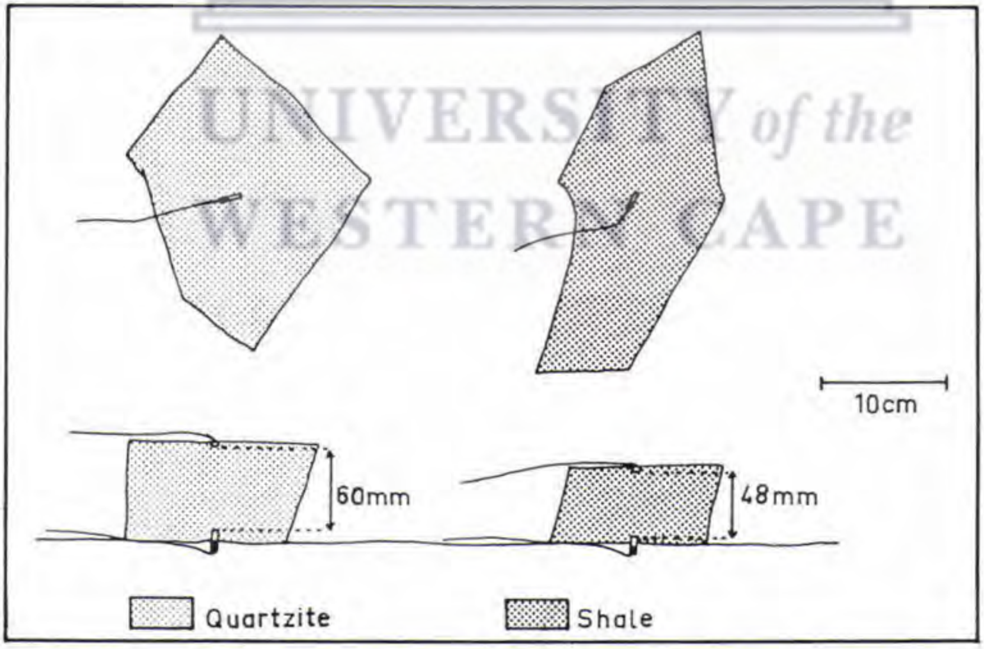


Figure 76. Experimental set-up for temperature monitoring on a shale and quartzite clast at the Waaihoek Peak logger station.

Small temperature sensors with a casing diameter of 4mm and a length of 25mm were placed in a 2mm deep groove in the centre of the clast surface. The sensing tips, with a diameter of 2mm, were placed in contact with the rock at the end of the groove. Epoxy resin mixed with rock dust from the sample was used to secure the sensor and to obtain an albedo as close as possible to that of the rock surface. A second sensor of the same dimensions was placed in a 4mm diameter hole drilled in the bottom centre of the clast. A 10mm deep hole was drilled in the 60mm thick shale clast, while a 20 mm deep hole was drilled in the 82mm thick quartzite. The sensing tips of the two sensors were placed directly above each other. Internal temperature gradients were thus measured over an effective distance of 48mm in the shale and 60mm in the quartzite.

The difference in dimensions and thickness of the clasts will exert an influence on the results presented below. The use of smooth cut blocks of the same dimensions would have resulted in a better comparability between the two lithologies. Smooth cut surfaces themselves however increase albedo and create conditions unrepresentative of natural rock surfaces. In order to improve comparison of internal rock temperature data these are expressed here in °C/cm. This does not entirely solve the problem of measurement over different thicknesses because rock temperature does not decrease linearly with depth. Hypothetically, the internal temperature gradient, if measured in the same material, could be expected to be highest for the rock with the internal sensor placed closest to the surface (Fig. 77). Difference in shape of the clasts exerts a further control on the results presented below.

Internal temperature gradients

Daily trends in rock temperatures are presented for both the shale and quartzite for two days, one representative for clear conditions (3/1/1993) and the second for a

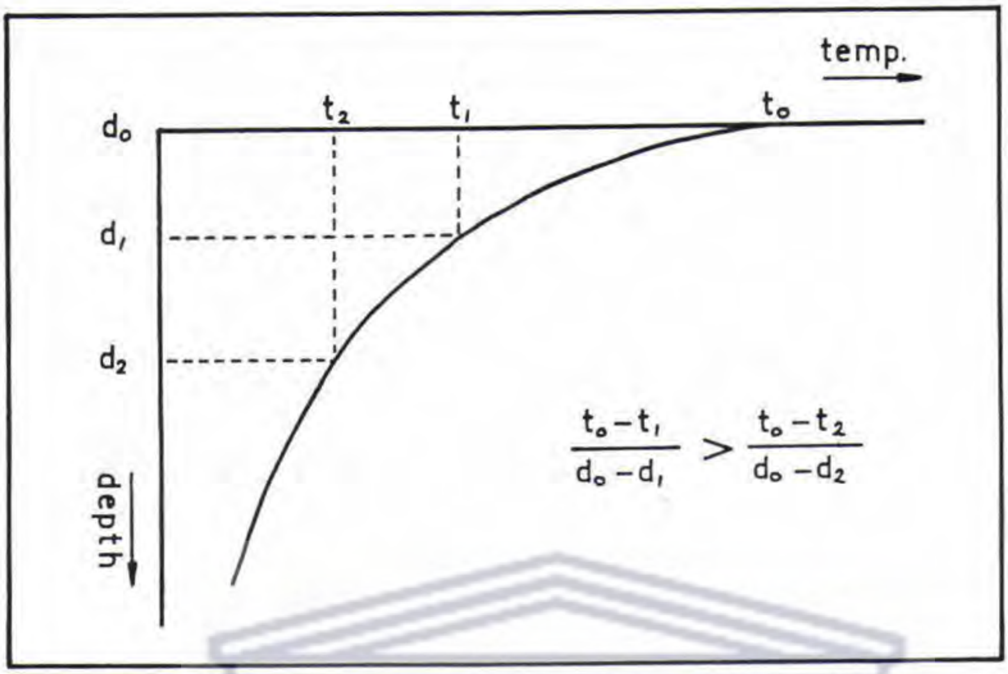


Figure 77. Hypothetical effect of depth of sensor placement beneath the rock surface on temperature gradient measurement, assuming an asymptotic temperature decrease with depth. Sensors at greater depth will register a smaller rock temperature gradient. Based on Oke (1987).

day with variable cloud cover (29/12/1992) (Fig. 78). Daily temperature extremes and ranges for both rocks are summarised in Table 29. Rock temperature gradients are graphically presented in Figure 79 for both days. For the day with clear sky conditions, a small temperature gradient exists during the night by radiational cooling at the surface (Fig. 79). Immediately following sunrise the temperature gradient increases to a maximum of 1.5°C/cm in the shale and of 0.58°C/cm in the quartzite at solar noon. Absolute maxima of internal temperature gradient reached during the 18 day record period is 2.0 °C/cm (shale) on 8/1/1993 and 0.7 °C/cm (quartzite) on 4/1/1993. After noon rapid rock surface cooling results in a rock temperature gradient reversal at about 17:30 SAST (South African Standard Time) for the quartzite and at 18:25 for the shale. A secondary peak in the temperature gradient occurs consistently in the evening at

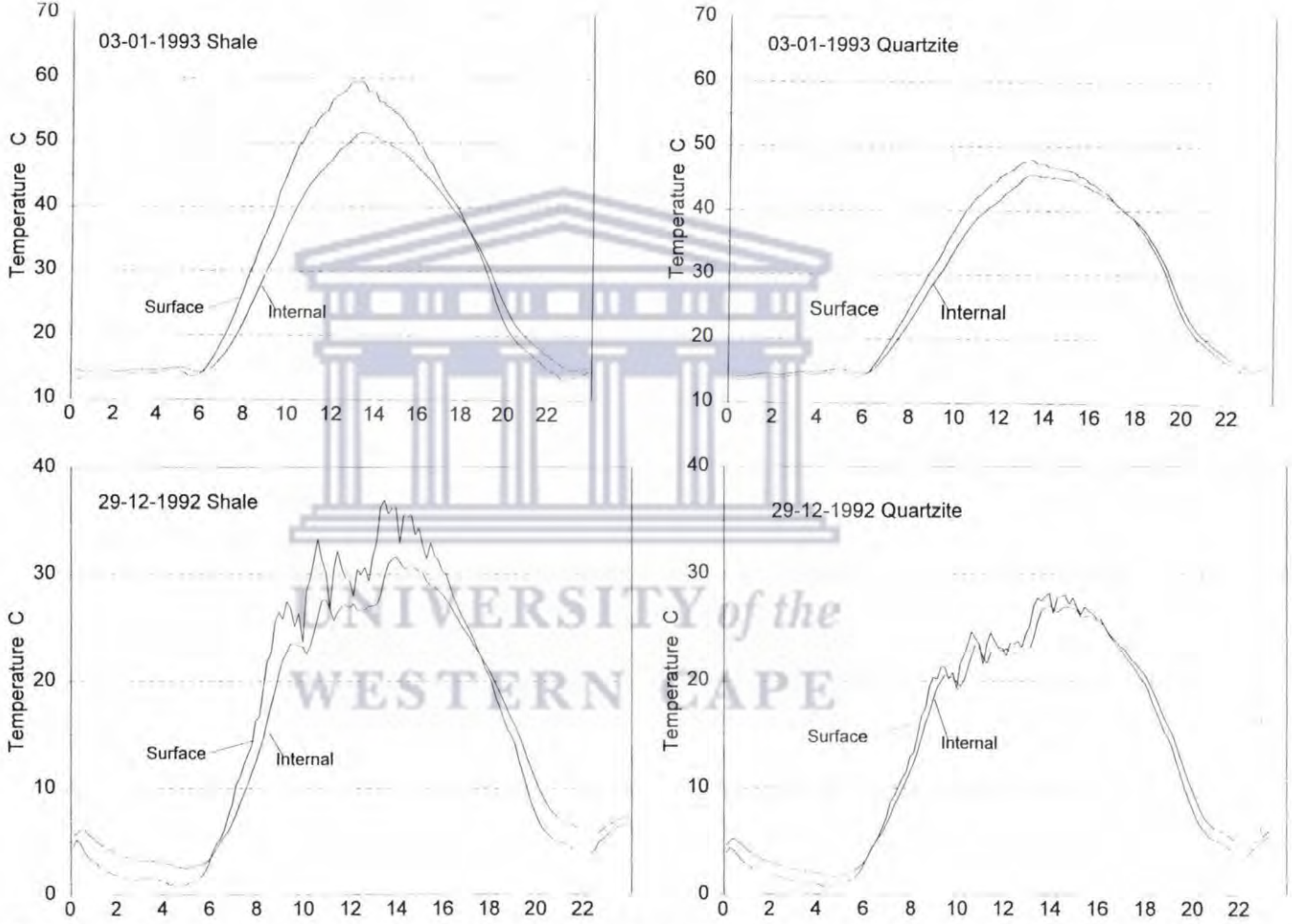


Figure 78. Daily temperature trends at the surface and interior of a shale and quartzite clast for both a clear day (03-01-1993) and a day with variable cloud cover (29-12-1992) at Waaihoek Peak (1900m a.s.l.).

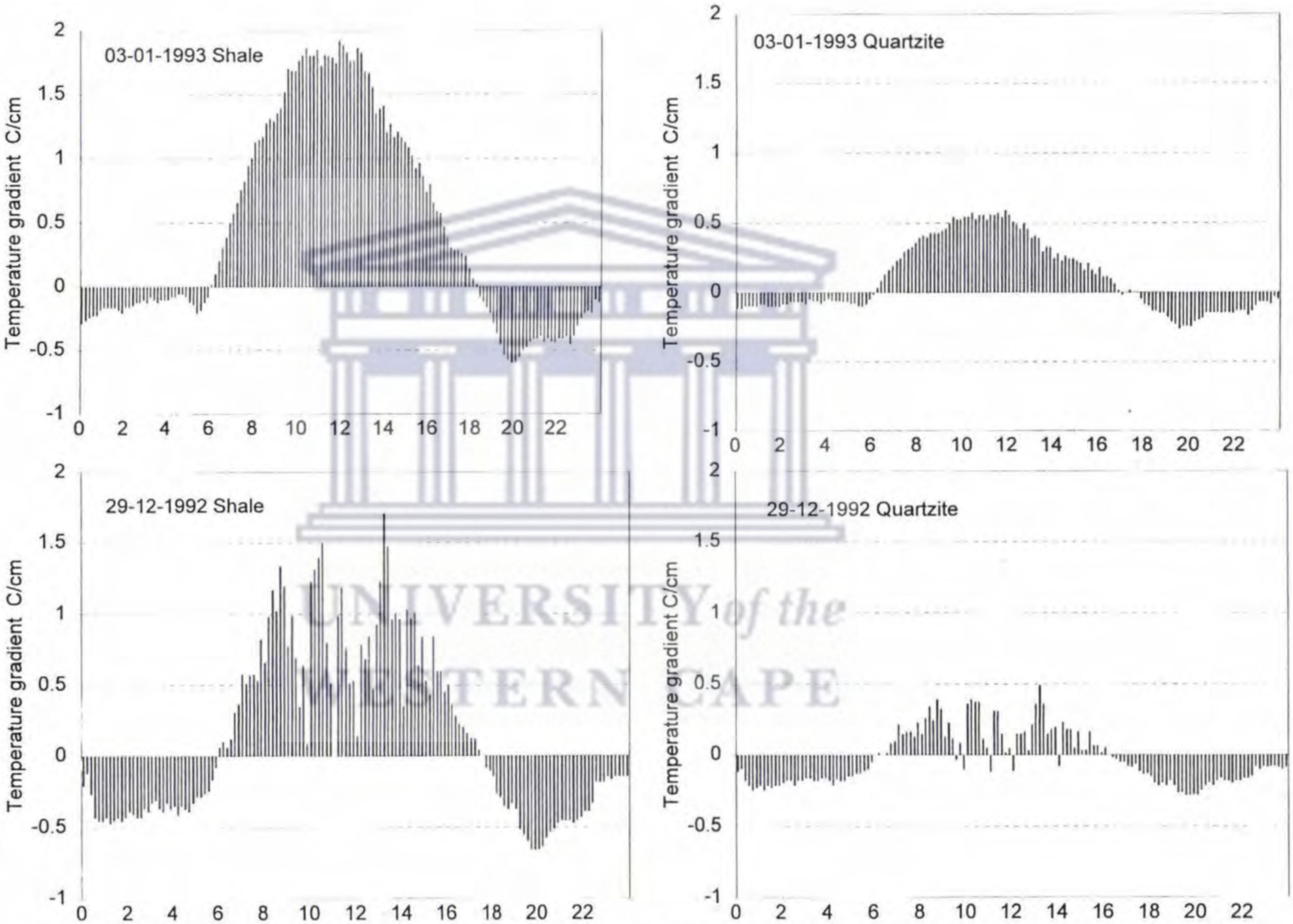


Figure 79. Temperature gradients in a shale and quartzite clasts for both a clear day (03-01-1993) and a day with variable cloud cover (29-12-1992) at Waaihoek Peak (1900m a.s.l.).

DATE	SHALE						QUARTZITE						Txs - Txq*
	SURFACE			INTERNAL			SURFACE			INTERNAL			
	Tx	Tn	Tx-Tn	Tx	Tn	Tx-Tn	Tx	Tn	Tx-Tn	Tx	Tn	Tx-Tn	
29-12	36.9	0.7	36.2	31.6	2.4	29.2	28.2	0.6	27.7	27.1	1.7	25.4	8.7
30-12	49.7	2.7	47.0	42.3	4.2	38.1	38.9	2.7	36.1	37.3	3.6	33.7	10.8
31-12	53.3	3.6	49.6	45.6	5.8	39.8	40.9	4.4	36.5	39.1	5.4	33.7	12.3
01-01	56.8	4.1	52.7	48.3	5.8	42.6	43.8	5.0	38.8	41.4	5.9	35.6	13.0
02-01	59.8	6.6	53.2	51.4	8.3	43.1	47.2	7.3	39.9	45.4	8.2	37.2	12.6
03-01	59.6	13.2	46.4	51.6	14.3	37.3	47.9	13.5	34.5	45.5	14.1	31.4	11.6
04-01	61.1	12.2	48.9	53.1	13.3	39.8	49.4	13.4	36.0	47.4	13.9	33.6	11.7
05-01	58.4	9.7	48.7	50.9	11.8	39.1	46.4	10.8	35.5	43.9	11.5	32.4	12.0
06-01	61.6	10.3	51.3	53.8	11.9	41.9	49.0	11.1	37.9	47.2	11.7	35.5	12.6
07-01	54.9	11.2	43.7	48.0	13.0	35.1	43.7	11.8	31.9	41.7	12.6	29.2	11.2
08-01	61.6	7.8	53.9	50.0	9.6	40.4	44.5	8.3	36.2	42.4	9.0	33.4	17.1
09-01	51.2	3.7	47.5	44.2	5.7	38.5	38.4	4.6	33.8	36.5	5.6	30.9	12.8
10-01	40.3	5.0	35.3	34.3	6.8	27.6	30.4	5.6	24.8	28.7	6.5	22.3	9.8
11-01	45.5	1.8	43.7	39.2	3.4	35.8	34.0	1.9	32.1	32.9	2.7	30.1	11.5
12-01	54.1	5.5	48.6	46.8	7.0	39.8	41.7	6.1	35.7	39.7	6.9	32.8	12.4
13-01	54.0	10.3	43.7	47.2	11.2	36.0	42.2	10.4	31.8	40.5	11.0	29.5	11.8
14-01	58.0	10.1	47.9	50.9	11.2	39.7	46.3	10.8	35.4	44.5	11.3	33.2	11.7
15-01	57.2	11.4	45.8	49.9	12.6	37.3	45.3	11.8	33.5	43.3	12.4	30.9	11.9
AVG			46.23			37.22			33.92			31.25	11.99
STD			4.95			3.98			3.97			3.91	1.62

Txs-Txq* = Maximum shale surface temperature minus maximum quartzite surface temperature

Table 29. Summary of daily temperature extremes recorded in the shale and quartzite clasts.

about 20:00 for both lithologies, when a gradient of -0.5°C/cm and -0.25°C/cm is obtained for the shale and quartzite respectively. Internal temperature gradients in the quartzites are about half of those in the shale during the 24 hour cycle.

Surface temperature variability

Rates of warming and cooling of the rock surface under clear sky conditions are graphically presented in Figure 80. After equal cooling/warming rates during the night and morning the warming rates of the quartzite increase rapidly up to 1°C/10 min. The

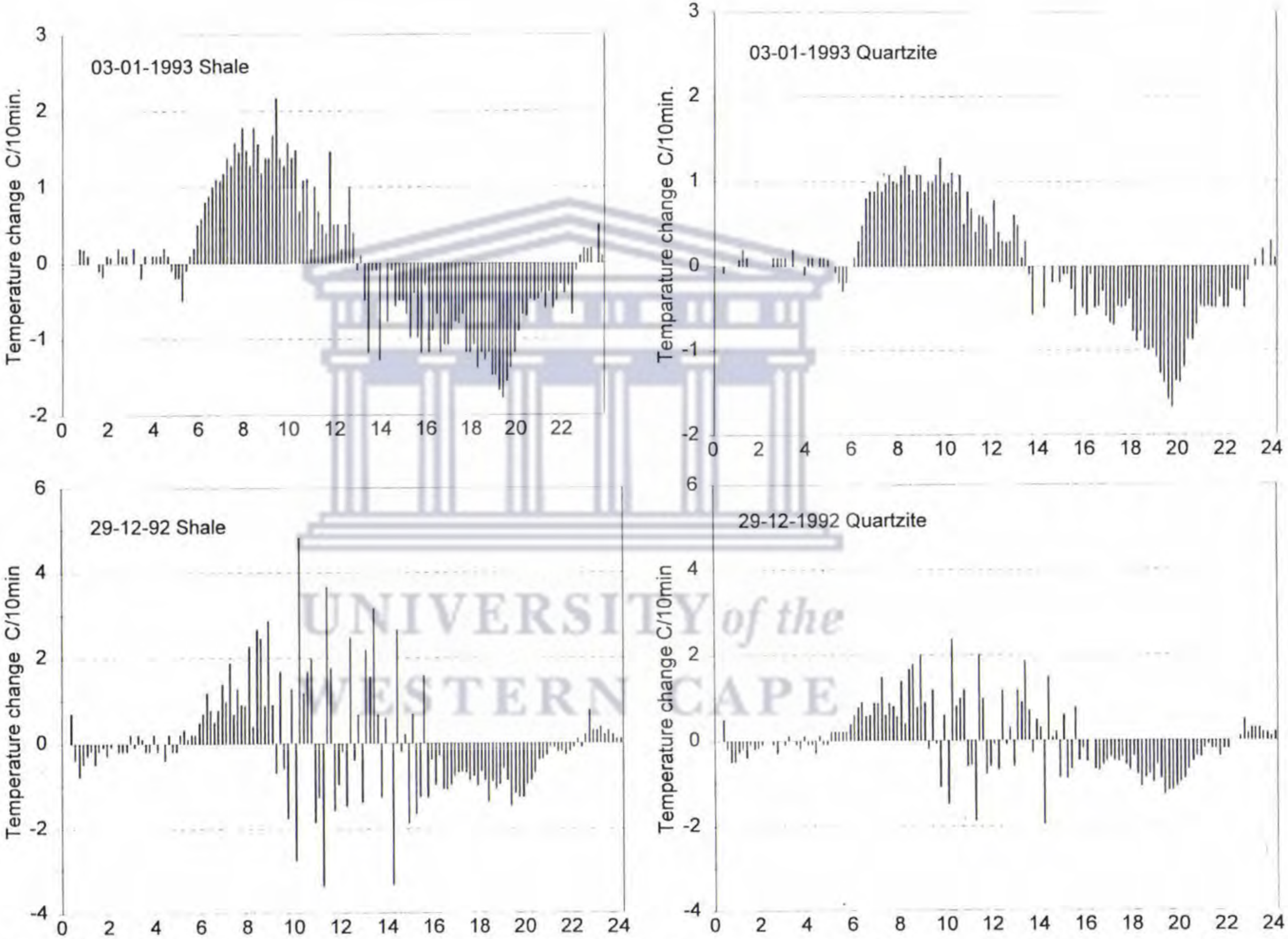


Figure 80. Surface temperature change over 10 minute intervals on a shale and quartzite clast for both a clear day (03-01-1993) and a day with variable cloud cover (29-12-1992) at Waaihoek Peak (1900m a.s.l.).

increase in rate of warming of the shale surface is more gradual but reaches values of 1.7 °C/10 min. Immediately after solar noon cooling rates increase to -1.7 °C/10 min for quartzite and -1.8°C/10 min for the shale surface (negative values indicate cooling). Cooling rates of the quartzite in the afternoon are about 0.4°C/10min lower than for the shale surface. This difference disappears once the peak value is reached in the early evening.

Effects of cloud cover

Effects of cloud cover on internal temperature gradient and warming/cooling rates of rock surfaces can be illustrated by the data record of 29/12/1992 (Figs. 78,79,80). On this day maximum rock surface temperatures are about 20°C lower than recorded on 3/1/1993.

In broad terms the temperature curves and derived data follow the same trends as under clear sky conditions. Spikes in the morning and afternoon temperatures are caused by variable cloud cover. Temperature gradients for both rock surfaces are highly variable in response and range between 0 and 1.7°C/cm (shale) and -0.2 and 0.5°C/cm (quartzite). A secondary peak of negative temperature gradients is again obtained at about 20:00 (Fig. 79). Similarly as on 3/1/1993 temperature gradients for the quartzite are about half of those in the shale.

The record on rock surface temperature change (Fig. 80) indicates highly variable rates of both warming an cooling in response to alternating direct insolation and shading. Temperature change occurs at rates between -3.7 and 5°C/10 min in shale and -2 and 2.3°C/10 min in quartzite. These values are substantially higher than those obtained under clear sky conditions (Fig. 80). This feature may be attributed to additional solar radiation inputs due to reflection from surrounding cloud surfaces (c.f.

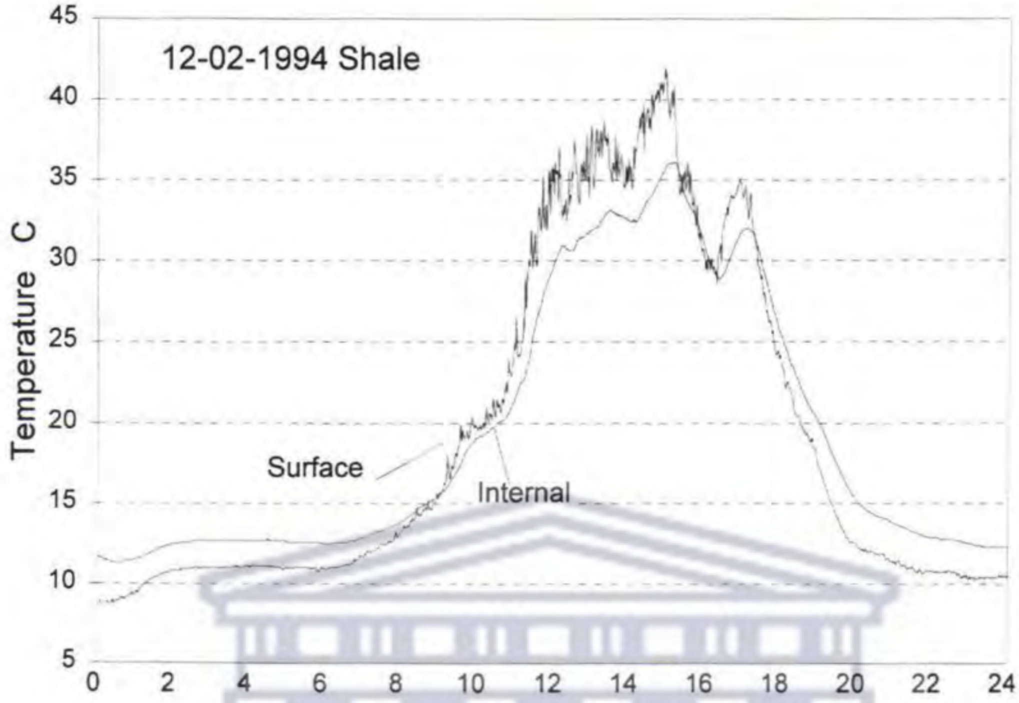
Oke, 1987, p.27).

6.3.4. Short term rock temperature variations (1minute interval)

More detailed data on rock temperature response to sudden fluctuations in solar radiation input were obtained from a third monitoring set up. This used the same construction and rock samples as for the 10-minute monitoring series, but here temperatures were recorded every minute over one full 24 hour period on 12/2/1994. The motivation to log every minute comes from the notion that high thermal stress levels may be induced over very short time intervals causing thermal shock (Yatsu, 1988; Hall and Hall, 1991). Results of the rock temperature record are presented in Figures 81, 82 and 83. The data do confirm that rock surface temperature can be highly. variable over very short time periods that are not reflected in the 24-hour or even the 10-minute temperature records. These very sudden temperature changes are however restricted to the rock surface only as they do not affect the internal rock temperature record.

A frequency distribution of rock temperature gradients that develop on a one minute basis over the 24 hour period of record is tabulated in Table 30. The values range from -0.6 to 1.8 °C/cm for the shale and from -0.2 to 1.2 °C/cm for the quartzite. These values fall within the range obtained by the 10 min. record for the shale, but indicate higher temperature gradients for the quartzite in the one minute record. 82).

The data for rock surface temperature change show a high variability with warming and cooling of the surface continuously alternating (Fig.83). Both lithologies show very similar distributions of values that vary between -2.4 and 3.5°C/min.(Table 30). These rates are significantly higher at both extremes than suggested by the 10 minute interval records. On the other hand, rates of temperature change do not exceed



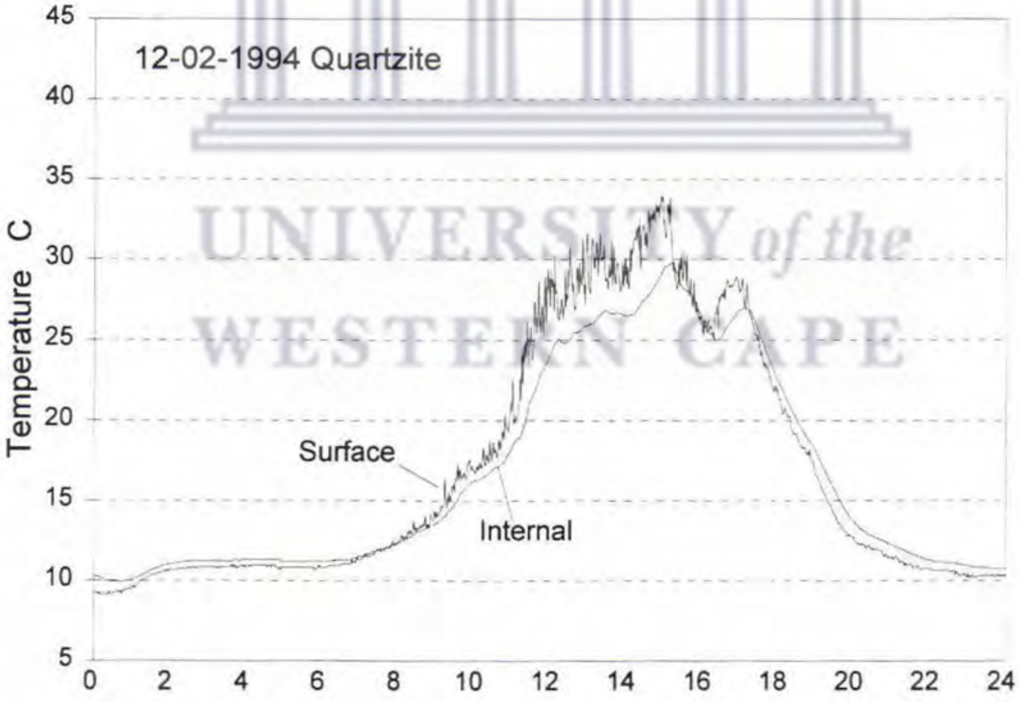


Figure 81. Daily temperature trends at the surface and interior of a shale and quartzite clast on a day with variable cloud cover (12-02-1994) at Waaihoek Peak (1900m a.s.l.).

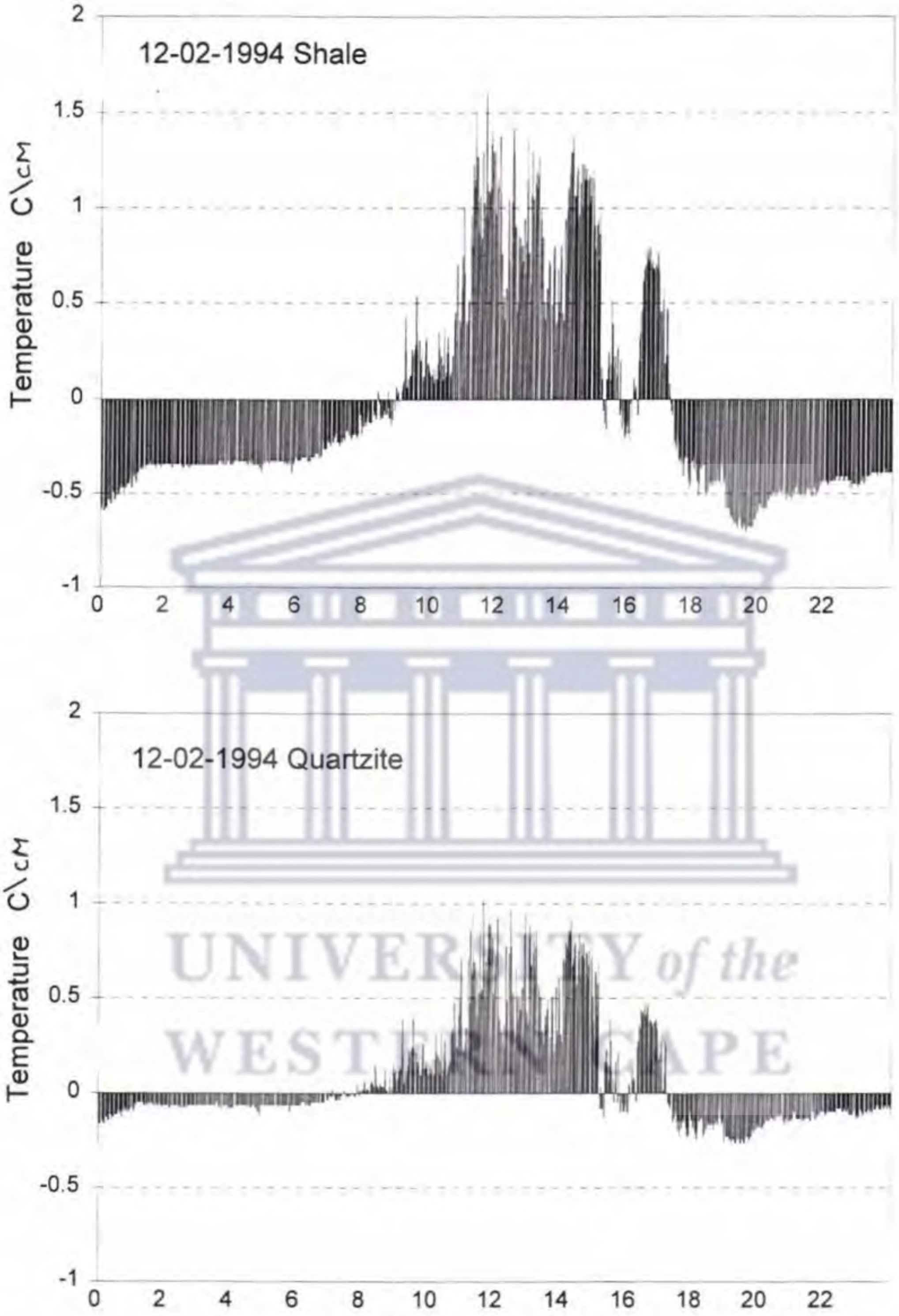
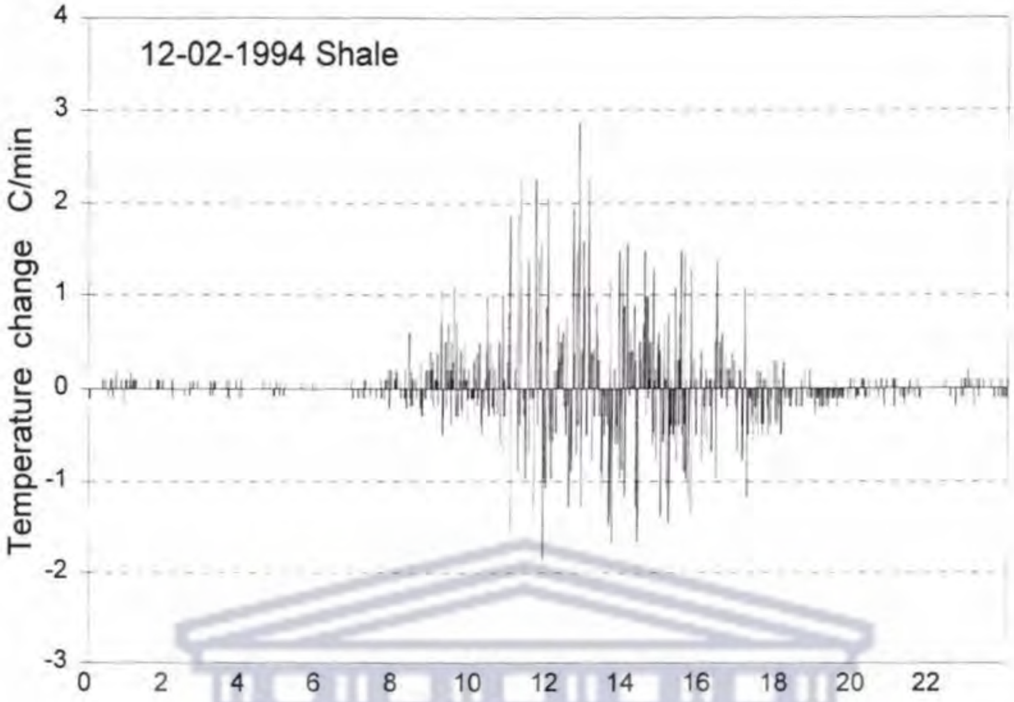


Figure 82. Temperature gradients in a shale and quartzite on a day with variable cloud cover (12-02-1994) at Waaihoek Peak (1900m a.s.l.).



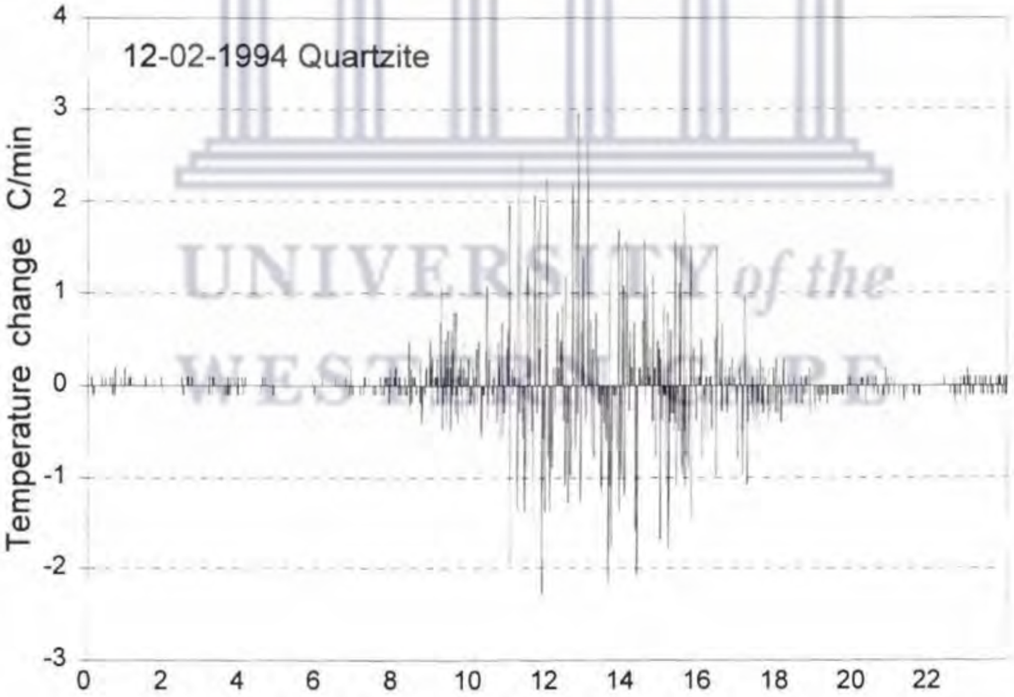


Figure 83. Surface temperature change over 1 minute intervals on a shale and quartzite clast on a day with variable cloud cover (12-02-1994) at Waaihoek Peak (1900m a.s.l.).

Internal temperature gradient			Surface temperature change per minute		
°C/cm	Shale	Quartzite	°C/min	Shale	Quartzite
> -2	0	0	>-3	0	0
-2.0≥ t > -1.8	0	0	-3≥t>-2.8	0	0
-1.8≥t>-1.6	0	0	-2.8≥t>-2.6	0	0
-1.6≥t>-1.4	0	0	-2.6≥t>-2.4	0	1
-1.4≥t>-1.2	0	0	-2.4≥t>-2.2	0	1
-1.2≥t>-1.0	0	0	-2.2≥t>-2.0	2	3
-1.0≥t>-0.8	0	0	-2.0≥ t > -1.8	1	3
-0.8≥t>-0.6	49	0	-1.8≥t>-1.6	3	5
-0.6≥t>-0.4	329	0	-1.6≥t>-1.4	9	8
-0.4≥t>-0.2	471	69	-1.4≥t>-1.2	17	13
-0.2≥t>0	126	846	-1.2≥t>-1.0	11	16
0.2>t≥0	90	179	-1.0≥t>-0.8	19	15
0.4>t≥0.2	67	144	-0.8≥t>-0.6	23	28
0.6>t≥0.4	76	88	-0.6≥t>-0.4	49	42
0.8>t≥0.6	72	78	-0.4≥t>-0.2	85	79
1.0>t≥0.8	52	35	-0.2≥t>0	804	815
1.2>t≥1.0	63	1	0.2>t≥0	226	224
1.4>t≥1.2	38	0	0.4>t≥0.2	62	53
1.6>t≥1.4	5	0	0.6>t≥0.4	35	36
1.8>t≥1.6	1	0	0.8>t≥0.6	22	27
2.0>t≥1.8	0	0	1.0>t≥0.8	18	13
≥2.0	0	0	1.2>t≥1.0	11	11
			1.4>t≥1.2	10	7
			1.6>t≥1.4	10	10
			1.8>t≥1.6	2	5
			2.0>t≥1.8	7	5
			2.2>t≥2.0	1	7
			2.4>t≥2.2	5	2
			2.6>t≥2.4	1	2
			2.8>t≥2.6	0	1
			3.0>t≥2.8	1	2
			≥3.0	1	1

Table 30. Frequency distribution of temperature gradients and rates of surface temperature change in a shale and quartzite clast on 12-2-1994 at Waaihoek Peak (1900m a.s.l.)

±0.2°C/min. in the clasts at depth of 48mm (shale) and 60mm (quartzite).

6.3.5. Summary

The rock thermal regime monitored in the Waaihoek range has been summarised in Table 31. The daily maximum rock surface temperatures provide a first characterisation of the rock surface thermal regime in both summer and winter. It appears that winter maxima obtained at all sites are moderate due to low solar radiation, high cloud cover and snow cover incidence. Sun-exposed sandstone surfaces

Diurnal temperatures	Shale(1993-4)	Sandstone (1991-4)	
	Sun-exp.	Shaded	Sun-exp.
Winter			
Absolute maximum temp.	35.3	19	28.5
Maximum diurnal range	34.3	12.5	18.9
Summer			
Absolute maximum temp.	52.1	39.9	46.6
Maximum diurnal range	41.1	24.7	33.4

10 min. rock temperature record (29/12/92-15/01/93)	Shale	Sandstone
Maximum surface temperature	61.6	49.0
Maximum diurnal range	53.9	39.9
Maximum internal temperature gradient (° C/cm)	2.0	0.7
Maximum surface warming rate (°C/min)	0.5	0.23
Maximum surface cooling rate (°C/min)	0.35	0.19

1 min. rock temperature record (12/2/1994)	Shale	Sandstone
Maximum internal temperature gradient (°C/cm)	1.6	1.1
Maximum surface warming rate (°C/min)	2.8	2.9
Maximum surface cooling rate (°C/min)	1.8	2.3

Table 31. Summary of the rock thermal record from the Waaihoek mountains.

obtain higher temperatures than shaded surfaces in both seasons but this difference is highest in summer under clear radiation conditions. The absolute maxima obtained in summer for both sandstone and shale are very similar and in the lower range of typical rock surface maxima characteristic for hot desert environments (Brunsden, 1979; Kerr et al, 1984). Variation in rock properties between shale and sandstone appears to have little influence on daily maximum temperatures in both seasons, but may be primarily a function of the sensor locations. Rock maximum temperature variations between the two lithologies appear also more influenced by differences in site characteristics, particularly microclimate, rather than thermal properties of the lithologies.

The data on daily temperature ranges suggest that only moderate values are obtained on sandstone surfaces in winter, which are unlikely to cause any significant thermal fatigue. The shale surface, however, reaches daily temperature ranges up to 35°C on clear days without snowcover. Microclimate, especially cloud and snowcover, appears important in determining the actual distribution pattern of the daily temperature range values. During summer clear radiation weather, as defined in McGreevy (1985), results in significantly higher daily temperature ranges on sun-exposed than on shaded rock surfaces due to higher maximum temperatures obtained at daytime. Highest daily ranges, over 40°C, are reached for the shale under clear radiation weather with dry rock and high air temperature conditions. The values obtained for the sandstone are distinctly lower than for the shale and reach maximum daily temperature range values of about 33°C (Table 31).

Rock temperature measurements on a shale and quartzite clasts at the same site in summer indicate rock surface maximum temperatures in the shale to be on average 12°C higher than for the quartzite. Daily maxima obtained from both clasts surfaces are also significantly higher than those obtained from rock cracks. As expected, both records do, however, clearly point out that highest daily maxima occur on sun-exposed rock surfaces under clear sky conditions in summer. Cloud cover has been shown to significantly reduce maximum rock surface temperatures obtained, but little influences internal temperature gradients. High frequency logging further shows that internal rock temperature gradients obtain two diurnal peaks; the first near solar noon during maximum heating, the second , and lower peak, in the early evening at maximum cooling. During the heating phase, higher internal rock temperature gradients are recorded in shale, relative to the sandstone (Table 31). Rock surface warming and cooling rates take place over very short time intervals and are only adequately monitored using a one minute logging interval. Maximum values reach up to 3.5 °C/min for both lithologies.

6.3.6. Discussion

The absolute maximum temperatures obtained from both rock cracks and clast surfaces suggest that thermal regimes in summer compare well with those of hot desert environments (Brunsden, 1979; Kerr et al., 1984; Goudie, 1989). The absolute maxima obtained here of 61°C remain significantly lower than the exceptional values recorded by Peel (1974) on basalt and varnished sandstone of 80°C. Daily temperature range data are not as abundant as surface maximum temperatures but may be as high as 50 °C (Ravina and Zaslavsky, 1974). The maximum diurnal temperature ranges recorded at the shale surface of over 53°C are in excess of this value and even the quartzitic surface obtained a maximum diurnal range of 47°C.

Despite the considerable record on rock temperatures in hot desert environments the issue of whether these values are sufficient to induce effective thermal fatigue remains unresolved without equal consideration of rock thermal and mechanical properties (e.g. Yatsu, 1988; Goudie, 1989, Cooke et al., 1993). Direct solution of the problem by thermoelastic and heat conduction theories remains very difficult, however, as most constants involved are dependent on temperature (Yatsu, 1988, p. 123).

The role of rock thermal properties

The role of rock thermal properties in controlling rock thermal regimes is frequently stressed (e.g. Brunsden, 1979; Kerr et al., 1984; Yatsu, 1988). Richter and

Simmons (1974) observed that rocks with high density microcracks obtained very low expansion coefficients when heated, as expansion could be accommodated within the crack spaces. Thermal stress values may consequently be reduced. Differences in the shale and quartzite clast thermal regimes also emphasize the importance of rock properties, such as albedo, heat conductivity and specific heat, in determining actual thermal stress induced. The higher temperatures at the shale surface can readily be attributed to the lower albedo due to its dark brown-grey surface, as compared with the light grey quartzite. The internal temperature gradient i the shale clast is twice as high as that recorded for the quartzite. The temperature gradient in the clasts is determined by the ability of the material to conduct heat received at the surface through the rock, and not by maximum temperatures at the rock surface (Kerr et al., 1984, p. 307). A low heat conductivity will result in less effective heat dispersal and will thus create a high difference between rock surface and internal rock temperature. Low heat conductivity values will further enhance high rock surface temperatures. Both these considerations suggest a lower heat conductivity for the shale than for the quartzite and well explain the differences in thermal regimes between the two lithologies. Heat conductivity values for local lithologies could not be obtained to further verify these statements. A further consideration in explaining the difference in temperature gradient between the two lithologies is the closer proximity of the two sensors in the shale, relative to the quartzite, as explained earlier. This effect can, however, not explain the consistent value difference observed, as the effect by the positioning of the two sensors is a function of the actual temperature gradient present.

The role of rock moisture

A condition that is recognised to favour thermal fatigue is the presence of moisture, to the extent that Cooke et al. (1993) distinguish between dry and moist insolation weathering. Due to its high thermal expansion coefficient water is considered to generate sufficient pressure on walls of capillaries to eventually cause fracturing under diurnal temperature ranges of 10-50°C (Birot, 1962). Smith (1977) considers mechanical weathering most active at limestone surfaces with high diurnal temperature ranges where moisture is available. Although porosity values of intact local lithologies are very low (Table 5), considerable moisture may be present in micro-fractures. As diurnal temperature ranges are appreciable even in rock cracks (Tables 27, 28) moisture insolation weathering may be considered to enhance fracture propagation under these conditions. The presence of moisture can not be considered a limiting factor in winter (see chapter 4). In summer limited rainfall and fog-drip may provide moisture, particularly to the coastal mountain ranges exposed to southeasterly winds in summer.

Evaluation of thermoclasty by thermal shock

The data record from the quartzite and shale clasts provides some clues to the potential for thermal shock due to insolation, as opposed to fire. First, it must be considered that the one-minute interval record obtained significantly higher surface warming/cooling rates than the ten-minute record. This indicates the need for continuous temperature recording when considering thermal shock. Diurnal or even ten-minute interval records provide little information in this respect. However, internal temperature gradient values are similar to the ten- and one-minute interval records. Maximum temperature gradient values are obtained during the heating phase around noon. The difference in values between the two lithologies has been explained above by differences in thermal conductivity. Values obtained in this study compare well with those of Smith (1977), Winkler and Rice (1977) and Kerr et al. (1984) and are typically around 1°C/cm, although values of up to 2°C/cm are obtained here for the shale. In comparison, Ravina and Zaslavsky (1974) recorded values up to 7°C/cm.

Surface warming rates for both lithologies reach up to over 3°C/min and cooling rates as rapid as 2°C/min. Peak values, however, have a duration of less than two minutes with a rapid alternation of cooling and warming in response to passing clouds and consequent variations in radiation flux. Total duration for the day is between ten and twenty minutes. These temperature fluctuations are limited to the rock surface with warming/cooling rates at 4.8cm and 6.0cm depth, for the shale and quartzite respectively, being limited to 0.2°C/min. Hall and Hall (1991) argue that a temperature change of ≥2°C/min is sufficient to generate permanent strain in various rock types. Even if this value cannot be directly applied to the lithologies used in this study the measured values, up to 3.5°C/min, do indicate that the potential for rock breakdown by thermal shock is high.

In conclusion, reconnaissance field observations on weathering features suggest the widespread occurrence of fire-induced spalling in the entire fynbos region.The field observations on polygonal rock surface cracking are suggestive of effective thermal shock in both shale and quartzite clasts and have been complemented with microclimatic monitoring in the field. Although daily rock thermal regimes in summer are characteristic of those obtained in hot desert environments, no conclusive link with processes could be made. Numerous studies have emphasized the importance of thermal properties and their control on rock temperature has been shown here. The importance of rock mechanical properties and their dependence on temperature has been discussed by, amongst others, Ollier and Ash, 1982; Yatsu, 1988; Goudie et al.,

1992. Mathematical solution of the problem of thermal stress in rocks remains, however, difficult due to the temperature dependency of most of the variables involved in the thermoelastic and heat conduction theories concerned (Yatsu, 1988). Thus, it remains not possible to relate observed temperatures to effective thermal stress induced. Quantification of relevant rock properties would provide more valuable data but conclusions could still only be produced in terms of likeliness of permanent strain induced, unless actually measured.The importance of the record obtained here is that it accurately describes the rock thermal regime in which thermoclasty is to operate. A sound basis has thus been laid for the necessary experimental measurements of stress induced by the thermal regimes monitored in the field.

6.4. THE ROCK TEMPERATURE RECORD AND CRYOCLASTIC WEATHERING

6.4.1. Introduction

Łoziński (1906) considered the mechanical splitting of rocks by frost weathering a primary characteristic on which he defined the periglacial facies. Despite general acceptance of the importance of frost weathering in periglacial environments Ives (1973, p. 1) identified the "efficacy of freeze-thaw processes in the role of bedrock disintegration" as a major gap in existing geomorphological knowledge. This point was reiterated nearly ten years later by French (1981) and McGreevy (1981). Problems related to the allocation of freeze-thaw to mechanically fractured bedrock include both the uncertainty as to the actual mechanisms involved in frost weathering, as well as the difficulty to isolate effects caused by freeze-thaw from other mechanical weathering processes (McGreevy, 1981; Hall, 1991). The various hypotheses on frost weathering mechanisms have been reviewed on several occasions (McGreevy, 1981; Whalley and McGreevy, 1983; Trenhaile, 1987; Yatsu, 1988). Each will only briefly be outlined here.

9% Volumetric expansion

The operative process in freeze-thaw weathering has long been considered to be the 9% volumetric expansion of freezing water, which may exert pressures of 62MPa at -5°C, increases to 115MPa at -10°C and attains a maximum value of 214MPa at -22°C (Bridgman, 1912). As first pointed out by Grawe (1936) such pressures can only be achieved in a closed system containing only water, conditions which may not represent those encountered in the field. Further, even the most resistant rocks would fracture at stresses of one-tenth of the theoretical maximum pressure (Trenhaile, 1987). Battle (1960) suggested that a closed system can be produced in a water filled rock crack when rapid freezing seals the crack opening by forming an ice cap. Tricart (1970) argued that in such cases high pressures would only develop if frost penetrates deep enough to freeze all water, but Yatsu (1988) points out that the water expansion upon freezing may cause crack propagation by hydraulic pressure and flow of unfrozen water towards the crack tip.

Factors favouring rock breakdown by the volumetric expansion of freezing water include a high degree of saturation in rocks (Mellor, 1970; McGreevy, 1981), while Lautridou (1971) suggests that a freezing duration of at least ten hours is required for breakdown to occur at temperatures between 0 and -5°C in saturated rock. Water will however freeze over a range of temperatures depending on the size of the pores in which the water is found (Mellor (1970). McGreevy and Whalley (1982) point out that in many instances water in rocks freezes at temperatures between 0 and -3°C. This suggests that low amplitude frost cycles of sufficient duration may cause effective rock breakdown (McGreevy and Whalley, 1982).

Others found that most freezing expansion of saturated porous and jointed rocks takes place at temperatures between 0 and -5°C (Mellor, 1970; Douglas et al, 1987; Matsuoka, 1990, 1991). Consensus appears to exist that rapid rates of freezing increase rates of rock breakdown, as this will favour approximation of a closed system (Battle, 1960), reduce water loss by evaporation (Lautridou and Ozouf, 1978) and enhance the development of hydraulic pressures (Powers, 1945).

Hydraulic pressure

The hydraulic pressure hypothesis was developed by Powers (1945). The pressure is suggested to be generated by the expulsion of water away from the advancing ice front by ice growth and the associated volumetric expansion. Controlling factors are porosity and permeability of the material; the rate of freezing, as this controls the rate of water displacement, and degree of water saturation. The surface layer of the freezing rock must be saturated otherwise ice growth could be accommodated without water expulsion. Although Powers' hypothesis has been favourably received by both researchers in the building industry and geomorphologists (McGreevy, 1981; Trenhaile, 1987; Yatsu, 1988) the question remains when rock is moist, what is the moisture gradient and how deep does saturation go?

Ice segregation in rocks

In analogy of Taber's (1929) work on frost heaving in soils, Collins (1944) suggested that scaling in concrete could be attributed to ice segregation in layers parallel to the cooling surface. The capillary theory of frost damage has found theoretical support from Everett (1961) and well explains the results of Potts (1970) experimental study in which samples only half immersed in water showed significantly higher rates of shattering than fully immersed rocks. Walder and Hallet (1985, 1986) and Hallet et al. (1991) have provided important theoretical and experimental support for this hypothesis. Walder and Hallet suggest that water migration to freezing sites in microcracks does not depend on saturation of rocks and will occur at sustained freezing temperatures between about -5 and -15°C. Taber (1950) states that temperatures a few degrees below 0°C are sufficient if the rock is fine grained, permeable and permit continued saturation during freezing.

The adsorpted water hypothesis

Dunn and Hudec (1966) found that when subjecting clay-rich carbonate rocks to freezing up to 50% of the adsorbed water may remain unfrozen at temperatures of -40°C. Greatest shattering was found to take place in rocks with the largest amounts of unfrozen water during freezing. The authors found that in rocks containing clay minerals repeated wetting and drying results in the build up of ordered water layers at the charged clay surfaces. If the pore spaces are very small the rigidly adsorbed water may fill them and exert pressure against the confining walls (Dunn and Hudec, 1966, 1972). This may be further enhanced by repulsion of the free boundaries of ordered water layers (Fahey, 1983). Yatsu (1988) has pointed out that this process is in essence that of hydration and dehydration and not dependent on freeze-thaw cycles. McGreevy (1981) however, considered its effectiveness much enhanced at low temperatures as under freezing conditions the alignment of molecules becomes more rigid and repulsive forces become greater. In contrast, Hudec (1973, 1980) found that the number of ordered water layers decreases with temperature lowering. Freezing can thus be viewed as a drying process causing desorbtion in saturated sorption-sensitive rocks (Hudec, 1980). Water thus expelled into larger pores may consequently freeze and cause rock breakdown by normal frost action (Trenhaile, 1987). It may thus be suggested that although temperature fluctuations cause repeated adsorbtion and desorbtion which may contribute to physical rock breakdown it may operate synergistic with, but is not restricted to, freeze-thaw conditions and associated processes.

Crystallization pressure

The crystallization pressure exerted by ice crystal growth from a melt has been investigated by Connell and Tombs (1971), who measured stresses up to 20kPa. These stresses are considerable lower than the tensile strength of even the weakest rocks. Factors facilitating continued crystal growth are an permeable system of small pores enabling migration of supercooled water and slow freezing rates (McGreevy, 1981).

As indicated above a wide variety of factors control rock behaviour under freeze-thaw conditions which can broadly be grouped under material properties, temperature and moisture controls (McGreevy, 1981; Matsuoka, 1991). Material properties of the Peninsula sandstone and quartzite have been described in section 2.2.3.. Results of basic rock surface freeze-thaw monitoring are presented to provide a first indication of frost activity which will be evaluated against the theoretical considerations of the various working hypotheses and their controls.

6.4.2. Rock surface freeze-thaw cycles

Rock surface freeze-thaw cycles were recorded using the same sensors as applied in the assessment of thermal stress at both the Waaihoek Peak and Mt. Superior logger sites. The position of the sensors and the temperature characteristics obtained from them are described in section 6.3.2.

Results of the rock temperature analysis are presented in Appendix 7 and are summarised in Table 32. Diurnal minimum temperatures below 0°C occur with an annual frequency between 39 and 77 days (shaded sandstone) and between 58 and 75 days (sun-exposed sandstone) (Table 32). Frost intensity at the sandstone surfaces is largely restricted to temperatures between 0 and -2°C. Temperatures down to -4°C occur with frequencies between 11 and 32 days annually (Table 32). Monthly frost frequencies for the shaded and sun-exposed sandstone are very similar for temperatures below -2°C. The 1993 record suggests that both frequency and intensity of the frost cycles at the shale surface are somewhat higher than for the sun-exposed sandstone (App. 7).

6.4.3. Discussion

The significance of the freeze-thaw cycles recorded at the two sites in relation to effective frost weathering needs to be tested against the conditions and restraints on the various mechanisms invoked under the label 'freeze-thaw'. These relate not only to thermal requirements but also to rock physical and chemical properties and moisture availability and distribution in the rock as discussed earlier. A lack of rock moisture data during the recorded frost cycles, limited rock property analysis and the inability to conduct long term experimental work on the behaviour of local lithologies under different frost cycles inhibit any measure of conclusiveness to this discussion.

Intact Peninsula sandstone and quartzite, tested at the Centre de Géomorphologie at Caen, France, possess very low porosity values with average pore diameters of 0.13µm (sandstone) and 0.045µm (quartzite) (Table 5, p. 24). Experimentation at the Centre de Géomorphologie by J.-C. Ozouf, tested 1.5kg saturated samples placed under diurnal temperature cycles between +15°C and -12°C.

Year	Sandstone						Shale		
	Shaded			Sun-exposed			Sun-exposed		
Temp. (°C)	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
1992									
≤-8	0	0	0	0	0	0		no data	
-8<t≤-6	0	0	0	0	0	0			
-6<t≤-4	0	3	0	0	3	0			
-4<t≤-2	0	32	1	0	29	0			
-2<t≤0	1	42	24	0	38	15			
Total	1	77	25	0	70	15			
1993							(May-December)		
≤-8	0	0	0	0	0	0	0	0	0
-8<t≤-6	0	0	0	0	0	0	0	2	0
-6<t≤-4	0	3	0	0	2	0	0	5	0
-4<t≤-2	0	12	2	0	11	0	0	17	1
-2<t≤0	3	24	9	2	45	16	1	46	11
Total	3	39	11	2	58	16	1	70	12
1994							(January-April)		
≤-8	0	0	0	0	0	0	0	0	0
-8<t≤-6	0	0	0	0	0	0	0	0	0
-6<t≤-4	0	0	0	0	3	0	0	0	0
-4<t≤-2	0	21	0	0	22	0	0	0	0
-2<t≤0	2	46	26	1	59	35	0	0	0
Total	2	60	26	1	75	35			

Table 32. Annual frequency and intensity of diurnal freeze/thaw cycles in sandstone and shale at Waaihoek Peak (1900m a.s.l.) and Mt.Superior (1860m a.s.l.), respectively.

No visible deterioration was detected in either lithologies after 150 cycles. After 397 cycles microcracks, visible in the sandstone samples at the start of the experiments, were widened, accompanied by a weight loss of 0.15% and 0.67% respectively. These results appear to confirm the conclusion by Lautridou (1988) that sandstones with porosities less than 6% are non-frost susceptible. In the light of the discussion by Walder and Hallet (1986) and Hallet et al. (1991) these experiments suggest a rock resistance to breakdown by the volumetric expansion of freezing water, but are not adequate to assess microfracture widening by water migration to freezing sites in such cracks. Significant migration of water and its sustainance is however difficult to imagine in a rock with a total porosity of less than 3%.

A major limitation of these experiments is the fact that the lithologies in the field are extensively jointed and chemically weathered with the effect of increasing total porosity values to as high as 46%. Thus, the potential for water penetration in the rock in the field could be substantially higher than for the intact rock samples used in the laboratory experiments. This would greatly increase efficacy of the freeze-thaw cycles recorded.

The record of freeze-thaw cycles remains difficult to assess without knowledge of what constitutes an effective freeze-thaw cycle for the local lithologies. In the absence of facilities for experimental freeze-thaw studies any guidelines are restricted to results from other studies. Rock expansion in jointed or porous rock has been shown to take place at temperatures slightly below 0°C (Mellor, 1970; Douglas et al., 1987; Matsuoka, 1988). Matsuoka (1990, 1991) considers a temperature of -2°C as the critical value for fracture generation in jointed and porous rock; a value also arrived at by Hallet et al. (1991). Assuming a threshold value of -2°C for the jointed and pre-weathered Peninsula sandstone effective freeze-thaw cycles occur with a frequency of 21 and 35 days/yr at the shaded sandstone surface, and with a frequency of 25 and 32 days/yr at the sun-exposed sandstone, in 1992 and 1994 respectively. A total of 24 days are recorded for the sun-exposed shale surface in 1993. At both sites no rock deterioration was recorded. In relation to wider field observations in the Peninsula sandstone temperatures appear to be favourable only for sporadic frost activity in the summit regions of the inland mountain ranges which reach considerably higher altitudes than the coastal mountains. It does seem plausible that at selected sites in the summit areas micro-climatic conditions are favourable for effective freeze-thaw action on pre-weathered or jointed rock.

The high efficacy of bedrock shattering at Mt. Superior, particularly in relation with the surrounding sandstone as well as the Victoria Peak site, remains unexplained. Conditions for hydration shattering appear more favourable at Victoria Peak as discussed earlier, which argues for a higher effectiveness of frost-related mechanisms at Mt. Superior. Verification by means of experimentation is much needed to arrive at more conclusive answers.

CH 7. DISCUSSION AND CONCLUSIONS

7.1. CONTEMPORARY SOIL FROST ACTIVITY IN THE WESTERN CAPE MOUNTAINS - A SYNTHESIS

The contemporary soil frost activity may be discussed by means of a synthesis of the data on environmental controls, field observations and movement monitoring sites. The summit areas of the Mediterranean mountains of the Western Cape experience a mean annual air temperature of around +10°C. Under this temperature regime only surficial, diurnal frost cycles occur from May to September. Despite an average of 74 frost days a year at Waaihoek Peak, field observations and results from dowel sites and flexible tubes, yielded no evidence in favour of frost-induced soil processes. On a regional scale, the general paucity of geomorphological evidence for soil frost activity is striking. The following environmental controls were identified to explain the absence of frost-related landforms.

I) Over 90% of the Western Cape mountains are underlain by arenites of the Table Mountain Group. Particle size analysis indicates that the sediments derived from these lithologies are too coarse to allow for the formation of segregation ice. This means that irrespective of climatic controls sediment properties do not allow for geomorphological features related to soil frost, to develop over most of the Western Cape mountains.

ii) Needle-ice growth requires a soil surface temperature of at least -2°C (Outcalt, 1971; Lawler, 1988). The frequency of frost days which meet this criteria is extremely small due to the following factors.

  a) High precipitation values in winter result in the presence of snow on an estimated 31 days/yr. On 57% of the frost days recorded temperatures remained between 0 and -2°C due to the presence of an insulating snow cover.

b) The presence of vegetation raises the plain of greatest heat exchange above the soil surface which effectively reduces the diurnal temperature extremes experienced at the soil surface.

c) High soil moisture levels and the occurrence of overland flow imply that significant amounts of latent heat are released when freezing temperatures are reached. The zero-curtain effect is suggested to be particularly effective in controlling frost intensity in the Western Cape mountains.

d) Higher albedo values for the light-coloured sandstone surfaces result in less effective radiation exchange with the atmosphere, reducing frost frequency-intensity in these materials, relative to the darker-coloured shales.

High soil moisture levels are maintained throughout the cold season and form no limiting factor to effective soil frost activity in the region.

Cryogenic activity in the Western Cape mountains is restricted to sites underlain by sediment from the Cedarberg Shale. The occurrence of frost processes where this lithology is exposed, is limited by i) steep slope gradients maintained by overlying sandstone caprock, ii) the presence of coarse sandstone-derived debris mantles overlying the shale-derived sediments, and iii) the altitude at which the outcrops occur. Only three sites were identified where cryogenic landforms are widespread, namely Victoria Peak, Mt. Superior and Matroosberg. Here, the frost-susceptible material is exposed at gently sloped summits at altitudes of 1600m a.s.l. or higher. Climatic monitoring at Mt.Superior indicated 12 and 16 soil frost cycles with temperatures below -2°C, under snow free conditions, for 1993 and 1994, respectively. Despite these relatively low numbers of effective frost days the ground surface morphology is dominated by cryogenic landforms at this site.

Field observations, results from dowel sites, vertical movement profiles and sedimentological characteristics of the landforms described, indicate frost processes to be limited to needle-ice growth, resulting in frost creep, ejection and vertical tilting of clasts and patterned ground formation. Frost penetration depths are limited to the upper 6cm of the sediment at present.

Environmental controls on soil frost activity at the two monitoring sites may be compared to evaluate their relative importance. First, precipitation totals at Waaihoek Peak in winter are close to double those at Mt. Superior. However, the number of snow days at both sites during 1993 and 1994 is estimated to be very similar. Also, the duration of high soil moisture levels is very similar at both sites. High soil moisture levels and overland flow at Waaihoek Peak results in a distinct zero-curtain effect. This effect is considered an important control in limiting frost intensity at this site. Second,. vegetation must be considered a dependent factor in its control on soil frost action. The lower vegetation densities at Mt. Superior may be suggested to be a result of, rather than a control on, more effective soil disruption by frost processes. The greater percentage of a bare soil surface does, however, allow for greater nocturnal heat loss at the soil surface and therefore more severe frost cycles. It appears that the explanation for the difference in frost activity between the two sites is, despite some differences in climatic parameters, is mainly given by the differences in material properties at the two sites. The coarse sediment textures associated with the Table Mountain Group arenites do only allow for pore ice and no segregation ice has been observed.

Considering textural control on soil frost phenomena, studies of these features in arctic and alpine regions are in many cases reported from terrain underlain by glacial till (Goldthwait, 1976; Ballantyne and Matthews, 1983; Seppälä, 1987; Jetchik and Allard, 1990; Krüger, 1994), which possesses soil textural characteristics ideally suited for patterned ground development (Goldthwait, 1976). In non-glacial sediments patterned ground occurrence is frequently reported to be related to underlying lithology. Sediments with abundant soil frost features are reported from lithologies that weather to a regolith with a significant amount of fines, such as carbonate rocks (Jahn, 1958; Washburn, 1989; Hallet and Prestrud, 1986; Butler and Malanson, 1989); argillaceous sedimentary rocks (Jahn, 1958; Smith, 1988; Butler and Malanson, 1989; Wilson, 1992), igneous rocks (Hastenrath, 1973, 1977; Mackay and Mathews, 1974; Graf, 1973; Hall, 1979; 1983; Price, 1991; Boelhouwers, 1988;1994, Pérez, 1992) and deeply weathered schists (Stocker, 1989). In contrast, little mention is given in the literature of lithologies associated with the absence of frost features, although the sediments themselves are described to be coarse (e.g. Warburton, 1991). Ballantyne (1986), however, reports on the matrix of debris mantles from the Torridon Sandstone Formation in Northern Scotland to be predominantly composed of medium to coarse sand. Only pore ice was observed in this material and patterned ground was absent. Wilson (1992) observed micro-patterned ground to be limited to sites where peat layers were eroded, but did not occur over large areas underlain by the Comeragh Conglomerate-Sandstone Formation. In both cases are the sediments exposed to diurnal frost cycles only. From this, and the findings of this study, it appears that coarse arenaceous lithologies, in particular, may be associated with the lack of frost-susceptible regolith. This has serious implications for the application of periglacial geomorphology in paleoenvironmental reconstructions as discussed below under 7.3.

7.2. THE WESTERN CAPE MOUNTAINS: AN ACTIVE PERIGLACIAL ENVIRONMENT?

7.2.1. Definition of the periglacial environment

In answering this question I should first consider what constitutes a periglacial environment. Unfortunately, ever since it was originally proposed by Łoziński (1909, 1912) debate has continued on the exact definition of the term periglacial. At present the most widely held opinion is that a periglacial environment is distinguished from others by the operation of frost action processes at intensities sufficient to significantly affect or shape the landforms in that environment (e.g. French, 1976; Washburn, 1979; Williams and Smith, 1989; Thorn, 1992).

An alternative view has been put forward by Péwé (1969) and Harris (1988) who regard the periglacial environment to be synonymous with permafrost regions. This is however considered overly restrictive by most, while Thorn (1992) points out that it is illogical to define the term by a thermal criterion only. Warburton (1992) considers Péwé's (1969) definition inappropriate as in many cases it is not possible to distinguish between the geomorphology of permafrost and non-permafrost cold climate areas. Alternatively, Warburton (1992) proposes that the term periglacial should be redefined towards Łoziński's (1912) original definition, namely as a spatial term describing a geographic zone immediately adjacent to existing or former glaciers/ice sheets. The problem created by restricting the term periglacial by spatial criteria is that it fails to include those frost-dominated environments that may not have experienced glaciation in the past.

As it appears that the broadest definition is most widely accepted at present, this will be adopted here. Adhering to the geomorphological criteria for the term periglacial a problem remains with the subjectivity involved in deciding what constitutes *intensive* frost action and its *significant* effect on the morphology of the landscape. If, on the one hand, the occurrence of permafrost is considered overly restrictive, can areas subjected to diurnal frost cycles only be considered periglacial? To answer this question the environment of diurnal frost activity must first be identified more carefully in geomorphological terms.

7.2.2. Environments of diurnal frost action

Frost activity induced by diurnal freeze-thaw cycles is characterised by needle ice growth, which has been reported to be of dominant importance in shaping surface morphology and sediment transport, particularly in the low-latitude mountain environments of eastern and southern Africa (e.g. Troll, 1944; Hastenrath, 1973; Hastenrath and Wilkinson, 1973; Hanvey and Marker, 1992) the Andes (e.g. Schubert, 1973; Hastenrath, 1977; Pérez, 1984, 1992), and the sub-Antarctic islands (e.g. Hall 1979, 1983). In these environments diurnal frost occurs at intensities sufficient for its effects to significantly affect the surface morphology of the terrain. These regions can be more accurately described in terms of the factors determining the operation of needle-ice growth, and other environmental factors that limit needle-ice activity to create/modify landforms.

Controls on the occurrence of needle ice growth are relatively well established compared with other frost processes (Lawler, 1988). The thermal controls on needle-ice growth are quantitatively founded in the algorithm established by Outcalt (1971), while Meentemeyer and Zippin (1981) quantified the relationship between soil moisture and texture controls on needle-ice growth. Lawler (1988), in reviewing the environmental limits on needle-ice growth, was able to identify broad zonal boundaries where needle-ice activity can be expected. The occurrence of needle-ice growth does, however, not imply the presence of a landscape geomorphologically modelled by this process as its morphological effects may be overshadowed by other geomorphic processes. Needle-ice may further occur at frequencies insufficient to morphologically manifest itself in areas of diurnal frost. On the other hand, diurnal frost activity becomes of lesser importance in environments where more intense frost allows for segregation ice growth at depth. Lawler (1988) suggests that needle-ice activity is restricted to areas outside of the permafrost zone.

Periglacial environments exposed to high frequencies of diurnal frost are not characterised by the severity of freeze/thaw cycles but, rather, by the high frequency of occurrence of a soil frost process particularly effective in manifesting itself morphologically. Its operation results in a very distinct suite of geomorphological features characterised by active soil surfaces on which vegetation colonization is inhibited (Gradwell, 1954; Pérez, 1987; Boelhouwers, unpubl. data), and the proliferation of micro-patterned ground (Troll, 1944; Schubert, 1973; Hall, 1979, 1983; Pérez, 1984; 1992). As such, in environments where diurnal frost processes dominate geomorphic activity, a distinct surface morphology is created and such regions may be regarded distinct from areas of seasonal frost and permafrost. For example, the distinction between seasonal and diurnal frost cycles has been used to explain the presence of patterned ground populations of different size in one area (Warburton, 1990; Boelhouwers, 1994). The occurrence of needle-ice growth outside the permafrost zone, as suggested by Lawler (1988), further points towards the distinctiveness of the type of periglacial environment under discussion here.

7.2.3. Periglacial activity in the Western Cape mountains

For the Western Cape mountains the spatial patterns of frost, moisture and soil texture control on needle-ice growth well explain the geographic distribution of soil frost features in the region. The overriding importance of textural control results in the occurrence of a few islands of soil frost activity in the region. Although the frequency of frost cycles is not high the high soil moisture levels in this winter rainfall mountain environment result in highly effective frost action at these sites. The preservation of the needle-ice induced morphology of the terrain is made possible by the dry summer months which are geomorphologically inactive.

If accepting a definition of the term periglacial in its widest sense the Western Cape mountains, as a whole, are not an active periglacial environment. Islands of periglacial activity do however occur in the summit region above 1600m a.s.l.. The use of the term periglacial in this case has become so imprecise that it reveals nothing about the distinctiveness of the type of periglacial activity encountered these areas. It is proposed therefore that these sites are more accurately referred to as islands dominated by diurnal soil frost activity.

7.3. EVALUATION OF PLEISTOCENE CRYOGENIC ACTIVITY IN THE WESTERN CAPE MOUNTAINS

The observations regarding the present-day frost action environment and other recent observations on relict landforms provide new information allowing a review of cryogenic activity in the Western Cape mountains during the Quaternary.

7.3.1. The pre-Quaternary environment

The Cape Fold Belt came into existence following uplift by crustal shortening which ceased at about 215Myr, while the Western Cape has been a passive continental margin ever since the breakup of Gondwana (140-100Myr). Thus, the Paleozoic arenites that make up the Western Cape mountains have been subjected to subaerial weathering and denudation since at least the Cretaceous.

Throughout the Tertiary, up to about 14Myr, conditions are considered to have been warm and humid with intense chemical weathering of various rock types (Lambrechts, 1983). The previously subtropical conditions had changed to a

Mediterranean climate by 5Myr. The significance of the Tertiary warm and humid conditions lies in the fact that, if over 50m deep chemical weathering profiles could develop in local granites, advanced chemical weathering will have modified the sandstones underlying the mountain ranges. Under present-day conditions sandstone weathering surfaces are dominated by pseudo-karst features related to solution weathering. As solution weathering is considered to dominate the contemporary weathering environment this will certainly have been the case for the entire Tertiary period. Such a prolonged period of chemical action would have been able to effectively enhance rock porosity of the quartzitic sandstone an quartzites. Solution of the secondary quartz kitting between the sandstone grains can be expected to have been effective to considerable depth. Porosity values up to 39% have been measured in sandstone affected by solution in the Waaihoek Peak area. The largest solution weathering forms observed at present may to a large extent be considered paleo-weathering features. Tors developed by widening of joints over 2m wide and several metres depth, such as found in the Slanghoek Peak area, are considered relicts of this Tertiary deep chemical weathering.

Road cuttings in the mountain passes of Franschhoek, the Hex River and Du Toitskloof reveal gully incision in the deeply weathered granite of Tertiary age and are described by Rooy (unpubl.data). These gullies developed prior to deposition of the extensive slope deposits that cover the mountains at present and obscure the gullies from the surface topography. As these deposits are argued to be of Pleistocene age (see below) a considerably wetter phase, dominated by erosion, must have preceded a period during which debris accumulation dominated. The density of gullies found indicates higher precipitation values than at present. No attempt has yet been made to date the gully infill deposits and so no minimum age of gully incision can be given.

7.3.2. Pleistocene debris production

It is considered that the main geomorphological manifestation of the cold phases of the Pleistocene in the Western Cape has been the extensive deposition of coarse diamictons throughout the region (Linton, 1969; Butzer, 1973a; Lewis, 1988a). Some basic observations will assist in the evaluation of their nature. First, the widespread occurrence of these debris mantles and their stratigraphic positioning indicates that they formed subsequent to the phase of deep chemical weathering in the Tertiary and are the result of a change in regional environmental conditions. Second, Rooy (unpubl.data) has shown the existence of different temporal phases of debris accumulation in the Du Toitskloof valley. Third, a uniform characteristic is the high clast content of the material. The diamictons vary from matrix- to clast-supported to openwork boulder accumulations. Most of these deposits appear as massive, structureless deposits, frequently in the form of colluvial rubble mantles. Observations in the gully infill deposits mentioned above also reveal no sedimentary structures. Sedimentological observations in recent debris flow deposits indicate characteristics distinctly different from those observed in the paleo-deposits of the gully infills (Duiker and Van Duffelen, 1994). No evidence for flow behaviour in the infill material could be found suggesting that deposition took place under relatively dry conditions. Fourth, at present, these deposits are stable and no significant debris accumulation takes place. In contrast, signs of fluvial erosion are evident throughout the region. Sediment movement monitoring in the Waaihoek Peak area further bears out the immobility of these deposits.

Pleistocene debris production mechanisms

The origin of the slope deposits and their paleoclimatic significance remains debatable and centres around the origin of the high angular clast content of the debris.

The generally angular nature of the clasts has lead several authors to conclude that the material is cryoclastic in origin (Linton, 1969; Helgren and Butzer, 1972; Butzer 1973a,b; Lewis, 1988a). This perception has, however, come under critical scrutiny by Hall (1991). Hall points out that angularity is a clast characteristic undiagnostic of frost action as it can be formed by several mechanical weathering processes. He further points out that freeze-thaw frequently operates in close association with other weathering mechanisms like salt and hydration weathering. On this basis, he refutes the allocation of freeze-thaw as an explanation.

Observations in this study have provided more data on what mechanisms, other than freeze-thaw, may be responsible for the mechanical fracturing of local lithologies and its release from rockwalls. These include fracturing under thermal stress, particularly by fires; slab failures by dilatation; and rockfalls triggered by seismic activity. Salt weathering mechanisms were found to be of low importance, based on the absence of field evidence for the presence of salts and the generally highly leached conditions in these mountains. Hydration mechanisms are effectively excluded by the absence of argillaceous or other sorption-sensitive components in local lithologies. The mechanical release mechanisms identified may now be evaluated in context of the paleodeposits in the Western Cape.

Thermal stress

Fracturing under influence by fires is probably the most dominant mechanical weathering mechanism at present in the region. However, it mainly operates on rock materials in close proximity of fuel, that is biomass, and as such plays an insignificant role on the rockwalls of the Western Cape mountains, which often reach heights of over 100m and are well out of reach of fires. Yet, it are these rockwalls that have produced the materials that blanket their footslopes. Second, measurement of rock temperatures in this study show that effects of thermal shock are limited to the surface of the rock and are thus incapable of release of larger blocks from rockwalls. Third, the influence of thermal fatigue under diurnal temperature cycles remains debatable and no direct evidence for its occurrence, or proof to the contrary, exists. However, diurnal temperature ranges have been shown to be considerable higher on sun-exposed rocks in this study and it is on these rock faces where highest debris production would then be expected. Observations in the Du Toitskloof valley by Rooy (unpubl.data) and during the regional survey in this study, show the contrary to be the case in the field. One may thus conclude that, if thermal fatigue played a role in debris production in the Western Cape mountains, it will have been subordinate to release mechanisms that favoured shaded sites.

Slab failure and rockfall by seismic activity

Slab failure deposits have been observed at few isolated sites. Where present they have sometimes supplied large volumes of clasts which have accumulated to form a scree cone (e.g. Du Toitskloof valley) or clasts have formed a veneer across the debris mantle beneath the cliff (e.g. Matroosberg). Slab failures are, however, sporadic in occurrence and cannot explain the ubiquitous presence of debris mantles across the slopes of the Western Cape mountains. The same argument can be used to discount the role of seismic activity in the region. No evidence exists of periods of increased seismic activity in the entire region to account for the widespread acceleration of rockfall activity.

A case for cryoclastic weathering

As pointed out above, regional environmental change must be invoked to explain the onset of, what probably have been several phases, of widespread debris production in the region. None of the mechanisms discussed above can explain the field observations. However, conditions for freeze-thaw action would have been favourable during the colder phases of the Pleistocene. First, it has been shown that intact arenites of the Table Mountain Group are not frost-susceptible. However, chemical alteration by solution has also been shown to significantly increase porosity to values that Lautridou (1988) considers susceptible for frost shattering. The extensive period of Tertiary deep chemical weathering may thus be expected to have primed the rock faces to allow significant water intake. The high fracture porosity of the material can be argued to have further aided the water migration into the rock. It may thus be proposed that significant amounts of rock moisture can be stored in the rock faces, given suitable climatic conditions. This situation is, however, not very different under present day conditions. Field evidence for recent rockfalls is however scarce.

A general temperature reduction allowing for the rock moisture to freeze could result in an increase in rockfall rates on a regional scale. In the light of experimental studies on frost action in jointed or porous rock (Mellor, 1970; Douglas et al., 1987; Matsuoka, 1990), fracture generation could take place at temperatures as high as -2°C on pre-weathered and jointed sandstone in the Western Cape, if sufficient moisture were present and of long enough duration. The temperatures encountered during the coldest phases of the Pleistocene may in simplistic terms be estimated by lowering the present-day temperatures by 5°C. This is the amount of temperature decrease established for the Last Glacial Maximum at about 18.000yr BP by Talma and Vogel (1991) for the southern Cape. A characterisation of temperature regimes is provided in Table 33. From this table it is apparent that effective freeze-thaw cycles would occur on snow-free rock surfaces from April to September. Ground surfaces would remain frozen over several weeks in the period from June to August but no permafrost would have occurred in the region. This agrees well with the proposed mechanisms and environmental conditions under which formation of the boulder streams at Matroosberg took place (see section 3.4.4.). In terms of freeze-thaw cycles, frequency and intensity would have been sufficient to allow for significant frost action on rock faces, considering the temperature criteria discussed in section 6.4.3. As current understanding supports the notion that the Western Cape was characterised by similar seasonal precipitation patterns as at present moisture supply would not have been a limiting criteria for this region.

In conclusion, the various arguments in favour and against a cryoclastic origin of the coarse debris mantles in the Western Cape, have been reconsidered upon the new data available from this study. From these it appears that conditions have been favourable for effective frost action to have taken place over a wide area in the higher parts of the Western Cape mountains. No other processes can be evoked to

Table 33. Temperature and frost regimes at Waaihoek Peak under a 5°C temperature lowering.

	Air (+1.5m)	Soil Surface	Rock Surface
Mean annual temperature	4.8 °C	6.5 °C	5.4 - 7.4 °C
Frost season	April - December	April - November	April - November
Annual frost frequency:			
t < 0 °C	152	172	-
t < -5 °C	62	74	40 - 60
t < -10 °C	8	0	3

satisfactorily explain the full set of characteristics of the angular debris encountered in the region. Although a cryoclastic origin is favoured here no new data as to the extent of Pleistocene temperature lowering can be offered. As long it is not known what constitutes an effective frost cycle for the local lithologies, no answer can be provided to this question. Freeze-thaw experimental studies linked to field evidence are the only way in which this can be achieved.

7.3.3. Interpretation of alluvial footslope deposits

Alluvial conglomeratic fan deposits are of widespread occurrence in at the footslopes of the Western Cape mountains. They have been morphometrically described in the Hex River valley by Booysen (1974). Outstanding characteristics are the extraordinary volumes of coarse boulder material that have been transported over extended distances, frequently over low gradient terrain (e.g. Booysen, 1974). At present the conglomerates are stable and incised by narrow stream channels. Booysen (1974) considered the deposits of Tertiary age, but their weathering status and intricate association with the surrounding debris mantles discussed above, suggest the conglomerates to be of similar age as the Pleistocene slope deposits. The question regarding the origin of the fans deposits is, under what circumstances could large volumes of coarse debris be transported in a fluvial environment? Sänger (1988a) used the necessity for high flood magnitude events to suggest the fans to be fluvioglacial outwash deposits. The existence of widespread glaciation in the region is however refuted by a lack of evidence. Glacial features found by Sänger (1988a) could, upon inspection of his sites at Matroosberg, invariably be related to outcrops of the Paleozoic Pakhuis tillite Formation. Further consideration of the Pleistocene periglacial environment, based on Table 33, may provide new clues.

Considerable support exists for precipitation during the Last Glacial Maximum experiencing an extended rainy season over a wider region at intensities similar to the present-day (e.g. Deacon et al., 1984; Meadows and Sugden, 1990). In combination with the estimation of Pleistocene glacial temperature conditions in Table 33 this suggests that most of the annual precipitation would have fallen in the form of snow in the summit regions of the mountains. General air temperature conditions and the thermal behaviour of snow would have allowed this to accumulate over most of the winter season. At present precipitation totals exceed 2000mm/yr of which over 70% falls in winter in the areas under consideration. Extensive and a deep snow cover can thus be expected to have build up during the Pleistocene glacial periods. Due to the high seasonality in Mediterranean regions summer conditions would allow complete meltout of the seasonal snow pack. It is thus suggested that rapid melt at the end of winter would have released large volumes of meltwater. This would then have been capable of transporting much of the debris produced in the steep upper catchments over the frost season. Seasonal snow melt is thus suggested an alternative source for the high magnitude floods that need to be invoked for the deposition of the footslope conglomerates in the Western Cape mountains.

Much of the debates on Pleistocene morphodynamics in the region remain of a speculative nature. The ideas presented here may at best be used as working hypotheses against which new findings can be tested. They also point out some topics at which attention may be focussed to arrive at more conclusive statements regarding the origin of the relict deposits that still dominate much of today's landscape. First, more rigorous and comprehensive sedimentological studies should be undertaken to reveal the nature of both present-day and relict slope deposits. The study of active slope processes and their resulting morphological and sedimentological characteristics has proved a successful strategy enabling the positive identification of various types of relict periglacial slope deposits (Van Steijn, 1988; Francou, 1990; Hétu, 1991; Hétu et al., in press). Such an approach may be used in the southern African context, particularly in the continuing debate regarding the interpretation of deposits in the eastern and Western Cape possibly associated with debris flows. Further, the uncertainty regarding the age of the relict deposits should be addresses by exploring some of the more recent surface exposure dating techniques now being developed.

A second strategy should focus on further experimental studies on the cryoclastic origin of the angular debris. Quantification of the controls governing behaviour local materials under freeze-thaw may allow for more reliable use of geomorphological features in paleoenvironmental reconstruction for the region. As yet, the origin of the angular debris cannot be conclusively related to freeze-thaw without further experimental studies involving other weathering mechanisms.

7.4. CONCLUSIONS

This study aims to describe and establish the regional extent of active cryogenic features in the Western Cape mountains. Further, the nature and intensity of frost processes and their controls is established by environmental monitoring of climate and sediment movement rates, as well as soil textural analysis. The contribution of frost-induced processes to debris production in the Western Cape mountains is also considered.

Field observations

The higher parts of the mountains in the winter-rainfall region of the Western

Cape are for 90% underlain by quartzitic sandstone and quartzites of the Table Mountain Group. During the regional survey no evidence for active soil frost processes was found in these areas, with the exception of a single site at Matroosberg. On the other hand, three sites, at elevations at or above 1600m a.s.l., on loamy soil from the Cedarberg Shale show widespread evidence of cryogenic activity. Frost processes at other sites at similar elevation and lithology are restricted by steep slope gradients and/or coarse, sandstone-derived debris mantles overlying the shales. The soil frost features observed take the form of micro-patterned ground and turf- and stone-banked steps and lobes. Sedimentary structures show evidence of needle-ice growth, resulting in frost creep at the surface, ejection and vertical tilting of clasts, and vertical and lateral sorting resulting in micro-patterned ground formation. Frost penetration is limited to 6cm depth. Comparison with other studies shows the sorted micro-patterned ground to be characteristic for needle-ice induced forms in environments subjected to diurnal frost. Turf- and stone-banked steps and lobes, normally described for areas of seasonal frost, are here well-developed under diurnal frost conditions in shallow soils.

Environmental controls on frost processes

Climate monitoring on sandstones at Waaihoek Peak (1900m a.s.l.) and shales (Mount Superior, 1860m a.s.l.) shows the Western Cape mountains to be subjected to diurnal frost only. Waaihoek Peak and Mount Superior experience, respectively, on average 74 and 51 frost days a year. However, needle-ice growth requires a soil surface temperature of at least -2°C (Outcalt, 1971). Based on this requirement effective soil frost days occurred on only 12 days in 1991 at Waaihoek Peak, and on 14 and 16 days at Mt. Superior in 1993 and 1994, respectively. The frequency of effective soil frost days is extremely small due to the following factors.

I) High precipitation values in winter result in the presence of snow on an estimated 31 days/yr. On 57% of the frost days recorded temperatures remained between 0 and -2°C due to the presence of an insulating snow cover.

ii) The presence of vegetation raises the plain of greatest heat exchange above the soil surface which effectively reduces the diurnal temperature extremes experienced at the soil surface.

iii) High winter precipitation totals result in high soil moisture levels and the occurrence of overland flow. These imply that significant amounts of latent heat are released when freezing temperatures are reached. The zero-curtain effect is suggested to be particularly effective in controlling frost intensity in the Western Cape mountains.

iv) Higher albedo values for the light-coloured sandstone surfaces result in less effective radiation exchange with the atmosphere, reducing frost frequency-intensity in these materials, relative to the darker-coloured shales.

High soil moisture levels are maintained throughout the cold season and form no limiting factor to effective soil frost activity in the region.

Particle size analysis and moisture data, related to the experimental values obtained by Meentemeyer and Zippin (1981), strongly indicate that the sediments from the arenites of the Table Mountains Group are too coarse to allow for the formation of segregation ice. This means that, irrespective of climate controls, sediment properties do not allow for geomorphological features related to soil frost, to develop over most of the Western Cape mountains. From these results, and the few reports elsewhere, it appears that coarse arenaceous regolith may be considered non-frost susceptible in diurnal-frost environments.

Soil movement by frost

Soil movement monitoring in sandy debris mantles at Waaihoek Peak was done by flexible tube, dowels, soil pins and painted stone sites. Slow mass movement by creep or solifluction could not be shown to take place in the sandy debris and appears to be stable under present climate conditions. Dowel sites and soil pin transects indicate surface erosion rates between 0.6 and 4.6 mm/yr, but are considered over-estimates as soil accumulation is not taken into account. Soil transport rates are highly variable and much of the sediment is moved only over short distances to be deposited again behind obstructions on the same slope. The values obtained here therefore give no indication of erosion rates on a slope or catchment scale.

Clast mobility, monitored by painted stone transects over 2 years, is highly variable with only between 8 and 33% of clasts per transect showing movement over distances between 26 and 73 mm/yr. On the west-facing slope both the number of mobile clasts and their average movement rate increased in downslope direction. Based on the soil pin results, this is tentatively linked to enhanced surface erosion of the debris matrix. Comparison with similar studies elsewhere suggests that no creep or solifluction processes are involved in the regolith transport, but is, rather, related to erosion by surface runoff. At Mount Superior, pebble columns in a stone-banked lobe show movement profiles and rates very similar to those caused by needle-ice induced frost creep in other field and experimental studies.

Weathering

Field observations on weathering show a wide spectrum of chemical, mechanical and biological processes to contribute to debris production in the Western Cape mountains. Chemical weathering features dominate in the field at present, while fires may be considered the most important agent for mechanical weathering at present. More detailed observations were made on thermoclastic and cryoclastic weathering.

Rock thermal regimes are described for both sandstone and shale on seasonal, daily and minute time scales. Winter temperatures are moderate in all respects, but summer rock surface maxima for both lithologies are very similar to those reported from hot desert environments. Rock maximum temperature variations between the two lithologies, where measured in rock cracks, appear more influenced by differences in site characteristics, particularly micro-climate, rather than thermal properties of the lithologies. Daily temperature ranges in summer reach over 40°C in shale and 33°C in sandstone. Whether these values are sufficient to induce effective thermal fatigue remains unresolved, but do provide an accurate description of the natural thermal regimes under which these processes are to operate in the field.

Rock temperature measurement on shale and sandstone clasts at the same site in summer indicates rock surface maximum temperatures in the shale to be on average 12°C higher than in quartzite. Daily maxima are also significantly higher than those obtained from rock cracks. Internal rock temperature gradients obtain two diurnal peaks; the first at noon during maximum heating, the second, and lower peak, in the early evening at maximum cooling. Internal rock temperature gradients reach up to 1.5°C/cm (shale) and 0.58°C/cm (sandstone), the difference being explained by differences in thermal conductivity between the two lithologies. Maximum heating rates of up to 3.5°C/min are obtained for both lithologies. The latter values are well above the threshold value of 2°C/min, reported by Richter and Simmons (1974), and others, to result in permanent strain by thermal shock. However, no visible damage could be reported from the clasts used in the monitoring. It remains impossible to relate observed temperatures to effective thermal stress induced. Quantification of relevant rock properties would provide more valuable data, but conclusions could still only be produced in terms of likeliness of permanent strain induced, unless actually measured.

Rock temperatures were recorded in cracks in sandstone and shale to assess the potential role of cryoclasty in rock weathering. A lack of rock moisture data, limited rock property analysis and the inability to conduct experimental work on the behaviour of local lithologies under frost cycles inhibit any measure of conclusiveness to this question. Based on results from other studies, a temperature of -2°C is considered the critical value for fracture generation in jointed and porous rock. Assuming this value valid for jointed and pre-weathered sandstone effective freeze-thaw cycles occurred with a frequency of 21 and 35 days on a shaded sandstone site in 1992 and 1994. A frequency of 24 days is recorded for the sun-exposed shale in 1993. At both sites no rock deterioration was noted. However, it does seem plausible that at selected sites in the summit areas micro-climatic conditions are favourable for effective freeze-thaw action on pre-weathered or jointed rock.

The Western Cape mountains: an active periglacial environment?

Environments of diurnal frost are characterised by needle-ice growth, which has been reported to be of dominant importance in shaping surface morphology and sediment transport, particularly in the low-latitude mountain environments of eastern and southern Africa, the Andes and the sub-Antarctic islands. Adhering to the most widely accepted definition of a periglacial environment, namely the operation of frost processes at intensities sufficient to significantly affect or shape landforms, areas subjected to diurnal frost processes may thus be considered periglacial. However, periglacial environments exposed to diurnal frost are not characterised by the severity of freeze-thaw cycles but, rather, by the high frequency of occurrence of a soil frost process particularly effective in manifesting itself morphologically. Its operation results in a suite of geomorphological features that are very distinct from those in areas of seasonal frost and permafrost.

For the Western Cape mountains the spatial patterns of frost, moisture and soil texture control on needle-ice growth, well explain the geographic distribution, nature and movement of soil frost features in the region. Accepting a definition of the term periglacial in its widest sense the Western Cape mountains, as a whole, are not an active periglacial environment. However, islands of periglacial activity do occur in the summit region over 1600m a.s.l.. The use of the term periglacial in this case has become so imprecise that it reveals nothing about the distinctiveness of the type of periglacial activity encountered in these areas. These sites in the Western Cape mountains are more accurately referred to as islands dominated by diurnal soil frost activity.

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APPENDIX 1. INSTRUMENTATION USED IN THE MICRO-CLIMATIC MONITORING

1.1. Data loggers

Model 120-02EX data loggers manufactured by Mike Cotton Systems, Cape Town, were used for the project from 29-11-1991. The simpler model MCS 101, used in 1990-1991, has essentially similar specifications. The following specifications of the 120-02-EX are as supplied by the manufacturer.

Specifications

Real time clock	Better than 5 seconds/month.
Analog channels	12, at 3 optional DC ranges to accommodate input spans of ±20mV, 200mV and ±2000mV signals. Two AC ranges are provided to accommodate continuous AC signals or sampled AC signals.
Digital channels	4, CMOS compatible, maximum frequency 1000Hz.
Digital accuracy	0 to 8000 counts per log period.
Scan period	Analog channels are scanned once per minute, digital channels accumulated over scan period
Log period	Two independent log periods may be selected from 1 minute to 24 hours. All sensors are logged in parallel, that is simultaneously, at log time.
Output programs	Instantaneous, totalled, average, maximum and minimum, time of max/min, 360 wind direction algorithm.
Internal storage	2000 data points FIFO buffer.
Output device	Built-in solid state memory module recorder,
Power	12 V 50milli-amp solar cell panel, charging a gel cell battery.

1.2. Temperature sensors

Temperature transducers models MCS 151 and 153 were used throughout the monitoring programme. These have the following specifications:

Specifications

MCS 151

This sensor has a thermal inertia approximately equal to a large mercury thermometer. The sensor is mounted in a 75mm long, thick walled aluminium tube.

Size	8mm diameter x 75mm.
Response time	

Other specifications as for MCS 153 sensor.

MCS 153

This sensor has a low thermal inertia allowing rapid temperature changes. The sensor is mounted in a 25mm long, thin walled, plated brass tube.

Size	4mm diameter x 25mm.
Response time	
Weight	50mg

Measuring range	-20^0 to +70^{o}C
Accuracy	±0.2^{0}C at 25^{0}C
Resolution	±0.1^{0}C
Output signal	Analog output voltage proportional to temperature.
Power requirements	4.8 to 6.5V at 300 micro-amps.

Calibration

Before installation in the field all sensors were calibrated to improve linearity and comparison between the sensors, using the two point auto-calibration facility of the logger. This was done by connecting all sensors to the logger. All sensors were then inserted in a beaker with ice and water and stirred continuously until all sensors were stable. At this stage a low end value of 0.2^{0}C was entered for all temperature channels. A high end value was established by inserting the sensors in a beaker of water with a temperature of 34^{0}C (determined with a mercury thermometer).

Installation

MCS 151 sensors were used for air and soil temperature measurement. Sensors placed in the air were shielded from direct incoming solar radiation by reflective aluminium, placed 4cm above and on the sides of the sensor. No shielding from indirect radiation from the ground surface was put in place.

MCS 153 sensors were used for all rock temperature measurements.

Maintenance

The sensing elements are sealed solid state devices and the calibration elements inserted by MC Systems are stable and therefore do not require periodic calibration. Long term stability is better than 0.03^{0}C per month under normal use.

1.3. Soil moisture sensors

The application of nylon soil moisture sensors, also known as Bouyoucous blocks, is based on the changes in electrical resistivity of the sensor due to changes in relative moisture content. They consist of an inner mesh electrode wrapped in nylon material and an outer mesh electrode enclosing the sensor. The sensor is excited by a AC reference signal to prevent a polarizing effect from the electrodes formed by the chemical composition of the soil. The moisture content of the nylon material equilibrates with the soil moisture where the drier the nylon material the greater the resistance between the two electrode meshes.

Specifications

Measuring range	0 - 100% moisture content
Operating temperature	-10^0 to +50^{0}C
Accuracy	Soil dependent
Response time	5 - 20 minutes, depending on soil type
Active area	25cm^2
Size	70 x 18 x 4mm

Calibration

The nylon soil moisture sensors were calibrated using the auto-calibration facility on the logger as part of the installation process. To use this method, the sensors must be placed at a low and high known soil moisture content. The logger learns these values and calculates the correct offset and multiplier for each sensor.

All moisture sensors were connected to the logger at the monitoring site. A low end value of 0 was assigned to the air dry sensors. Next, soil from the hole where the sensors were to be installed was placed in a tray and over saturated with water. The sensors were placed in the tray, making sure that each had good contact with the slurry by rubbing the sensor with the material. Once all sensors had stabilised a value of 100 was assigned to the sensors in this state. The loggers thus record a series of values from 0 to 100 between air dry state and a state of saturation.

The soil moisture sensors at -5cm at Waaihoek Peak and Mount Superior were more accurately calibrated during January 1995 to allow an estimation of moisture content by percentage weight, as required for a comparison with the data of Meentemeyer and Zippin (1981) (see section 4.4.2.).

The sensor was placed in a tray with soil from the site and saturated with water. The soil and sensor were left to dry. Periodically, small samples were taken from the tray to establish the soil moisture content by gravimetric method with simultaneous reading of the logger-recorded values. Due to the slow drying of the soil and the short duration of the field visit, only upper values are available.

Logger value	Soil moisture content (weight wet sample - dry weight / dry weight x 100%)	
	Waaihoek Pk	Mt. Superior
100	21.5	44.0
99	21.4	44.0
95	20.6	42.8
90	19.3	39.6

1.4. Tipping bucket raingauges

MCS 160 Tipping Bucket Raingauges (TBR) were used to monitor precipitation. They adhere to the following specifications as supplied by the manufacturer.

Specifications

Orifice	203.0±0.2mm diameter brass rim.
Funnel	125mm deep throat copper funnel.
Outer housing	White epoxy sprayed aluminium.
Base	White epoxy sprayed die cast aluminium, integral bubble level.
Filters	Fine stainless mesh steel on all openings.
Bucket capacity	0.2mm
Bearings	Stainless steel.
Outlets	2x15mm OD waste or check gauge.
Sensor	Switch with electronically stretched 120mS pulse duration.
Calibration	Individual bucket adjustment using nylon stop screws.
Accuracy	±1% at 1-100mm per hour.

Size	230mm diameter x 430mm height.
Mounting	Adjustable stainless steel 3 leg arrangement with 3 holes for permanent fixture.

Installation

The tipping bucket raingauges were placed directly on the ground and fixed with steel pens. Adjustments were made to achieve a horizontal position of the TBR using the bubble level at the base.

Calibration

After installation TBR magnet position was checked for correct distance between it and the sensor, that is allowing free bucket movement and confirmed detection of this movement on the data logger.

Calibration of measurement was done by applying a known amount of water to the system and calculating the volume of water used per tip. The latter should be set to measure a volume to the equivalent of 0.2mm. This volume is known by multiplying the area of funnel x 0.2mm. This is $32365.5\text{mm}^2 \times 0.2\text{mm} = 6.47\text{mm}^3$.
One tip is 6.47cc. Using a measuring glass 100cc were poured into the system and the number of tips read from the logger. The bucket tip volume is derived from

Bucket tip = Volume used / Number of tips

With the use of the adjustment screws at the end stop of the bucket the volume at which tipping takes place can be increased or decreased. No need for adjustment was found after initial installation. No further calibration was done to the TBRs.

APPENDIX 2. YEARLY AND MONTHLY TEMPERATURES AT WAAIHOEK PEAK AND MOUNT SUPERIOR.

Waaihoek Peak

MONTH	+1.5m	+0.1m	-0.01m	-0.1m	-0.2m	-0.3m	MOIST1	MOIST2	MOIST3	PRECIP.
Jan	3	4	4	4	4	1	3	3	3	3
Feb	3	5	5	5	5	2	3	3	3	3
Mar	3	5	5	5	4	2	3	3	3	3
Apr	4	4	5	4	3	1	4	4	4	4
May	4	4	5	4	2	1	4	4	4	4
Jun	3	3	4	3	2	1	3	3	3	3
Jul	4	3	4	2	1	0	4	4	4	4
Aug	4	4	5	3	2	1	4	4	4	4
Sep	4	4	5	3	2	1	4	4	4	4
Oct	3	3	3	2	2	0	3	3	3	3
Nov	2	2	2	1	2	0	2	2	2	2
Dec	3	3	3	2	3	0	3	3	3	3
Year avg.	3.3	3.7	4.2	2.7	2.7	0.8	3.3	3.3	3.3	3.3

Mt. Superior

MONTH	+0.1m	-0.01m	-0.05m	-0.1m	-0.14m	MOIST1	MOIST2	MOIST3	PRECIP.
Jan	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1
May	2	2	2	2	2	2	2	2	1
Jun	2	2	2	2	2	2	2	2	1
Jul	2	2	2	2	2	2	2	2	1
Aug	2	2	2	2	2	2	2	2	1
Sep	2	2	2	2	2	2	2	2	1
Oct	2	2	2	2	2	2	2	2	2
Nov	2	2	2	2	2	2	2	2	2
Dec	2	2	2	2	2	2	2	2	2
Year avg.	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.3

Table 2.1. Years of record for all sensors used at Waaihoek Peak and Mt. Superior.

Average monthly air and soil temperatures at Waaihoek Peak (1900m a.s.l.)

Month	AVE+1.5	MAX+1.5	MIN+1.5	AVE+0.1	MAX+0.1	MIN+0.1	AVE-0.01	MAX-0.01	MIN-0.01	AVE-0.1	MAX-0.1	MIN-0.1	AVE-0.2	MAX-0.2	MIN-0.2	AVE-0.3	MAX-0.3	MIN-0.3
Jan	15.8	23.4	10.2	17.5	30.5	8.7	22.1	42.1	10.8	19.7	25.3	15.4	19.2	23.1	16.2	18.2	19.2	16.3
Feb	14.6	22.0	9.8	16.0	28.7	8.6	20.5	38.8	10.8	18.1	23.3	14.4	19.2	24.2	15.7	17.5	19.1	16.7
Mar	14.9	21.9	10.4	15.1	27.2	8.6	18.1	34.1	10.1	16.4	20.9	13.0	17.1	20.7	15.5	15.2	16.6	14.4
Apr	10.3	15.4	6.4	9.6	18.3	4.6	10.0	17.7	5.7	9.5	12.7	7.2	9.9	13.9	8.7	9.8	10.6	9.4
May	7.5	11.6	4.3	6.8	14.0	2.6	6.2	11.5	2.9	5.6	8.2	3.7	6.2	8.2	5.5	6.3	7.0	5.9
Jun	3.8	7.3	0.8	3.7	8.0	0.8	2.9	6.3	0.6	2.9	4.7	1.6	3.5	4.7	3.2	4.0	4.4	3.7
Jul	4.1	7.6	1.1	3.4	8.2	-0.1	2.1	5.0	-0.0	2.1	3.7	0.8	1.2	2.3	0.8			
Aug	4.6	8.8	0.7	4.7	11.9	0.2	3.4	8.4	0.3	2.7	4.5	1.2	3.1	4.8	2.4	2.5	3.1	2.0
Sep	6.5	11.8	2.0	7.5	16.9	1.6	6.2	13.6	2.0	5.7	9.2	3.4	5.7	8.4	4.6	5.3	6.4	4.5
Oct	9.4	15.7	4.7	10.9	23.4	3.4	11.9	24.4	4.8	10.5	15.3	6.8	10.0	14.2	7.9			
Nov	12.7	19.4	7.3	14.6	28.6	5.8	16.4	31.2	8.3	15.8	22.2	10.5	15.0	18.0	12.4			
Dec	13.6	21.0	8.2	15.6	29.9	6.7	18.1	31.7	9.7	17.1	22.5	12.6	16.6	21.9	11.1			
Year	9.8	15.5	5.5	10.4	20.5	4.3	11.5	22.1	5.5	10.5	14.4	7.6	10.6	13.7	8.7			

Average monthly air and soil temperatures at Mt. Superior (1860m a.s.l.)

Month	AVE+0.1	MAX+0.1	MIN+0.1	AVG-0.01	MAX-0.01	MIN-0.01	AVE-0.05	MAX-0.05	MIN-0.05	AVE-0.1	MAX-0.1	MIN-0.1	AVE- 14	MAX-0.14	MIN-0.14
Jan	18.4	33.7	8.6	25.9	58.4	8.5	21.5	32.5	14.2	20.3	25.3	16.9	19.8	23.1	17.8
Feb	18.1	32.7	9.1	22.5	52.5	7.7	20.9	32.1	14.1	19.9	24.5	16.9	19.3	22.0	17.7
Mar	15.7	28.7	8.4	17.9	43.6	7.0	17.4	26.9	12.1	17.7	22.0	15.0	17.5	20.2	16.0
Apr	12.2	21.9	6.3	13.7	32.5	5.5	12.6	18.7	9.2	13.1	16.0	11.4	13.2	15.1	12.1
May	7.7	15.9	3.3	7.4	20.2	1.9	6.5	10.9	4.0	6.9	9.2	5.5	7.1	8.6	6.1
Jun	4.6	10.2	1.2	4.2	11.7	0.6	3.0	5.5	1.6	3.3	4.7	2.4	3.4	4.4	2.8
Jul	3.5	8.8	-0.1	3.9	10.2	0.7	2.6	4.9	1.3	2.7	4.0	1.9	2.8	3.7	2.2
Aug	5.4	13.4	0.3	6.7	20.0	-0.2	4.2	8.5	1.7	4.4	6.7	2.9	4.0	5.5	2.9
Sep	8.2	17.2	2.0	8.7	22.4	1.7	6.8	12.6	3.3	7.9	10.9	5.9	6.7	8.6	5.3
Oct	12.2	24.6	4.0	15.8	38.9	3.5	12.3	21.0	6.6	14.0	18.6	10.7	11.1	14.1	9.1
Nov	13.1	25.9	4.2	17.9	42.3	3.6	15.1	24.3	8.9	18.5	23.4	15.1	14.1	17.1	12.1
Dec	15.0	29.0	6.4	26.2	55.3	10.2	16.9	26.0	10.5	20.2	25.3	16.5	15.9	19.1	13.6
Year	11.2	21.8	4.5	14.2	34.0	9.2	11.6	18.7	7.3	12.4	15.9	10.1	11.3	13.5	9.8

Table 2.2. Average monthly air and soil temperatures at Waaihoek Peak and Mt. Superior.

MONTH		AVE+1.5	MAX+1.5	MIN+1.5	AVE+0.1	MAX+0.1	MIN+0.1	AVE-0.01	MAX-0.01	MIN-0.01	AVE-0.1	MAX-0.1	MIN-0.1	AVE-0.2	MAX-0.2	MIN-0.2	AVE-0.3	MAX-0.3	MIN-0.3
January																			
	90				17.2	26.7	9.5	23.5	45.8	10.1	19.7	24.7	15.7	19.9	23.1	17.5	18.2	19.2	16.3
	91																		
	92	15.6	23.4	10.2	17.0	29.9	8.1	21.6	34.9	12.4	19.7	24.3	16.1	19.6	25.0	14.8			
	93	16.0	23.6	10.3	17.8	32.0	8.8	22.3	47.3	9.3	19.7	25.7	15.0	18.3	21.9	16.2			
	94	15.8	23.3	10.0	18.1	33.4	8.4	21.0	40.3	11.3	19.8	26.4	14.7	19.1	22.3	16.4			
avg		15.8	23.4	10.2	17.5	30.5	8.7	22.1	42.1	10.8	19.7	25.3	15.4	19.2	23.1	16.2	18.2	19.2	16.3
February																			
	90				15.8	24.6	10.2	20.2	39.4	10.7	19.0	23.0	16.4	25.4	29.0	22.2	18.3	19.9	17.4
	91				14.8	26.4	8.0	25.1	48.3	11.5	17.4	21.5	14.4	18.9	21.5	17.1	16.8	18.3	15.9
	92	13.9	21.2	9.3	15.1	27.2	7.8	19.2	30.1	11.6	18.1	22.8	14.6	18.1	25.9	10.6			
	93	14.3	21.5	9.2	16.1	31.1	7.6	17.6	36.2	8.2	16.9	23.3	12.1	15.1	22.8	11.9			
	94	15.6	23.3	10.7	18.0	34.4	9.5	20.6	40.0	11.8	19.2	25.8	14.5	18.7	21.6	16.7			
avg		14.6	22.0	9.8	16.0	28.7	8.6	20.5	38.8	10.8	18.1	23.3	14.4	19.2	24.2	15.7	17.5	19.1	16.7
March																			
	90				13.9	23.1	8.3	16.9	32.8	8.6		19.9	12.9	18.8	21.2	17.0	15.3	16.8	14.4
	91				13.4	23.4	8.2	21.0	40.5	11.0	15.5	19.2	13.0	16.7	19.0	15.1	15.1	16.5	14.3
	92	14.6	21.5	10.2	14.5	24.8	7.9	16.4	25.1	10.4	15.7	19.8	12.8						
	93	15.7	22.8	11.1	17.3	32.2	9.7	19.3	42.1	9.9	17.9	23.3	14.2	17.7	23.1	15.2			
	94	14.3	21.3	10.0	16.3	32.5	8.8	16.8	29.9	10.7	16.6	22.5	12.4	16.6	19.4	14.6			
avg		14.9	21.9	10.4	15.1	27.2	8.6	18.1	34.1	10.1	16.4	20.9	13.0	17.5	20.7	15.5	15.2	16.6	14.4
April																			
	90				7.6	12.2	4.3	8.8	16.1	5.0	9.1	11.0	7.9	10.7	11.9	10.0	9.8	10.6	9.4
	91	11.9	17.6	7.7				12.6	19.0	8.3									
	92	9.4	14.2	5.7	8.9	15.9	4.2	8.9	15.5	4.2	8.8	11.8	6.8						
	93	8.2	12.8	4.5	9.1	19.4	3.5	7.6	15.8	3.4	7.8	11.6	5.1	8.0	15.2	5.1			
	94	11.7	17.0	7.8	12.9	25.6	6.3	12.1	22.2	7.5	12.1	16.6	9.0	12.5	14.5	11.1			
avg		10.3	15.4	6.4	9.6	18.3	4.6	10.0	17.7	5.7	9.5	12.7	7.2	10.4	13.9	8.7	9.8	10.6	9.4
May																			
	90				5.8	9.7	2.8	5.5	10.6	2.8	5.7	7.1	4.7	7.0	7.9	6.3	6.3	7.0	5.9
	91	8.8	13.2	5.9				8.7	13.4	5.4									
	92	7.0	10.8	3.5	6.4	11.2	2.4	5.1	10.3	1.5	5.0	7.2	3.5						
	93	6.3	10.1	3.2	6.8	15.6	2.1	5.2	11.4	1.7	5.5	8.7	3.1						
	94	7.8	12.2	4.6	8.4	19.6	3.0	6.3	11.6	3.3	6.1	9.7	3.6	6.8	8.5	4.7			
avg		7.5	11.6	4.3	6.8	14.0	2.6	6.2	11.5	2.9	5.6	8.2	3.7	6.9	8.2	5.5	6.3	7.0	5.9
June																			
	90				4.3	6.8	2.0	3.2	6.4	1.5	3.4	4.3	2.7	4.7	5.3	4.2	4.0	4.4	3.7
	91	3.9	7.7	1.1				2.9	7.0	0.2									
	92	4.2	7.7	0.9	3.4	7.0	0.4	3.1	6.7	0.4	3.0	4.4	1.9						
	93																		
	94	3.2	6.5	0.4	3.6	10.2	0.2	2.3	5.1	0.2	2.5	5.3	0.2	3.0	4.0	2.1			
avg		3.8	7.3	0.8	3.7	8.0	0.8	2.9	6.3	0.6	2.9	4.7	1.6	3.8	4.7	3.2	4.0	4.4	3.7

Table 2.3. Monthly air and soil temperatures at Waaihoek Peak (1990-1994).

MONTH	AVE+1.5	MAX+1.5	MIN+1.5	AVE+0.1	MAX+0.1	MIN+0.1	AVE-0.01	MAX-0.01	MIN-0.01	AVE-0.1	MAX-0.1	MIN-0.1	AVE-0.2	MAX-0.2	MIN-0.2	AVE-0.3	MAX-0.3	MIN-0.3
July																		
90																		
91	3.3	7.3	0.6				2.7	5.4	0.6									
92	4.1	7.3	1.0	2.7	6.2	-0.0	1.7	4.6	-0.6	1.3	2.5	0.6						
93	5.3	8.3	2.2	5.0	10.5	0.8	3.2	7.0	0.7	2.9	5.0	1.0						
94	3.9	7.3	0.8	2.4	7.9	-1.1	0.8	3.1	-0.9				1.5	2.3	0.8			
avg	4.1	7.6	1.1	3.4	8.2	-0.1	2.1	5.0	-0.0	2.1	3.7	0.8	1.5	2.3	0.8			
August																		
90				3.8	8.8	0.1	2.7	8.7	0.2	2.3	3.7	1.4	3.6	4.6	2.9	2.5	3.1	2.0
91	3.5	8.1	-1.1				3.1	6.5	-0.4									
92	4.2	8.1	0.9	3.0	7.3	-0.1	3.0	6.7	0.3	2.6	4.2	1.5						
93	5.4	9.8	1.6	5.8	14.5	0.4	4.6	10.6	1.2	3.1	5.6	0.9						
94	5.2	9.3	1.6	6.1	17.0	0.3	3.5	9.4	0.2				3.4	5.1	2.0			
avg	4.6	8.8	0.7	4.7	11.9	0.2	3.4	8.4	0.3	2.7	4.5	1.2	3.5	4.8	2.4	2.5	3.1	2.0
September																		
90				6.3	13.7	1.4	6.2	17.0	1.1	5.3	8.1	3.4	6.5	8.3	5.2	5.3	6.4	4.5
91	4.5	9.2	-0.2				2.2	4.4	0.1									
92	6.4	11.7	2.4	6.1	12.6	1.4	5.5	11.1	1.2	4.8	7.3	2.8						
93	7.2	13.3	2.4	8.5	20.5	1.3	9.8	21.4	4.7	7.1	12.3	3.9						
94	7.9	13.0	3.4	9.1	20.7	2.3	7.1	14.0	2.8				6.5	8.6	4.0			
avg	6.5	11.8	2.0	7.5	16.9	1.6	6.2	13.6	2.0	5.7	9.2	3.4	6.5	8.4	4.6	5.3	6.4	4.5
October																		
90																		
91																		
92	7.0	12.5	2.7	7.4	15.4	1.9	8.6	15.9	2.9	7.9	11.5	5.0						
93	11.1	18.3	5.9	13.2	28.3	4.6	15.7	34.8	6.3	13.2	19.1	8.6	12.5	15.4	10.4			
94	10.0	16.2	5.3	12.0	26.6	3.7	11.6	22.6	5.2				9.9	13.0	5.5			
avg	9.4	15.7	4.7	10.9	23.4	3.4	11.9	24.4	4.8	10.5	15.3	6.8	11.2	14.2	7.9			
November																		
90																		
91																		
92																		
93	12.6	19.5	7.1	14.6	28.6	5.6	17.1	35.0	7.3	15.8	22.2	10.5	15.2	18.4	12.7			
94	12.7	19.4	7.6	14.5	28.7	6.0	15.8	27.4	9.3				14.8	17.6	12.1			
avg	12.7	19.4	7.3	14.6	28.6	5.8	16.4	31.2	8.3	15.8	22.2	10.5	15.0	18.0	12.4			
December																		
90																		
91	14.5	22.5	9.1	16.1	28.9	7.4	19.7	31.4	11.3	18.0	22.9	14.2	17.9	27.4	9.1			
92																		
93	12.8	19.9	7.4	14.9	29.5	6.0	17.2	33.2	8.3	16.1	22.2	11.0	15.6	18.8	13.2			
94	13.4	20.7	8.2	15.9	31.2	6.8	17.6	30.6	9.5				16.4	19.7	13.9			
avg	13.6	21.0	8.2	15.6	29.9	6.7	18.1	31.7	9.7	17.1	22.5	12.6	16.6	21.9	12.1			
YEAR	9.8	15.5	5.5	10.4	20.5	4.3	11.5	22.1	5.5	10.5	14.4	7.6	10.9	13.7	8.8			

Table 2.3. Monthly air and soil temperatures at Waaihoek Peak (1990-1994) (continued).

Month	AVE+0.1	MAX+0.1	MIN+0.1	AVE-0.01	MAX-0.01	MIN-0.01	AVE-0.05	MAX-0.05	MIN-0.05	AVE-0.1	MAX-0.1	MIN-0.1	AVE-0.14	MAX-0.14	MIN-0.14	days missing
93																
94	18.4	33.7	8.6	25.9	58.4	8.5	21.5	32.5	14.2	20.3	25.3	16.9	19.8	23.1	17.8	0
avg.	18.4	33.7	8.6	25.9	58.4	8.5	21.5	32.5	14.2	20.3	25.3	16.9	19.8	23.1	17.8	0
February																
93																
94	18.1	32.7	9.1	22.5	52.5	7.7	20.9	32.1	14.1	19.9	24.5	16.9	19.3	22.0	17.7	0
avg.	18.1	32.7	9.1	22.5	52.5	7.7	20.9	32.1	14.1	19.9	24.5	16.9	19.3	22.0	17.7	0
March																
93																
94	15.7	28.7	8.4	17.9	43.6	7.0	17.4	26.9	12.1	17.7	22.0	15.0	17.5	20.2	16.0	0
avg.	15.7	28.7	8.4	17.9	43.6	7.0	17.4	26.9	12.1	17.7	22.0	15.0	17.5	20.2	16.0	0
April																
93																
94	12.2	21.9	6.3	13.7	32.5	5.5	12.6	18.7	9.2	13.1	16.0	11.4	13.2	15.1	12.1	0
avg.	12.2	21.9	6.3	13.7	32.5	5.5	12.6	18.7	9.2	13.1	16.0	11.4	13.2	15.1	12.1	0
May																
93	7.3	15.1	3.1	6.1	17.7	1.1	6.0	10.3	3.6	6.2	8.4	4.7	6.6	8.0	5.5	0
94	8.1	16.7	3.4	8.8	22.7	2.8	6.9	11.5	4.4	7.6	9.9	6.2	7.7	9.1	6.7	0
avg.	7.7	15.9	3.3	7.4	20.2	1.9	6.5	10.9	4.0	6.9	9.2	5.5	7.1	8.6	6.1	0
June																
93	6.3	13.2	2.3	3.5	11.9	-0.5	3.1	6.2	1.5	3.2	4.8	2.1	3.5	4.6	2.7	0
94	3.0	7.2	0.1	5.0	11.4	1.8	2.8	4.8	1.6	3.4	4.5	2.6	3.4	4.2	2.8	0
avg.	4.6	10.2	1.2	4.2	11.7	0.6	3.0	5.5	1.6	3.3	4.7	2.4	3.4	4.4	2.8	0
July																
93	4.1	9.1	0.7	2.9	7.1	0.9	3.1	5.3	1.8	3.1	4.4	2.2	3.4	4.4	2.8	0
94	2.8	8.5	-0.9	4.9	13.2	0.5	2.1	4.4	0.9	2.4	3.7	1.6	2.2	3.0	1.7	0
avg.	3.5	8.8	-0.1	3.9	10.2	0.7	2.6	4.9	1.3	2.7	4.0	1.9	2.8	3.7	2.2	0
August																
93	5.1	12.0	0.5	4.2	13.2	-0.4	3.8	7.4	1.7	3.5	5.5	2.3	3.7	5.0	2.8	0
94	5.7	14.9	0.1	9.2	26.7	-0.1	4.6	9.7	1.8	5.3	8.0	3.6	4.3	6.0	3.1	0
avg.	5.4	13.4	0.3	6.7	20.0	-0.2	4.2	8.5	1.7	4.4	6.7	2.9	4.0	5.5	2.9	0
September																
93	9.2	19.1	2.3	8.6	23.6	1.1	7.5	14.5	3.5	7.2	10.7	4.9	7.4	9.5	5.8	0
94	7.2	15.2	1.8	8.9	21.2	2.2	6.0	10.8	3.1	8.6	11.2	6.9	6.0	7.6	4.8	0
avg.	8.2	17.2	2.0	8.7	22.4	1.7	6.8	12.6	3.3	7.9	10.9	5.9	6.7	8.6	5.3	0
October																
93	12.7	25.7	4.0	15.1	38.6	2.4	13.6	23.2	7.5	12.5	17.1	9.3	12.4	15.4	10.4	0
94	11.8	23.4	4.0	16.4	39.2	4.5	10.9	18.9	5.6	15.4	20.1	12.1	9.9	12.7	7.7	0
avg.	12.2	24.6	4.0	15.8	38.9	3.5	12.3	21.0	6.6	14.0	18.6	10.7	11.1	14.1	9.1	0
November																
93	14.1	27.4	4.9	18.8	42.7	4.6	16.0	25.4	9.6	14.7	19.1	11.7	14.7	17.5	12.8	0
94	12.1	24.4	3.5	17.0	42.0	2.6	14.3	23.1	8.1	22.3	27.7	18.6	13.5	16.6	11.4	0
avg.	13.1	25.9	4.2	17.9	42.3	3.6	15.1	24.3	8.9	18.5	23.4	15.1	14.1	17.1	12.1	0
December																
93	14.5	27.7	6.0	32.3	63.7	14.8	16.4	25.8	10.0	15.5	20.4	12.0	15.2	18.5	13.0	0
94	15.4	30.3	6.7	20.1	46.9	5.6	17.3	26.3	10.9	25	30.3	21.1	16.5	19.7	14.3	0
avg.	15.0	29.0	6.4	26.2	55.3	10.2	16.9	26.0	10.5	20.2	25.3	16.5	15.9	19.1	13.6	0
Year	11.2	21.8	4.5	14.2	34.0	4.2	11.6	18.7	7.3	12.4	15.9	10.1	11.3	13.5	9.8	0

Table 2.4. Monthly air and soil temperatures at Mount Superior (1993-1994).

Lapse rates at Waaihoek Peak

MONTH	1900m	260m*	lapse rate C/1000m	MONTH	1900m	260m*	lapse rate C/1000m
January				July			
91				91	3.3	12.3	5.5
92	15.6	23.9	5.0	92	4.1	11.8	4.7
93	16.0	23.8	4.8	93	5.3	13.6	5.1
94	15.8			94	3.9		
February				August			
91				91	3.5	11.3	4.8
92	13.9	22.7	5.3	92	4.2	11.9	4.7
93	14.3	22.7	5.1	93	5.4	13.4	4.9
94	15.6			94	5.2		
March				September			
91				91	4.5	14.1	5.9
92	14.6	22.4	4.8	92	6.4	14.1	4.7
93	15.7	23.4	4.7	93	7.2	15.7	5.2
94	14.3			94	7.9		
April				October			
91	11.9	19.3	4.5	91			
92	9.4	17.4	4.9	92	7.0	16.3	5.7
93	8.2	16.7	5.2	93	11.1	18.4	4.4
94	11.7			94	10.0		
May				November			
91	8.8	16.3	4.6	91			
92	7.0	13.5	4.0	92			
93	6.3	14.3	4.9	93	12.6	20.9	5.0
94	7.8			94	12.7		
June				December			
91	3.9	12.6	5.3	91	14.5	22.2	4.7
92	4.2	12.1	4.8	92			
93				93	12.8	22.0	5.6
94	3.2			94	13.4		
				YEAR	9.8	17.1	5.0

Table 2.5. Lapse rate values for Waaihoek Peak (1991-1993)

APPENDIX 3. DAILY AIR AND SOIL TEMPERATURES AT WAAIHOEK PEAK AND MOUNT SUPERIOR.

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Section B: Mount Superior

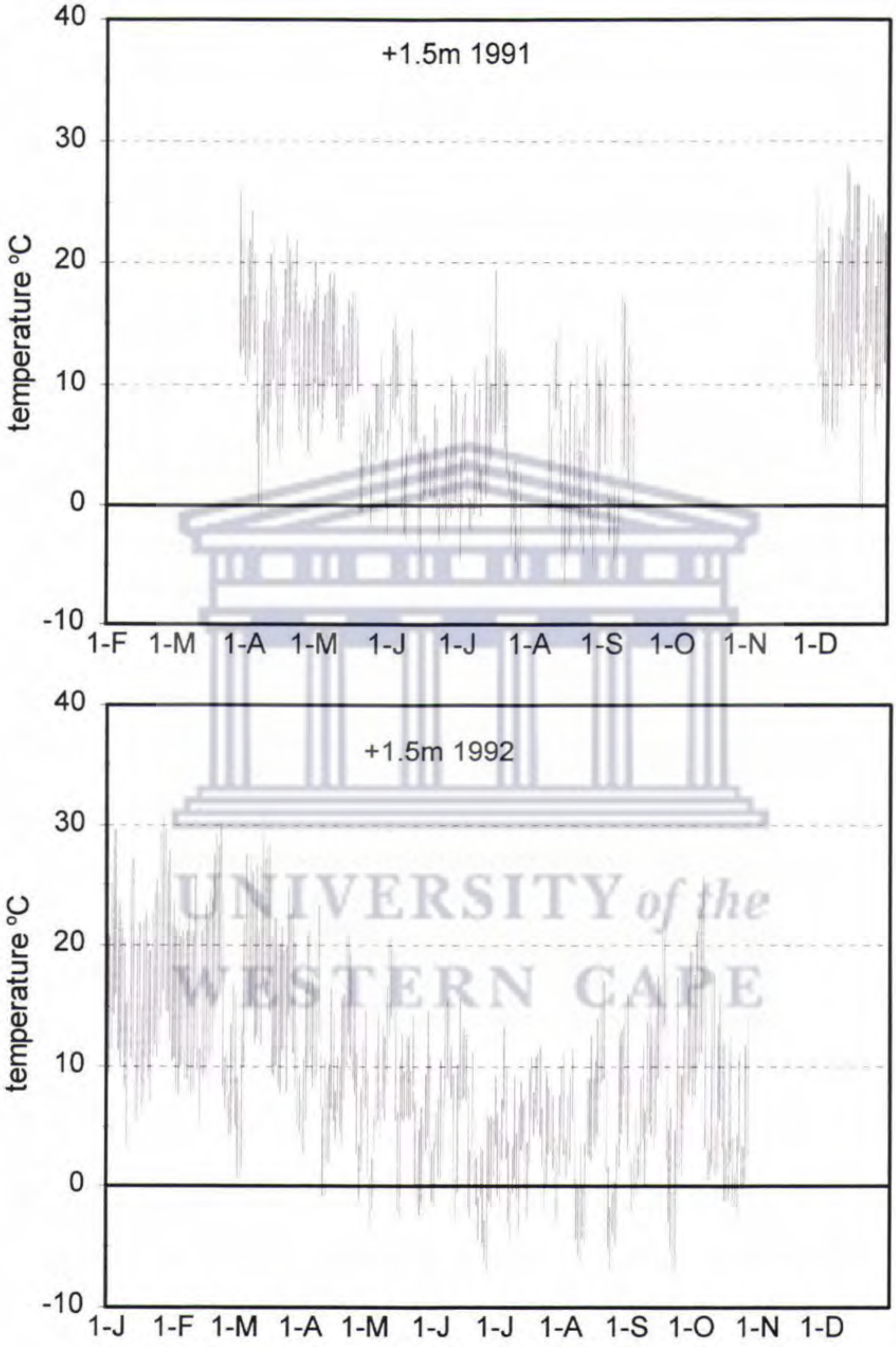
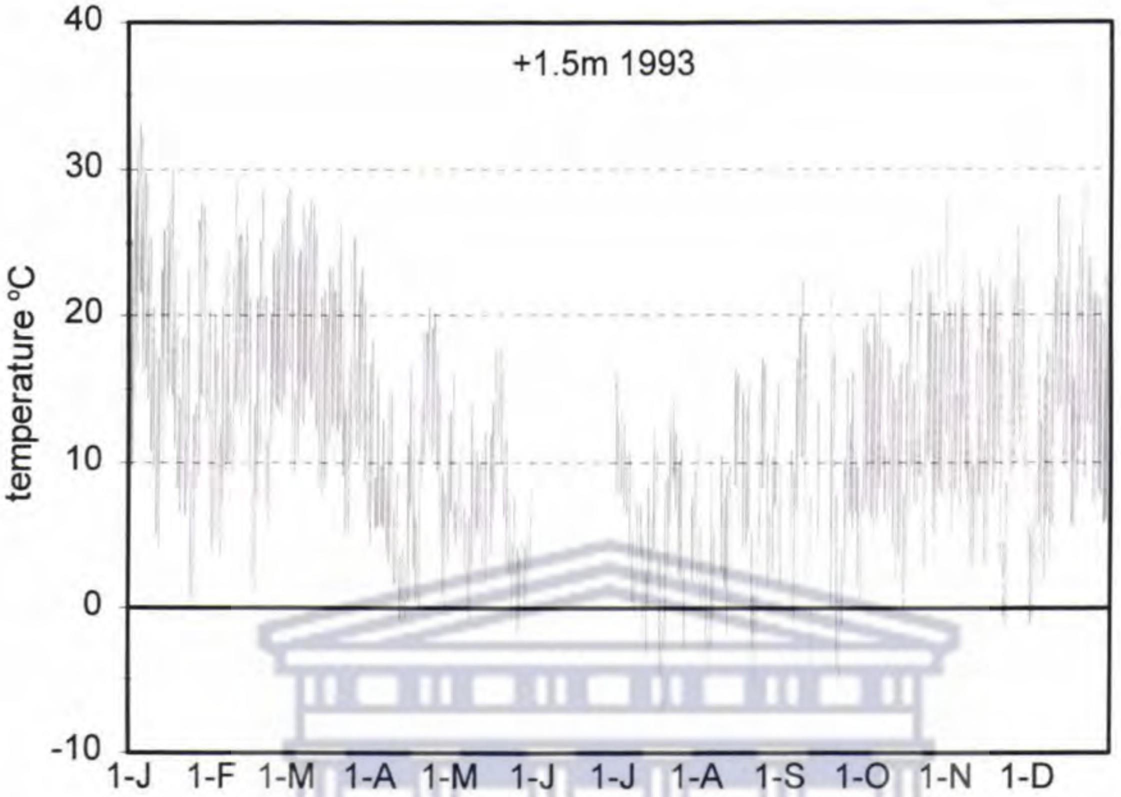


Figure 3.1. Air temperatures at +1.5m (Waaihoek Peak, 1991-1994).



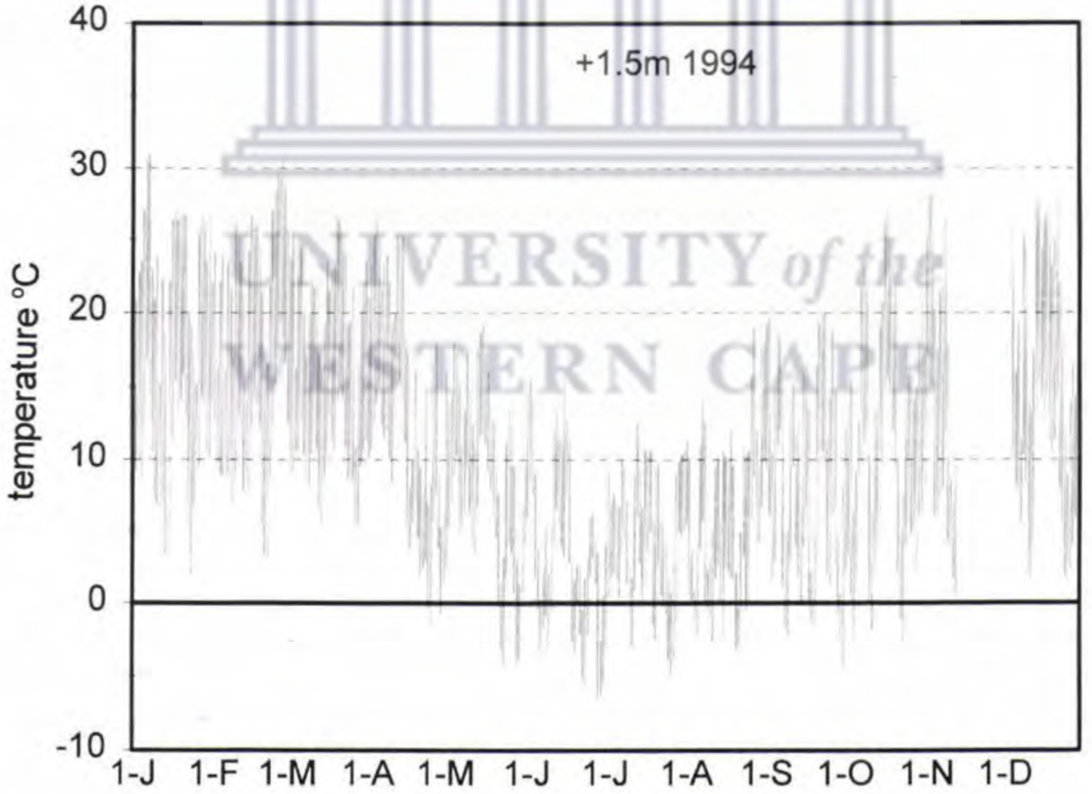


Figure 3.1. Air temperatures at +1.5m (Waaihoek Peak, 1991-1994) (continued).

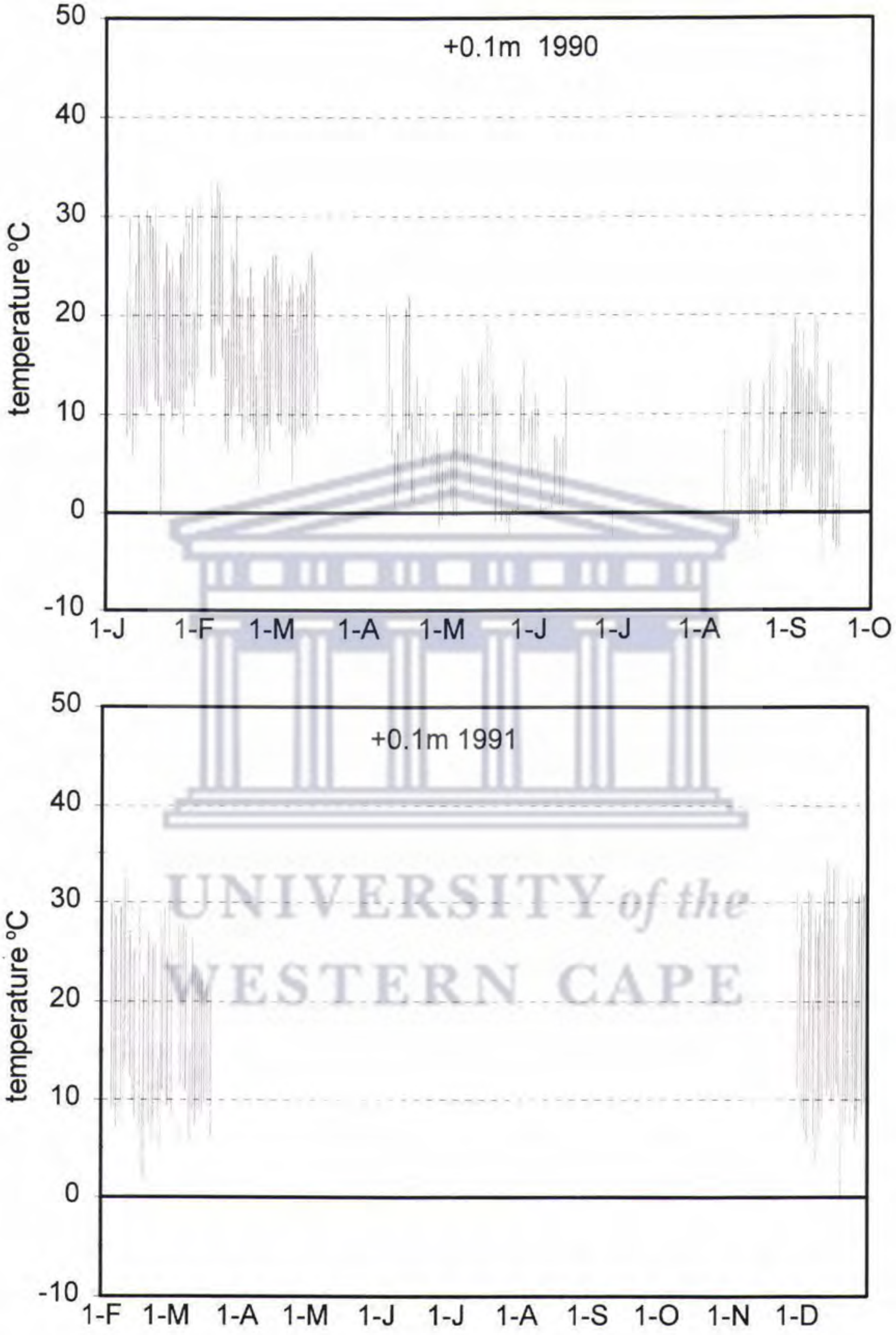
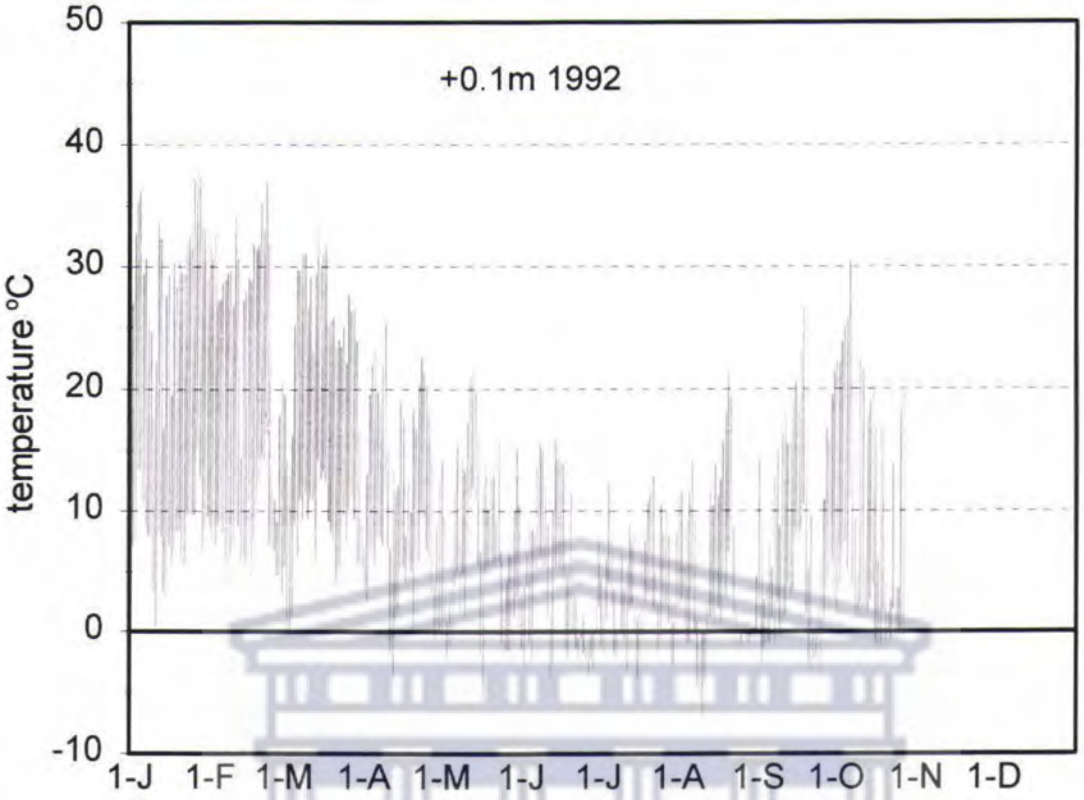


Figure 3.2. Air temperatures at +0.1m (Waaihoek Peak, 1990-1994).



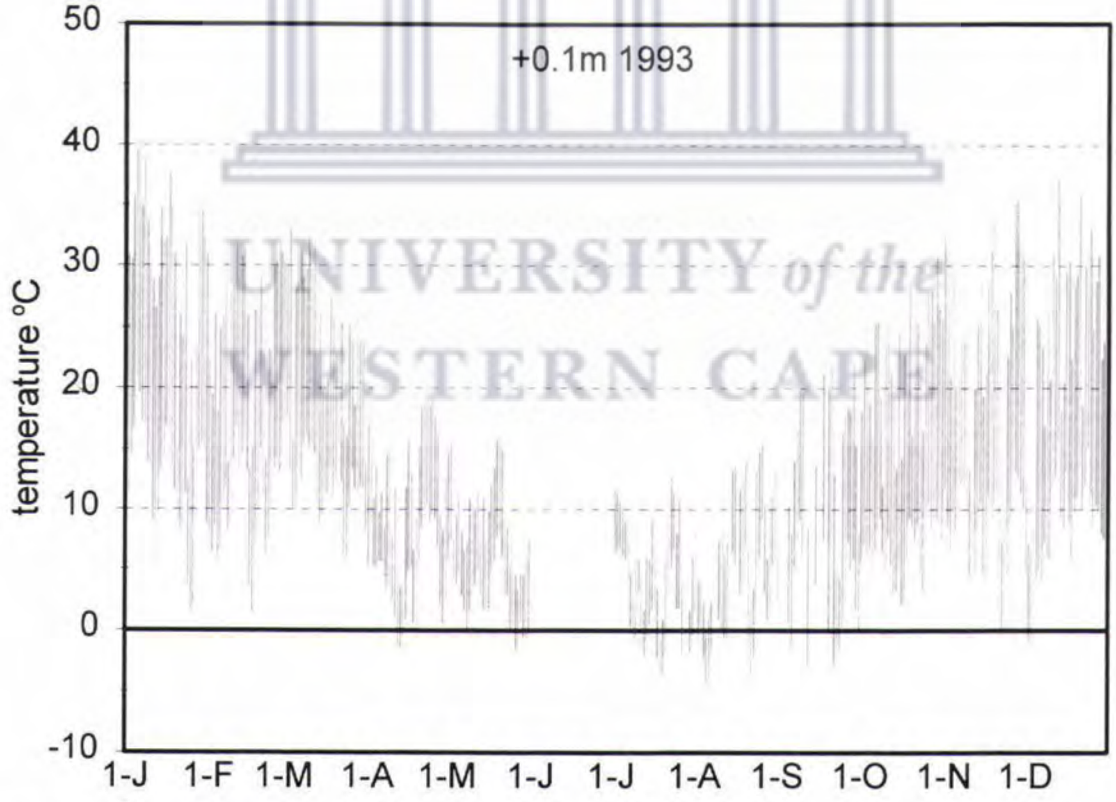


Figure 3.2. Air temperatures at +0.1m (Waaihoek Peak, 1990-1994) (continued).

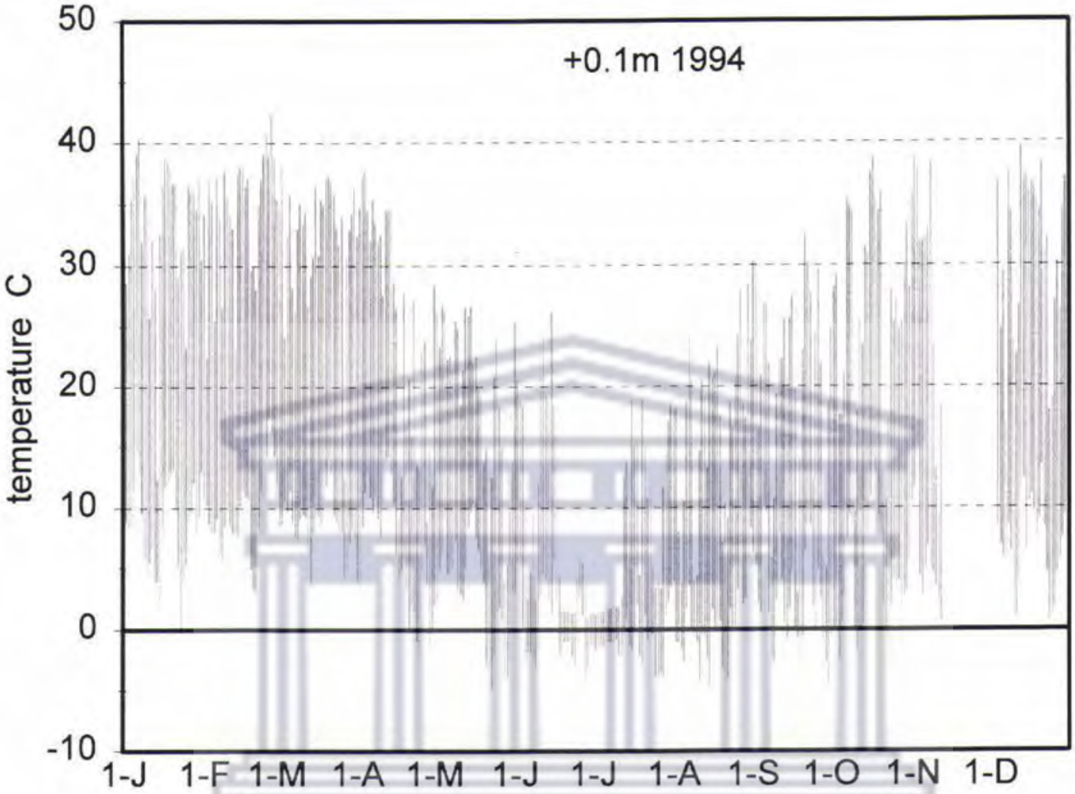
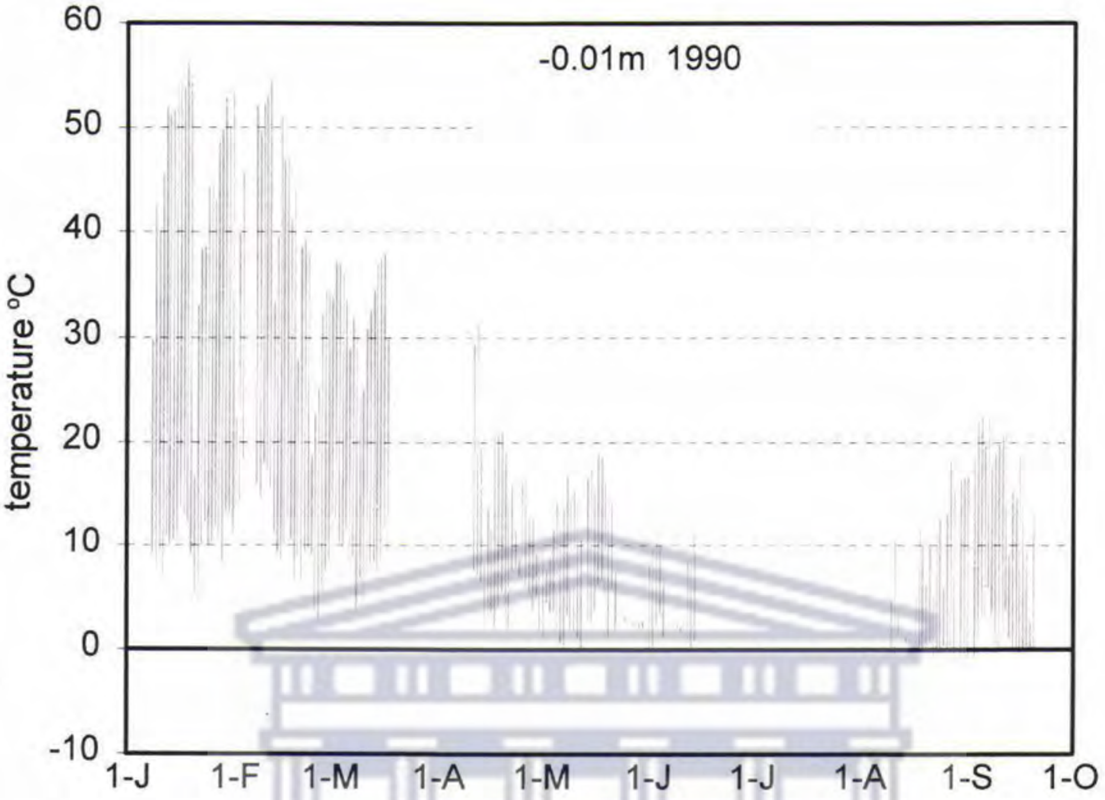


Figure 3.2. Air temperatures at +0.1m (Waaihoek Peak, 1990-1994) (continued).



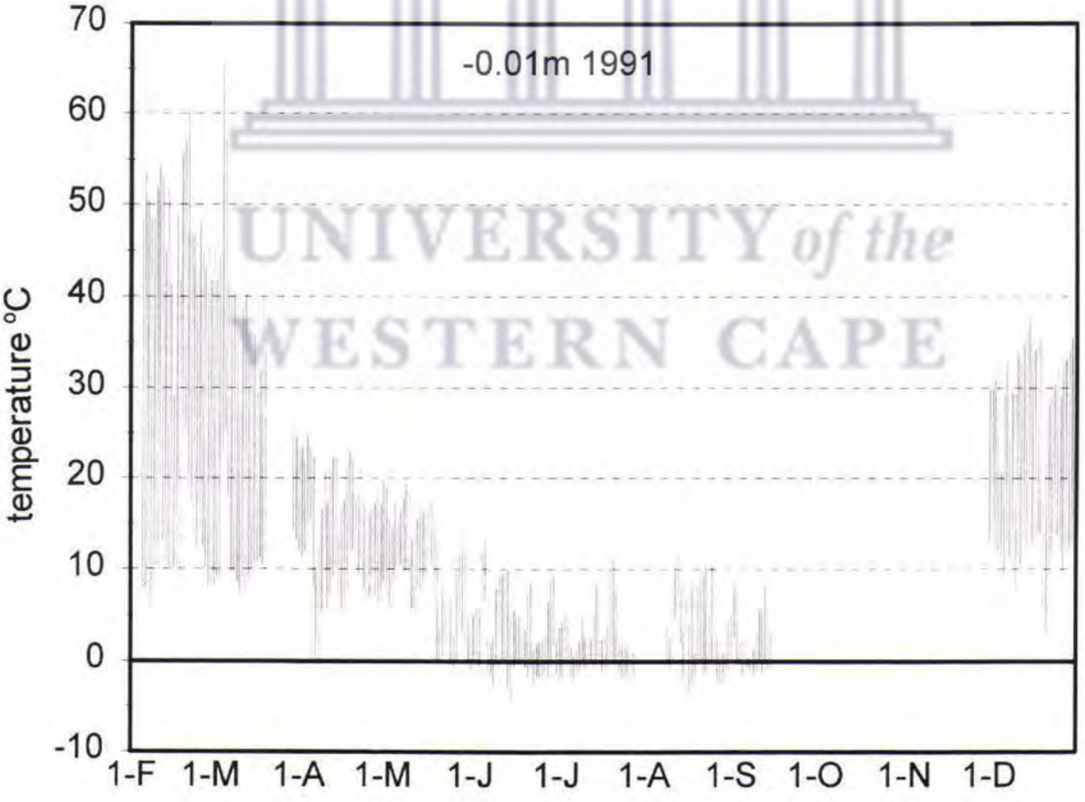


Figure 3.3. Soil surface temperatures (Waaihoek Peak, 1990-1994).

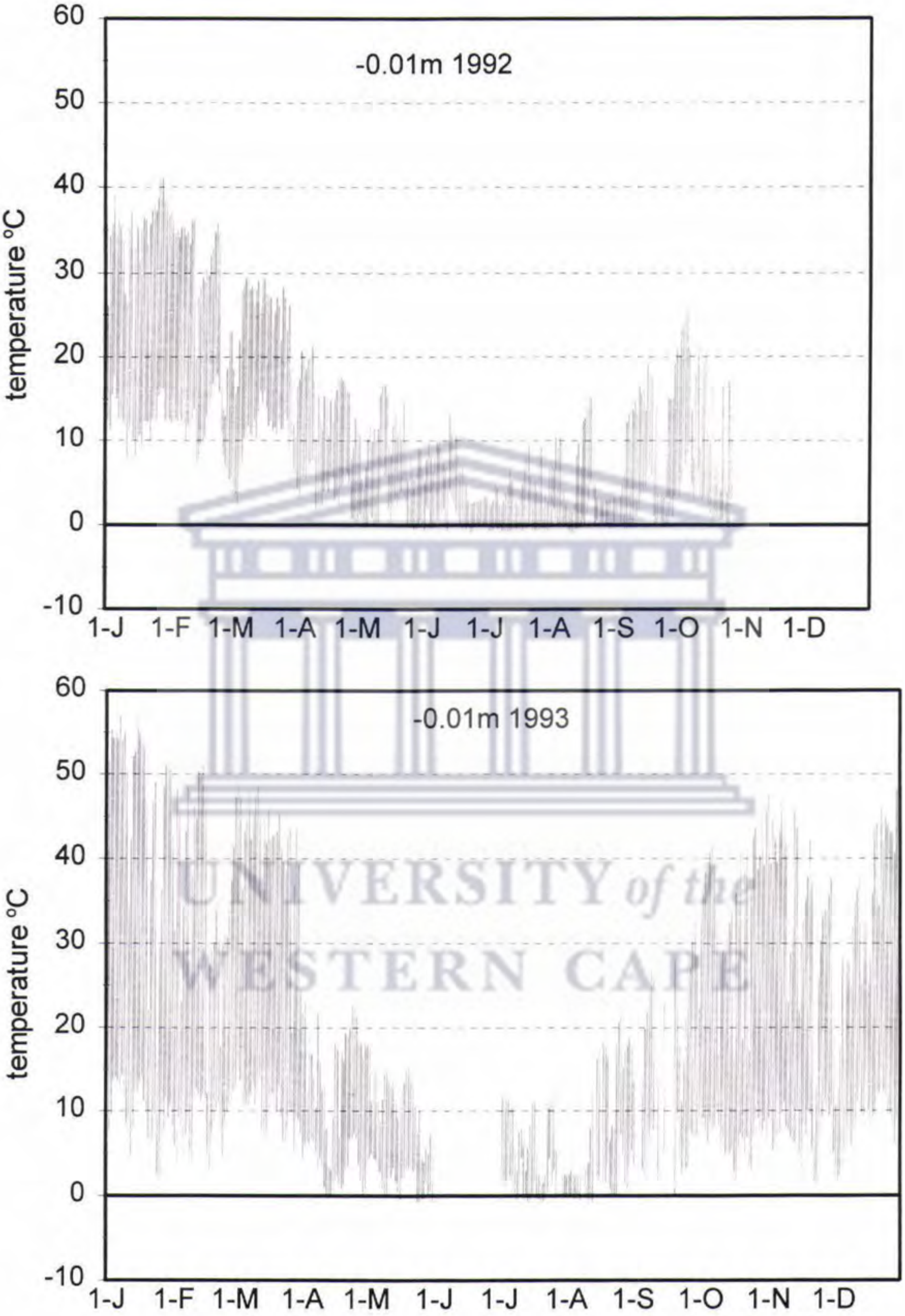


Figure 3.3. Soil surface temperatures (Waaihoek Peak, 1990-1994) (continued).

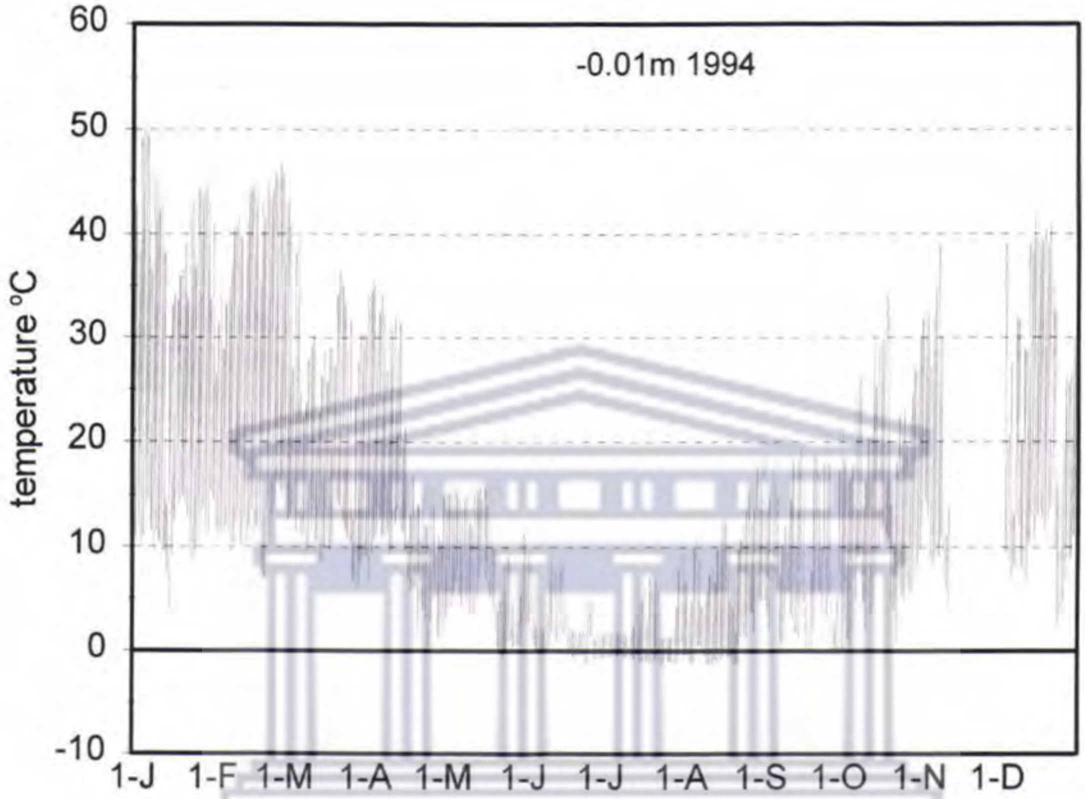


Figure 3.3. Soil surface temperatures (Waaihoek Peak, 1990-1994) (continued).

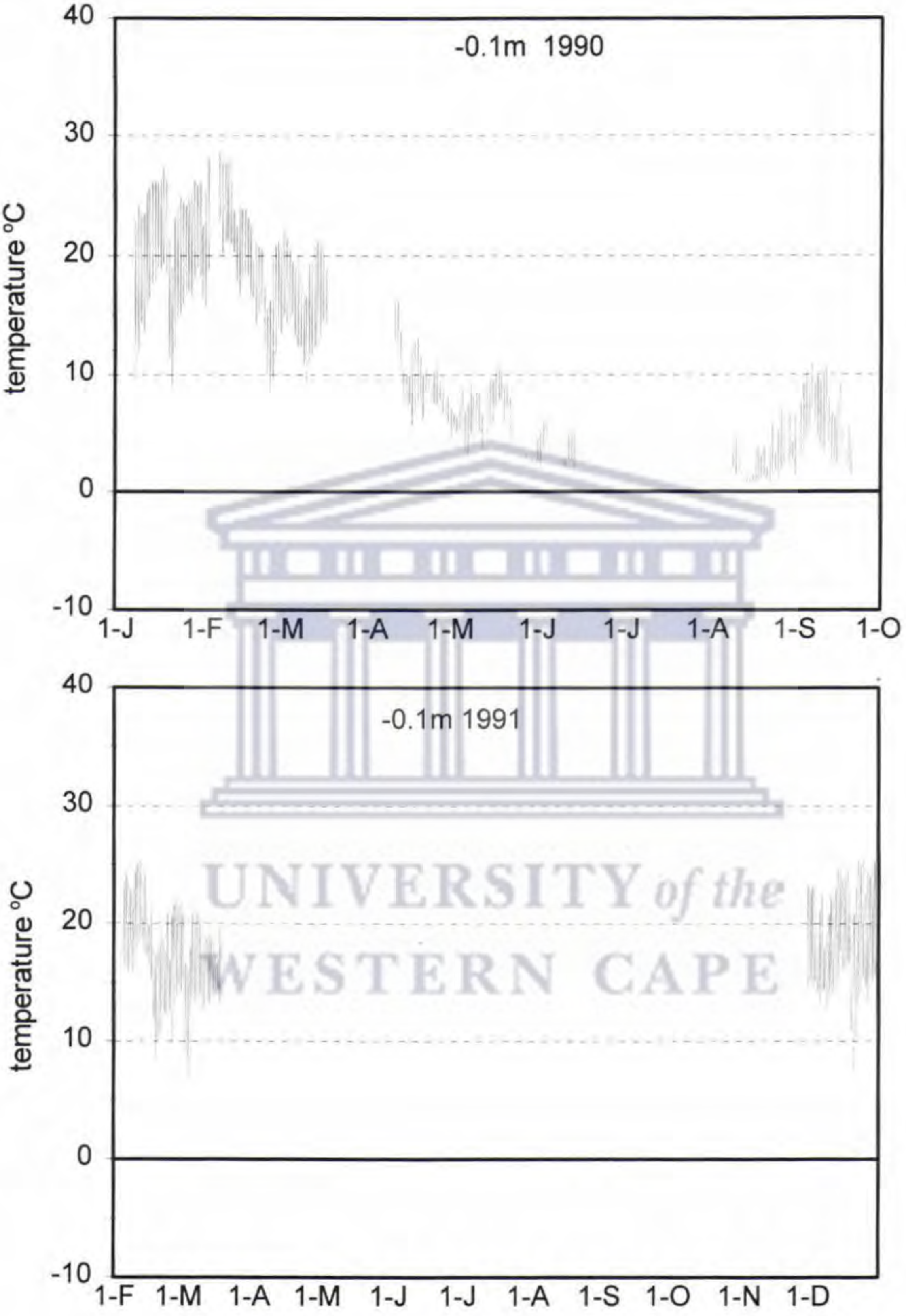


Figure 3.4. Soil temperatures at -0.1m (Waaihoek Peak, 1990-1994).

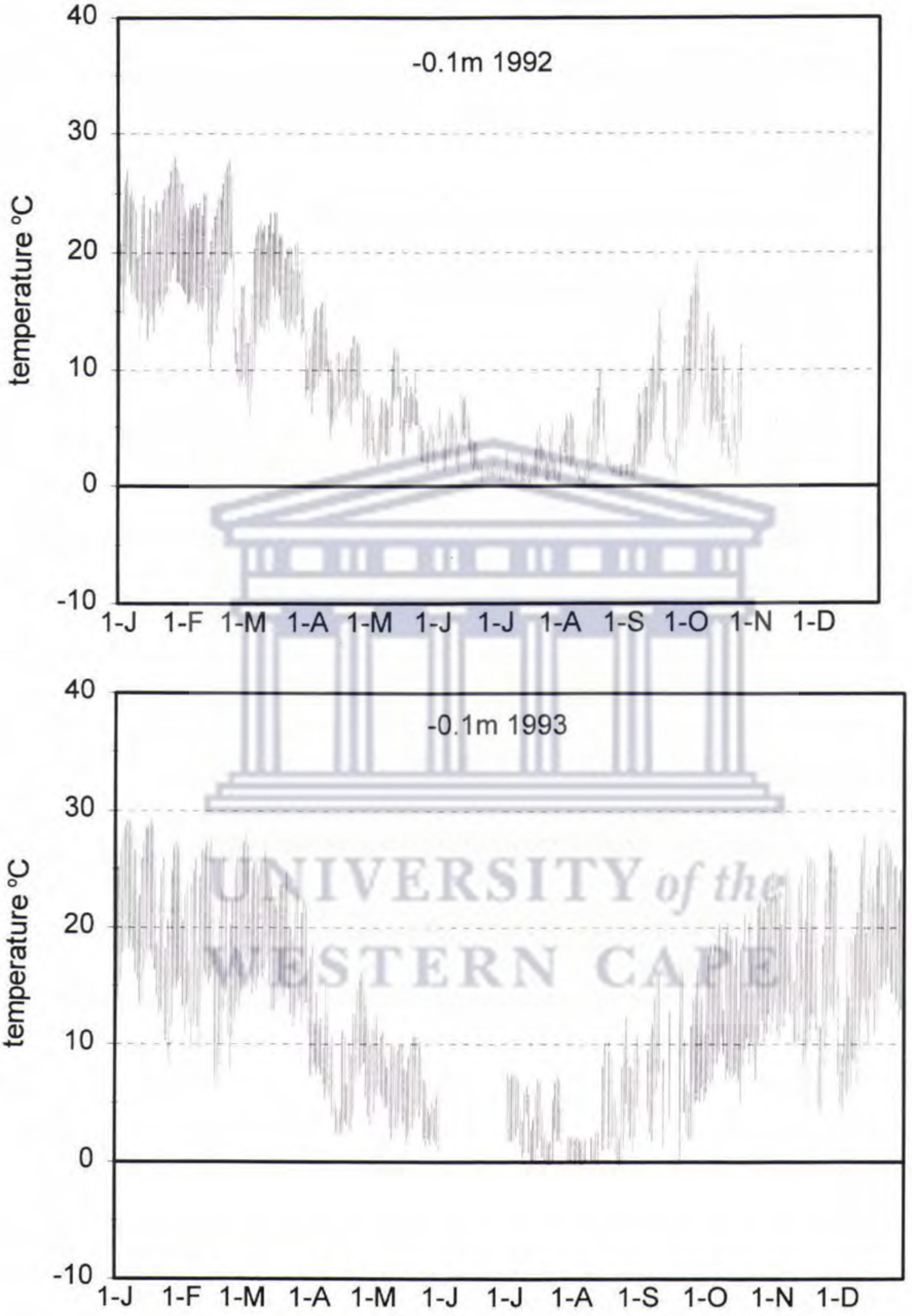


Figure 3.4. Soil temperatures at -0.1m (Waaihoek Peak, 1990-1994) (continued).

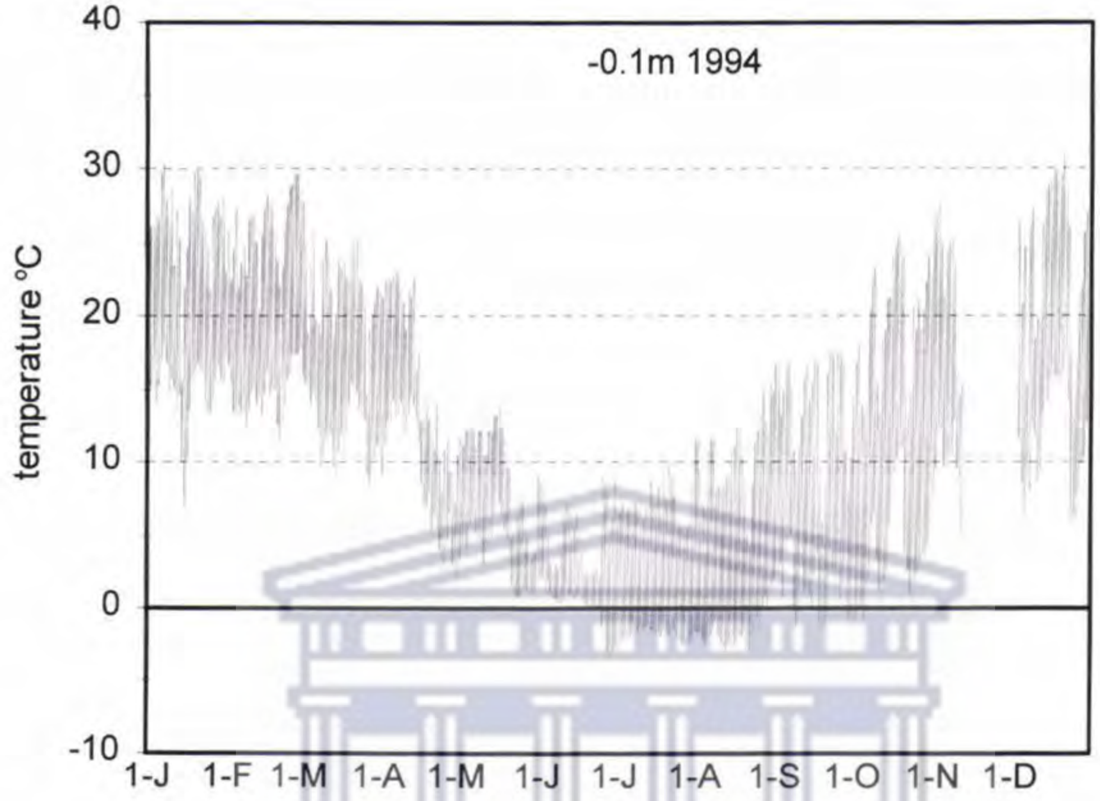


Figure 3.4. Soil temperatures at -0.1m (Waaihoek Peak, 1990-1994) (continued).

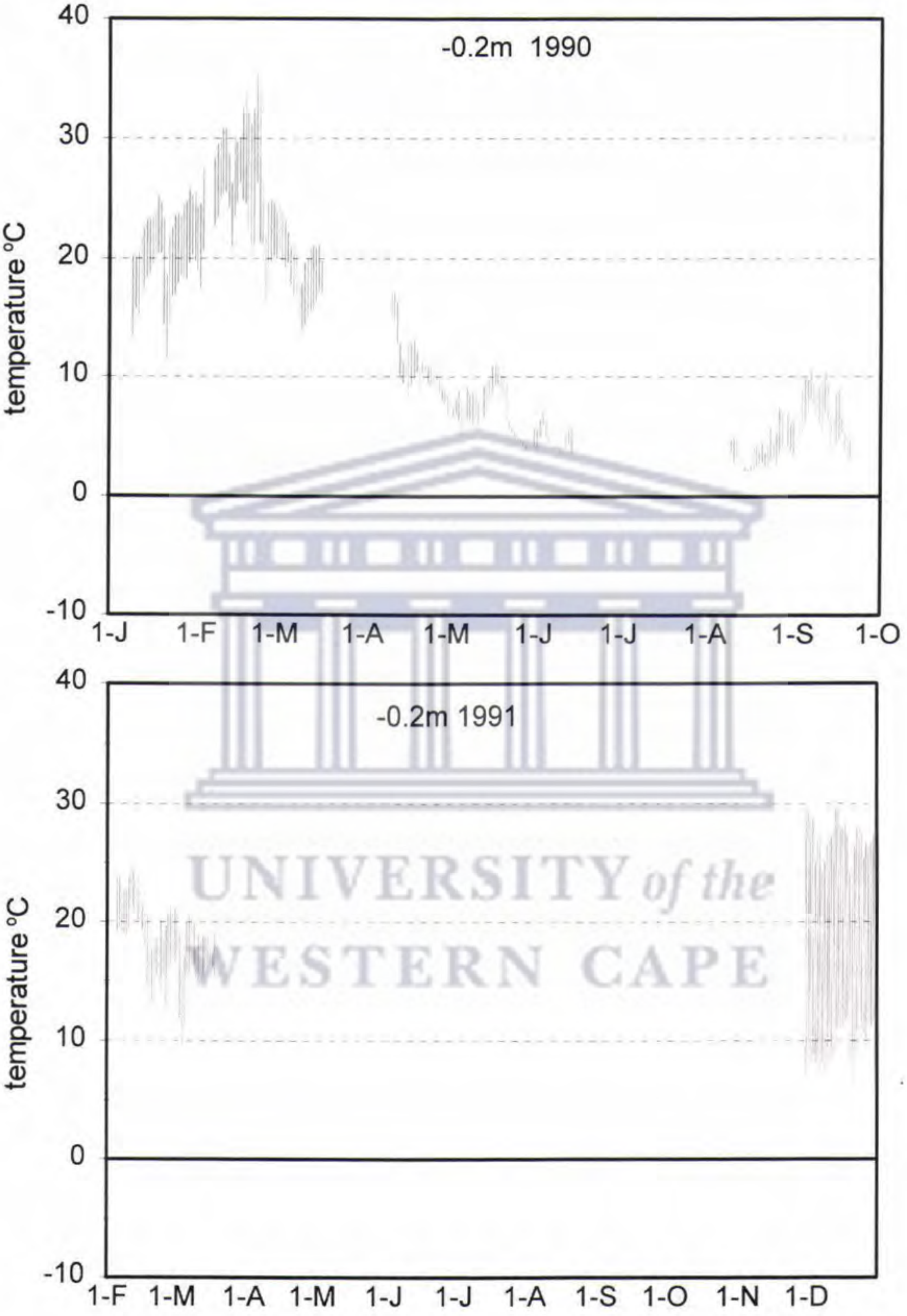


Figure 3.5. Soil temperatures at -0.2m (Waaihoek Peak, 1990-1994).

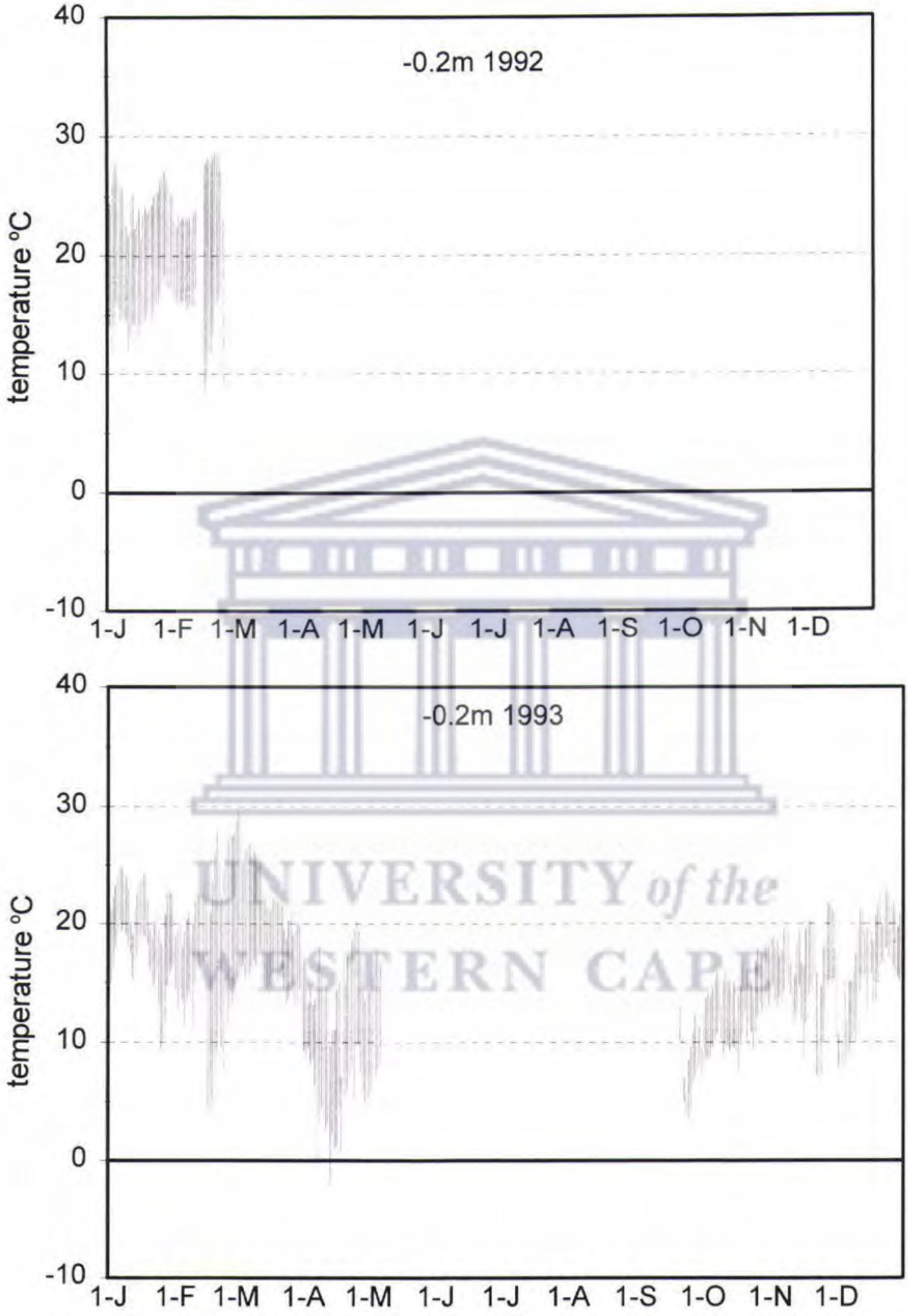


Figure 3.5. Soil temperatures at -0.2m (Waaihoek Peak, 1990-1994) (continued).

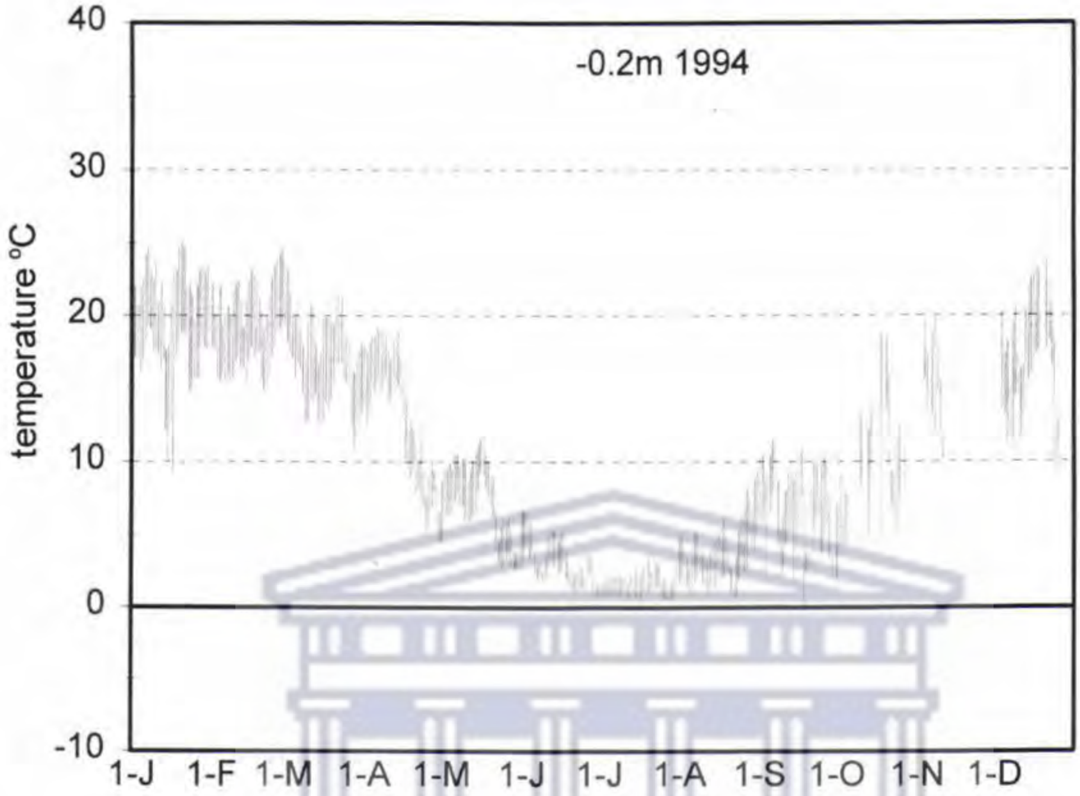


Figure 3.5. Soil temperatures at -0.2m (Waaihoek Peak, 1990-1994) (continued).

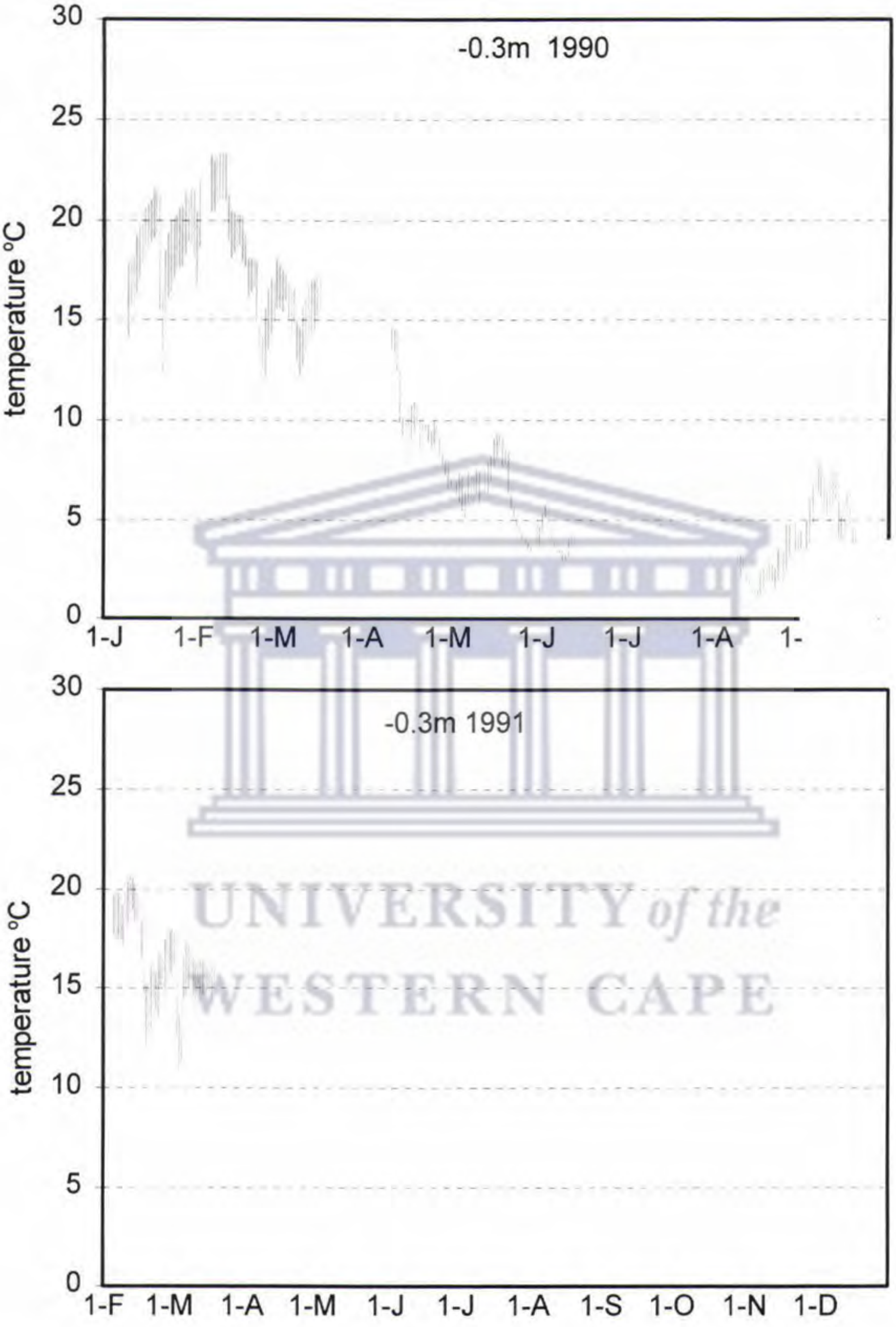


Figure 3.6. Soil temperatures at -0.3m (Waaihoek Peak, 1990-1991).

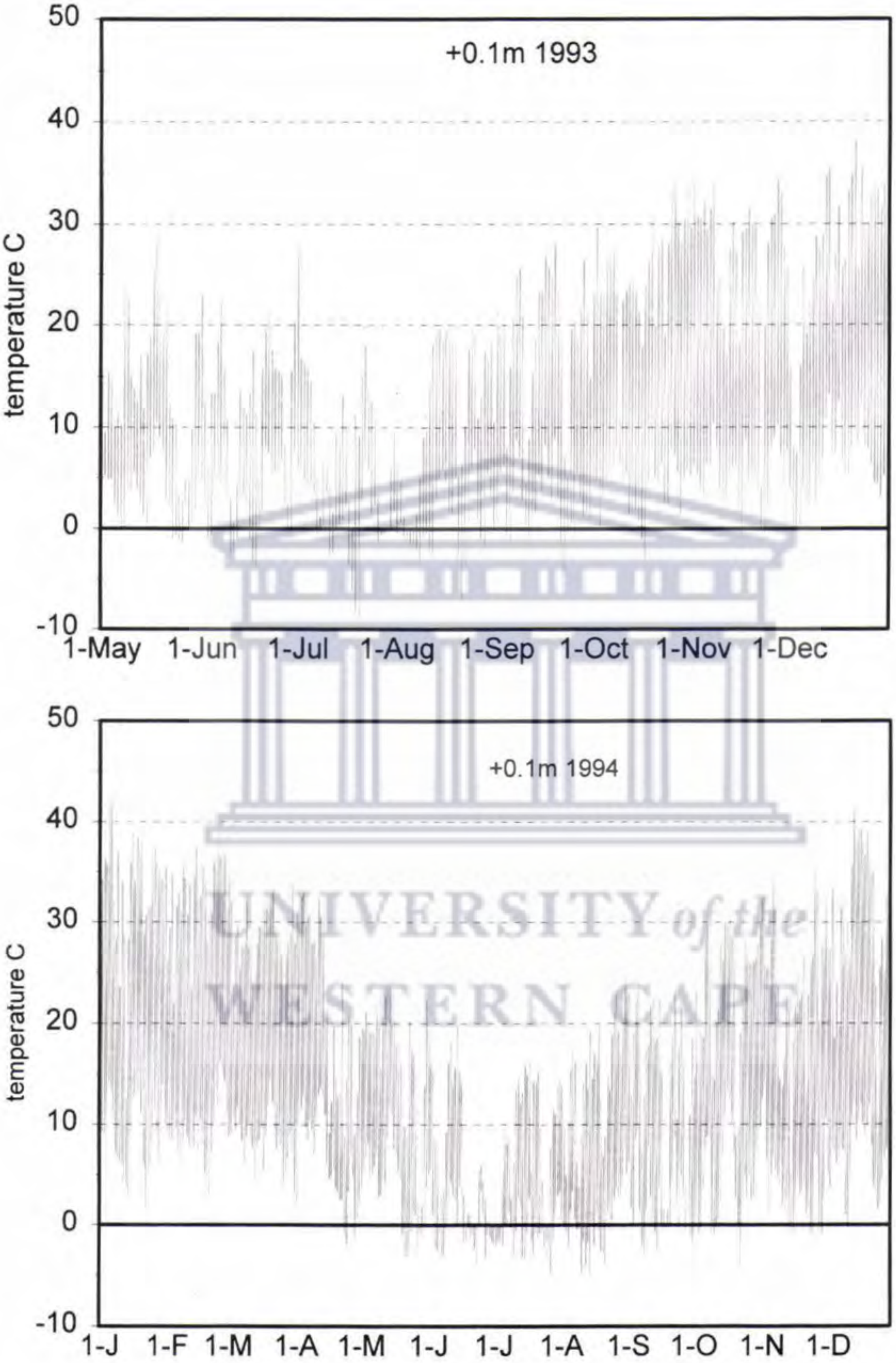


Figure 3.7. Air temperatures at +0.1m (Mt. Superior, 1993-1994).

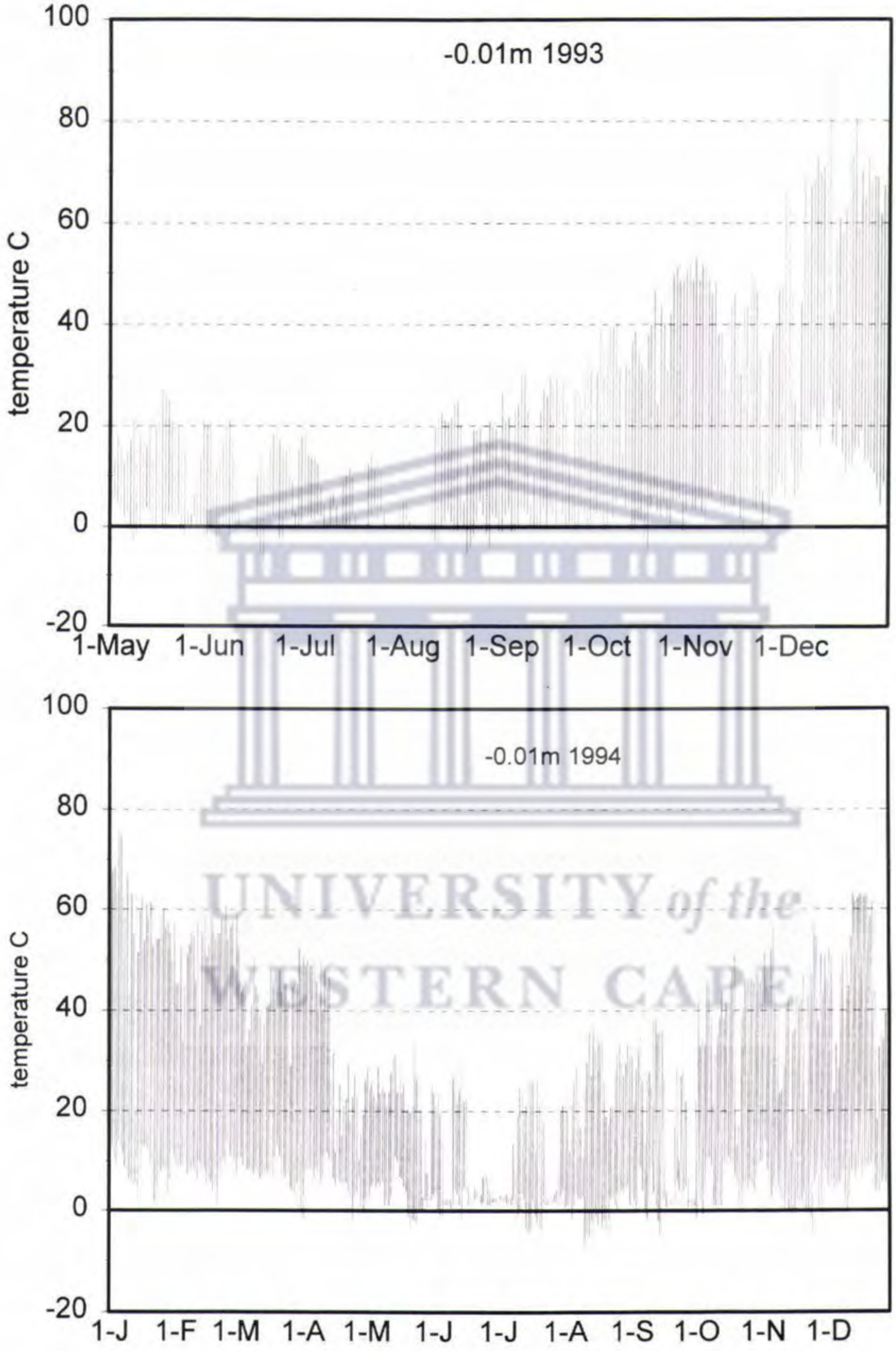


Figure 3.8. Soil surface temperatures (Mt. Superior, 1993-1994).

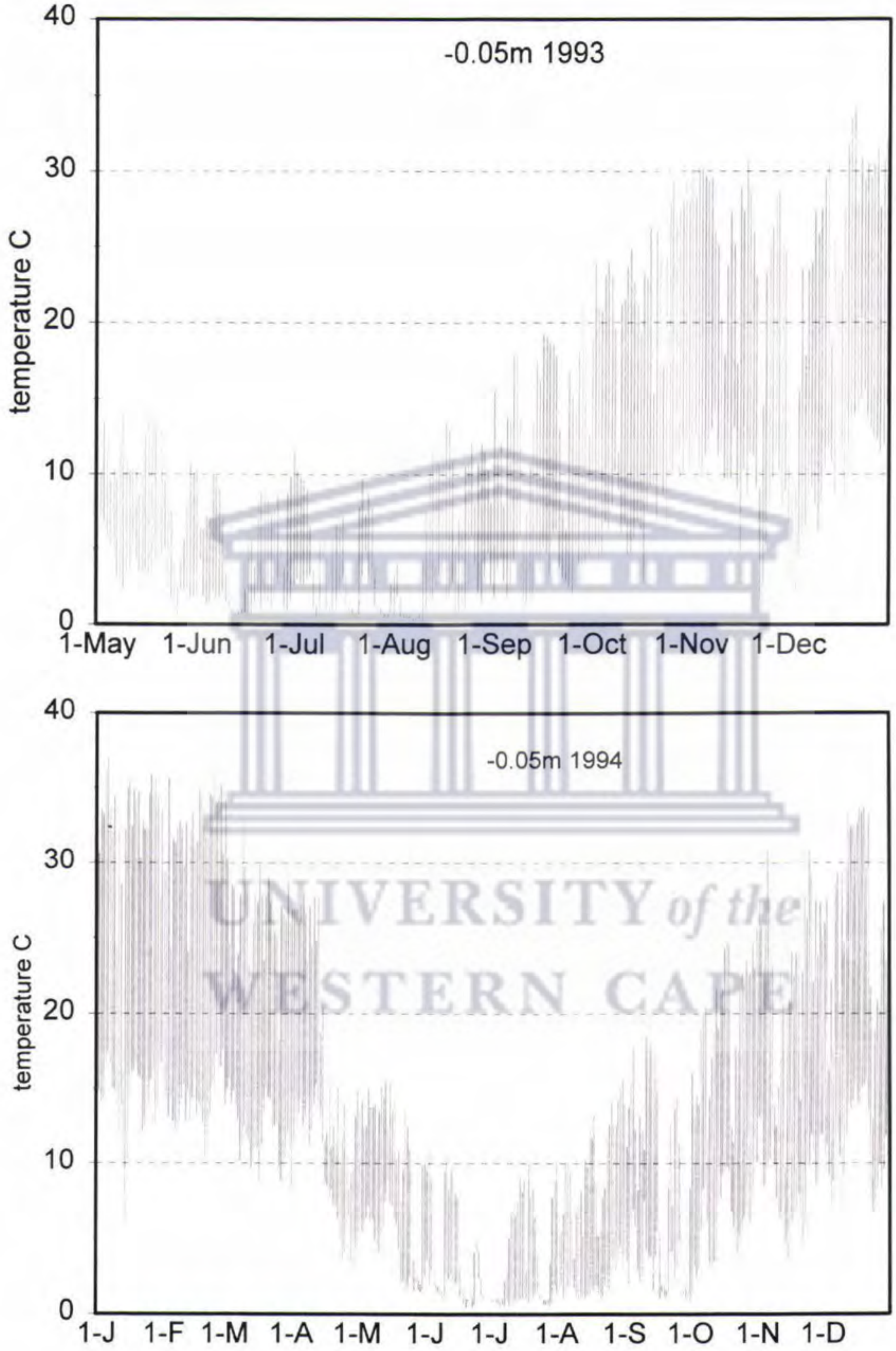


Figure 3.9. Soil temperatures at -0.05m (Mt. Superior, 1993-1994).

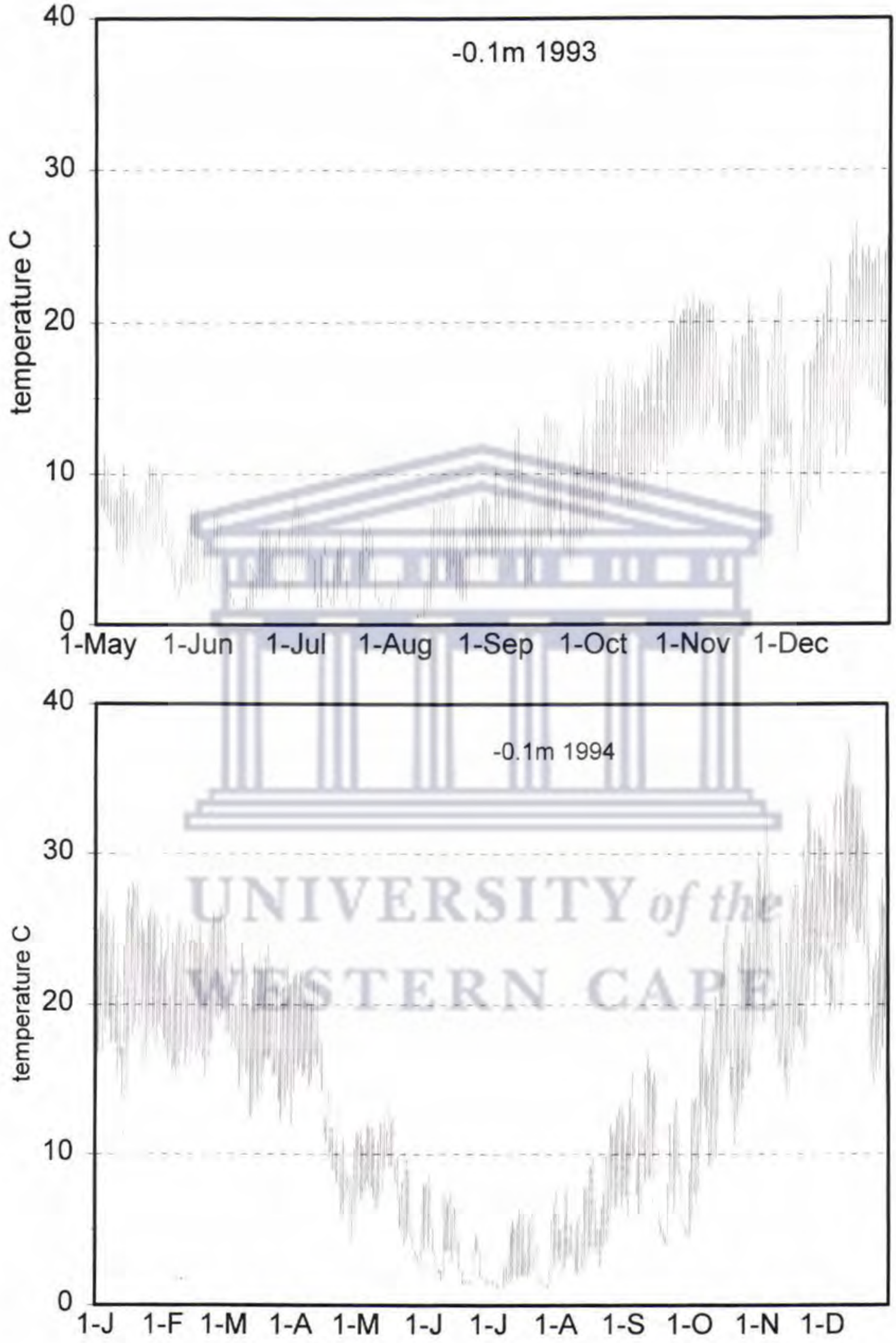


Figure 3.10. Soil temperatures at -0.1m (Mt. Superior, 1993-1994).

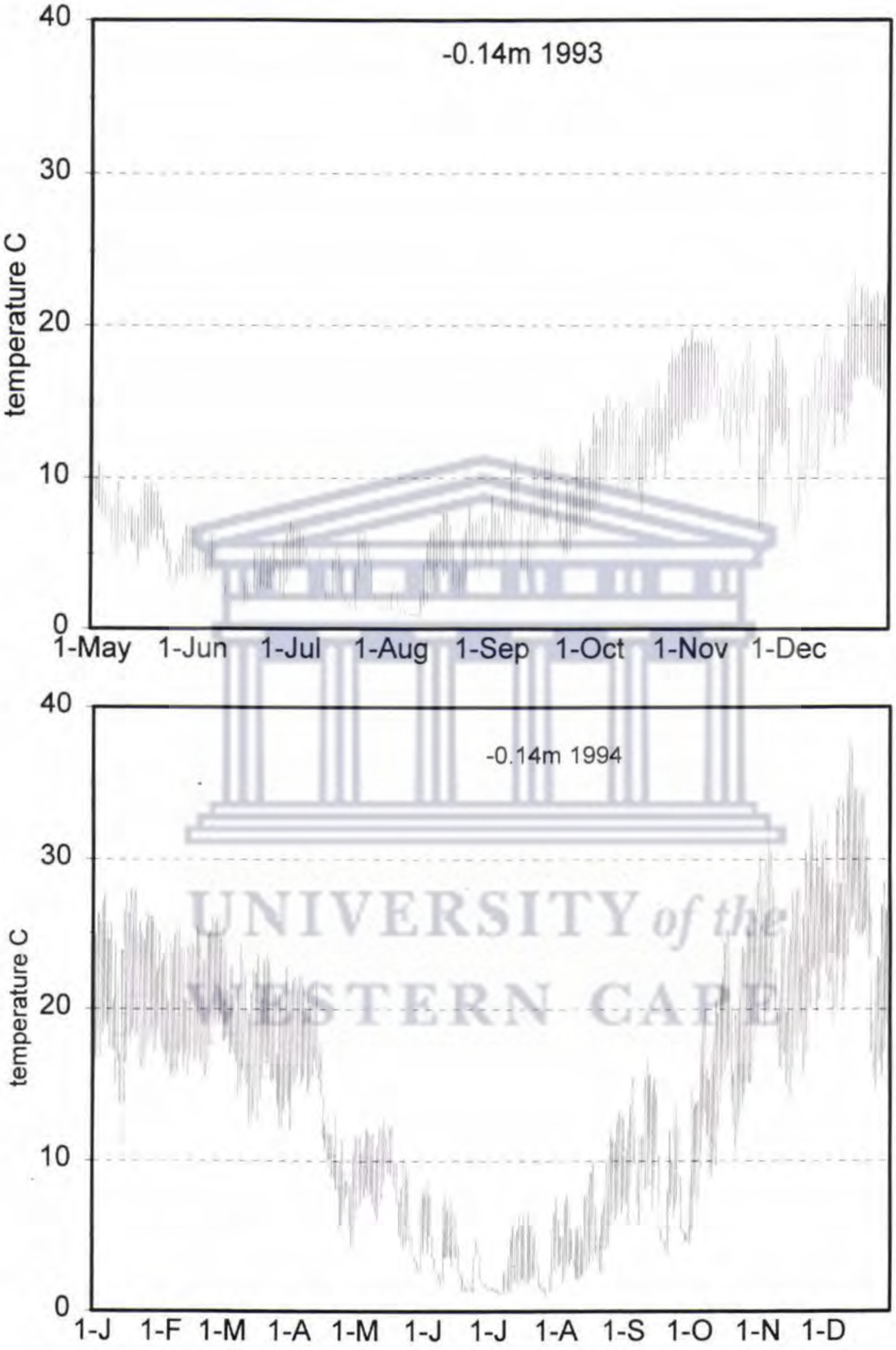


Figure 3.11. Soil temperatures at -0.14m (Mt. Superior, 1993-1994).

APPENDIX 4. MONTHLY AND YEARLY TOTALS OF AIR AND SOIL FROST FREQUENCY AND INTENSITY AT WAAIHOEK PEAK AND MOUNT SUPERIOR

Contents: Page

Section A: Monthly and yearly totals of days with temperatures below 0°C

Section B: Monthly totals of frost frequency and intensity

	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0
APR	0	0	2.8	0	0	4.4	0	0	0	0	0	0	0	0	0.7
MAY	1.3	0	5.8	1.8	0	8.9	0	0	5	0	0	0	0	0	0
JUN	5.3	1.4	15.4	5	1.3	12.3	0.5	0	15.6	0	0	8.3	0	0	0
JUL	4.1	0.8	10.9	4.6	0	17.6	1.5	0	24.6	0	0	12.6	0	0	0
AUG	5.4	1.5	12.6	4.8	0.8	15.4	1.3	0	18.1	0	0	10.3	0	0	0
SEP	2.3	0.5	7.9	3	0	9.3	0.8	0	9.8	0	0	3	0	0	0.5
OCT	0.3	0	4.7	0	0	6	0	0	1	0	0	1.3	0	0	0
NOV	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
DEC	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
YEAR	18.7	4.2	62.1	19.2	2.1	76.1	4.1	15.6	58.5	0	0	35.5	0	0	1.2

Table 4.1. Average number of days with temperatures below 0°C at Waaihoek Peak (1990-1994).

	+0.1m			-0.01M			-0.05M			-0.1M			-0.14M		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0
MAY	1.5	0	6.5	0	0	9	0	0	0	0	0	0	0	0	0
JUN	7	2	14	3	1.5	10.5	0	0	0	0	0	0	0	0	0
JUL	7.5	2	18	0	0	3.5	0	0	0	0	0	0	0	0	0
AUG	3	0	15.5	1	0	16	0	0	0	0	0	0	0	0	0
SEP	1.5	0	10.5	0	0	8	0	0	0	0	0	0	0	0	0
OCT	0	0	4	0	0	4.5	0	0	0	0	0	0	0	0	0
NOV	0	0	4.5	0.5	0	6	0	0	0	0	0	0	0	0	0
DEC	0	0	1	0	0	0.5	0	0	0	0	0	0	0	0	0
YEAR	20.5	4	77	4.5	1.5	61	0	0	0	0	0	0	0	0	0

Table 4.2. Average number of days with temperatures below 0°C at Mount Superior (1993-1994).

1990	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
MONTH	AVE	MAX	MIN	AVE.	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN															
FEB				0	0	0	0	0	0	0	0	0	0	0	0
MAR				0	0	0	0	0	0	0	0	0	0	0	0
APR				0	0	1	0	0	0	0	0	0	0	0	0
MAY				2	0	10	0	0	0	0	0	0	0	0	0
JUN				0	0	1	0	0	0	0	0	0	0	0	0
JUL															
AUG				4	1	10	0	0	9	0	0	0	0	0	0
SEP				2	0	6	0	0	6	0	0	0	0	0	0
OCT															
NOV															
DEC															
YEAR				8	1	28	0	0	15	0	0	0	0	0	0

1991	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN															
FEB		0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR		0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	0	0	2				0	0	2						
MAY	0	0	4				0	0	6						
JUN	4	0	14				4	0	27						
JUL	7	1	13				6	0	27						
AUG	6	1	17				4	0	19						
SEP	4	1	7				3	0	14						
OCT															
NOV															
DEC		0	1	0	0	1	0	0	0	0	0	0	0	0	0
YEAR	21	3	58	0	0	1	17	0	95	0	0	0	0	0	0

1992	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0		0	
MAR	0	0	0	0	0	1	0	0	0	0	0	0		0	
APR	0	0	3	0	0	4	0	0	1	0	0	0		0	
MAY	1	0	10	2	0	11	0	0	7	0	0	0		0	
JUN	4	2	15	8	4	19	0	0	16	0	0	18		0	
JUL	3	1	12	5	0	16	0	0	26	0	0	0		0	
AUG	9	4	11	11	2	17	0	0	14	0	0	2		0	
SEP	3	1	9	8	0	12	0	0	14	0	0	0		0	
OCT	1	0	8	0	0	9	0	0	2	0	0	0		0	
NOV															
DEC															
YEAR	21	8	68	34	6	89	0	0	80	0	0	20		0	

1993	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	0	0	3	0	0	8	0	0	1	0	0	0	0	0	2
MAY	0	0	5	0	0	7	0	0	8	0	0	0	0	0	0
JUN															
JUL	3	1	7	2	0	12	0	0	14	0	0	7	0	0	0
AUG	3	0	10	3	0	14	0	0	12	0	0	11	0	0	0
SEP	1	0	7	1	0	9	0	0	1	0	0	1	0	0	0
OCT	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
NOV	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0
DEC	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0
YEAR	7	1	37	6	0	58	0	0	36	0	0	19	0	0	2

1994	+1.5m			+0.1m			-0.01m			-0.1m			-0.2m		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	0	0	3	0	0	4	0	0	0	0	0	0	0	0	0
MAY	4	0	4	3	0	7	0	0	4	0	0	0	0	0	0
JUN	11	2	16	7	0	17	0	0	17	0	0	7	0	0	0
JUL	3	0	11	7	0	25	0	0	31		0		0	0	0
AUG	3	1	11	1	0	18	1	0	19		0		0	0	0
SEP	1	0	8	1	0	10	0	0	5		0		0	0	1
OCT	0	0	5	0	0	8	0	0	1		0		0	0	0
NOV	0	0	0	0	0	0	0	0	0		0		0	0	0
DEC	0	0	0	0	0	0	0	0	0		0		0	0	0
YEAR	22	3	58	19	0	90	1	0	77	0	0	7	0	0	1

Table 4.3. Number of days with temperatures below 0°C at Waaihoek Peak (1990-1994).

1993	+0.1m			-0.01M			-0.05M			-0.1M			-0.14M		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN															
FEB															
MAR															
APR															
MAY	0	0	5	0	0	12	0	0	0	0	0	0	0	0	0
JUN	1	0	11	6	3	18	0	0	0	0	0	0	0	0	0
JUL	7	3	13	1	1	13	0	0	0	0	0	0	0	0	0
AUG	5	0	16	2	0	19	0	0	0	0	0	0	0	0	0
SEP	1	0	8	0	0	12	0	0	0	0	0	0	0	0	0
OCT	0	0	2	0	0	6	0	0	0	0	0	0	0	0	0
NOV	0	0	3	0	0	2	0	0	0	0	0	0	0	0	0
DEC	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
1993	14	3	60	9	4	82	0	0	0	0	0	0	0	0	0

1994	+0.1m			-0.01M			-0.05M			-0.1M			-0.14M		
MONTH	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0
MAY	3	0	8	0	0	6	0	0	0	0	0	0	0	0	0
JUN	13	4	17	0	0	3	0	0	0	0	0	0	0	0	0
JUL	8	1	23	0	0	8	0	0	0	0	0	0	0	0	0
AUG	1	0	15	0	0	13	0	0	0	0	0	0	0	0	0
SEP	2	0	13	0	0	4	0	0	0	0	0	0	0	0	0
OCT	0	0	6	0	0	3	0	0	0	0	0	0	0	0	0
NOV	0	0	6	0	0	10	0	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
1994	27	5	91	0	0	51	0	0	0	0	0	0	0	0	0

Table 4.4. Number of days with temperatures below 0°C at Mount Superior (1993-1994).

SENSOR: +1.5m		1990	1991			1992			1993			1994			+1.5m 1990-1994 Average		
MONTH	TEMP.		AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	< -8					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2					0	0	1	0	0	3	0	0	1	0.0	0.0	1.7
	2 - 4					0	0	1	0	0	1	0	0	2	0.0	0.0	1.3
	4 - 5					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	>5					31	31	29	31	31	27	31	31	28	31.0	31.0	28.0
FEB	< -8					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2					0	0	0	0	0	1	0	0	0	0.0	0.0	0.3
	2 - 4					0	0	0	0	0	3	0	0	2	0.0	0.0	1.7
	4 - 5					0	0	2	1	0	2	0	0	0	0.3	0.0	1.3
	>5					29	29	27	27	28	22	28	28	26	28.0	28.3	25.0
MAR	< -8					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2					0	0	3	0	0	0	0	0	0	0.0	0.0	1.0
	2 - 4					1	0	0	0	0	0	0	0	0	0.3	0.0	0.0
	4 - 5					1	0	1	0	0	0	0	0	0	0.3	0.0	0.3
	>5					29	31	27	31	31	31	31	31	31	30.3	31.0	29.7
APR	< -8		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0		0	0	2	0	0	3	0	0	3	0	0	3	0.0	0.0	2.8
	0 - 2		0	0	0	1	0	3	3	0	7	0	0	2	1.0	0.0	3.0
	2 - 4		1	0	3	3	1	6	3	2	5	2	0	4	2.3	0.8	4.5
	4 - 5		1	0	3	2	0	1	2	1	2	2	0	1	1.8	0.3	1.8
	>5		28	30	22	24	29	17	22	27	13	26	30	20	25.0	29.0	18.0
MAY	< -8		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4		0	0	0	0	0	0	0	0	0	0	0	2	0.0	0.0	0.5
	-4 - -2		0	0	1	0	0	5	0	0	0	0	0	2	0.0	0.0	2.0
	-2 - 0		0	0	3	1	0	5	0	0	5	4	0	0	1.3	0.0	3.3
	0 - 2		2	0	3	4	2	2	4	0	6	0	2	4	2.5	1.0	3.8
	2 - 4		3	1	2	3	1	2	6	1	7	1	2	3	3.3	1.3	3.5
	4 - 5		1	1	1	1	1	2	2	5	4	2	0	5	1.5	1.8	3.0
	>5		25	29	21	22	27	15	19	25	9	24	27	15	22.5	27.0	15.0
JUN	< -8		0	0	0	0	0	0				0	0	0	0.0	0.0	0.0
	-8 - -6		0	0	0	0	0	2				0	0	3	0.0	0.0	1.7
	-6 - -4		0	0	1	1	0	2				1	0	2	0.7	0.0	1.7
	-4 - -2		0	0	7	1	1	2				3	1	6	1.3	0.7	5.0
	-2 - 0		4	0	7	2	1	9				4	1	5	3.3	0.7	7.0
	0 - 2		9	1	7	7	1	5				7	4	3	7.7	2.0	5.0
	2 - 4		6	6	1	4	6	2				3	8	4	4.3	6.7	2.3
	4 - 5		0	4	0	4	0	0				1	1	1	1.7	1.7	0.3
	>5		11	19	7	11	21	8				11	15	6	11.0	18.3	7.0

Table 4.5. Monthly total of frost frequency and intensity at +1.5m (Waaihoek Peak, 1991-1994).

SENSOR: +1.5m		1990	1991			1992			1993			1994			+1.5m 1990-1994 Average		
MONTH	TEMP.	AVE	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6		0	0	0	0	0	0	0	0	1	0	0	0	0.0	0.0	0.3
	-6 - -4		1	0	4	0	0	1	0	0	1	0	0	1	0.3	0.0	1.8
	-4 - -2		1	1	3	1	0	6	1	0	4	1	0	5	1.0	0.3	4.5
	-2 - 0		5	0	6	2	1	5	2	1	1	2	0	5	2.8	0.5	4.3
	0 - 2		5	3	5	5	0	6	3	1	6	4	3	9	4.3	1.8	6.5
	2 - 4		4	7	5	6	5	7	4	5	6	8	2	5	5.5	4.8	5.8
	4 - 5		1	2	1	1	3	2	2	1	1	5	2	5	2.3	2.0	2.3
	>5		11	15	4	16	22	4	16	22	8	11	24	1	13.5	20.8	4.3
AUG	< -8		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6		0	0	1	0	0	2	0	0	1	0	0	0	0.0	0.0	1.0
	-6 - -4		0	0	5	1	0	8	0	0	1	0	0	0	0.3	0.0	3.5
	-4 - -2		1	0	5	5	0	0	1	0	4	0	0	6	1.8	0.0	3.8
	-2 - 0		5	1	6	3	4	1	2	0	4	3	1	6	3.3	1.5	4.3
	0 - 2		2	2	1	1	3	4	5	3	5	6	1	6	3.5	2.3	4.0
	2 - 4		4	2	3	2	4	8	4	2	4	2	4	5	3.0	3.0	5.0
	4 - 5		4	1	0	2	0	2	0	0	2	2	2	2	2.0	0.8	1.5
	>5		7	17	2	17	20	6	15	26	6	18	23	6	14.3	21.5	5.0
SEP	< -8		0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6		0	0	0	0	0	2	0	0	0	0	0	0	0.0	0.0	0.5
	-6 - -4		0	0	2	0	0	1	0	0	3	0	0	1	0.0	0.0	1.8
	-4 - -2		1	0	4	2	0	3	0	0	0	0	0	2	0.8	0.0	2.3
	-2 - 0		3	1	1	1	1	3	1	0	4	1	0	5	1.5	0.5	3.3
	0 - 2		0	3	2	4	0	6	4	1	4	5	1	5	3.3	1.3	4.3
	2 - 4		3	0	4	4	3	5	0	0	2	2	1	6	2.3	1.0	4.3
	4 - 5		0	0	0	3	2	2	2	1	2	1	2	1	1.5	1.3	1.3
	>5		7	10	1	16	24	8	18	29	6	21	26	10	15.5	22.3	6.3
OCT	< -8					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4					0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2					0	0	1	0	0	0	0	0	2	0.0	0.0	1.0
	-2 - 0					1	0	7	0	0	1	0	0	3	0.3	0.0	3.7
	0 - 2					5	1	7	0	0	2	1	0	3	2.0	0.3	4.0
	2 - 4					5	5	5	1	0	5	3	0	5	3.0	1.7	5.0
	4 - 5					1	1	0	0	0	2	0	0	3	0.3	0.3	1.7
	>5					15	20	7	30	31	21	27	31	15	24.0	27.3	14.3
NOV	< -8								0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6								0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4								0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2								0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0								0	0	2	0	0	0	0.0	0.0	1.0
	0 - 2								1	0	0	0	0	2	0.5	0.0	1.0
	2 - 4								0	0	5	0	0	1	0.0	0.0	3.0
	4 - 5								2	1	2	2	0	1	2.0	0.5	1.5
	>5								27	29	21	10	12	8	18.5	20.5	14.5
DEC	< -8		0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6		0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4		0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2		0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0		0	0	1				0	0	2	0	0	0	0.0	0.0	1.0
	0 - 2		0	0	1				0	0	2	0	0	4	0.0	0.0	2.3
	2 - 4		0	0	0				2	0	3	0	0	1	0.7	0.0	1.3
	4 - 5		0	0	2				0	0	0	1	0	2	0.3	0.0	1.3
	>5		31	31	27				29	31	24	27	28	21	29.0	30.0	24.0

Table 4.5. Monthly total of frost frequency and intensity at +1.5m
(Waaihoek Peak, 1991-1994) (continued).

SENSOR: +0.1m		1990			1991			1992			1993			1994			+0.1m 1990-1994 average		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0				0	0	0	0	0	3	0	0	1	0.0	0.0	1.0
	0 - 2	0	0	0				0	0	1	0	0	0	0	0	0	0.0	0.0	0.3
	2 - 4	0	0	0				0	0	3	0	0	1	0	0	3	0.0	0.0	1.8
	4 - 5	0	0	0				0	0	0	0	0	0	0	0	2	0.0	0.0	0.5
	>5	24	24	24				31	31	27	31	31	27	31	31	25	29.3	29.3	25.8
FEB	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0.0	0.0	0.6
	2 - 4	0	0	0	0	0	1	0	0	2	0	0	3	0	0	2	0.0	0.0	1.6
	4 - 5	0	0	0	0	0	1	0	0	3	0	0	1	0	0	1	0.0	0.0	1.2
	>5	25	25	25	24	24	21	29	29	24	28	28	22	28	28	25	26.8	26.8	23.4
MAR	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0.0	0.0	0.2
	0 - 2	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0.0	0.0	0.6
	2 - 4	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0.0	0.0	0.6
	4 - 5	0	0	0	0	0	1	1	0	0	0	0	1	0	0	2	0.2	0.0	0.8
	>5	17	17	16	20	20	17	30	31	27	31	31	30	31	31	28	25.8	26.0	23.6
APR	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	1	0	0	0	0	0	0	0.0	0.0	0.3
	-4 - -2	0	0	0				0	0	0	0	0	0	0	0	1	0.0	0.0	0.3
	-2 - 0	0	0	1				0	0	3	0	0	8	0	0	3	0.0	0.0	3.8
	0 - 2	0	0	5				1	0	5	2	0	4	0	0	3	0.8	0.0	4.3
	2 - 4	1	0	4				3	1	3	2	1	5	1	0	4	1.8	0.5	4.0
	4 - 5	3	0	1				2	0	3	1	1	1	1	0	3	1.8	0.3	2.0
	>5	16	20	9				24	29	15	25	28	12	28	30	16	23.3	26.8	13.0
MAY	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	1	0	0	0	0	0	2	0.0	0.0	0.8
	-4 - -2	0	0	1				0	0	3	0	0	0	0	0	5	0.0	0.0	2.3
	-2 - 0	2	0	9				2	0	7	0	0	7	3	0	0	1.8	0.0	5.8
	0 - 2	4	5	4				3	2	5	3	0	8	1	0	3	2.8	1.8	5.0
	2 - 4	5	0	4				4	1	2	4	0	9	1	0	7	3.5	0.3	5.5
	4 - 5	1	2	3				2	1	4	4	3	4	1	1	6	2.0	1.8	4.3
	>5	17	22	8				20	27	9	20	28	3	25	30	8	20.5	26.8	7.0
JUN	< -8	0	0	0				0	0	0				0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0				0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	1				0	0	1	0.0	0.0	0.7
	-4 - -2	0	0	0				1	0	9				0	0	7	0.3	0.0	5.3
	-2 - 0	0	0	1				7	4	9				7	0	9	4.7	1.3	6.3
	0 - 2	4	4	7				5	4	2				8	8	3	5.7	5.3	4.0
	2 - 4	2	0	5				2	4	1				3	2	5	2.3	2.0	3.7
	4 - 5	2	0	0				4	1	2				1	4	2	2.3	1.7	1.3
	>5	6	10	1				11	17	6				11	16	3	9.3	14.3	3.3

Table 4.6. Monthly total of frost frequency and intensity at +0.1m (Waaihoek Peak, 1990-1994).

SENSOR:+0.1m		1990			1991			1992			1993			1994			+0.1m 1990-1994 average		
MONTH	TEMP	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8							0	0	0	0	0	1	0	0	0	0.0	0.0	0.3
	-8 - -6							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4							0	0	0	0	0	3	0	0	1	0.0	0.0	1.3
	-4 - -2							0	0	7	1	0	2	0	0	7	0.3	0.0	5.3
	-2 - 0							5	0	9	1	0	6	7	0	17	4.3	0.0	10.7
	0 - 2							7	5	7	7	2	6	9	11	3	7.7	6.0	5.3
	2 - 4							9	5	8	3	5	4	6	3	3	6.0	4.3	5.0
	4 - 5							5	2	0	2	2	0	2	2	0	3.0	2.0	0.0
	>5							5	19	0	14	21	6	7	15	0	8.7	18.3	2.0
AUG	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	2	0	0	1	0	0	0	0.0	0.0	0.8
	-6 - -4	0	0	0				0	0	3	0	0	1	0	0	3	0.0	0.0	1.8
	-4 - -2	0	0	5				3	0	1	0	0	7	0	0	4	0.8	0.0	4.3
	-2 - 0	4	1	6				8	2	11	3	0	6	1	0	11	4.0	0.8	8.5
	0 - 2	4	2	7				3	9	8	4	1	2	5	0	5	4.0	3.0	5.5
	2 - 4	4	4	0				2	2	4	5	3	4	4	2	5	3.8	2.8	3.3
	4 - 5	2	0	1				3	1	0	1	2	1	1	1	0	1.8	1.0	0.5
	>5	7	14	2				12	17	2	14	25	4	20	28	3	13.3	21.0	2.8
SEP	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	2				0	0	1	0	0	2	0	0	1	0.0	0.0	1.5
	-4 - -2	0	0	2				4	0	6	0	0	2	0	0	4	1.0	0.0	3.5
	-2 - 0	2	0	2				4	0	5	1	0	5	1	0	5	2.0	0.0	4.3
	0 - 2	2	1	3				4	3	5	1	0	4	1	0	6	2.0	1.0	4.5
	2 - 4	1	0	6				4	2	16	3	0	5	4	1	3	3.0	0.8	7.5
	4 - 5	1	0	3				2	0	1	0	0	1	1	0	3	1.0	0.0	2.0
	>5	13	18	1				16	25	5	20	31	3	23	29	8	18.0	25.8	4.3
OCT	< -8							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2							0	0	0	0	0	0	0	0	2	0.0	0.0	0.7
	-2 - 0							0	0	9	0	0	1	0	0	6	0.0	0.0	5.3
	0 - 2							5	1	9	0	0	5	0	0	4	1.7	0.3	6.0
	2 - 4							3	3	5	0	0	5	0	0	7	1.0	1.0	5.7
	4 - 5							3	2	0	1	0	4	3	0	2	2.3	0.7	2.0
	>5							16	21	4	30	31	16	28	31	10	24.7	27.7	10.0
NOV	< -8										0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6										0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4										0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2										0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0										0	0	2	0	0	0	0.0	0.0	1.0
	0 - 2										1	0	1	0	0	1	0.5	0.0	1.0
	2 - 4										0	0	8	0	0	3	0.0	0.0	5.5
	4 - 5										0	0	1	0	0	4	0.0	0.0	2.5
	>5										29	30	18	12	12	4	20.5	21.0	11.0
DEC	< -8				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0				0	0	1				0	0	2	0	0	0	0.0	0.0	1.0
	0 - 2				0	0	1				0	0	3	0	0	5	0.0	0.0	3.0
	2 - 4				0	0	2				2	0	5	0	0	1	0.7	0.0	2.7
	4 - 5				0	0	1				0	0	3	0	0	2	0.0	0.0	2.0
	>5				31	31	26				29	31	18	28	28	20	29.3	30.0	21.3

Table 4.6. Monthly total of frost frequency and intensity at +0.1m (Waaihoek Peak, 1990-1994) (continued).

SENSOR: -0.01m		1990			1991			1992			1993			1994			-0.01m 1990-1994 Average		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0				0	0	0	0	0	2	0	0	0	0.0	0.0	0.5
	2 - 4	0	0	0				0	0	0	0	0	1	0	0	0	0.0	0.0	0.3
	4 - 5	0	0	0				0	0	0	0	0	1	0	0	1	0.0	0.0	0.5
	>5	24	24	24				31	31	31	31	31	27	31	31	30	29.3	29.3	28.0
FEB	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0.0	0.0	0.6
	4 - 5	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0.0	0.0	0.8
	>5	25	25	25	24	24	23	29	29	29	28	28	22	28	28	28	26.8	26.8	25.4
MAR	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	1	0	0	0	0	0	3	0	0	0	0	0	0	0.0	0.0	0.8
	4 - 5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.2
	>5	17	17	15	20	20	20	31	31	28	31	31	31	31	31	31	26.0	26.0	25.0
APR	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0.0	0.0	0.6
	0 - 2	0	0	3	0	0	0	0	0	5	2	0	11	0	0	4	0.4	0.0	4.6
	2 - 4	0	0	5	0	0	0	1	0	8	3	2	6	1	0	3	1.0	0.4	4.4
	4 - 5	0	0	2	1	0	1	2	0	6	0	0	2	1	0	1	0.8	0.0	2.4
	>5	20	20	10	29	30	27	27	30	11	25	28	10	28	30	22	25.8	27.6	16.0
MAY	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	6	0	0	7	0	0	8	0	0	4	0.0	0.0	5.0
	0 - 2	0	0	10	2	0	2	2	0	14	1	0	7	5	0	7	2.0	0.0	8.0
	2 - 4	10	8	14	3	2	3	11	0	7	8	0	12	5	3	6	7.4	2.6	8.4
	4 - 5	2	0	1	2	1	2	2	1	0	4	3	4	0	2	4	2.0	1.4	2.2
	>5	17	21	4	24	28	18	16	30	3	18	28	0	21	26	10	19.2	26.6	7.0
JUN	< -8	0	0	0	0	0	0	0	0	0				0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0				0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	1	0	0	0				0	0	0	0.0	0.0	0.3
	-4 - -2	0	0	0	0	0	4	0	0	0				0	0	0	0.0	0.0	1.0
	-2 - 0	0	0	2	2	0	22	0	0	16				0	0	17	0.5	0.0	14.3
	0 - 2	1	0	7	9	2	1	11	0	10				16	8	10	9.3	2.5	7.0
	2 - 4	11	6	5	11	8	0	8	9	4				8	7	3	9.5	7.5	3.0
	4 - 5	1	0	0	5	2	0	5	1	0				3	2	0	3.5	1.3	0.0
	>5	1	6	0	3	18	2	6	21	0				3	13	0	3.3	15.0	0.5

Table 4.7. Monthly total of frost frequency and intensity at -0.01m
(Waaihoek Peak, 1990-1994).

SENSOR:-0.01m		1990			1991			1992			1993			1994			-0.01m 1990-1994 Average		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8				0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6				0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4				0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2				0	0	1	0	0	0	0	0	0	0	0	0	0.0	0.0	0.3
	-2 - 0				6	0	26	0	0	26	0	0	14	0	0	31	1.5	0.0	24.3
	0 - 2				13	8	1	24	0	5	11	1	9	29	16	0	19.3	6.3	3.8
	2 - 4				4	10	0	7	15	0	3	9	3	2	5	0	4.0	9.8	0.8
	4 - 5				3	4	0	0	5	0	9	0	2	0	4	0	3.0	3.3	0.5
	>5				2	6	0	0	11	0	5	20	0	0	6	0	1.8	10.8	0.0
AUG	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0.0	0.0	0.5
	-4 - -2	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0.0	0.0	1.8
	-2 - 0	0	0	8	4	0	10	0	0	14	0	0	12	1	0	19	1.3	0.0	15.8
	0 - 2	7	4	13	7	3	1	15	3	14	11	0	7	7	1	8	11.8	2.8	10.8
	2 - 4	10	1	0	4	5	0	6	10	2	3	11	5	12	1	3	8.8	7.0	2.5
	4 - 5	3	1	0	2	2	2	6	2	1	0	0	1	5	4	0	4.0	2.3	1.0
	>5	1	15	0	6	13	1	4	16	0	13	20	2	6	25	1	7.5	22.3	1.0
SEP	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	5	3	0	14	0	0	14	0	0	1	0	0	5	0.8	0.0	9.8
	0 - 2	1	0	9	5	4	0	7	0	9	2	0	2	3	0	8	4.5	1.0	7.0
	2 - 4	4	1	4	5	4	1	4	8	3	0	0	7	4	2	7	4.3	3.8	5.5
	4 - 5	1	0	0	1	0	0	2	1	1	0	0	1	1	0	4	1.3	0.3	1.5
	>5	13	18	1	1	7	0	17	21	3	24	31	10	22	28	6	19.3	26.3	5.0
OCT	< -8							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2							0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0							0	0	2	0	0	0	0	0	1	0.0	0.0	1.0
	0 - 2							1	0	10	0	0	1	0	0	5	0.3	0.0	5.3
	2 - 4							4	1	8	0	0	4	0	0	6	1.3	0.3	6.0
	4 - 5							1	2	1	0	0	4	0	0	5	0.3	0.7	3.3
	>5							21	24	6	31	31	22	31	31	14	27.7	28.7	14.0
NOV	< -8										0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6										0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4										0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2										0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0										0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2										0	0	3	0	0	0	0.0	0.0	1.5
	2 - 4										1	0	1	0	0	0	0.5	0.0	0.5
	4 - 5										0	0	0	0	0	1	0.0	0.0	0.5
	>5										29	30	26	12	12	11	20.5	21.0	18.5
DEC	< -8				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2				0	0	0				0	0	2	0	0	0	0.0	0.0	0.7
	2 - 4				0	0	1				0	0	2	0	0	2	0.0	0.0	1.7
	4 - 5				0	0	0				0	0	3	0	0	1	0.0	0.0	1.3
	>5				31	31	30				31	31	24	28	28	25	30.0	30.0	26.3

Table 4.7. Monthly total of frost frequency and intensity at -0.01m (Waaihoek Peak, 1990-1994) (continued).

SENSOR: -0.1m		1990			1991			1992			1993			1994			-0.1m 1990-1994 Averag		
MONTH	TEMP	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	4 - 5	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	>5	24	24	24				31	31	31	31	31	31	31	31	31	29.3	29.3	29.3
FEB	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	4 - 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	>5	24	25	25	24	24	24	29	29	29	28	28	28	28	28	28	26.6	26.8	26.8
MAR	< -8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	4 - 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	>5	17	17	17	20	20	20	31	31	31	31	31	31	31	31	31	26.0	26.0	26.0
APR	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0				0	0	0	0	0	0	0	0	1	0.0	0.0	0.3
	2 - 4	0	0	0				0	0	3	3	1	14	0	0	4	0.8	0.3	5.3
	4 - 5	0	0	0				2	0	1	1	1	1	2	0	1	1.3	0.3	0.8
	>5	20	20	20				28	30	26	26	28	15	28	30	24	25.5	27.0	21.3
MAY	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0				0	0	6	0	0	10	0	0	10	0.0	0.0	6.5
	2 - 4	6	5	9				12	3	14	7	0	12	10	3	6	8.8	2.8	10.3
	4 - 5	4	3	12				5	2	3	2	3	5	0	2	6	2.8	2.5	6.5
	>5	19	21	8				14	26	8	22	28	4	21	26	9	19.0	25.3	7.3
JUN	< -8	0	0	0				0	0	0				0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0				0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0				0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0				0	0	3	0.0	0.0	1.0
	-2 - 0	0	0	0				0	0	18				0	0	4	0.0	0.0	7.3
	0 - 2	0	0	1				9	8	11				14	0	21	7.7	2.7	11.0
	2 - 4	11	6	12				12	9	1				13	12	2	12.0	9.0	5.0
	4 - 5	2	4	1				5	5	0				3	1	0	3.3	3.3	0.3
	>5	1	4	0				4	11	0				0	17	0	1.7	10.7	0.0

Table 4.8. Monthly total of frost frequency and intensity at -0.1m (Waaihoek Peak, 1990-1994).

SENSOR: -0.1m		1990			1991			1992			1993			1994			-0.1m 1990-1994 Averag		
MONTH	TEMP	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8							0	0	0	0	0	0		0		0.0	0.0	0.0
	-8 - -6							0	0	0	0	0	0		0		0.0	0.0	0.0
	-6 - -4							0	0	0	0	0	0		0		0.0	0.0	0.0
	-4 - -2							0	0	0	0	0	0		0		0.0	0.0	0.0
	-2 - 0							0	0	0	0	0	7		0		0.0	0.0	2.3
	0 - 2							26	12	6	10	4	17		0		18.0	5.3	7.7
	2 - 4							5	15	14	11	7	3		0		8.0	7.3	5.7
	4 - 5							0	2	3	6	3	1		0		3.0	1.7	1.3
	>5							0	2	8	1	16	0		31		0.5	16.3	2.7
AUG	< -8	0	0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-2 - 0	0	0	0				0	0	2	0	0	11		0		0.0	0.0	4.3
	0 - 2	10	5	17				15	11	24	13	5	11		0		12.7	5.3	17.3
	2 - 4	8	9	4				11	5	3	4	10	3		0		7.7	6.0	3.3
	4 - 5	3	2	0				1	4	1	4	1	2		1		2.7	2.0	1.0
	>5	0	5	0				4	11	1	6	15	0		30		3.3	15.3	0.3
SEP	< -8		0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-8 - -6		0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-6 - -4		0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-4 - -2		0	0				0	0	0	0	0	0		0		0.0	0.0	0.0
	-2 - 0		0	0				0	0	0	0	0	1		0		0.0	0.0	0.3
	0 - 2		0	5				7	4	16	1	0	5		0		2.7	1.3	8.7
	2 - 4		1	7				6	5	8	2	0	5		0		2.7	2.0	6.7
	4 - 5		1	4				5	2	1	3	0	2		0		2.7	1.0	2.3
	>5		18	4				12	19	5	19	31	8		30		10.3	32.7	5.7
OCT	< -8							0	0	0	0	0	0		0		0.0	0.0	0.0
	-8 - -6							0	0	0	0	0	0		0		0.0	0.0	0.0
	-6 - -4							0	0	0	0	0	0		0		0.0	0.0	0.0
	-4 - -2							0	0	0	0	0	0		0		0.0	0.0	0.0
	-2 - 0							0	0	0	0	0	0		0		0.0	0.0	0.0
	0 - 2							1	0	4	0	0	0		0		0.3	0.0	1.3
	2 - 4							2	2	8	0	0	0		0		0.7	0.7	2.7
	4 - 5							2	1	2	0	0	1		0		0.7	0.3	1.0
	>5							22	24	13	31	31	30		31		17.7	28.7	14.3
NOV	< -8										0	0	0		0		0.0	0.0	0.0
	-8 - -6										0	0	0		0		0.0	0.0	0.0
	-6 - -4										0	0	0		0		0.0	0.0	0.0
	-4 - -2										0	0	0		0		0.0	0.0	0.0
	-2 - 0										0	0	0		0		0.0	0.0	0.0
	0 - 2										0	0	0		0		0.0	0.0	0.0
	2 - 4										0	0	1		0		0.0	0.0	0.3
	4 - 5										0	0	3		0		0.0	0.0	1.0
	>5										30	30	26		12		10.0	14.0	8.7
DEC	< -8				0	0	0				0	0	0		0		0.0	0.0	0.0
	-8 - -6				0	0	0				0	0	0		0		0.0	0.0	0.0
	-6 - -4				0	0	0				0	0	0		0		0.0	0.0	0.0
	-4 - -2				0	0	0				0	0	0		0		0.0	0.0	0.0
	-2 - 0				0	0	0				0	0	0		0		0.0	0.0	0.0
	0 - 2				0	0	0				0	0	0		0		0.0	0.0	0.0
	2 - 4				0	0	0				0	0	1		0		0.0	0.0	0.3
	4 - 5				0	0	0				0	0	2		0		0.0	0.0	0.7
	>5				31	31	31				31	31	28		28		20.7	30.0	19.7

Table 4.8. Monthly total of frost frequency and intensity at -0.1m (Waaihoek Peak, 1990-1994) (continued).

SENSOR: -0.2m		1990			1991			1992			1993			1994			-0.2m 1990-1994 Averag		
MONTH	TEMP	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	< -8	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	4 - 5	0	0	0				0	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	>5	24	24	24				31	31	31	31	31	31	31	31	31	29.3	29.3	29.3
FEB	< -8	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	0	0	0	0				0	0	1	0	0	0	0.0	0.0	0.2
	4 - 5	0	0	0	0	0	0				0	0	2	0	0	0	0.0	0.0	0.4
	>5	25	25	25	24	24	24				28	28	25	28	28	28	21.0	21.0	20.4
MAR	< -8	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	4 - 5	0	0	0	0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	>5	17	17	17	20	20	20				31	31	31	31	31	31	24.8	24.8	24.8
APR	< -8	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0							0	0	2	0	0	0	0.0	0.0	0.7
	0 - 2	0	0	0							0	0	3	0	0	0	0.0	0.0	1.0
	2 - 4	0	0	0							4	0	5	0	0	0	1.3	0.0	1.7
	4 - 5	0	0	0							1	0	4	0	0	1	0.3	0.0	1.7
	>5	20	20	20							25	30	16	30	30	29	25.0	26.7	21.7
MAY	< -8	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4	1	0	1							0	0	0	6	3	10	3.5	1.5	5.5
	4 - 5	4	4	5							0	0	0	4	1	1	4.0	2.5	3.0
	>5	24	25	23							6	6	6	21	27	20	25.5	29.0	24.5
JUN	< -8	0	0	0										0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0										0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0										0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0										0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0										0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0										8	1	15	4.0	0.5	7.5
	2 - 4	2	0	5										16	16	14	9.0	8.0	9.5
	4 - 5	9	6	8										4	3	1	6.5	4.5	4.5
	>5	3	8	1										2	10	0	2.5	9.0	0.5

Table 4.9. Monthly total of frost frequency and intensity at -0.2m (Waaihoek Peak, 1990-1994).

SENSOR: -0.2m		1990			1991			1992			1993			1994			-0.2m 1990-1994 Averag		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8										0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6										0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4										0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2										0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0										0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2										0	0	0	28	11	31	28.0	11.0	31.0
	2 - 4										0	0	0	3	20	0	3.0	20.0	0.0
	4 - 5										0	0	0	0	0	0	0.0	0.0	0.0
	>5										0	0	0	0	0	0	0.0	0.0	0.0
AUG	< -8	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2	0	0	0							0	0	0	5	1	19	2.5	0.5	9.5
	2 - 4	15	7	19							0	0	0	19	8	10	17.0	7.5	14.5
	4 - 5	3	8	2							0	0	0	2	8	2	2.5	8.0	2.0
	>5	3	6	0							0	0	0	5	14	0	4.0	10.0	0.0
SEP	< -8	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2	0	0	0							0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0	0	0	0							0	0	0	0	0	1	0.0	0.0	0.5
	0 - 2	0	0	0							0	0	0	0	0	2	0.0	0.0	1.0
	2 - 4	1	0	5							0	0	2	4	2	8	2.5	1.0	7.5
	4 - 5	3	1	5							1	0	2	3	2	5	3.5	1.5	6.0
	>5	16	19	10							10	11	7	23	26	13	24.5	28.0	15.0
OCT	< -8										0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6										0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4										0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2										0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0										0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2										0	0	0	0	0	1	0.0	0.0	0.5
	2 - 4										0	0	0	0	0	2	0.0	0.0	1.0
	4 - 5										0	0	0	1	0	4	0.5	0.0	2.0
	>5										31	31	31	30	31	9	30.5	31.0	20.0
NOV	< -8										0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6										0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4										0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2										0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0										0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2										0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4										0	0	0	0	0	0	0.0	0.0	0.0
	4 - 5										0	0	0	0	0	0	0.0	0.0	0.0
	>5										30	30	30	12	12	7	21.0	21.0	18.5
DEC	< -8				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-8 - -6				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-6 - -4				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-4 - -2				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	-2 - 0				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	0 - 2				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	2 - 4				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	4 - 5				0	0	0				0	0	0	0	0	0	0.0	0.0	0.0
	>5				31	31	31				31	31	31	28	28	22	30.0	30.0	26.0

Table 4.9. Monthly total of frost frequency and intensity at -0.2m
(Waaihoek Peak, 1990-1994) (continued).

SENSOR: '+0.1m		1993			1994			**1993-1994 AVERAGE**		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	**AVE**	**MAX**	**MIN**
JAN	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	1	0	0	1
	2 - 4				0	0	3	0	0	3
	4 - 5				0	0	1	0	0	1
	>5				31	31	26	31	31	26
FEB	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	2	0	0	2
	4 - 5				0	0	0	0	0	0
	>5				28	28	26	28	28	26
MAR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	2	0	0	2
	4 - 5				0	0	1	0	0	1
	>5				31	31	28	31	31	28
APR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	3	0	0	3
	0 - 2				0	0	1	0	0	1
	2 - 4				1	0	7	1	0	7
	4 - 5				1	0	3	1	0	3
	>5				28	30	16	28	30	16
MAY	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	4	0	0	2
	-2 - 0	0	0	5	3	0	4	1.5	0	4.5
	0 - 2	3	0	7	2	2	3	2.5	1	5
	2 - 4	5	2	8	1	1	5	3	1.5	6.5
	4 - 5	2	2	2	0	0	3	1	1	2.5
	>5	21	27	9	25	28	12	23	27.5	10.5
JUN	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	1	0	0	0.5
	-4 - -2	0	0	4	0	0	6	0	0	5
	-2 - 0	1	0	7	13	4	10	7	2	8.5
	0 - 2	4	1	1	2	6	4	3	3.5	2.5
	2 - 4	4	2	7	4	4	6	4	3	6.5
	4 - 5	0	2	4	1	1	1	0.5	1.5	2.5
	>5	21	25	7	10	15	2	15.5	20	4.5

Table 4.10. Monthly total of frost frequency and intensity at +0.1m
(Mount Superior, 1993-1994).

SENSOR: +0.1m		1993			1994			**1993-1994 AVERAGE**		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	**AVE**	**MAX**	**MIN**
JUL	< -8	0	0	2	0	0	0	0	0	1
	-8 - -6	0	0	1	0	0	0	0	0	0.5
	-6 - -4	0	0	0	0	0	1	0	0	0.5
	-4 - -2	1	0	3	0	0	9	0.5	0	6
	-2 - 0	6	3	7	8	1	13	7	2	10
	0 - 2	4	3	6	4	6	4	4	4.5	5
	2 - 4	3	2	5	9	1	4	6	1.5	4.5
	4 - 5	3	1	3	1	1	0	2	1	1.5
	>5	14	22	4	9	22	0	11.5	22	2
AUG	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	1	0	0	0	0	0	0.5
	-6 - -4	0	0	0	0	0	2	0	0	1
	-4 - -2	0	0	7	0	0	6	0	0	6.5
	-2 - 0	5	0	8	1	0	7	3	0	7.5
	0 - 2	3	5	6	5	0	8	4	2.5	7
	2 - 4	7	0	2	5	1	5	6	0.5	3.5
	4 - 5	1	1	3	2	1	1	1.5	1	2
	>5	15	25	4	18	29	2	16.5	27	3
SEP	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	3	0	0	0	0	0	1.5
	-4 - -2	0	0	0	0	0	3	0	0	1.5
	-2 - 0	1	0	5	2	0	10	1.5	0	7.5
	0 - 2	3	0	7	4	4	7	3.5	2	7
	2 - 4	1	0	6	1	0	3	1	0	4.5
	4 - 5	1	1	0	5	1	2	3	1	1
	>5	24	29	9	18	25	5	21	27	7
OCT	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	2	0	0	1
	-4 - -2	0	0	1	0	0	0	0	0	0.5
	-2 - 0	0	0	1	0	0	4	0	0	2.5
	0 - 2	0	0	6	0	0	4	0	0	5
	2 - 4	0	0	3	1	0	8	0.5	0	5.5
	4 - 5	0	0	7	2	0	2	1	0	4.5
	>5	31	31	13	28	31	11	29.5	31	12
NOV	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	1	0	0	2	0	0	1.5
	-2 - 0	0	0	2	0	0	4	0	0	3
	0 - 2	1	0	1	1	0	7	1	0	4
	2 - 4	0	0	6	0	0	5	0	0	5.5
	4 - 5	0	1	5	0	0	4	0	0.5	4.5
	>5	29	29	15	29	30	8	29	29.5	11.5
DEC	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	2	0	0	0	0	0	1
	0 - 2	0	0	1	0	0	3	0	0	2
	2 - 4	2	0	5	0	0	5	1	0	5
	4 - 5	0	0	5	0	0	2	0	0	3.5
	>5	29	31	18	31	31	21	30	31	19.5

Table 4.10. Monthly total of frost frequency and intensity at +0.1m
(Mount Superior, 1993-1994) (continued).

SENSOR: -0.01m		1993			1994			1993-1994 AVERAGE		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JAN	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	2	0	0	2
	2 - 4				0	0	2	0	0	2
	4 - 5				0	0	0	0	0	0
	>5				31	31	27	31	31	27
FEB	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	1	0	0	1
	2 - 4				0	0	2	0	0	2
	4 - 5				0	0	1	0	0	1
	>5				28	28	24	28	28	24
MAR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	2	0	0	2
	2 - 4				0	0	2	0	0	2
	4 - 5				0	0	1	0	0	1
	>5				31	31	26	31	31	26
APR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	3	0	0	3
	0 - 2				0	0	2	0	0	2
	2 - 4				0	0	4	0	0	4
	4 - 5				0	0	2	0	0	2
	>5				30	30	19	30	30	19
MAY	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	2	0	0	3	0	0	2.5
	-2 - 0	0	0	10	0	0	3	0	0	6.5
	0 - 2	2	0	7	2	0	7	2	0	7
	2 - 4	4	2	9	3	2	6	3.5	2	7.5
	4 - 5	4	0	1	1	0	3	2.5	0	2
	>5	21	29	2	25	29	9	23	29	5.5
JUN	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	1	0	0	0	0	0	0.5
	-6 - -4	0	0	3	0	0	0	0	0	1.5
	-4 - -2	0	0	2	0	0	1	0	0	1.5
	-2 - 0	6	3	12	0	0	2	3	1.5	7
	0 - 2	4	2	8	5	1	16	4.5	1.5	12
	2 - 4	3	2	4	12	12	8	7.5	7	6
	4 - 5	6	0	0	0	2	2	3	1	1
	>5	11	23	0	13	15	1	12	19	0.5

Table 4.11. Monthly total of frost frequency and intensity at -0.01m (Mount Superior, 1993-1994).

SENSOR: -0.01m		1993			1994			1993-1994 AVERAGE		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	3	0	0	1.5
	-4 - -2	0	0	0	0	0	4	0	0	2
	-2 - 0	1	1	13	0	0	1	0.5	0.5	7
	0 - 2	13	8	11	1	0	17	7	4	14
	2 - 4	3	2	6	15	11	6	9	6.5	6
	4 - 5	4	3	1	1	1	0	2.5	2	0.5
	>5	10	17	0	14	19	0	12	18	0
AUG	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	1	0	0	0.5
	-6 - -4	0	0	3	0	0	4	0	0	3.5
	-4 - -2	0	0	2	0	0	3	0	0	2.5
	-2 - 0	2	0	14	0	0	5	1	0	9.5
	0 - 2	8	7	8	0	0	8	4	3.5	8
	2 - 4	4	0	3	1	0	8	2.5	0	5.5
	4 - 5	4	0	0	2	0	1	3	0	0.5
	>5	13	24	1	28	31	1	20.5	27.5	1
SEP	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	1	0	0	0.5
	-4 - -2	0	0	0	0	0	2	0	0	1
	-2 - 0	0	0	12	0	0	1	0	0	6.5
	0 - 2	1	0	7	7	2	14	4	1	10.5
	2 - 4	3	0	10	1	5	6	2	2.5	8
	4 - 5	0	1	1	0	0	2	0	0.5	1.5
	>5	26	29	0	22	23	4	24	26	2
OCT	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	1	0	0	1	0	0	1
	-4 - -2	0	0	1	0	0	0	0	0	0.5
	-2 - 0	0	0	4	0	0	2	0	0	3
	0 - 2	0	0	7	0	0	8	0	0	7.5
	2 - 4	0	0	8	0	0	4	0	0	6
	4 - 5	0	0	6	1	0	4	0.5	0	5
	>5	31	31	4	30	31	12	30.5	31	8
NOV	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	1	0	0	0.5
	-4 - -2	0	0	1	0	0	0	0	0	0.5
	-2 - 0	0	0	1	0	0	9	0	0	5
	0 - 2	1	0	5	0	0	7	0.5	0	6
	2 - 4	0	0	7	1	0	5	0.5	0	6
	4 - 5	0	0	3	0	0	1	0	0	2
	>5	29	30	13	29	30	7	29	30	10
DEC	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	1	0	0	0.5
	0 - 2	0	0	0	0	0	1	0	0	0.5
	2 - 4	0	0	0	0	0	7	0	0	3.5
	4 - 5	0	0	1	0	0	2	0	0	1.5
	>5	31	31	30	31	31	20	31	31	25

Table 4.11. Monthly total of frost frequency and intensity at -0.01m (Mount Superior, 1993-1994) (continued).

SENSOR: -0.05m		1993			1994			**1993-1994 AVERAGE**		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	**AVE**	**MAX**	**MIN**
JAN	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				31	31	31	31	31	31
FEB	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				28	28	28	28	28	28
MAR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				31	31	31	31	31	31
APR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	5	0	0	5
	4 - 5				1	0	1	1	0	1
	>5				29	30	24	29	30	24
MAY	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	1	0	5	1	1	6	1	0.5	5.5
	2 - 4	4	2	15	5	3	5	4.5	2.5	10
	4 - 5	4	1	3	1	0	6	2.5	0.5	4.5
	>5	22	28	8	24	27	14	23	27.5	11
JUN	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	6	5	24	15	12	21	10.5	8.5	22.5
	2 - 4	14	4	5	4	3	8	9	3.5	6.5
	4 - 5	8	0	1	6	3	1	7	1.5	1
	>5	2	21	0	5	12	0	3.5	16.5	0

Table 4.12. Monthly total of frost frequency and intensity at -0.05m
(Mount Superior, 1993-1994).

SENSOR: -0.05m		1993			1994			1993-1994 AVERAGE		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	12	9	19	17	12	31	14.5	10.5	25
	2 - 4	6	4	10	13	4	0	9.5	4	5
	4 - 5	4	1	2	1	1	0	2.5	1	1
	>5	9	17	0	0	14	0	4.5	15.5	0
AUG	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	9	7	20	0	0	24	4.5	3.5	22
	2 - 4	6	2	8	11	1	6	8.5	1.5	7
	4 - 5	2	1	2	8	0	1	5	0.5	1.5
	>5	14	21	1	12	30	0	13	25.5	0.5
SEP	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	7	6	6	12	3	3	9.5
	2 - 4	2	0	12	3	0	9	2.5	0	10.5
	4 - 5	3	0	7	0	0	4	1.5	0	5.5
	>5	25	30	4	21	24	5	23	27	4.5
OCT	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	2	0	0	1
	2 - 4	0	0	2	1	0	9	0.5	0	5.5
	4 - 5	0	0	4	0	0	1	0	0	2.5
	>5	31	31	25	30	31	19	30.5	31	22
NOV	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	1	0	0	0	0	0	0.5
	2 - 4	0	0	1	0	0	2	0	0	1.5
	4 - 5	1	0	2	0	0	3	0.5	0	2.5
	>5	29	30	26	30	30	25	29.5	30	25.5
DEC	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	0	0	2	0	0	0	0	0	1
	4 - 5	0	0	1	0	0	0	0	0	0.5
	>5	31	31	28	31	31	31	31	31	29.5

Table 4.12. Monthly total of frost frequency and intensity at -0.05m (Mount Superior, 1993-1994) (continued).

SENSOR: -0.1m		1993			1994			**1993-1994 AVERAGE**		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	**AVE**	**MAX**	**MIN**
JAN	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				31	31	31	31	31	31
FEB	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				28	28	28	28	28	28
MAR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				31	31	31	31	31	31
APR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	2	0	0	2
	>5				30	30	28	30	30	28
MAY	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	1	0	0	0	0	0	0.5
	2 - 4	4	2	10	4	3	6	4	2.5	8
	4 - 5	4	2	8	1	1	4	2.5	1.5	6
	>5	23	27	12	26	27	21	24.5	27	16.5
JUN	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	7	5	13	10	7	12	8.5	6	12.5
	2 - 4	13	3	16	7	8	16	10	5.5	16
	4 - 5	9	4	1	8	3	1	8.5	3.5	1
	>5	1	18	0	5	12	1	3	15	0.5

Table 4.13. Monthly total of frost frequency and intensity at -0.1m
(Mount Superior, 1993-1994).

SENSOR: -0.1m		1993			1994			**1993-1994 AVERAGE**		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	**AVE**	**MAX**	**MIN**
JUL	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	10	9	18	14	11	26	12	10	22
	2 - 4	8	2	9	16	6	5	12	4	7
	4 - 5	8	7	4	1	2	0	4.5	4.5	2
	>5	5	13	0	0	12	0	2.5	12.5	0
AUG	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	9	6	14	0	0	2	4.5	3	8
	2 - 4	7	4	13	9	1	21	8	2.5	17
	4 - 5	4	2	2	9	2	2	6.5	2	2
	>5	11	19	2	13	28	6	12	23.5	4
SEP	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	1	0	9	0	0	1	0.5	0	5
	4 - 5	2	0	5	4	1	5	3	0.5	5
	>5	27	30	16	26	29	24	26.5	29.5	20
OCT	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	0	0	0	0	0	0	0	0	0
	4 - 5	0	0	0	0	0	1	0	0	0.5
	>5	31	31	31	31	31	30	31	31	30.5
NOV	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	0	0	1	0	0	0	0	0	0.5
	4 - 5	0	0	1	0	0	0	0	0	0.5
	>5	30	30	28	30	30	30	30	30	29
DEC	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	0	0	0	0	0	0	0	0	0
	4 - 5	0	0	1	0	0	0	0	0	0.5
	>5	31	31	30	31	31	31	31	31	30.5

Table 4.13. Monthly total of frost frequency and intensity at -0.1m
(Mount Superior, 1993-1994) (continued).

SENSOR: -0.14m		1993			1994			**1993-1994 AVERAGE**		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	**AVE**	**MAX**	**MIN**
JAN	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				31	31	31	31	31	31
FEB	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				28	28	28	28	28	28
MAR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				31	31	31	31	31	31
APR	< -8				0	0	0	0	0	0
	-8 - -6				0	0	0	0	0	0
	-6 - -4				0	0	0	0	0	0
	-4 - -2				0	0	0	0	0	0
	-2 - 0				0	0	0	0	0	0
	0 - 2				0	0	0	0	0	0
	2 - 4				0	0	0	0	0	0
	4 - 5				0	0	0	0	0	0
	>5				30	30	30	30	30	30
MAY	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	2	1	7	4	3	5	3	2	6
	4 - 5	6	2	4	1	0	1	3.5	1	2.5
	>5	23	28	20	26	28	25	24.5	28	22.5
JUN	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	4	4	7	8	6	10	6	5	8.5
	2 - 4	16	5	21	11	9	18	13.5	7	19.5
	4 - 5	9	4	2	6	3	2	7.5	3.5	2
	>5	1	17	0	5	12	0	3	14.5	0

Table 4.14. Monthly total of frost frequency and intensity at -0.14m (Mount Superior, 1993-1994).

SENSOR: -0.14m		1993			1994			1993-1994 AVERAGE		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	7	6	13	15	12	23	11	9	18
	2 - 4	11	5	9	16	8	8	13.5	6.5	8.5
	4 - 5	5	7	9	0	8	0	2.5	7.5	4.5
	>5	8	13	0	0	3	0	4	8	0
AUG	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	9	6	11	0	0	4	4.5	3	7.5
	2 - 4	7	4	11	16	4	21	11.5	4	16
	4 - 5	3	3	5	9	7	4	6	5	4.5
	>5	12	18	4	6	20	2	9	19	3
SEP	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	1	0	4	0.5	0	2
	2 - 4	0	0	5	6	6	6	3	3	5.5
	4 - 5	2	0	3	1	1	6	1.5	0.5	4.5
	>5	28	30	22	22	23	14	25	26.5	18
OCT	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	1	0	0	0.5
	2 - 4	0	0	0	1	0	2	0.5	0	1
	4 - 5	0	0	0	0	0	2	0	0	1
	>5	31	31	31	30	31	26	30.5	31	28.5
NOV	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	0	0	0	0	0	0	0	0	0
	4 - 5	0	0	0	0	0	0	0	0	0
	>5	30	30	30	30	30	30	30	30	30
DEC	< -8	0	0	0	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0	0	0	0
	2 - 4	0	0	0	0	0	0	0	0	0
	4 - 5	0	0	0	0	0	0	0	0	0
	>5	31	31	31	31	31	31	31	31	31

Table 3.14. Monthly total of frost frequency and intensity at -0.14m (Mount Superior, 1993-1994) (continued).

APPENDIX 5. MONTHLY AND DAILY SOIL MOISTURE LEVELS AND PRECIPITATION TOTALS FOR WAAIHOEK PEAK AND MOUNT SUPERIOR

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Section A: Monthly average soil moisture and precipitation

Section B: Daily soil moisture and precipitation

Month	MOIST -0.05m	MOIST -0.15m	MOIST -0.3m	PRECIP (mm)	Days Missing	Month	MOIST -0.05m	MOIST -0.15m	MOIST -0.3m	PRECIP (mm)	Days Missing
January						July					
90						90					
91						91	84.9	76.6	87.6	415.0	3
92	5.3	5.5	7.2	0.8	0	92	87.5	87.8	91.1	416.2	0
93	7.9	8.7	16.8	9.6	0	93	89.1	89.9	91.7	883.0	3
94	28.5	57.1	60.5	65.0	0	94	88.6	89.7	92.1	326.2	0
avg	13.9	23.7	28.2	25.1	0.0	avg	87.5	86.0	90.6	510.1	1.5
February						August					
90						90					
91						91	85.1	76.9	87.1	219.4	8
92	18.9	15.4	16.5	198.4	0	92	82.1	81.9	84.3	121.4	0
93	35.1	35.5	32.7	78.8	0	93	84.6	85.0	87.8	83.4	4
94	9.6	25.5	24.6	7.6	0	94	84.6	87.7	88.0	76.2	0
avg	21.2	25.5	24.6	94.9	0.0	avg	84.1	82.9	86.8	125.1	3.0
March						September					
90						90					
91						91	89.2	81.7	90.9	238.0	15
92	58.6	77.9	85.8	172.4	0	92	86.8	87.9	90.3	198.8	0
93	9.8	11.7	11.5	16.0	0	93	73.6	80.2	80.8	49.6	7
94	24.8	11.1	8.7	34.6	0	94	81.6	88.8	84.8	181.0	0
avg	31.1	33.6	35.3	74.3	0.0	avg	82.8	84.6	86.7	166.9	5.5
April						October					
90						90					
91	57.6	36.1	69.6	69.0	0	91					
92	88.3	89.1	92.8	202.0	0	92	83.9	86.5	89.4	392.4	3
93	77.9	74.6	76.1	337.2	0	93	24.6	69.3	62.5	5.6	0
94	44.7	45.7	43.4	225.8	0	94	81.4	88.2	88.5	91.4	0
avg	67.1	61.4	70.5	208.5	0.0	avg	63.3	81.4	80.1	163.1	1.0
May						November					
90						90					
91	48.3	43.4	68.3	396.4	0	91					
92	88.6	89.5	91.6	154.0	0	92					
93	87.5	88.9	91.6	341.4	0	93	27.0	45.1	34.2	55.8	0
94	83.1	88.8	89.6	104.0	0	94	58.7	83.0	82.1	3.2	18
avg	76.9	77.6	85.3	249.0	0.0	avg	42.8	64.0	58.1	29.5	9.0
June						December					
90						90					
91	87.2	77.5	90.3	597.0	0	91	8.1	18.5	36.3	14.0	0
92	87.2	87.5	90.4	836.0	0	92					
93						93	59.3	81.8	85.0	100.6	0
94	89.6	91.0	92.4	875.8	0	94	58.8	67.2	66.2	38	3
avg	88.0	85.3	91.0	769.6	0.0	avg	42.1	55.9	62.5	50.9	1.0
						YEAR	58.4	63.5	66.7	2466.9	1.7

Table 5.1. Monthly average soil moisture levels and precipitation totals (Waaihoek Peak, 1990-1994).

Month	MOIST -0.05m	MOIST -0.1m	MOIST -0.14m	PRECIP (mm)	Days missing
January					
93					
94	2.9	9.4	17.7	8.4	0
avg.	2.9	9.4	17.7	8.4	0
February					
93					
94	0.7	4.0	11.2	8.2	0
avg.	0.7	4.0	11.2	8.2	0
March					
93					
94	3.1	2.8	4.9	21.6	0
avg.	3.1	2.8	4.9	21.6	0
April					
93					
94	43.0	44.9	46.4	78.0	0
avg.	43.0	44.9	46.4	78.0	0
May					
93	88.2	89.5	89.8		0
94	35.9	36.2	37.2	64.2	0
avg.	62.1	62.8	63.5	64.2	0
June					
93	85.3	87.3	87.9		0
94	90.5	91.4	91.6	236.4	0
avg.	87.9	89.4	89.8	236.4	0
July					
93	90.5	91.9	92.3		0
94	88.9	90.3	90.5	120.8	0
avg.	89.7	91.1	91.4	120.8	0
August					
93	80.2	82.8	84.2		0
94	81.5	83.1	83.4	285.5	0
avg.	80.9	83.0	83.8	285.5	0
September					
93	39.5	42.5	44.8		0
94	44.5	44.9	44.7	144.2	0
avg.	42.0	43.7	44.7	144.2	0
October					
93	15.0	21.2	24.2	4.4	0
94	60.9	62.4	62.0	56.2	0
avg.	37.9	41.8	43.1	30.3	0
November					
93	22.2	32.5	36.8	40.8	0
94	5.0	5.7	6.5	11.6	0
avg.	13.6	19.1	21.7	26.2	0
December					
93	33.2	35.6	39.7	106.6	0
94	23.8	24.9	25.5	47.4	0
avg.	28.5	30.3	32.6	77.0	0
Year	41.0	43.5	45.9	1100.8	0

Table 5.2. Monthly average soil moisture levels and precipitation totals (Mt. Superior, 1993-1994).

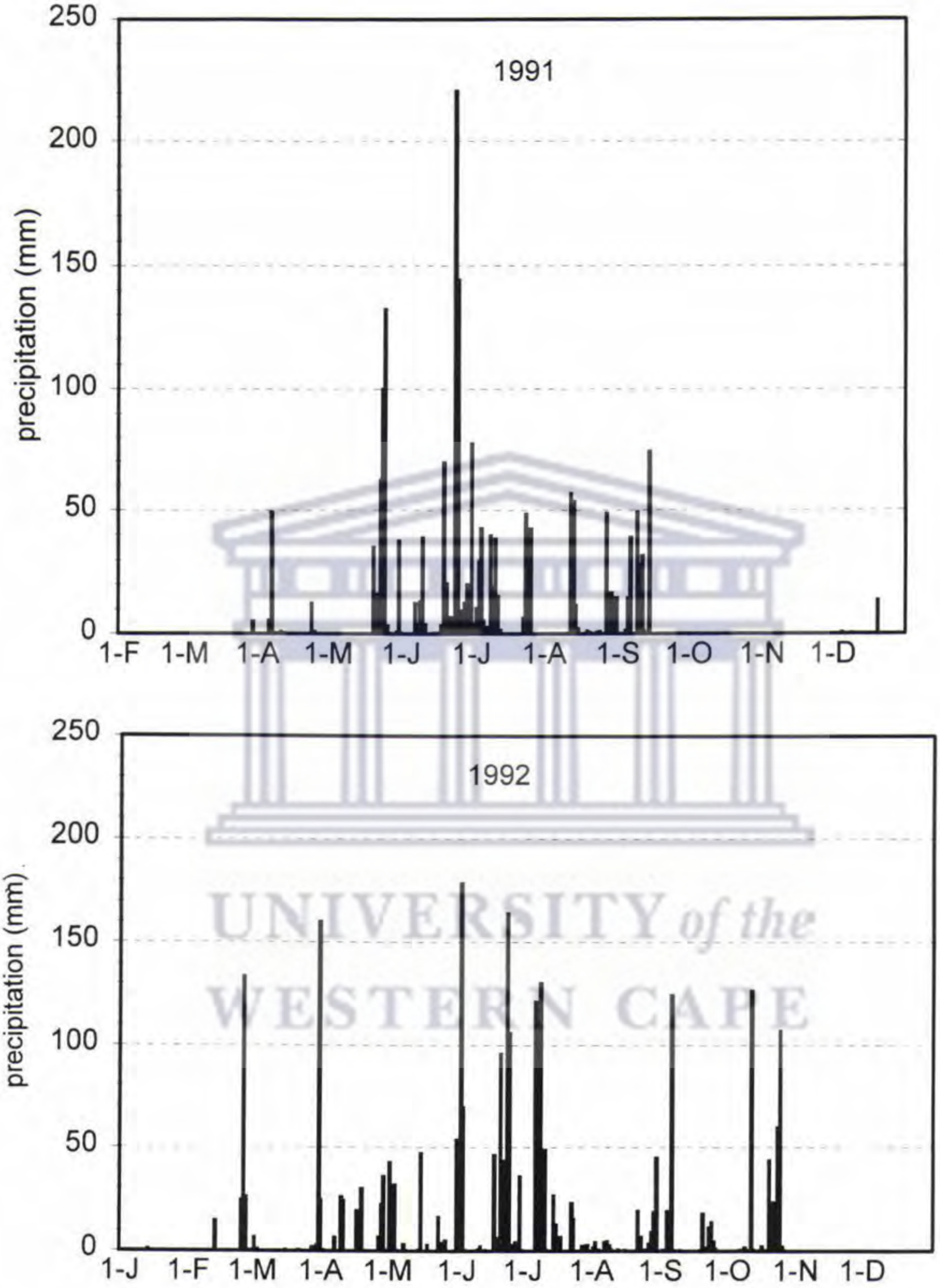


Figure 5.1. Daily precipitation totals for Waaihoek Peak (1991-1994).

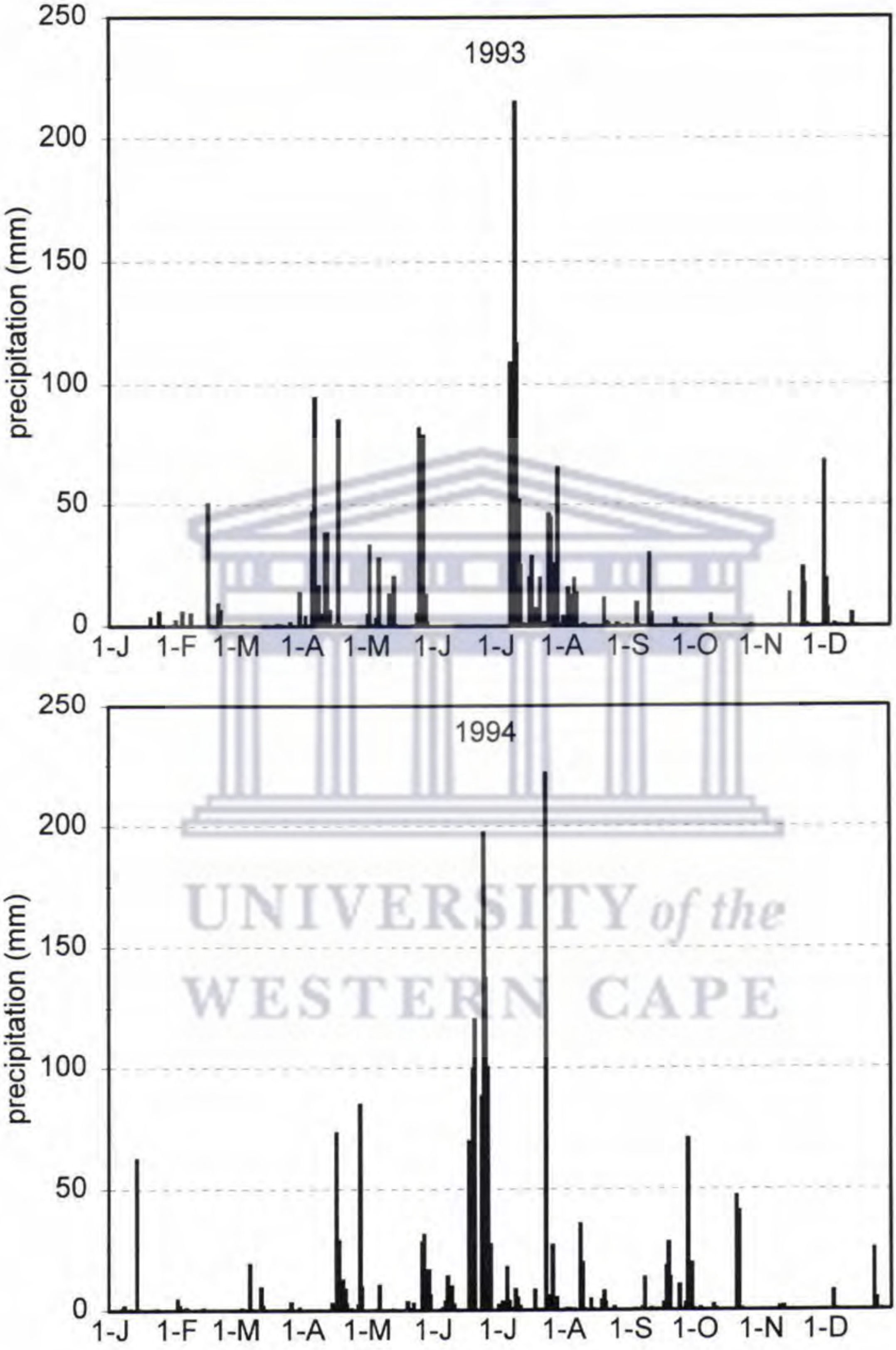


Figure 5.1. Daily precipitation totals for Waaihoek Peak (1991-1994) (continued).

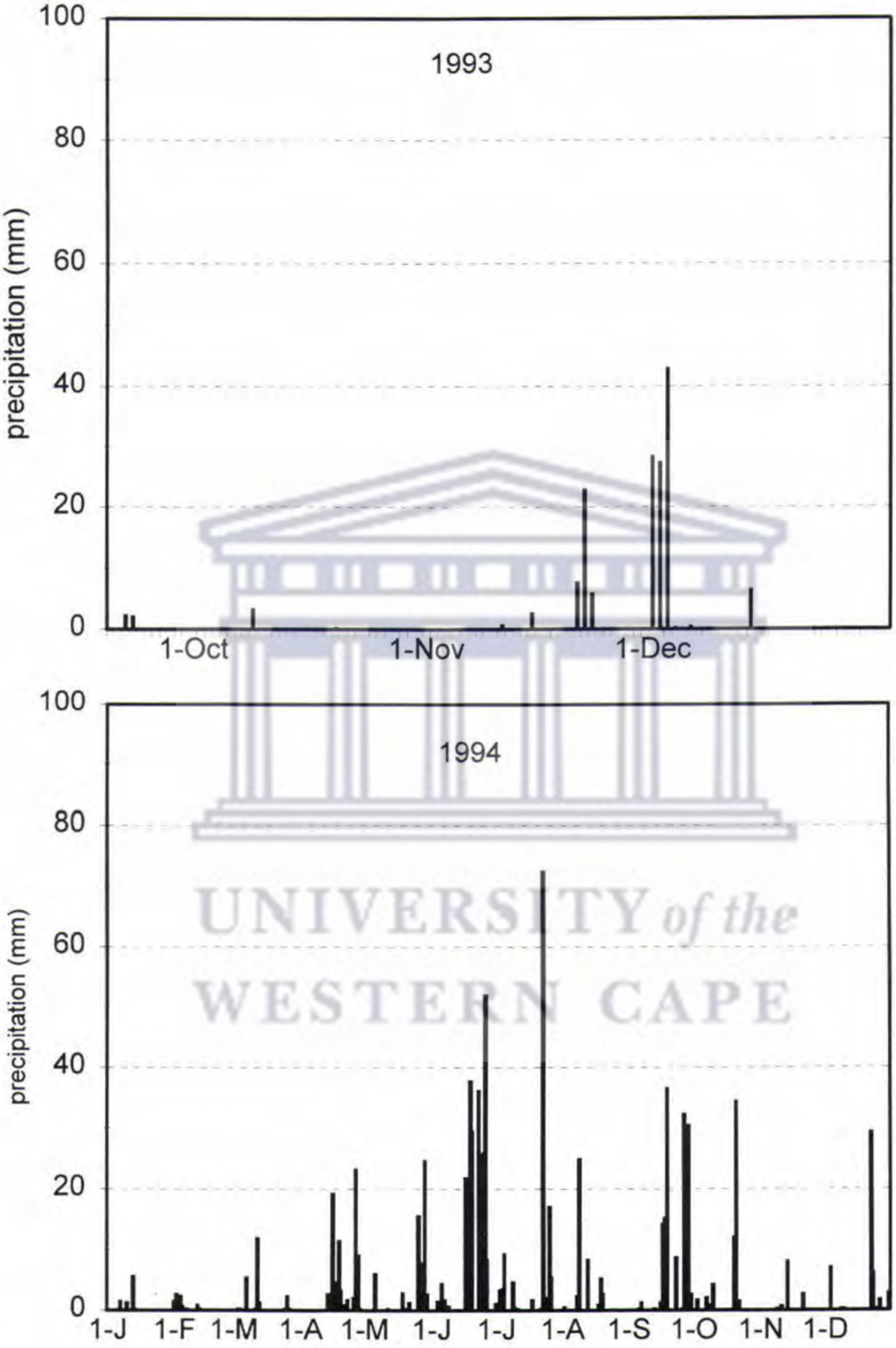


Figure 5.2. Daily precipitation totals for Mt. Superior (1993-1994).

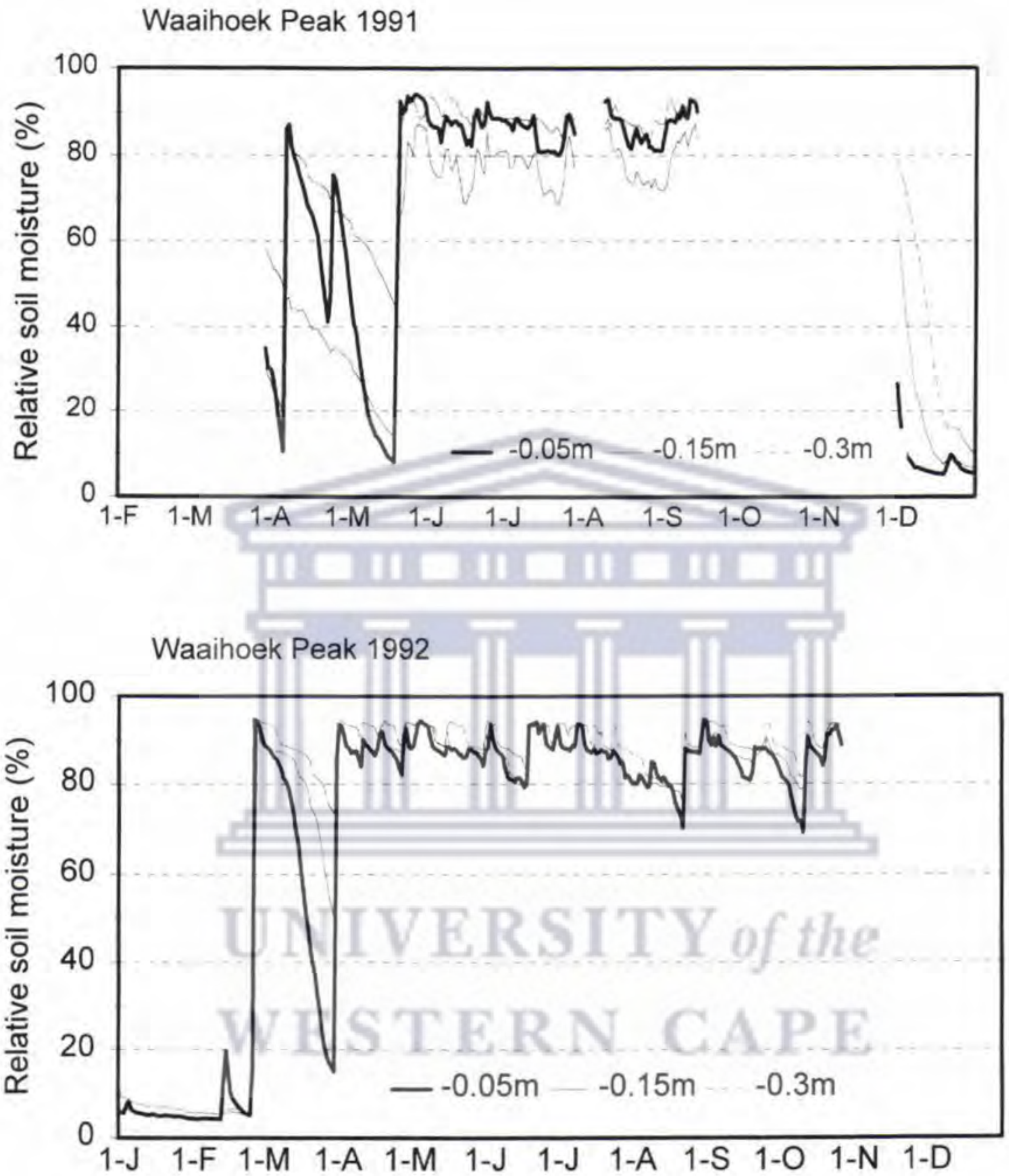
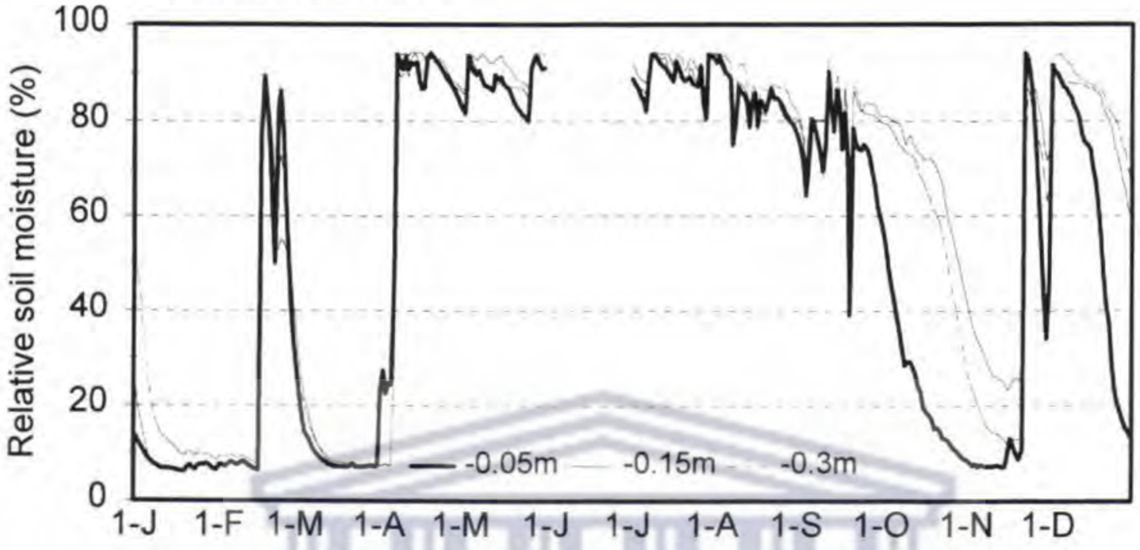


Figure 5.3. Daily relative soil moisture levels at Waaihoek Peak (1991-1994).

Waaihoek Peak 1993



Waaihoek Peak 1994

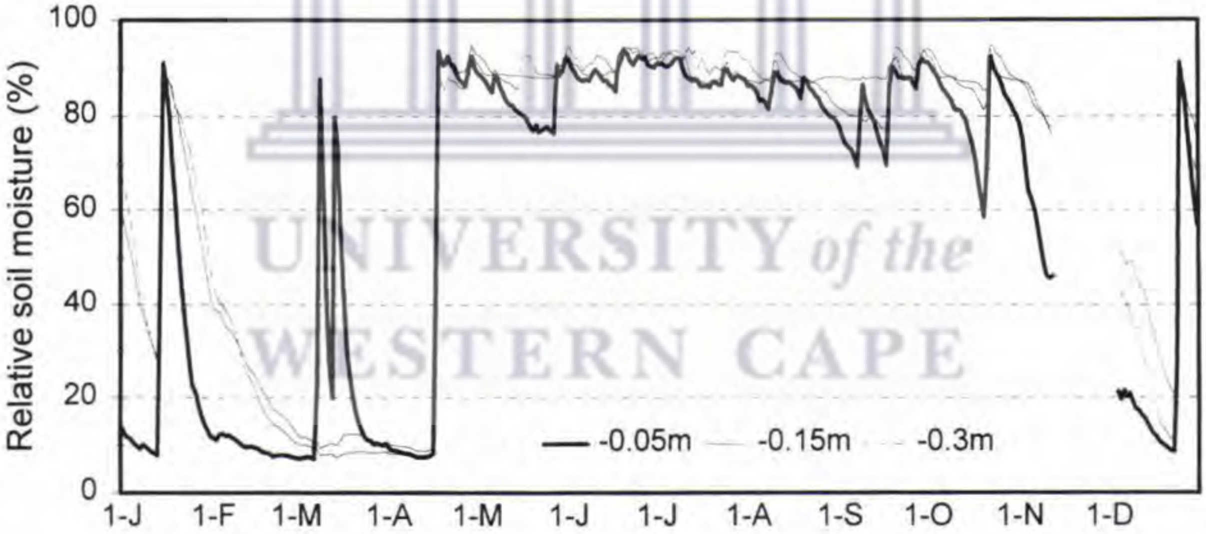
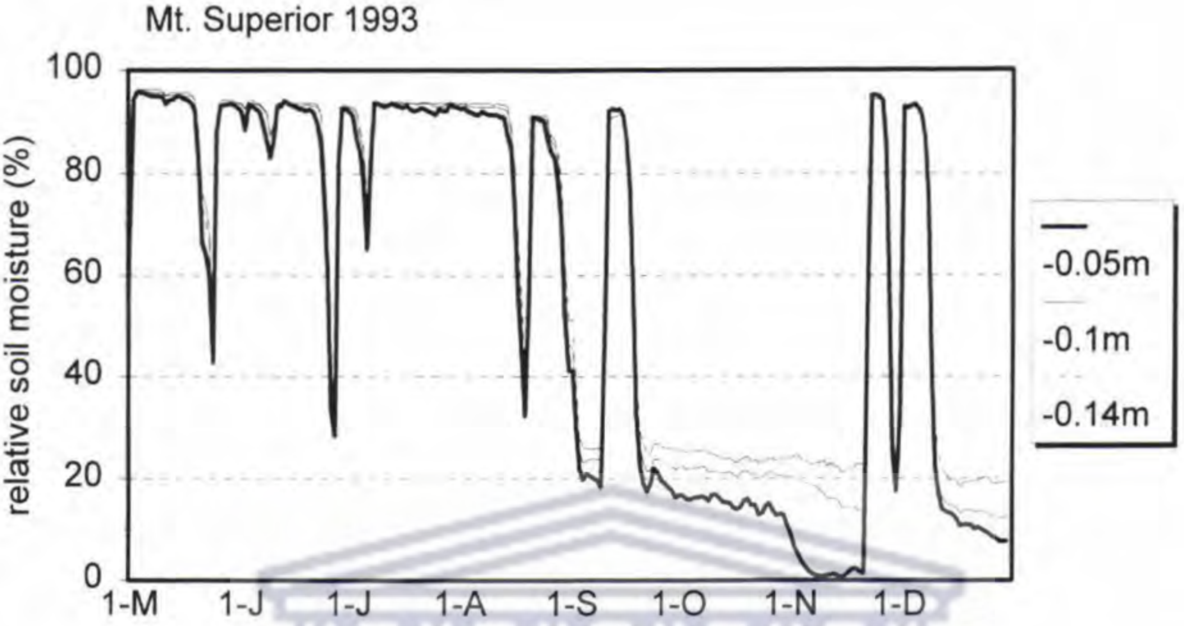


Figure 5.3. Daily relative soil moisture levels at Waaihoek Peak (1991-1994) (continued).



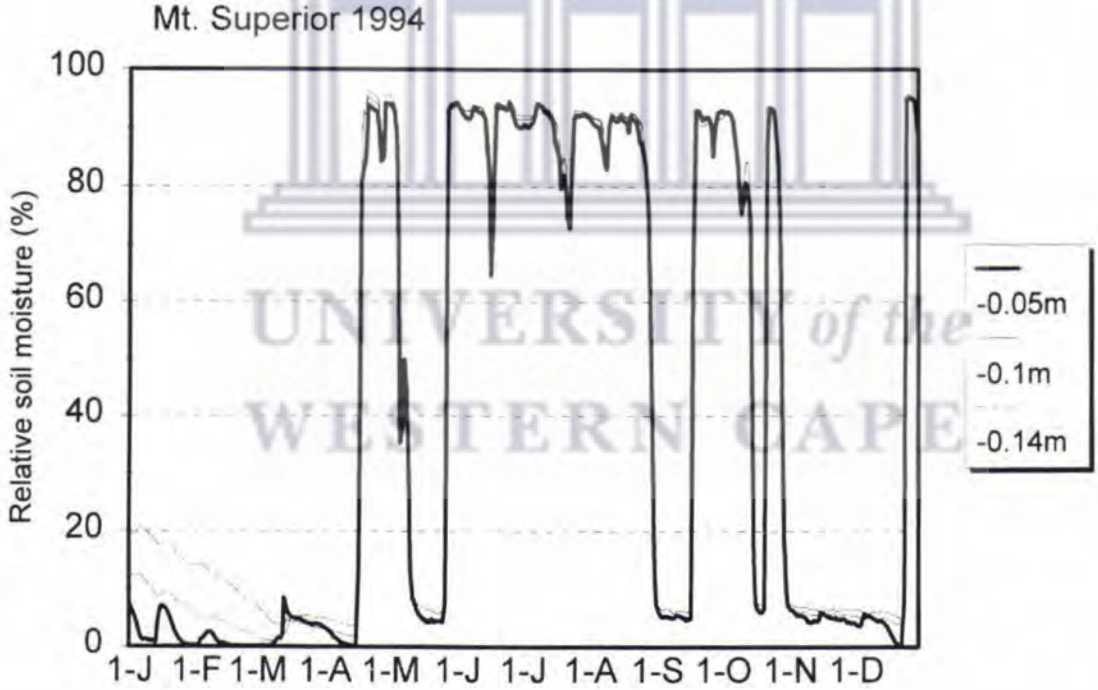


Figure 5.4. Daily relative soil moisture levels at Mt. Superior (1993-1994).

APPENDIX 6. PARTICLE SIZE ANALYSIS OF SOILS AT WAAIHOEK PEAK AND MOUNT SUPERIOR

Particle size analysis of soils near Waaihoek Peak and Mount Superior was done by means of the dry sieving method. Samples of minimally 200g were collected at two occasions, the first in both areas, the second in the Waaihoek Peak area only. After drying for 24h at 105°C the samples were sieved for fifteen minutes in the first series. Weights, expressed as a percentage of the total mass, are tabled here for each sieve and the collector pan. For the second series the samples were split after drying, followed by the same procedure as described. Values for both series of analyses are presented. The location of the samples is given in the accompanying figures.

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Percentage of particles passing 2mm aperture

ASSOCIATED LITHOLOGY	SAMPLE No.	SAMPLE DEPTH (cm)	SIEVE APERTURE					
			1mm 0 phi	0.5mm 1 phi	0.25mm 2 phi	0.125mm 3 phi	0.625mm 4 phi	<0.625mm <4 phi
SANDSTONE (Waaihoek Pk)	1	10	4.8	17.9	50.4	10.3	14.0	2.6
	2	10	8.3	13.3	39.1	23.4	8.7	7.2
	3	5	5.8	23.9	45.3	13.0	9.6	2.5
	4	1	1.7	14.9	57.7	20.2	3.3	2.3
	5	10	7.3	23.6	39.5	16.4	6.9	6.4
SHALE (Mt.Superior)	6	5	17.3	11.6	12.3	11.9	22.5	24.4
	7	7	8.0	5.8	14.5	16.6	24.6	30.5
	8	5	25.8	10.7	12.7	15.5	17.4	18.0
	9	15	20.6	12.5	8.1	9.1	4.9	44.9
	10	5	15.6	11.6	11.5	13.7	19.1	28.6
	11	5	14.0	13.2	10.6	13.0	17.1	32.1

Cumulative percentage of particles passing 2mm aperture

ASSOCIATED LITHOLOGY	SAMPLE No.	SAMPLE DEPTH (cm)	SIEVE APERTURE					
			1mm 0 phi	0.5mm 1 phi	0.25mm 2 phi	0.125mm 3 phi	0.625mm 4 phi	<0.625mm <4 phi
SANDSTONE (Waaihoek Pk)	1	10	100.0	95.2	77.3	26.9	16.7	2.6
	2	10	100.0	91.8	78.5	39.3	15.9	7.2
	3	5	100.0	94.2	70.4	25.1	12.1	2.5
	4	1	100.0	98.3	83.4	25.7	5.5	2.3
	5	10	100.0	92.7	69.1	29.6	13.2	6.4
SHALE (Mt.Superior)	6	5	100.0	82.7	71.1	58.8	46.8	24.4
	7	7	100.0	92.0	86.2	71.7	55.1	30.5
	8	5	100.0	74.3	63.6	50.9	35.4	18.0
	9	15	100.0	79.5	67.0	58.9	49.8	44.9
	10	5	100.0	84.4	72.8	61.4	47.7	28.6
	11	5	100.0	86.1	72.9	62.2	49.2	32.1

Table 6.1. Particle size analysis for soils in the Waaihoek Peak and Mount Superior area (first series).

SAMPLE No.	SAMPLE DEPTH (cm)	SIEVE APERTURE				
		1mm 0 phi	0.5mm 1 phi	0.25mm 2 phi	0.625mm 4 phi	<0.625mm <4 phi
12(i)		13.5	9.6	41.0	29.2	6.6
12(ii)		12.0	9.3	42.1	29.3	7.4
12	10	12.8	9.5	41.5	29.2	7.0
13(i)		17.2	28.7	30.3	17.1	6.8
13(ii)		15.6	28.9	30.2	18.4	7.0
13	10	16.4	28.8	30.2	17.8	6.9
14(i)		30.2	20.0	23.7	19.6	6.4
14(ii)		30.5	18.7	25.0	19.3	6.4
14	10	30.4	19.4	24.4	19.5	6.4
14A(i)		22.8	20.9	25.7	16.6	14.1
14A(ii)		17.7	23.4	23.0	21.3	14.6
14A	30	20.2	22.1	24.4	18.9	14.3
15(i)		8.6	24.7	34.2	26.8	5.6
15(ii)		10.5	24.8	39.0	19.9	5.7
15	10	9.6	24.8	36.6	23.3	5.7
15A(i)		22.7	19.9	35.5	16.5	5.4
15A(ii)		18.6	19.4	37.8	18.2	6.0
15A	40	20.7	19.7	36.7	17.3	5.7
16(i)		22.1	11.4	35.0	21.8	9.6
16(ii)		22.8	13.0	35.7	23.1	5.3
16	10	22.4	12.2	35.4	22.5	7.5
16A(i)		52.8	5.8	19.9	15.8	5.8
16A(ii)		40.8	6.6	25.1	18.4	9.1
16A	20	46.8	6.2	22.5	17.1	7.4
17(i)		17.6	12.6	33.5	29.2	7.1
17(ii)		21.1	13.0	32.7	25.8	7.5
17	10	19.3	12.8	33.1	27.5	7.3
17A(i)		17.6	18.7	33.9	22.7	7.2
17A(ii)		20.1	18.9	34.7	19.3	7.0
17A	30	18.8	18.8	34.3	21.0	7.1
18(i)		56.3	8.2	17.2	14.2	4.1
18(ii)		49.2	9.4	20.4	17.0	4.0
18	10	52.8	8.8	18.8	15.6	4.0
19(i)		21.4	17.5	35.4	24.9	0.8
19(ii)		18.7	16.6	35.4	28.5	0.8
19	5	20.0	17.0	35.4	26.7	0.8
20(i)		21.8	12.9	27.6	34.1	3.5
20(ii)		20.7	11.0	26.0	37.9	4.4
20	5	21.2	12.0	26.8	36.0	4.0
20A(i)		8.5	18.2	45.3	27.0	1.1
20A(ii)		8.2	20.8	45.4	24.0	1.6
20A	20	8.3	19.5	45.3	25.5	1.4
21(i)		10.9	13.8	34.7	38.6	2.0
21(ii)		10.4	13.3	33.7	39.0	3.5
21	10	10.7	13.6	34.2	38.8	2.8

SAMPLE No.	SAMPLE DEPTH (cm)	SIEVE APERTURE				
		1mm 0 phi	0.5mm 1 phi	0.25mm 2 phi	0.625mm 4 phi	<0.625mm <4 phi
22(i)		30.4	15.2	30.0	20.6	3.7
22(ii)		26.3	14.0	31.5	23.6	4.6
22	10	28.4	14.6	30.8	22.1	4.2
22A(i)		5.6	27.8	43.8	18.3	4.6
22A(ii)		4.9	26.6	44.1	19.5	4.9
22A	30	5.2	27.2	43.9	18.9	4.8
23(i)		4.0	17.2	44.4	33.1	1.3
23(ii)		4.0	16.8	45.2	32.3	1.8
23	5	4.0	17.0	44.8	32.7	1.5
24(i)		35.2	14.9	31.0	17.0	2.0
24(ii)		19.6	14.4	37.3	26.0	2.8
24	10	27.4	14.6	34.2	21.5	2.4
24A(i)		14.6	15.1	41.2	25.6	3.5
24A(ii)		14.5	15.4	40.9	25.5	3.7
24A	30	14.6	15.3	41.1	25.5	3.6
25(i)		31.7	23.0	23.6	18.3	3.4
25(ii)		30.8	24.3	23.8	18.2	2.9
25	3	31.3	23.6	23.7	18.3	3.2
25A(i)		10.6	42.7	26.1	16.5	4.1
25A(ii)		9.3	41.3	26.4	18.2	4.8
25A	10	9.9	42.0	26.3	17.4	4.4
26(i)		3.2	19.1	35.4	35.0	7.3
26(ii)		3.1	21.0	35.5	32.9	7.5
26	10	3.2	20.1	35.4	33.9	7.4
26A(i)		6.2	27.3	37.6	22.5	6.4
26A(ii)		6.1	27.4	36.9	23.0	6.7
26A	30	6.2	27.3	37.2	22.8	6.5
27(i)		10.7	12.7	41.4	31.9	3.5
27(ii)		13.4	14.2	40.3	28.9	3.1
27	7	12.1	13.5	40.8	30.4	3.3
28(i)		10.1	18.3	37.7	32.6	1.3
28(ii)		13.1	18.6	35.7	31.2	1.4
28	5	11.6	18.4	36.7	31.9	1.4
29(i)		14.4	9.6	35.8	37.8	2.5
29(ii)		16.3	9.9	34.8	35.9	3.0
29	5	15.4	9.7	35.3	36.8	2.8
30(i)		17.4	11.7	33.5	32.3	5.2
30(ii)		18.8	12.3	33.2	30.3	5.1
30	5	18.1	12.0	33.4	31.3	5.2
31(i)		7.5	12.7	40.1	33.9	5.7
31(ii)		6.7	13.4	40.7	33.6	5.3
31	10	7.1	13.0	40.4	33.8	5.5
31A(i)		9.0	12.8	41.3	31.0	5.6
31A(ii)		9.0	14.9	40.9	29.4	5.7
31A	30	9	13.9	41.1	30.2	5.6

Table 6.2. Particle size analysis for soils in the Waaihoek Peak area (second series).

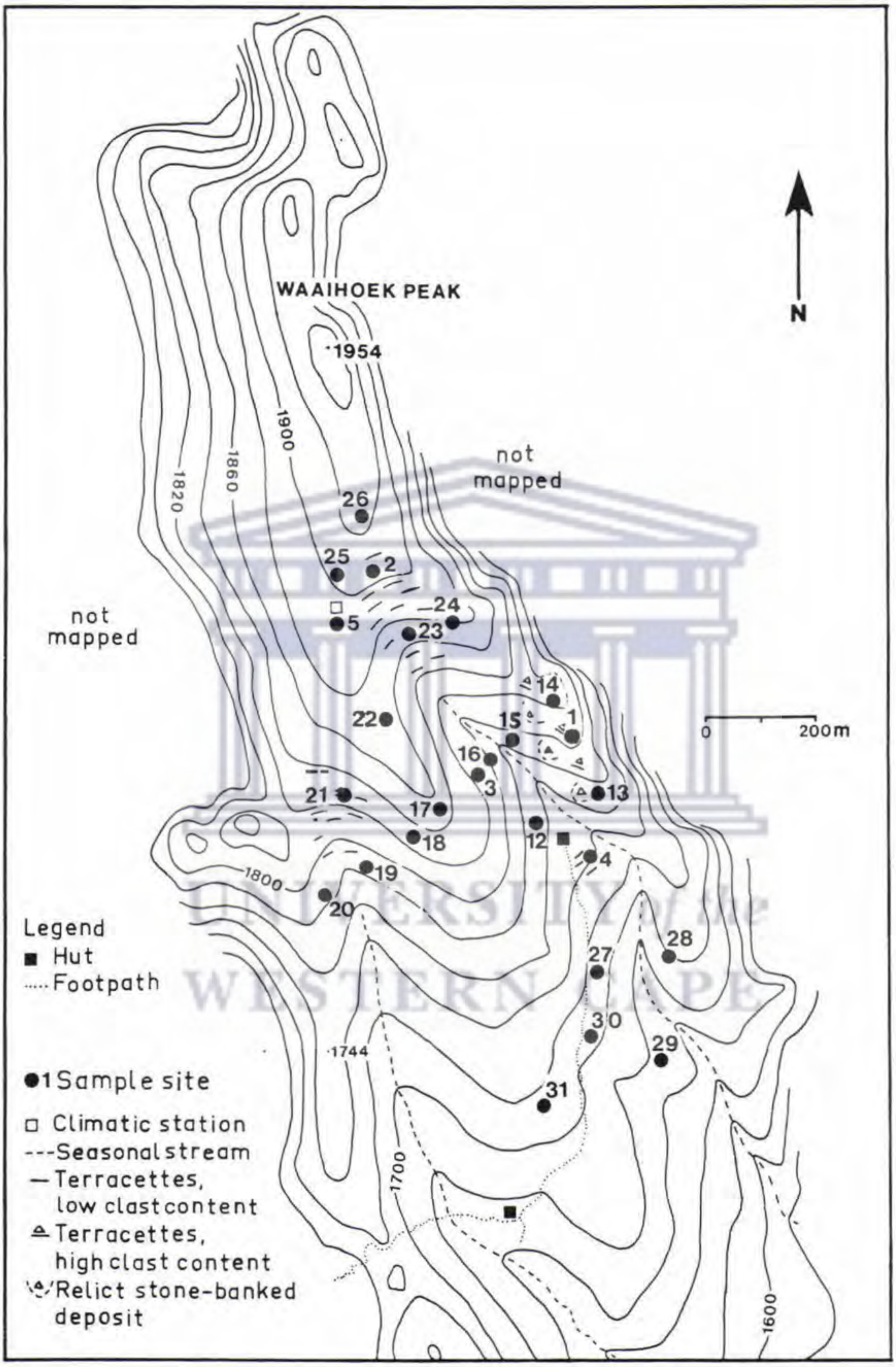


Figure 6.1. Location of sample sites in the Waaihoek Peak area.

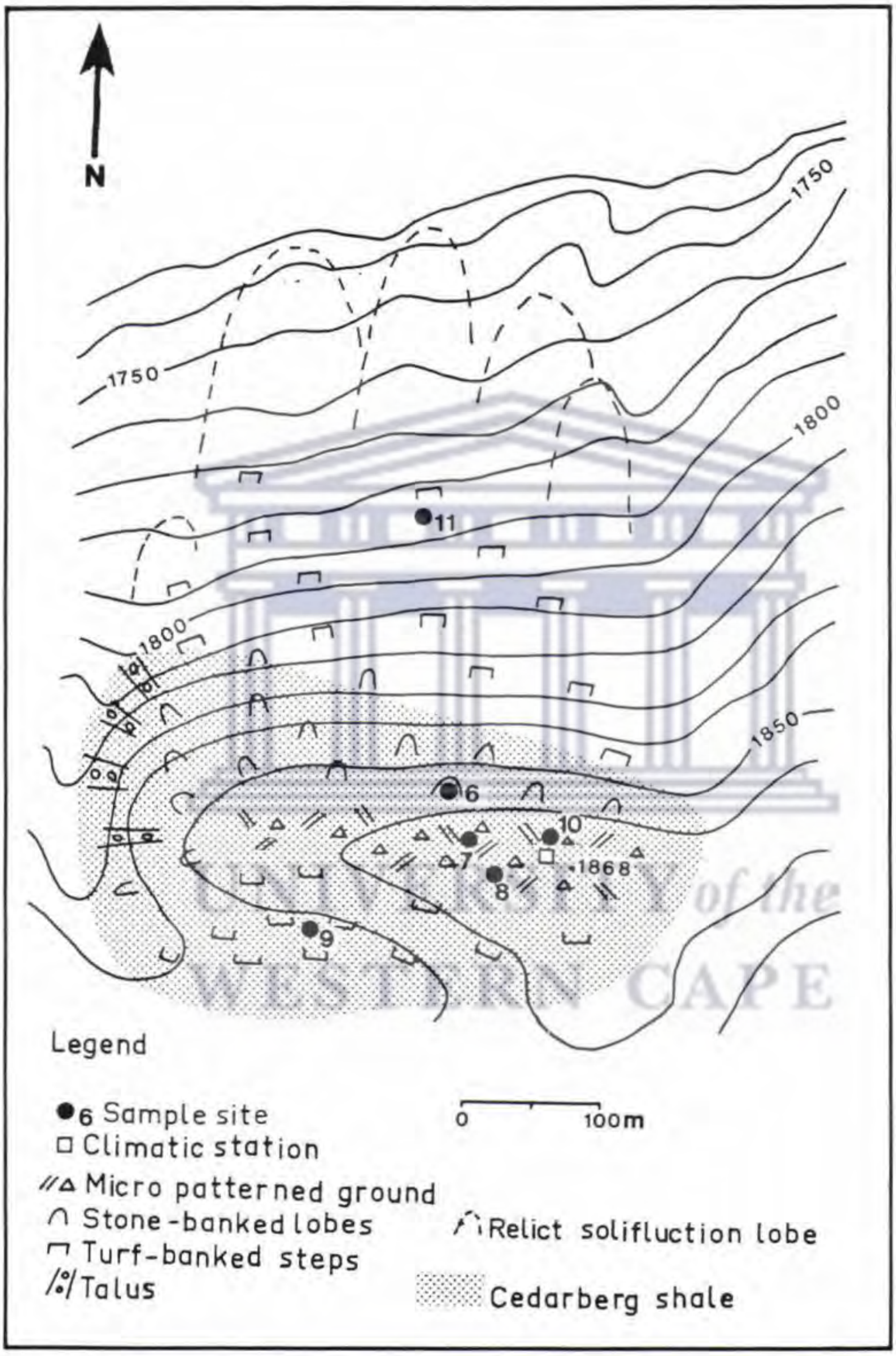


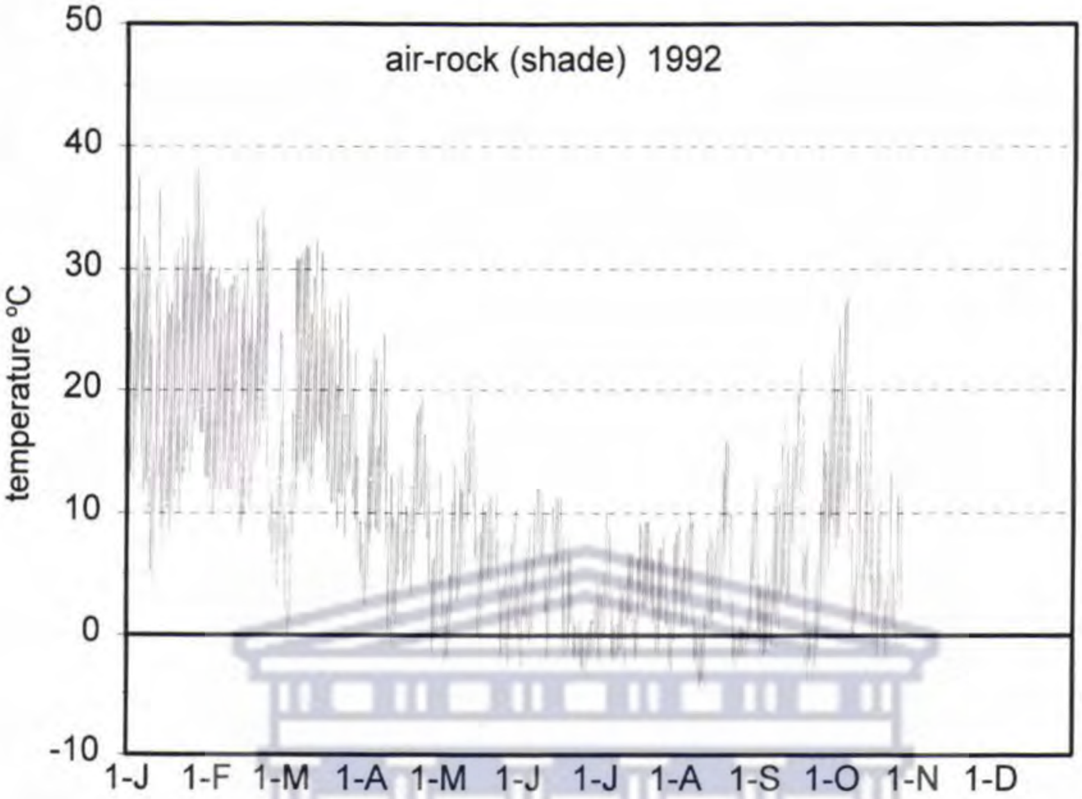
Figure 6.2. Location of sample sites in the Mount Superior area.

APPENDIX 7. DAILY TEMPERATURES, FROST FREQUENCY AND INTENSITY AT ROCK SURFACES AT WAAIHOEK PEAK AND MOUNT SUPERIOR

Contents Page

Section A: Daily temperatures at a sandstone and shale surface

Section B: Frost frequency and intensity at a sandstone and shale surface



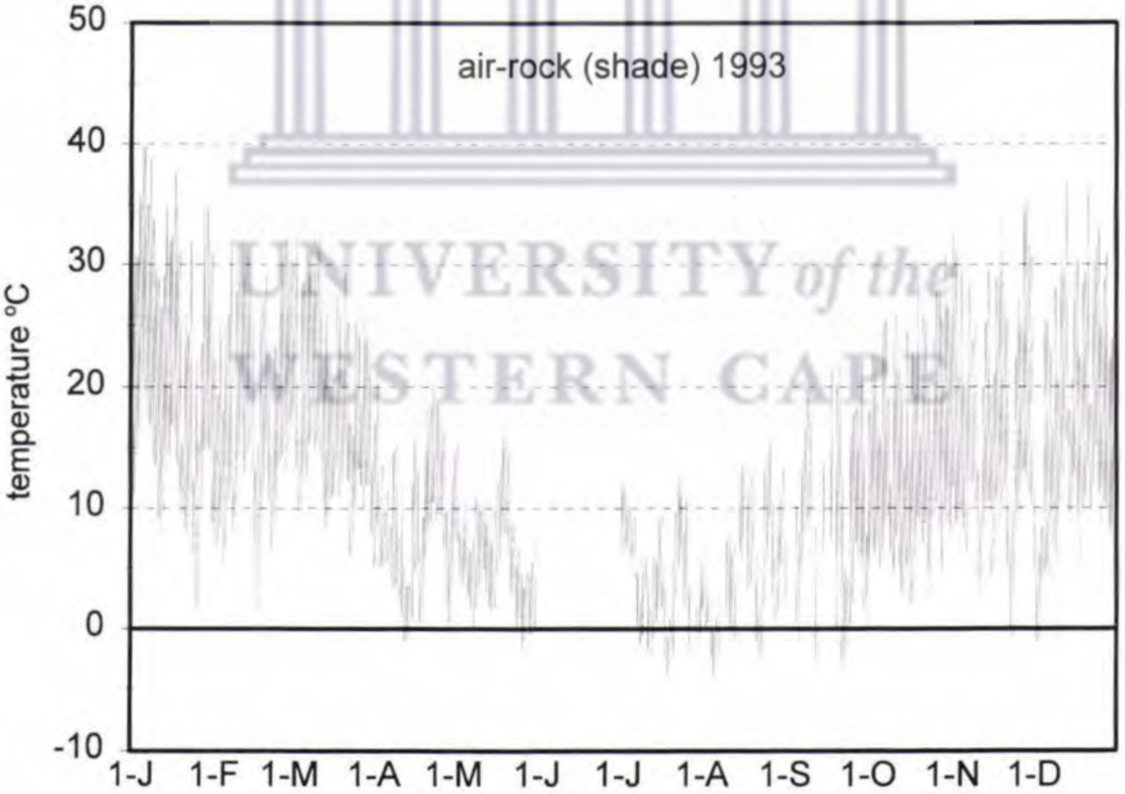


Figure 7.1. Daily temperatures at a shaded sandstone surface (Waaihoek Peak, 1992-1994).

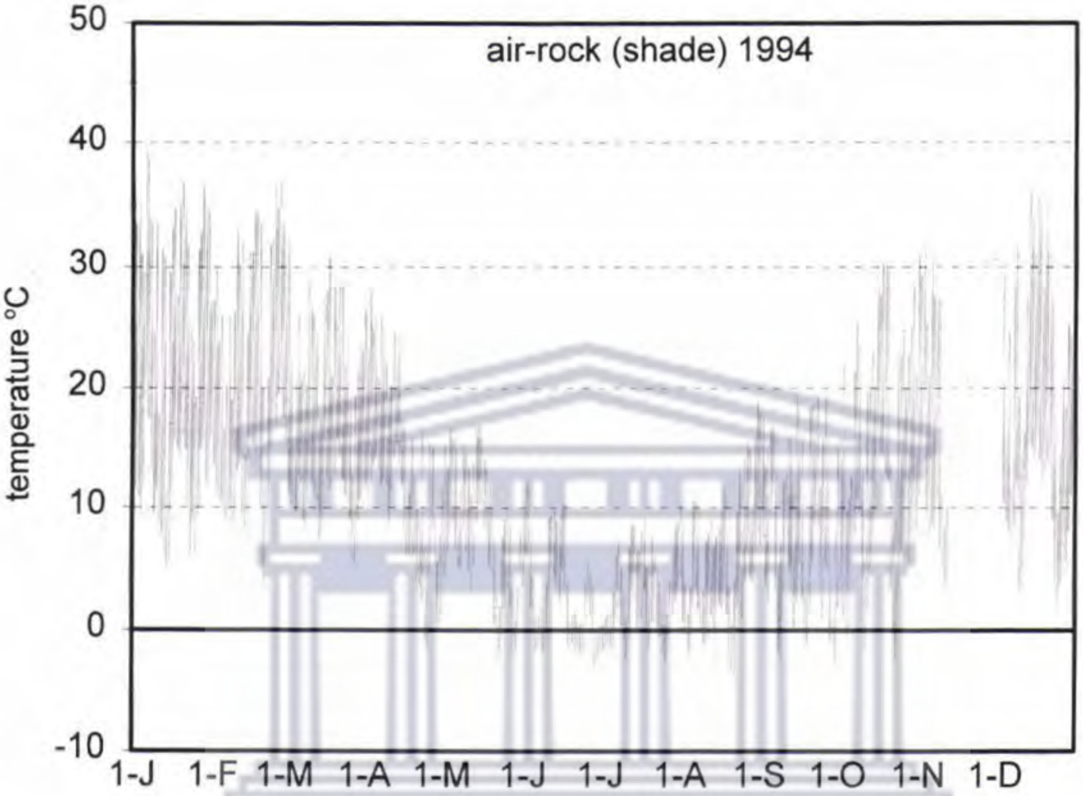


Figure 7.1. Daily temperatures at a shaded sandstone surface
(Waaihoek Peak, 1992-1994) (continued).

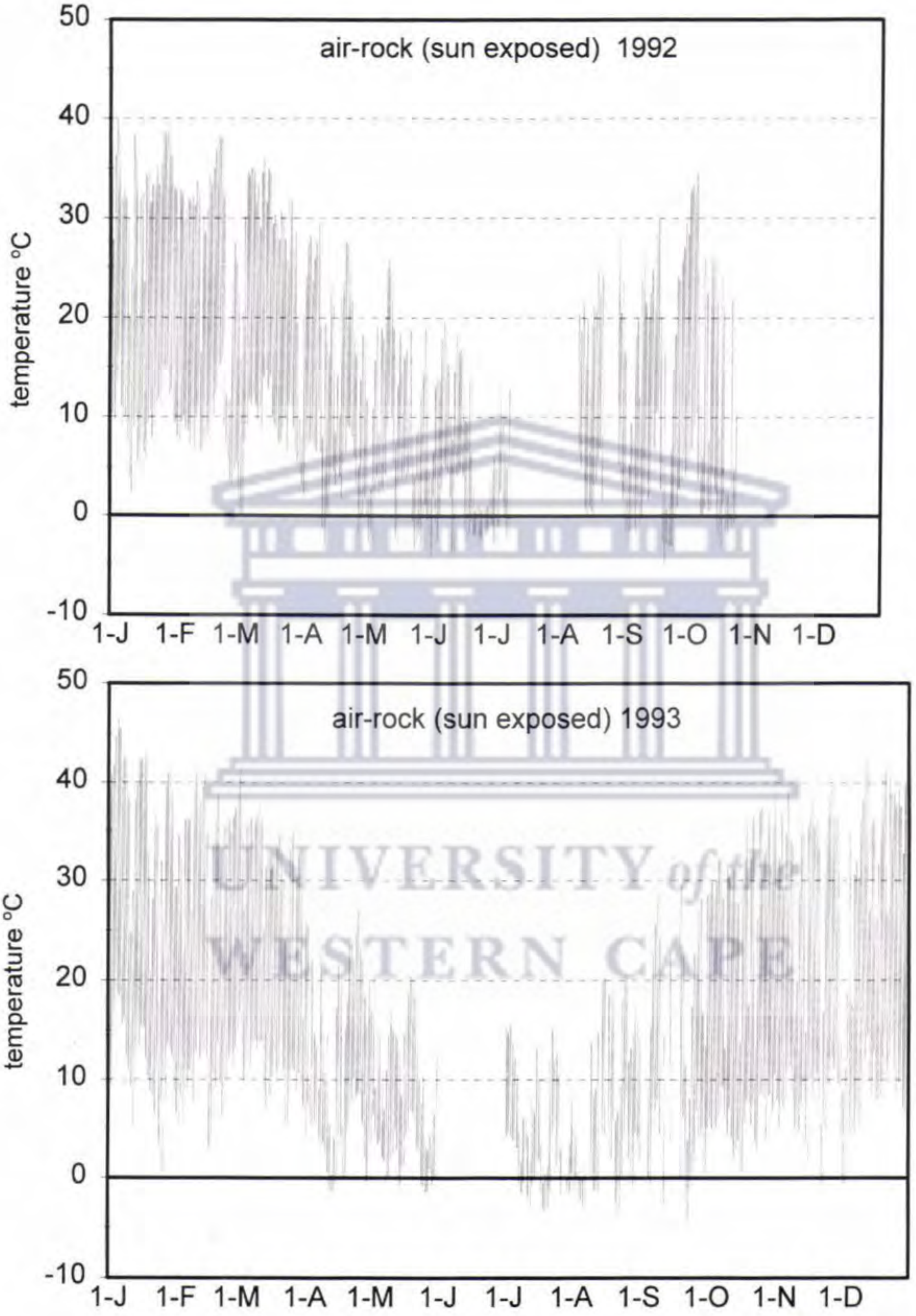


Figure 7.2. Daily temperatures at a sun-exposed sandstone surface (Waaihoek Peak, 1992-1994).

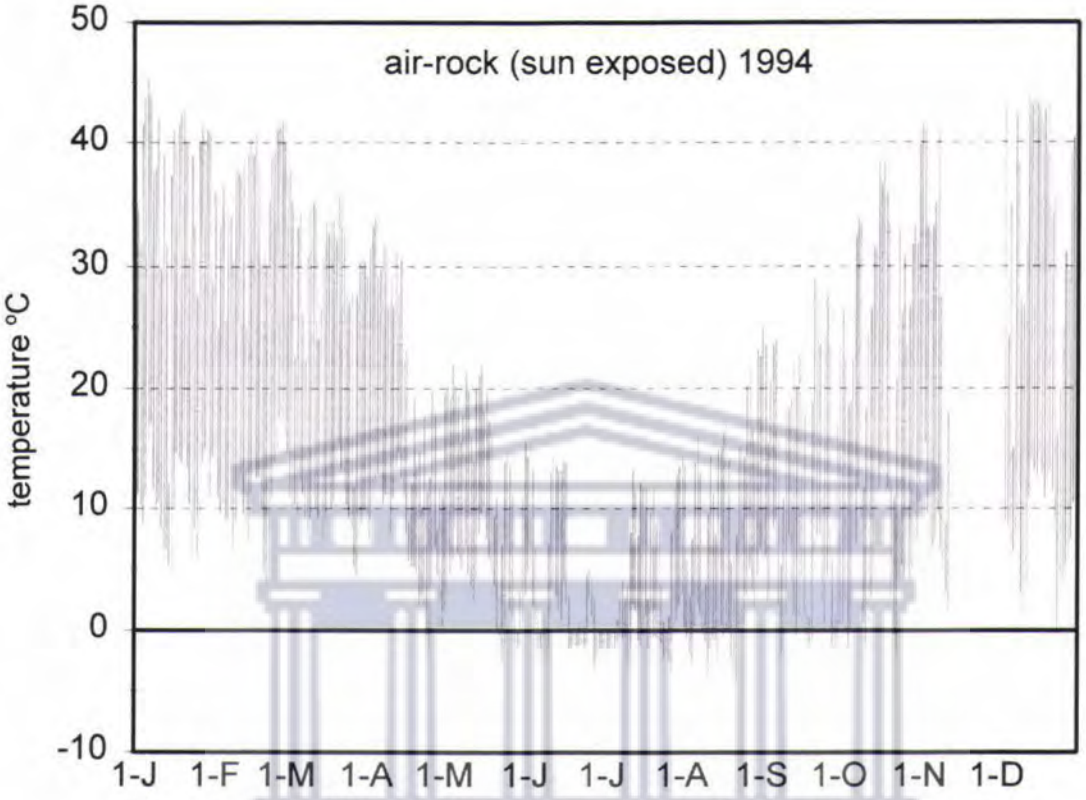


Figure 7.2. Daily temperatures at a sun-exposed sandstone surface (Waaihoek Peak, 1992-1994) (continued).

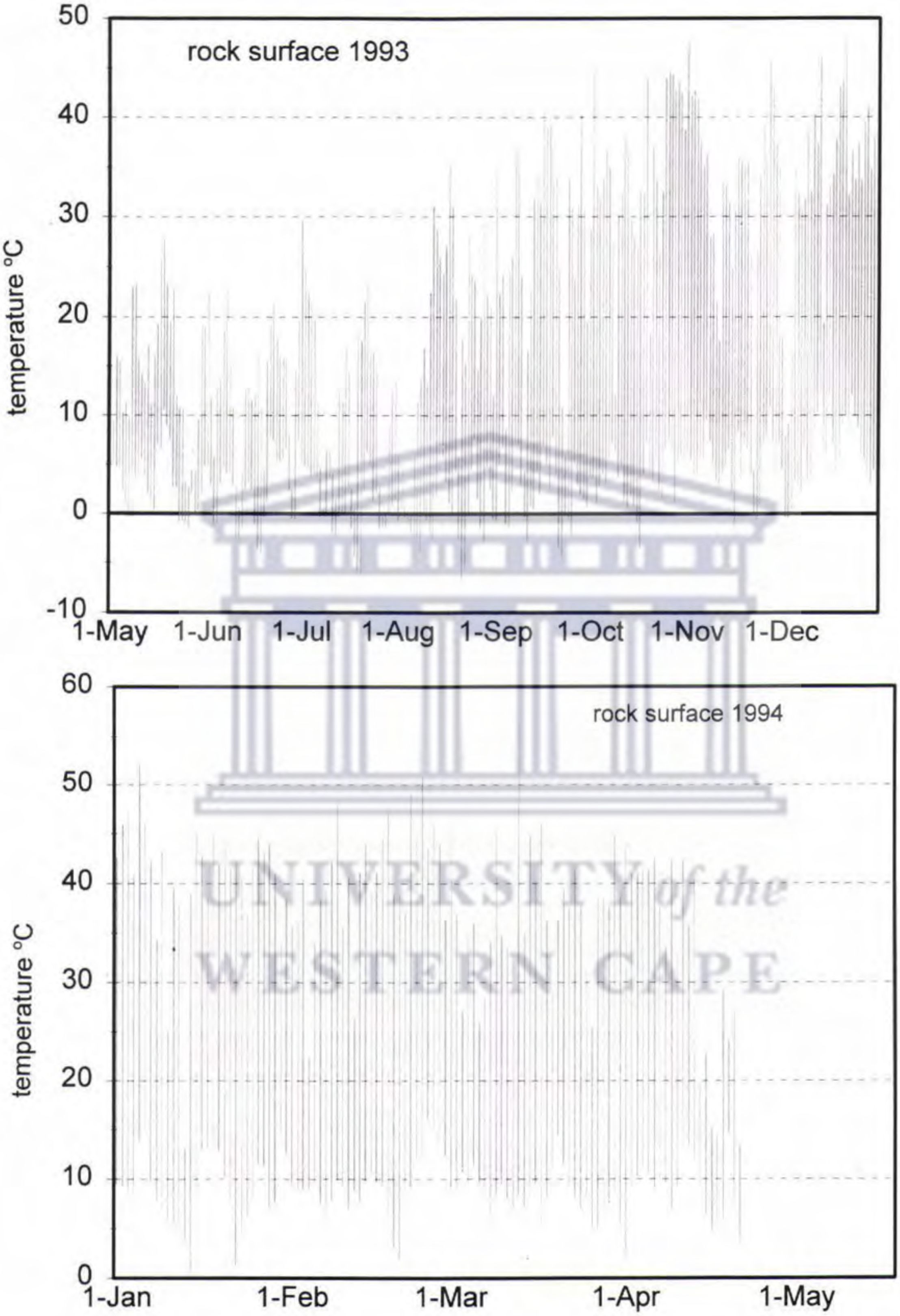


Figure 7.3. Daily temperatures at a sun-exposed shale surface
(Mount Superior, 1993-1994).

	Quartzite						Shale		
	E-facing			W-facing					
Year	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
1992									
< -8	0	0	0	0	0	0		no data	
-8 - -6	0	0	0	0	0	0			
-6 - -4	0	0	3	0	0	3			
-4 - -2	1	0	32	0	0	29			
-2 - 0	24	1	42	15	0	38			
total	25	1	77	15	0	70			
1993							(May-Dec)		
< -8	0	0	0	0	0	0	0	0	0
-8 - -6	0	0	0	0	0	0	0	0	2
-6 - -4	0	0	3	0	0	2	0	0	5
-4 - -2	2	0	12	0	0	11	1	0	16
-2 - 0	9	3	24	16	2	45	11	1	45
total	11	3	39	16	2	58	12	1	68
1994							(Jan-Apr)		
< -8	0	0	0	0	0	0	0	0	0
-8 - -6	0	0	0	0	0	0	0	0	0
-6 - -4	0	0	0	0	0	3	0	0	0
-4 - -2	0	0	21	0	0	22	0	0	0
-2 - 0	26	2	46	35	1	59	0	0	0
total	26	2	60	32	1	75			

Table 7.1. Annual frost frequency and intensity totals for sandstone and shale.

Quartzitic sandstone, E-facing (shaded)

1992	<0 - -2	<-2 - -4	<-4 - -6	<-6	1993	<0 - -2	<-2 - -4	<-4 - -6	<-6	1994	<0 - -2	<-2 - -4	<-4 - -6	<-6
J - F	0	0	0	0	J -F	0	0	0	0	J - F	0	0	0	0
M	0	0	0	0	M	0	0	0	0	M	0	0	0	0
A	3	0	0	0	A	3	0	0	0	A	2	0	0	0
M	6	3	0	0	M	5	0	0	0	M	3	3	0	0
J	9	8	0	0	J		no data			J	13	4	0	0
J	9	9	0	0	J	6	6	0	0	J	14	5	0	0
A	4	6	2	0	A	4	4	2	0	A	6	6	0	0
S	5	4	1	0	S	3	2	1	0	S	5	2	0	0
O	6	2	0	0	O	0	0	0	0	O	3	1	0	0
N		no data			N	1	0	0	0	N	0	0	0	0
D		no data			D	2	0	0	0	D	0	0	0	0
1992 total	42	32	3	0	1993 total	24	12	3	0	1994 total	46	21	0	0

Quartzitic sandstone, W-facing (sun-exposed)

1992	<0 - -2	<-2 - -4	<-4 - -6	<-6	1993	<0 - -2	<-2 - -4	<-4 - -6	<-6	1994	<0 - -2	<-2 - -4	<-4 - -6	<-6
J - F	0	0	0	0	J -F	0	0	0	0	J - F	0	0	0	0
M	1	0	0	0	M	0	0	0	0	M	0	0	0	0
A	4	1	0	0	A	7	0	0	0	A	2	1	0	0
M	6	7	0	0	M	9	0	0	0	M	4	3	0	0
J	9	9	2	0	J		no data			J	12	5	0	0
J	3	3	0	0	J	11	4	0	0	J	20	6	0	0
A	0	0	0	0	A	9	5	1	0	A	10	3	3	0
S	8	5	1	0	S	5	2	1	0	S	6	3	0	0
O	7	4	0	0	O	0	0	0	0	O	4	1	0	0
N		no data			N	2	0	0	0	N	0	0	0	0
D		no data			D	2	0	0	0	D	1	0	0	0
1992 total	38	29	3	0	1993 total	45	11	2	0	1994 total	59	22	3	0

Shale, sun-exposed

1993	<0 - -2	<-2 - -4	<-4 - -6	<-6	1994	<0 - -2	<-2 - -4	<-4 - -6	<-6
J-A		no data			J	0	0	0	0
M	7	0	0	0	F	0	0	0	0
J	7	3	1	0	M	0	0	0	0
J	11	2	2	1	A	0	0	0	0
A	10	7	1	1	M-D		no data		
S	6	3	1	0					
N	2	1	0	0					
D	2	0	0	0					
1993 total	45	16	5	2	1994 total	0	0	0	0

Table 7.2. Monthly frost frequency and intensity totals of daily minimum temperatures for sandstone and shale.

SANDSTONE 1992

1992	TEMP.	ROCK SHADE			ROCK SUN		
MONTH	RANGE	AVE	MAX	MIN	AVE	MAX	MIN
JAN	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	0	0	0	0
	-2	0	0	0	0	0	0
	0	0	0	0	0	0	0
	2	0	0	0	0	0	0
	4	0	0	1	0	0	2
	5	0	0	0	0	0	1
	>5	31	31	30	31	31	28
FEB	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	0	0	0	0
	-2	0	0	0	0	0	0
	0	0	0	0	0	0	0
	2	0	0	0	0	0	0
	4	0	0	1	0	0	2
	5	0	0	1	0	0	1
	>5	29	29	27	29	29	26
MAR	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	0	0	0	0
	-2	0	0	0	0	0	0
	0	0	0	0	0	0	1
	2	0	0	2	0	0	2
	4	0	0	1	0	0	0
	5	1	0	1	0	0	1
	>5	30	31	27	31	31	27
APR	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	0	0	0	0
	0	0	0	0	0	0	1
	-2	0	0	3	0	0	4
	2	1	0	4	1	0	3
	4	2	0	4	2	0	7
	5	2	0	4	1	0	3
	>5	25	30	15	26	30	12
MAY	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	0	0	0	0
	-2	0	0	3	0	0	7
	0	1	0	6	2	0	6
	2	6	0	6	4	0	4
	4	2	3	6	3	3	7
	5	1	2	4	3	0	3
	>5	21	26	6	19	28	4
JUN	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	8	0	0	2
	0	0	0	9	0	0	9
	-2	7	0	5	8	0	9
	2	6	6	1	5	7	2
	4	4	7	2	3	3	1
	5	4	0	5	4	1	6
	>5	9	17	0	10	19	1

1992	TEMP.	ROCK SHADE			ROCK SUN		
MONTH	RANGE	AVE	MAX	MIN	AVE	MAX	MIN
JUL	-8	0	0	0	no data		
	-6	0	0	0			
	-4	0	0	0			
	-2	0	0	8			
	0	5	0	8			
	2	7	3	7			
	4	8	5	6			
	5	5	3	0			
	>5	6	20	0			
AUG	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	2	0	0	0
	0	1	0	6	0	0	0
	-2	9	1	4	0	0	0
	2	2	8	10	0	0	6
	4	3	3	5	0	0	2
	5	6	1	2	1	0	1
	>5	10	18	2	13	14	5
SEP	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	1	0	0	0
	-2	0	0	4	0	0	1
	0	2	0	5	2	0	5
	2	5	2	7	4	2	8
	4	4	2	6	5	0	7
	5	2	1	1	1	0	4
	>5	17	25	6	18	28	5
OCT	-8	0	0	0	0	0	0
	-6	0	0	0	0	0	0
	-4	0	0	1	0	0	0
	0	0	0	2	0	0	4
	-2	0	0	6	1	0	7
	2	5	0	7	3	1	5
	4	3	2	3	3	1	2
	5	3	4	1	1	2	3
	>5	16	21	6	19	23	6
NOV - DEC		no data			no data		

Table 7.3. Monthly rock frost frequency and intensity totals for sandstone (Waaihoek Peak, 1992-1994).

SANDSTONE 1993

1993		shaded rock			sun-exposed rock		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN
JAN	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	2	0	0	2
	2 - 4	0	0	1	0	0	1
	4 - 5	0	0	0	0	0	0
	>5	31	31	28	31	31	28
FEB	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	1	0	0	1
	2 - 4	0	0	1	0	0	1
	4 - 5	0	0	0	0	0	0
	>5	28	28	26	28	28	26
MAR	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0
	2 - 4	0	0	0	0	0	0
	4 - 5	0	0	0	0	0	0
	>5	31	31	31	31	31	31
APR	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	3	1	0	7
	0 - 2	2	0	6	2	1	2
	2 - 4	2	2	4	1	1	6
	4 - 5	3	0	2	2	0	3
	>5	23	28	15	24	28	12
MAY	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	5	0	0	9
	0 - 2	3	0	9	3	0	6
	2 - 4	7	1	7	7	3	8
	4 - 5	1	3	4	2	1	4
	>5	20	27	6	19	27	4
JUN		no data					

1993		shaded rock			sun-exposed rock		
MONTH	TEMP.	AVE	MAX	MIN	AVE	MAX	MIN
JUL	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	1	0	6	0	0	4
	-2 - 0	4	2	6	8	1	11
	0 - 2	3	4	6	3	7	4
	2 - 4	6	3	2	4	3	4
	4 - 5	1	2	1	1	2	5
	>5	13	19	7	12	17	0
AUG	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	2	0	0	1
	-4 - -2	1	0	4	0	0	5
	-2 - 0	4	1	4	5	1	9
	0 - 2	1	3	7	4	4	4
	2 - 4	7	4	3	5	0	2
	4 - 5	1	1	0	2	1	4
	>5	13	22	7	11	25	2
SEP	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	1	0	0	1
	-4 - -2	0	0	2	0	0	2
	-2 - 0	1	0	3	2	0	5
	0 - 2	3	0	4	2	0	4
	2 - 4	1	0	3	2	1	2
	4 - 5	4	2	2	1	0	3
	>5	16	29	7	19	30	4
OCT	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	1	0	0	2
	2 - 4	0	0	4	0	0	6
	4 - 5	0	0	3	0	0	4
	>5	31	31	23	31	31	19
NOV	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	1	0	0	2
	0 - 2	0	0	1	1	0	1
	2 - 4	1	0	2	0	0	3
	4 - 5	0	0	4	0	0	2
	>5	29	30	22	29	30	22
DEC	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	2	0	0	2
	0 - 2	0	0	1	0	0	1
	2 - 4	2	0	1	2	0	1
	4 - 5	0	0	2	0	0	3
	>5	29	31	25	29	31	24

Table 7.3. Monthly rock frost frequency and intensity totals for sandstone (Waaihoek Peak, 1992-1994)(continued).

SANDSTONE 1994

1994	TEMP.	SHADED ROCK			SUN-EXPOSED ROCK		
MONTH	RANGE	AVG	MAX	MIN	AVG	MAX	MIN
JAN	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0
	2 - 4	0	0	0	0	0	0
	4 - 5	0	0	1	0	0	1
	>5	31	31	30	31	31	30
FEB	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0
	2 - 4	0	0	1	0	0	1
	4 - 5	0	0	1	0	0	1
	>5	28	28	26	28	28	26
MAR	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	0	0	0	0
	2 - 4	0	0	0	0	0	0
	4 - 5	0	0	0	0	0	1
	>5	31	31	31	31	31	30
APR	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	1
	-2 - 0	0	0	2	0	0	2
	0 - 2	0	0	2	0	0	1
	2 - 4	4	0	3	3	0	4
	4 - 5	0	0	1	1	0	2
	>5	26	30	22	26	30	20
MAY	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	3	0	0	3
	-2 - 0	4	0	3	4	0	4
	0 - 2	1	1	5	1	1	5
	2 - 4	1	4	2	1	3	4
	4 - 5	3	0	4	4	0	6
	>5	22	26	14	21	27	9
JUN	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	4	0	0	5
	-2 - 0	11	2	13	13	1	12
	0 - 2	5	9	2	3	11	5
	2 - 4	2	5	6	2	2	6
	4 - 5	1	2	2	2	2	1
	>5	11	12	3	10	14	1

1994		SHADED ROCK			SUN-EXPOSED ROCK		
MONTH	TEMP.	AVG	MAX	MIN	AVG	MAX	MIN
JUL	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	5	0	0	6
	-2 - 0	8	0	14	11	0	20
	0 - 2	5	9	7	9	10	3
	2 - 4	10	2	5	6	5	2
	4 - 5	3	2	0	3	1	0
	>5	5	18	0	2	15	0
AUG	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	3
	-4 - -2	0	0	6	0	0	3
	-2 - 0	2	0	6	2	0	10
	0 - 2	7	2	9	7	0	8
	2 - 4	4	5	5	4	3	4
	4 - 5	4	1	2	5	0	1
	>5	14	23	3	13	28	2
SEP	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	2	0	0	3
	-2 - 0	1	0	5	3	0	6
	0 - 2	3	1	4	1	2	6
	2 - 4	3	2	7	3	1	4
	4 - 5	1	0	2	0	0	4
	>5	22	27	10	23	27	7
OCT	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	1	0	0	1
	-2 - 0	0	0	3	0	0	4
	0 - 2	0	0	6	0	0	4
	2 - 4	3	0	4	0	0	7
	4 - 5	1	0	1	3	0	2
	>5	27	31	16	28	31	13
NOV	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	0
	0 - 2	0	0	1	0	0	1
	2 - 4	0	0	1	0	0	1
	4 - 5	0	0	0	0	0	1
	>5	12	12	10	12	12	9
DEC	< -8	0	0	0	0	0	0
	-8 - -6	0	0	0	0	0	0
	-6 - -4	0	0	0	0	0	0
	-4 - -2	0	0	0	0	0	0
	-2 - 0	0	0	0	0	0	1
	0 - 2	0	0	2	0	0	2
	2 - 4	0	0	3	0	0	3
	4 - 5	0	0	2	0	0	1
	>5	28	28	21	28	28	21

Table 7.3. Monthly rock frost frequency and intensity totals for sandstone (Waaihoek Peak, 1992-1994)(continued).

SHALE 1993

1993	TEMP.	ROCK		
MONTH	RANGE	AVG	MAX	MIN
JAN - APR		no data		
MAY	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	0
	-2 - 0	0	0	7
	0 - 2	3	0	7
	2 - 4	5	2	6
	4 - 5	3	2	3
	>5	20	27	8
JUN	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	1
	-4 - -2	0	0	3
	-2 - 0	1	0	7
	0 - 2	5	1	1
	2 - 4	3	2	7
	4 - 5	0	2	4
	>5	21	25	7
JUL	< -8	0	0	0
	-8 - -6	0	0	1
	-6 - -4	0	0	2
	-4 - -2	1	0	2
	-2 - 0	6	0	11
	0 - 2	3	5	3
	2 - 4	3	2	7
	4 - 5	3	2	2
	>5	15	22	3
AUG	< -8	0	0	0
	-8 - -6	0	0	1
	-6 - -4	0	0	1
	-4 - -2	0	0	7
	-2 - 0	4	1	10
	0 - 2	3	2	4
	2 - 4	6	0	2
	4 - 5	1	1	4
	>5	17	27	2
SEP	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	1
	-4 - -2	0	0	3
	-2 - 0	0	0	6
	0 - 2	2	0	6
	2 - 4	2	0	5
	4 - 5	0	1	2
	>5	26	29	7
OCT	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	1
	-2 - 0	0	0	1
	0 - 2	0	0	7
	2 - 4	0	0	8
	4 - 5	0	0	4
	>5	31	31	10
NOV	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	1
	-2 - 0	0	0	2
	0 - 2	1	0	1
	2 - 4	0	0	7
	4 - 5	0	1	2
	>5	29	29	17
DEC	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	0
	-2 - 0	0	0	2
	0 - 2	0	0	1
	2 - 4	2	0	6
	4 - 5	0	0	4
	>5	29	31	18

SHALE 1994

1994	TEMP.	ROCK		
MONTH	RANGE	AVG	MAX	MIN
JAN	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	0
	-2 - 0	0	0	0
	0 - 2	0	0	2
	2 - 4	0	0	1
	4 - 5	0	0	2
	>5	31	31	26
FEB	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	0
	-2 - 0	0	0	0
	0 - 2	0	0	1
	2 - 4	0	0	1
	4 - 5	0	0	0
	>5	28	28	26
MAR	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	0
	-2 - 0	0	0	0
	0 - 2	0	0	0
	2 - 4	0	0	0
	4 - 5	0	0	1
	>5	31	31	30
APR	< -8	0	0	0
	-8 - -6	0	0	0
	-6 - -4	0	0	0
	-4 - -2	0	0	0
	-2 - 0	0	0	0
	0 - 2	0	0	0
	2 - 4	0	0	2
	4 - 5	0	0	1
	>5	21	21	18
MAY - DEC		no data		

Table 7.4. Monthly rock frost frequency and intensity totals for a shale surface (Mount Superior, 1993-1994).