Antarctic Science 9 (2): 181–187 (1997)

Observations on “cryoplanation” benches in Antarctica

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Abstract: A series of benches on nunataks of Alexander Island (Antarctica) are described. An increase in bench size with distance away from the retreating glacier suggests an age spectrum. The benches have thermal contraction cracks (in bedrock) on shallower, upper sections of the risers as well as salt encrusted runnels on the steeper lower section of the tread. The benches also show a distinct orientational preference (orientated to the north through to west) and, from first principles, these seem to be the aspects with optimal freeze-thaw cycles and temperatures conducive to thermal stress fatigue. The extensive dilatation associated with the retreating glaciers is thought to play a significant role in the origin and development of the benches as the combination of extensive jointing and optimal process conditions are thought to constrain where benches begin. The jointing, aided by the thermal contraction cracking, then facilitates extension and continued weathering of the treads. It would appear that these benches are examples of so called “cryoplanation terraces” that have been reported as fossil forms in Europe and North America. The study of such active forms in the Antarctic may provide good analogues for fossil features found in the Northern Hemisphere.

Received 27 June 1996, accepted 6 January 1997

Key words: Antarctica, cryoplanation, dilatation, mountain benches, patterned ground, permafrost, weathering

Introduction

Although there is a substantial body of literature on cryoplanation (e.g. Demek 1969a & b, 1972, 1980, Boch & Krasnov 1951, Dylik 1957, Pinczés 1968, Reger & Péwé 1976, Evans 1994, Czudek 1995) the actual formative processes involved and the distribution of these features is still far from clear. At present the literature indicates that cryoplanation features comprise gently sloping erosion surfaces (treads) with steeper, weathered slopes (the risers) at their upper edges. They may frequently occur in sequences, one above another, but rarely circle an entire mountain. They seem to be associated with mechanical weathering (freeze-thaw usually being cited) on the risers but with mass movement on the treads; the whole is usually perceived as related to nivation. Geographically, they are frequently located in zones of continuous permafrost, but altitudinally are in zones with adequate snow to provide summer moisture, plus a substantial number of freeze-thaw cycles (athough this last point seems in many cases to be based on air temperature data). Based largely on climatic inferences, Nelson (1989) suggests that the cryoplanation terrace is the periglacial analogue of the glacial cirque. A number of recent studies (Thorn 1988, Thorn & Hall 1980, Hall 1980, 1985, Nyberg 1986, 1991) have, however, questioned the general concept of nivation as well as the ubiquitous acceptance of freeze-thaw in cold regions (Thorn 1992, Hall 1995).

The concept of cryoplanation (or any of its synonyms) is fraught with problems of terminology, process and, even its very existence as a separate entity (i.e. as distinct from nivation). There are few climatic data available to understand the process, and since the majority of studies from the Northern Hemisphere are, in the development of broad conceptual models and analogues, there has been no inclusion of the Antarctic. Indeed, the three most recent general discussions regarding the spatial distribution of these features, and their formative processes (Priesnitz 1988, Nelson 1989, Czudek 1995), do not cite any examples from Antarctica.

There is thus a need to include the Antarctic and other Southern Hemisphere information in the development of any general models. Interestingly, despite the variety of climatic and permafrost zones in Antarctica, there are very few direct references to cryoplanation. Strelin & Malagnino (1992) refer to the presence of cryoplanation terraces on James Ross Island, a dry (*c.* 137 mm annual precipitation), cold (mean annual temperature -13.5°C) island to the east of the Antarctic Peninsula, in an area of continuous permafrost. Transverse and longitudinal nivation hollows are also cited as occurring in this area – forms that are considered associated with cryoplanation. Corté (1983) also refers to cryoplanation terraces along the east coast of the Antarctic Peninsula. Sekyra (1969), working in the dry ‘oases’ of East Antarctica, also refers to “cryoplanation relief”. Although no detail is given, Sekyra (1969, p. 286) states that with respect to remodelling of the relief the greatest influence is glacifluvial action and “cryoplanation processes (origin of frost-riven cliffs, cryoplanation terraces, steep slopes, bounding-valley depressions, etc.)” – features that sound to be related more to ‘nivation’ than cryoplanation *per se*. Although Bockheim (1995), in a recent review of Antarctic permafrost and associated features, refers to the absence of terraces in the

Antarctic interior, Jordan & Van der Wateren (1993) do identify cryoplanation terraces in the ice-free region of Litell Rocks, in north Victoria Land; a cold, dry continuous permafrost region. Markov & Bodina (1961), in their map of periglacial formations in Antarctica, do not directly describe cryoplanation but they do show "nival terraces" – noted specifically at Cape Burn in Victoria Land, a region of very low mean annual temperatures and continuous permafrost. Myagkov (1979, p. 12) states that in the oases areas of McMurdo Sound, the "final stage of mountain planation is (the) 'deserption pediment' inclined by 30°"; a form which may be related to cryoplanation. Aniya & Hayashi (1989) refer to the "step-like topography" on exposed bedrock 272 m above sea level in East Antarctica and state that (p. 143) "At present, it appears that periglacial processes such as freeze-thaw, gelifluction and nivation are strongly working in this area". In much the same way, Simonov (1977), working in the maritime Antarctic environment of the South Shetland Islands, refers to (p. 227) "The flat-topped hills and stepped ledges... (that) ...owe their origin to nivation, which is extremely intense... (such that) ...nivation and frost weathering are among the present-day relief-forming processes". Other workers refer to neither cryoplanation nor nivation but do cite "terrace-like projections" (Korotkevich *et al.* 1973), "flat surfaces and step-like topography" (Aniya 1988), mountain "flank erosion surfaces" (Stephenson 1966), "block terraces" (Nichols 1960), "stepped slopes" (Miotke 1984) and, in the area of the present study, "stepped topography" (Taylor *et al.* 1979). In the Falkland Islands, Clark (1972) refers to altiplanation benches that are mantled with rubble derived from 'frost-riven crags'. This paper describes in detail benches discovered on nunatacks at the southern end of the Antarctic Peninsula.

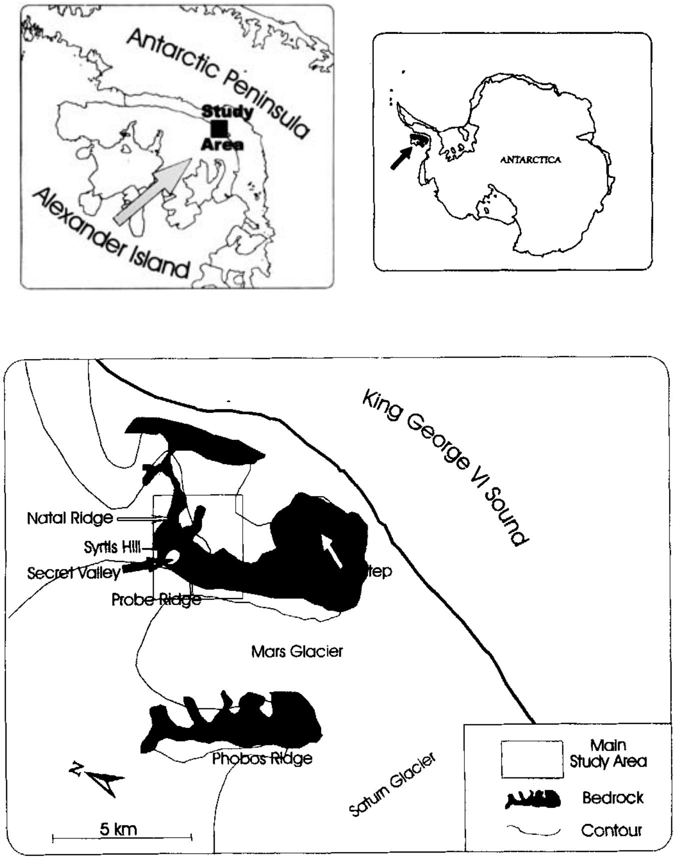

Fig. 1. Maps to show location of study area.

Study area

The study was undertaken (Fig. 1) on nunataks along the northeastern side of the Mars Glacier at the southern end of Alexander Island (71°50'S, 68°21'W). This area has a number of ice-free valleys and ridges, the term 'oases' being coined for such locations on Alexander Island (Stephenson 1938), which experience a cold, dry, continental type climate. Although there are no climatic stations near enough to the study area to be representative, data from loggers located in Viking Valley (Fig. 1) only 200–300 m below the surrounding peak tops have provided some information (Table I). Air temperatures have a summer mean of -2.4°C and winter mean of -11.5°C, with a winter minimum value of -35.2°C and a summer high of +6.0°C. Rock temperatures, however, show a very different picture (Table I), with a mean summer value of +5.9°C (low of -4.4°C, high of +24.4°C) but winter mean, minimum and high only slightly warmer than those of the air. Details of rock temperatures are given in Hall (in press). It is a region of continuous permafrost, with 0°C temperature and frozen ground being encountered at *c.* 0.27 m depth on 13 December 1992 on Syrtis Hill (Fig. 1). The active layer is thought to be in the order of 0.3–0.4 m thickness at the most open, snow-free locations and substantially thinner nearer to longer lasting snow (0°C at 0.15 m depth 1m from snow and 0°C at 10 mm depth at snow margin on same date).

Geologically the area consists of sandstones, conglomerates and argillaceous sedimentary rocks (Taylor *et al.* 1979). Much of the rock comprises arkose sandstone with sub-spherical, post-compaction concretions (Moncrieff 1989), sometimes leading to the name "cannonball sandstone" (Horne 1965). These siliceous nodules, held by a ferruginous

Table I. Temperature data (°C) from Viking Valley for the period 8 December 1992–7 August 1993.

	Summer mean	Summer maximum	Summer minimum	Winter mean	Winter minimum	Winter maximum
air temperature	-2.4	+6.0	-6.1	-11.5	-35.2	+1.9
rock temperature	+5.9	+24.4	-4.4	-11.4	-33.3	+2.6

cement whose age is considered to be post lithification (Thomson 1964), readily weather free. Mudstones, sometimes with lime carbonate nodules, shaley mudstones, and both light-coloured and dark-coloured orthoquartzitic sandstones are also found. These sedimentary rocks are horizontally, or near-horizontally, bedded. Faulting determines the linearity of the coast and the east-west orientation of the glaciers that cut the coast (Taylor *et al.* 1979). All the nunataks were covered by ice during the last glacial maximum, with an ice mass centred on Alexander Island (Sugden & Clapperton 1978). The small glacier that runs from the col between Syrtis Hill and Probe Ridge down in to Viking Valley (Fig. 1) is currently receeding as indicated by the end moraines found in the valley.

Observations

The benches were observed on and between Syrtis Hill and Probe Ridge, along Natal Ridge to the northeast and between Probe Ridge and Two Step (Fig. 1). The benches had risers 0.8–2.0 m in height, comprising weathered bedrock, and treads 2–12 m wide sloping at an angle of 1–10°, composed primarily of weathered debris (Fig. 2). The treads extended laterally 6–200 m. The smaller benches (*c.* 0.8 m riser, tread 2–3 m long and 6 m in lateral extent) were somewhat arcuate in plan and found lower down on the col between Syrtis Hill and Probe Ridge. They were discrete entities but, in some instances, appeared to be close to joining together. From their lower location and their proximity to the retreating Viking Valley glacier it is surmized that they are younger than the larger forms found above them closer to, and around, the ridge tops. The larger forms sometimes showed a break in slope on the tread, with a shallower upper section at an angle of 1–4° and a steeper lower section at an angle of 5–10°. Noticeably, the upper section displayed well formed circular or polygonal patterned ground, (sometimes grading into garlands), whereas the lower part of the tread exhibited well developed drainage runnels. Although both patterns and runnels could be observed in the other sections of the tread they were not well developed there. The patterns were *c.* 1 m in diameter, or cross-tread dimension in the case of garlands, with coarse borders 0.1–0.15 m in width. The borders were not just sorted but also showed a central crack *c.* 0.1 m in width within which the majority of the coarse debris accumulated (see below). The runnels were spaced *c.* 0.3–1.0 m apart, were 0.03–0.15 m in width and 0.02–0.10 m in depth, and were normally marked by either efflorescences of gypsum on the clast surfaces and/or a concentration of coarse debris (due to the removal of the fines) giving the impression of sorted stripes. Snow was observed at the base of the riser on some benches during December but was usually not very deep (<0.40 m) nor laterally extensive. The benches could be seen to have developed along lithologic boundaries.

Fig.2. View along the tread of a typical bench; riser at the back of the bench is on the left-hand side of the photograph (the riser is *c.* 2 m high).

The cliffs of Viking Valley and along the ridge from Probe Ridge to Two Step showed very marked dilatation sheets as a result of the glacial retreat. Although composed of horizontally bedded sediments, the cliffs exhibited extensive vertical cracks parallel to the relieving surface. These vertical joints were not observed on the ridge tops away from the cliff edges, i.e. away from the location of the recently receded ice cover. Jointing was also more closely spaced at the outer cliff face with increasing distance between joints, until their total disappearance, several metres in to the cliff (as viewed on the crumbling cliff tops).

The benches showed a distinct orientational preference. The best developed benches and components of a bench were orientated to the north-northwest. Benches were less well developed or, on the longer benches, phased out towards the south and northeast. The lithologic boundaries could be perceived by a slight break of slope but benches were not developed on the easterly aspects. A bench or succession of benches could be followed around Probe Hill with well developed features facing west and north, the features would diminish in height and width to the south and immediately to the east of north, and not be found at all facing east (Fig. 3). The best developed patterned ground was found on the treads of those benches orientated to the west–northwest. These aspect constraints occurred despite occurrence of the same lithologies and exposure of the same boundaries around the peaks and on both sides of the ridges.

The patterned ground forms are dealt with in detail elsewhere but warrant some comment here as they are developed on the benches and may be related to their formation. The patterned ground appears to be a previously undescribed variety that comprises a 'sorted, non-sorted' form (Fig. 4). The initial feature is believed to be a non-sorted ice wedge since the features are developed in continuous permafrost, exhibit a crack and, significantly, are found in bedrock (Fig. 5). Two mechanisms, that may be complementary, can explain the subsequent sorting. First, the weathering products of mudstones and shales can be sorted once there are sufficient fines to allow the development of segregation ice. The presence of segregation ice is indicated by bedrock heave and

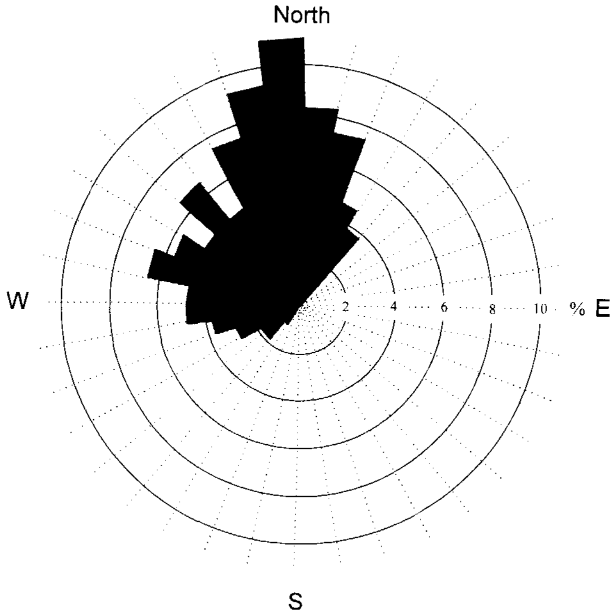

Fig. 3. Rose diagram to show the preferential orientation of benches.

by the occurrence of other sorted features close to the terraces. The second possible mechanism, is that of weathering of the bedrock along the crack junctions allowing coarse material to accumulate along the crack line. Observations certainly support this latter suggestion for, in several instances, with polygons of either raised or non-raised borders, including some in bedrock and not in weathered debris (Fig. 5), the borders are seen to have a distinct crack in which blocky material, of the same lithology as that in which the cracks have developed, has developed *in situ*. As there is no mechanism available for this debris to have been transported and then deposited in the crack, it must be associated with weathering of the rock around the crack. The whole is argued in detail elsewhere and it is only their presence that is significant, in the first instance, here.

Fig. 4. View of the 'sorted, non-sorted' patterns found on the upper part of the benches (features are *c.*1.6 m in diameter).

Fig. 5. To show the thermal contraction crack in bedrock.

Discussion

Snow, primarily as a source of moisture, is a major factor in either cryoplanation or nivation. In the study area, however, snowfall is extremely limited. In December, when much of the winter snow still remained on the ground, all but the base of the riser on the terraces were snow-free. Thus, unlike in the cryoplanation model suggested by Nelson (1989), elevation

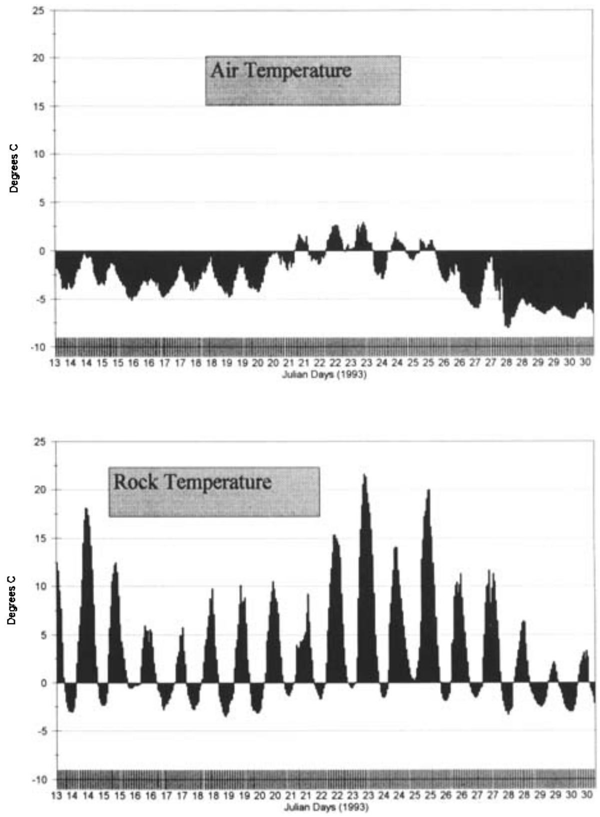

Fig. 6. Air and rock surface temperatures from Viking Valley.

constraints on snow accumulation are not applicable, either in terms of the availability of snow or snow as a protective element. The use of air temperature data in that model is considered misleading. Although the required "very small thawing indices" (Nelson 1989, p. 33) are found in the air temperature data, they do not reflect what happens to the rocks – where the actual weathering takes place. An example of the large difference between air and rock temperatures is shown in Fig. 6 where it can be seen that during the period the air experienced six freeze-thaw cycles (defined here simplistically, as three crossings of 0°C) the rock experienced 14; with diurnal events on all but one day. Rock temperatures clearly followed daily radiation patterns ($r^2 = +0.84$). The most significant difference between air and rock was, for the period shown, that air temperatures did not go above +3°C but the rock attained a surface temperature of +22°C; the recorded rock minimum was -4°C whilst that of the air was -8°C. A further example is that for the period 13 January–18 March (60 days encompassing "summer") the maximum air temperature was +5°C, the minimum -13°C with 16 freeze-thaw cycles whilst the rock surface had a high of +22°C, a minimum of -10°C and 49 freeze-thaw cycles (Hall in press).

Priesnitz (1988), in his review of literature on cryoplanation, notes orientation with respect to snow accumulation is often more important than orientation with respect to insolation. In the present study, the preferred orientation (Fig. 3) to the north-northwest indicates an orientation receiving a large amount of radiation. However, this orientation need not reflect snow accumulation as a result of wind directions or pre-existing topographic hollows. Rather, it could be that it is the sunward slopes that experience the greatest amount of geomorphic activity. On shaded slopes, even with a large body of snow, geomorphic activity will be low as there is no meltwater to drive it and only a very shallow active layer in which cryogenic processes can operate. On the sunward aspect there is the potential for weathering processes, mass movement, fluvial activity (small scale) and frost action in the ground. Therefore, it is argued that in high latitude situations protective shading could be detrimental to bench development and that it is the sunward slopes that experience the greatest geomorphic activity and thus exhibit benches; the whole being accentuated where the greatest snow accumulation, because of winds and the presence of topographic hollows, is also on the sunward slopes. In fact, measurements of taffoni size and occurrence, coupled with Schmidt hammer rebound values, show that the eastern aspect experiences the least weathering whilst the northern and western exposures have the greatest amount (Hall in press).

A variety of factors could be involved in the initiation and development of benches. In these horizontally bedded sediments it is the vertical dilatation joints that offer a ready means of exploitation commensurate with extension of the bench into the nunatak. It was most noticeable that the joints were being exploited insofar as blocks were seen to be loose and "toppling" along the weathered face of the riser (Fig. 7). The intersection of these joints with the horizontal bedding planes should provide ideal conditions for accentuated breakdown, but since dilatation effects had no orientational preference, other aspect-constrained processes must be involved in producing the observed orientation of the benches.

Whilst thermal contraction cracks cannot explain initiation, they may aid and accelerate growth. A number of authors have referred to the occurrence of both sorted and non-sorted patterned ground on benches (e.g. Demek 1969a) but have not linked it to bench development. Many of the benches at the higher elevations had well developed non-sorted patterned ground that frequently exhibited sorted margins (Fig. 4) and it was clear that these features were developed by the cracking of bedrock rather than in unconsolidated sediments as is usually the case with thermal contraction cracks (van Everdingen 1994). The vertical cracking of the bedrock by thermal stress further enhances the effects of the vertical dilatation joints by introducing an additional cracking component.

Weathering is suggested by all authors to play a major role in bench development and it is almost always freeze-thaw weathering that is perceived as the most active agent. With respect to freeze-thaw weathering, the requirements are (in broad terms) that there be water available in the rock and that it actually freeze. Although no rock moisture data are available, this is an arid region and ultrasonic data collected on the valley floor indicate dry rock conditions (except when wetted by glacier melt running down the valley). On the ridges there is certainly melt (rather than just sublimation) during the summer but the available snow is minimal. However, snow does accumulate at the break of slope between risers and treads of benches and it was here that noticeable undercutting of the bedrock risers takes place. The presence of water seems to be complemented by the necessary temperature requirements as there are certainly many diurnal freeze-thaw events at, and in the top few millimetres of, the rock surface. Thus, the potential for freeze-thaw weathering

Fig. 7. View across the tread of a bench showing the weathered bedrock on the riser.

does occur but would appear to be most effective, given moisture availability, on the western to northern aspects.

The availability of moisture from snow melt allows for weathering by wetting and drying; a slow process but one that exerts an effect in its own right and which also operates synergistically with freeze-thaw (Hall 1988,1993). Gypsum coatings were found on the rocks throughout the area and efflorescences of this mineral were also seen along the runnels on the lower sections of the benches. The occurrence of water also suggests that chemical weathering might occur as has been recently suggested (Balke *et al.* 1991) for Antarctica. However, no sign of chemical weathering (e.g. rinds) were seen in the rocks and so, partly because water supply was so limited and also because of it's low temperature (usually close to 0°C), chemical effects are considered minimal or non-existent.

Temperature ranges on the rocks were significant and here it was noticeable that the western and northern exposures experienced a far greater range than did the eastern – frequently in the order of 50% greater range and 65% higher temperatures (e.g. 19 degree range with maximum of 15.5°C on the eastern aspect and 28.5 degree range and maximum of 25.5°C on the northern and western aspects during 11–15 December 1992). The rate of change of temperature was far greater on the western and northern aspects and close to the 2°C per minute, proposed by Yatsu (1988) for thermal stress fatigue. Thus, with bedrock already fractured by dilatation joints and abetted by thermal contraction cracks, the potential for destruction by thermal stress fatigue must be considered a real possibility.

It is suggested that it may be thermal stress fatigue that first starts to exploit the pre-existing lines of weakness in the bedrock to initiate the benches; with the accumulation of snow this is enhanced by the addition of freeze-thaw, wetting and drying, and possibly salt weathering.

With the largest benches at the higher elevations and the smallest closer to the valley floor in proximity to the retreating Viking Glacier it is suggested that size is closely related to age. Temperature data and observations of such as the patterned ground and runnels in the weathered debris support the contention that these features are still actively growing.

In answer to the question of Priesnitz (1988), the weathering processes appear to work faster on the riser than on the surrounding surfaces. The key may well be that initiation is a combination of close, extensive jointing on the optimal aspect. Thus, contrary to the suggestion of Büdel (1982), it would seem that mountain benches (the result of "cryoplanation" in his terminology) are actively forming at the present time.

Conclusion

The origin of benches on mountain sides in periglacial regions appear to be far from clear and the absence of actual data regarding conditions on active benches has only served to confuse the issue. The forms here reported and referred to as "benches" do appear to fit to the general definitions of 'cryoplanation terraces' and the available evidence certainly indicates that these are active features. The limited data suggest that weathering processes are potentially more varied and effective on the northern to western aspects which could explain the preferred orientation of the benches. It is suggested that bench initiation could well be a function of preferential process occurrence coupled with extensive jointing as a result of dilatation. Once initiated, the banking of snow along the riser/tread junction enhances the weathering effects. The development of thermal contraction cracking on the tread together with on-going weathering and removal of debris by mass wasting and fluvial action (as evidenced by the runnels) both extends and maintains the bench form. Freeze-thaw weathering may certainly play a role but cannot be considered to be the dominant process without supporting evidence; thermal stress fatigue in cold regions with high radiation inputs may play a greater role. Clearly the evidence presented here does not answer the many questions regarding 'cryoplanation' but it does offer new information and indicates that such features are still forming. Finally, it would seem that the Antarctic might be an ideal place for further studies on these features, and hence a potential source of information that could be applied to the re-interpretation of fossil forms found in the Northern Hemisphere.

Acknowledgements

My most sincere thanks go to Dr David Drewry (Director) and Dr David Walton of the British Antarctic Survey for allowing me to participate in the Viking Valley project. Bill Block, David Wynn-Williams and Roger Worland provided much help in the field. Ian Meiklejohn was a source of many ideas and a valuable field companion. Funding for the research was kindly provided by the Foundation for Research and Development (South Africa) and this paper was presented at the 25th Arctic Workshop at Laval University, my attendance at which was kindly supported by the University of Northern British Columbia. Colin Thorn generously spent a great deal of time and effort in helping me rephrase and better conceptualize the whole problem for which I am extremely grateful; the errors and misunderstandings remain mine. I am also grateful for the very constructive comments by Professors Rapp and Karlén plus an anonymous referee.

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