On the origin of sheeting and laminae in granitic rocks: evidence from Antarctica, the Namib Desert and the Central Sahara

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CONTENTS

ABSTRACT

Studies of granitic rock outcrops have been carried out in the McMurdo Oasis, Antarctica, and in the Namib Desert to test hypotheses of formation of large scale sheeting structures and of laminae. Laminae were also investigated in the Central Sahara. Evidence from Antarctica strongly supports the contention that sheeting may be a secondary feature resulting from unloading: evidence from the Namib is more equivocal but offers some support for this hypothesis. Samples of laminae have been studied in thin section and by X-ray diffraction. The weathering processes in Antarctica and the Namib are physical, but in the Sahara chemical. Taffoni may form both with and without case hardening or desert varnish on the outside of rock outcrops, and by both physical and chemical weathering processes. The almost ubiquitous occurrence of laminae on granitic rocks suggests that their formation may be caused by inherent features in the rock, such as in-built stress, and that this factor should be investigated in detail.

1 INTRODUCTION

In spite of a large literature and much debate a number of the problems of the origin of major and minor landforms on granitic rocks have not yet been resolved. It may be contended that much of the difficulty lies in the assumption that similar landforms must be produced by one set of processes, and that it is therefore, possible to recognise forms and to deduce origins for them. By contrast it has been postulated that few landforms are the result of unique processes, and that many processes may be responsible for landforms which converge towards similar forms (e.g. White, 1945; Bertalanffy, 1950; Selby, 1977). If this last postulate is valid then it follows that the results of many processes must be similar and that each landform must be investigated in detail before any hypothesis of origin is adopted.

Two of the common features of granitic rock outcrops which have aroused much controversy are sheet structures and laminae. Both forms are very common on the granites of the Namib Desert and thin laminae are common on granites of the McMurdo Oasis, Antarctica: sheeting is not widespread in the McMurdo Oasis but its presence in certain places is believed to offer an opportunity to investigate one of the critical hypotheses which attempts to account for this phenomenon. Sheeting is very common on bornhardts of the central Sahara, but as there is strong evidence that these bornhardts have been exhumed from beneath an ancient deep weathering profile and their detailed history can no longer be deciphered (Vogt and Black, 1963; Birot *et al.*, 1955) they cannot be used to test hypotheses of the origin of sheeting.

1.1 Study areas

The McMurdo Oasis is a general term for the ice-free valleys of Victoria Land between 77°15'S and 77°45'S, and 160°E and 164°E. It consists of the Victoria Valley system, the Wright and Taylor Valleys which were cut by outlet glaciers from the continental ice sheet. The glaciers cut through the Transantarctic Mountains, but they have now retreated and left wide open troughs with valley walls cut in metamorphic and intruded acid plutonic rocks. The geology has been described by McKelvey and Webb (1962) and Allen and

Gibson (1962). The geomorphic development of the valley walls has been described by Selby (1971a). The few climatological data on the area have been summarised by Bull (1966). Winter temperatures fall as low as −62°C but in mid-summer screen temperatures may exceed +5°C for several days at a time. Precipitation is everywhere low but snowfall may exceed 10 cm a year in the eastern ends of the valleys and decline westwards. The relative humidity of the westerly winds ranges from 5% to 60% in midsummer with an average of around 45%. Near the coast the air from the east is more moist and relative humidities are commonly around 65% to 75%.

The climate, rocks and weathering phenomena of the central Namib Desert have been described by Goudie (1972), the climate by Schulze (1969), the soils by Scholz (1972) and the relationship between weathering phenomena and local climate by Besler (1972). Their descriptions will not be repeated here. The main Namib Plain is cut across the basement Damaran schist into which are intruded Salem granites (Clifford, 1967). To the east the plain is bounded by the Great Escarpment from which extend long spurs. The spurs are also predominantly of schist but granite intrusions outcrop in the core of many of them. In general granite outcrops near the coast have very low relief (1–4 m), in the central desert around Mirabib outcrops with the configuration of low bornhardts may rise 30 to 40 m above the plain, and near the escarpment some granite domes in spurs rise over 300 m above the plain.

In the area of the Mouydir Mountains and the Atakor, Hoggar Mountains central Sahara, there are many large granite bornhardts formed in a variety of coarse and fine-grained granitic rocks (Rognon, 1967). The weathering skins and taffoni formed on a group of bornhardts near Moulay Hassan, 24°40′N, 04°30′E, were investigated briefly during a traverse of the region.

2 SHEETING

2.1 Hypotheses

Many inselbergs and other exposures of massive rock in a variety of lithologies – granite, gneiss, quartzite, sandstone – are traversed by extensive curvilinear joints which transect closed joints and intruded dykes. These sheeting joints have a spacing, varying from about 0.3 m to 8 m, which becomes greater with depth from the surface; they are nearly parallel to each other and hence are approximately concentrically arranged (Dale, 1923; Twidale, 1971). Two schools of thought have arisen as a result of attempts to explain the frequent parallelism between sheet joints and the ground surface (Twidale, 1971, p. 63):

(1) that sheet structure developed as a secondary feature, parallel to the surface of the land, through the removal of overburden permitting stress release in the rock;

(2) that sheeting is a primary feature consequent upon internal structure in the rock so that the rock controls the surface relief.

The hypothesis of secondary origin through unloading was formally stated by Gilbert (1904) who argued that granitic rocks, whatever their origin, crystallise deep in the earth's crust under high pressure conditions. As erosion removes the superincumbent load hydrostatic pressures decrease and the relief of pressure is expressed in a series of fractures aligned tangentially to the direction of stress and hence approximately parallel to the ground surface. Gilbert's argument has been supported by many subsequent workers including Jahns (1943), Kieslinger (1958) and Bradley (1963). The mechanics of the unloading process have been examined by Johnson (1970) and by Brunner and Scheidegger (1973).

The unloading hypothesis is difficult to test in the field because the same evidence can be used to argue both for secondary unloading and for a primary origin. Sheeting joints occur in rocks like sandstones which are usually cut by bedding planes and orthogonal joint systems, as well as in granitic rocks which also have orthogonal joint systems – even if such joints are closed. It is thus reasonable to ask why, if these orthogonal joints existed, was the inherent stress not released along joints of the orthogonal system? It has been pointed out by Twidale (1971, p. 67) that on Dartmoor, England, the main topography of the edge of the moor is of Quaternary age yet the sheeting joints are of Cenozoic age. Thus the unloading hypothesis is not applicable. A further argument is that inselbergs, especially bornhardts, are commonly believed to survive because of their lack of jointing – which is an indication that they are in a state of compressive stress – yet some of the best developed sheeting structures to be seen anywhere occur on the bornhardts of the central Sahara. There thus seem to be strong arguments against unloading as a universal cause of sheeting.

An exceptional case to the last conclusion is the occurrence of sheeting in areas of Quaternary valley glaciation where it is presumably caused by loading of valley floors with ice and then rapid unloading after deglaciation; this last hypothesis is widely supported (Gilbert, 1904; Lewis, 1954; Harland, 1957; Soen, 1965).

A closely allied hypothesis is that of Soen (1965) who suggested that the granites of Sermersôq, south Greenland, are associated with a negative gravity anomaly and that because of a mass deficiency in the crust gravitational forces tend to raise the deficient rock masses above their surroundings so that initially a vertical compression is exerted on the higher levels of the granite and surrounding country rocks, but that once the mass deficiency is compensated uplift ceases and a relative decompression takes place favouring large-scale sheeting in the near-surface rocks.

The hypothesis that contractional or tensional strains are set up during the emplacement and cooling of a granite intrusion, and that this leads to primary sheeting structure, has been supported by a number of workers including Oxaal (1916) and Meunier (1961). Arguments and observations in favour of this hypothesis include the fact that compressive stresses at depth in mines frequently exceed the hydrostatic pressures which are exerted by the overburden. The most convincing argument, however, is that compressive stress offers in a single mechanism an explanation for the resistance and preservation of domed inselbergs and for the sheet structures characteristic of them (Twidale, 1971, p. 71). This hypothesis does not obviate the possibility that some sheeting may be caused by local unloading of ice, by facetting or by tectonic stresses.

If the compressive stress hypothesis is thus generally appliable then erosive processes will follow the line of joints and not the reverse.

2.2 Sheeting in Antarctica and the Namib

Sheet structures are not widely exposed in the McMurdo Oasis for the granite there is mostly well jointed. On the northern slopes of the Taylor Valley, however, above the

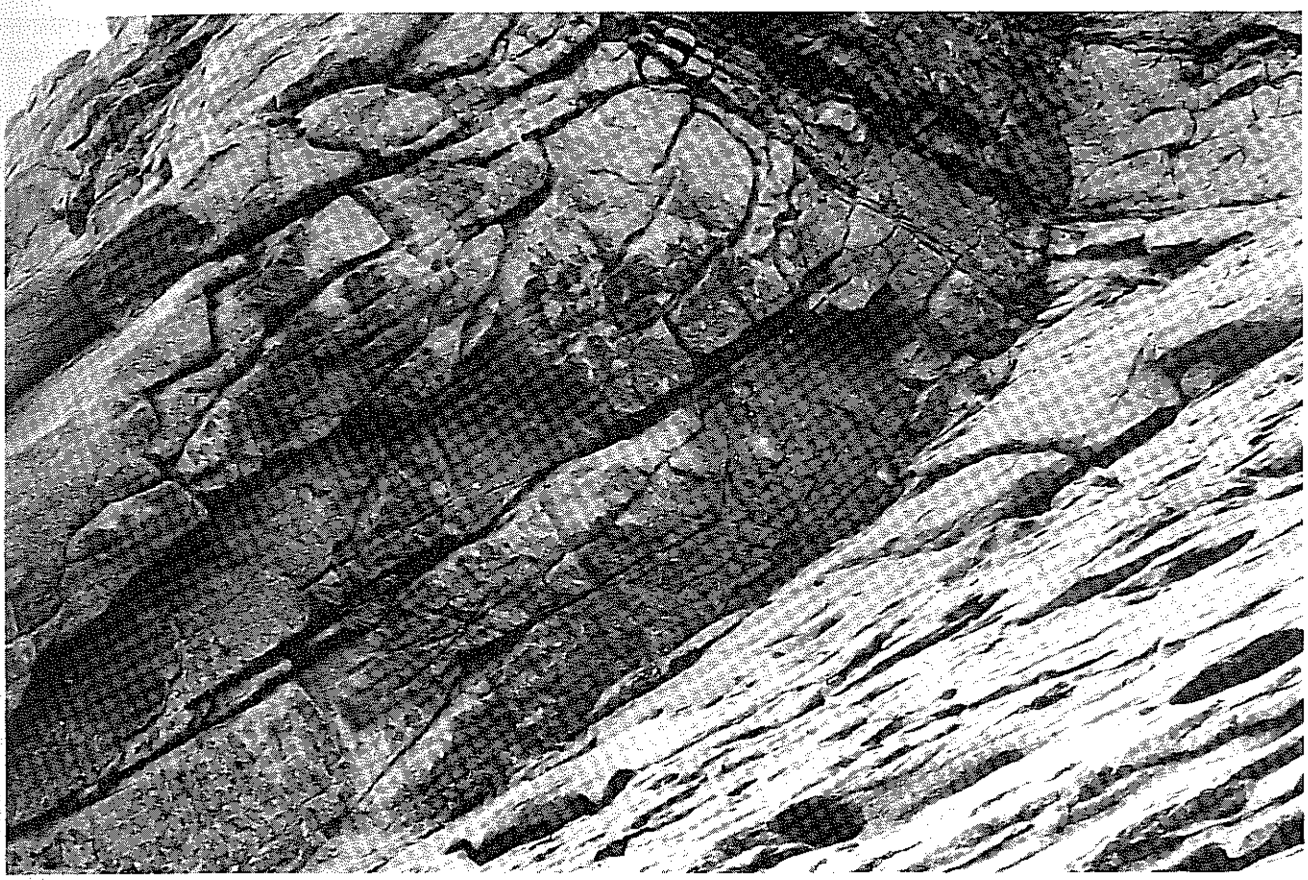


Plate 1. Joints in granite following the trend from the rectilinear slope to the free face, Taylor Valley, Antarctica.

Plate 2. Multiple dome forms in a granite outcrop surrounded by schists. The outcrop is close to the Great Escurpment, Namib Desert.

snout of the Taylor Glacier there is an exposure of joints in granite which is interpreted as supplying convincing evidence in favour of a secondary origin for sheeting. The exposed joints occur at the junction between the rectilinear slope inclined at about 35° and the free face above inclined at about 80°. The joints follow the change of slope almost exactly (Plate 1). It was shown by Selby (1971a) that the rectilinear slope increases its length by elimination of the free face above it, consequently the curved jointing is interpreted as a stress-release phenomenon adjusting to the evolving shape of the concavity between the free face and the rectilinear slope. It must be admitted that there are few places where so nice an adjustment can be seen, but there are also few places where the joint blocks are sufficiently long for the curvilinear sheeting joints to develop.

Where sheeting is reported from other glaciated valleys it is described as forming convex or domed surfaces. Such forms cannot exclude the possibility that the joints reflect internal structure. A concave form exactly located in the angle between two slope facets, one of which is growing at the expense of the other, however, would be a remarkable coincidence if it were reflecting an internal structure.

In the Namib Desert many of the domes are isolated features and cannot be used to test the hypothesis of primary or secondary origin for sheet structures. A number of the outcrops, however, consist of multiple domes separated by widely spaced (0.3 km or more) megajoints (Plate 2). If the hypothesis of primary origin were to be accepted then it would be necessary to conclude that groups of dome-shaped rock masses occur within one intrusion and that these domes have preserved their form as the surrounding and overlying schists have been stripped away.

It has been contended (Selby, 1977) that relief in the Namib Desert has evolved by processes of scarp retreat across bedrock with the Great Escarpment receding eastwards. If this hypothesis is justified the reduction of bornhardt size westwards is entirely conformable with a reduction of bornhardt volume by progressive sheeting parallel to the ground surface. The multiple-domed forms are also explicable by the incision of channels along megajoints and the development of sheeting parallel to the slopes above these channels. A primary origin for the compartmented domes would imply the existence of multi-domed intrusion forms.

3 LAMINAE

Laminae are scale, flake, flaggy or plate-like skins or shells of rock which are formed closely parallel to the surface of an outcrop (Twidale, 1971). Laminae may be up to 40 cm thick but are more commonly 1–5 cm thick: they conform closely to the rock surface even within tafforni or overhangs, beneath visors and on the outer surfaces of rounded boulders. The only general exception to this seems to be that they may intersect the walls of shallow pans (also called opferkesseln, gnammas, oricangas and kociolki). It seems evident then that laminae develop in conformity with the surface of almost any outcrop and that they continue to form as the rock body is reduced in volume. In the case of shallow pits it seems probable that pits may form in a surface already affected by lamination, but deeper pits (>10 cm) influence the formation of laminae (Plate 3).

Laminae develop in a great variety of rocks – granite, monzonite, syenite, quartzite, arkose, gneiss, limestone: they also develop in a great variety of climates ranging from the humid tropics through the subhumid and arid subtropical and temperate zones to the Arctic and Antarctic cold deserts (see Hedges, 1969; Dahl, 1966; Twidale, 1971, for reviews of the literature). They are thus very common features and likely to be produced by a variety of processes.

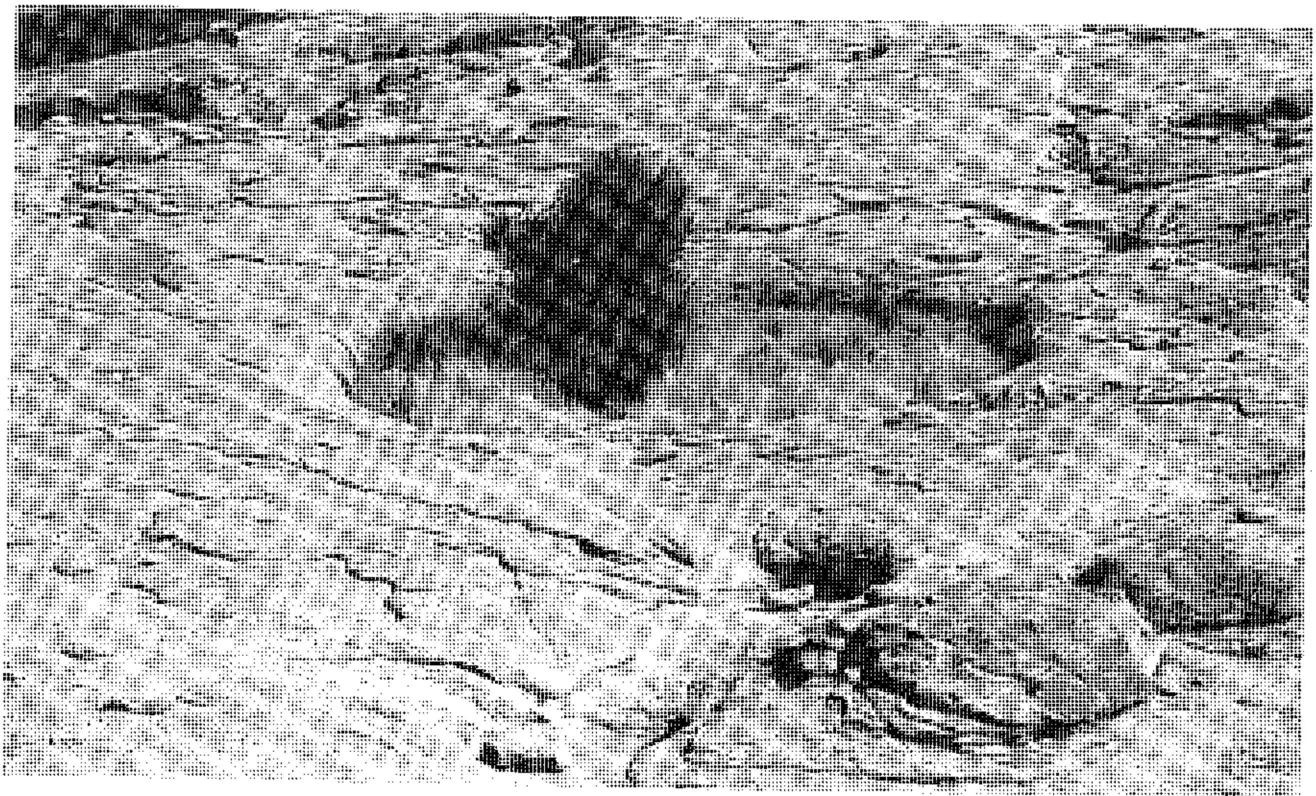
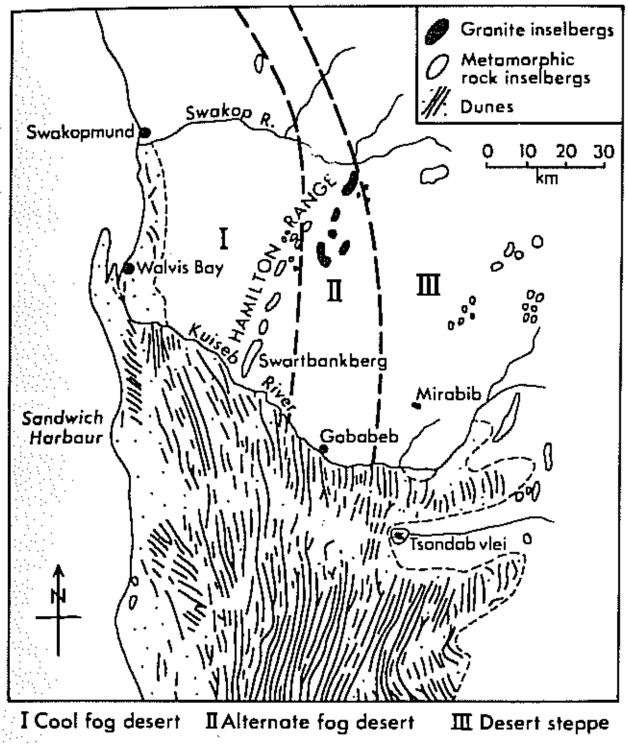


Plate 3. Laminae on the surface of a small bornhardt in the central Namib near Mirabib. The pan is over 1 metre deep but partly filled with grus and vegetation. The laminae conform with the shape of the outcrop.



Map 1. Locality map of the Central Namib Desert. The climatic zones are those of Besler (1972).

3.1 Laminae on granites from the Namib Desert

Field study of granite outcrops in the central Namib Desert has been carried out in the region of Gobabeb and Mirabib (Map 1). The granites of this region and their superficial weathering forms have been briefly described by Goudie (1972), Scholz (1972) and by Besler (1972) but no detailed analysis of the laminae is thought to have been carried out. One feature of the exfoliation of laminae from curved surfaces which these writers did not comment on is that many laminae are thinner at their edges than in the centre. This implies that such laminae being exfoliated from all flat or concave surfaces will initiate another concave depression or deepen an existing concavity, but convexities will be progressively eliminated. This observation may explain why so many of the interiors of Namib taffoni and overhangs have a multicellular appearance (Plate 4) and why boulders are rounded (Plate 5).

Specimens of laminae were removed from outcrops of granite in the Sout River bed about 5 km northwest of Gobabeb, and at Mirabib. The samples have been examined in thin section and by X-ray diffraction in the laboratory in the hope that they would provide information on the causes of lamination.

The specimens from Sout River were removed from outcrops which were greatly affected by honeycomb weathering and lamination (Plate 5) (see Goudie, 1972, p. 18–20 for descriptions). The granite has been weathered to form mushroom-shaped forms standing 1 to 2 m above a valley floor of alluvial silts and grus saturated with gypsum ($CaSO_4.2H_2O$), calcium carbonate and sodium chloride. In such an environment it seemed probable that salts, by crystallising in rock pores, could be responsible for rock weathering and the development of laminae.

In hand specimen and in thin section the rock samples showed only very slight yellow-brown discolouration of the outer surface and the discolouration was always around individual biotite crystals exposed at the rock surface. The biotite crystals appeared not to have suffered expansion and the colour had spread from the crystals only over the surface and not into the rock. Within the laminae there was no sign of chemical weathering; the biotites were unaltered, and the only defects in the rock appeared to be a rather greater separation of the individual crystals than might have been expected, but this effect could have been the result of the hammering, transport and sectioning of the sample.

Examination of the Sout River samples gave no indication of halite, calcium carbonate, gypsum or other soluble salts either within or adhering to the specimens. Approximate constituents of the rock were found to be: quartz 20%; plagioclase 45%; potash feldspar 22%; mica 13%.

In brief then the samples from Gobabeb gave no evidence of chemical weathering nor did they suggest the process of physical weathering which might have been responsible for their formation.

Ten samples of laminae were collected from a group of outcrops near Mirabib. Five of these samples were from scales on the outside of boulders. These scales were all encrusted with red-brown material. The other five samples came from within taffoni and overhangs.

In thin section the scales from the outside of boulders all showed substantial modification of the biotites. Some biotite

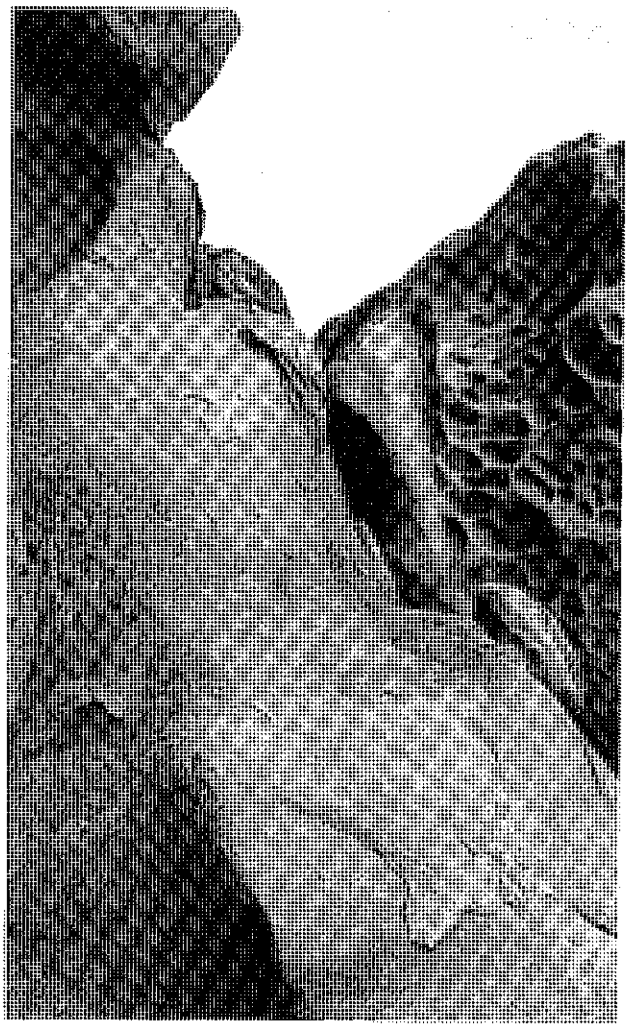


Plate 4. Multicellular weathering pits beneath an overhang, and laminae on convex and concave surfaces, Mirabib.

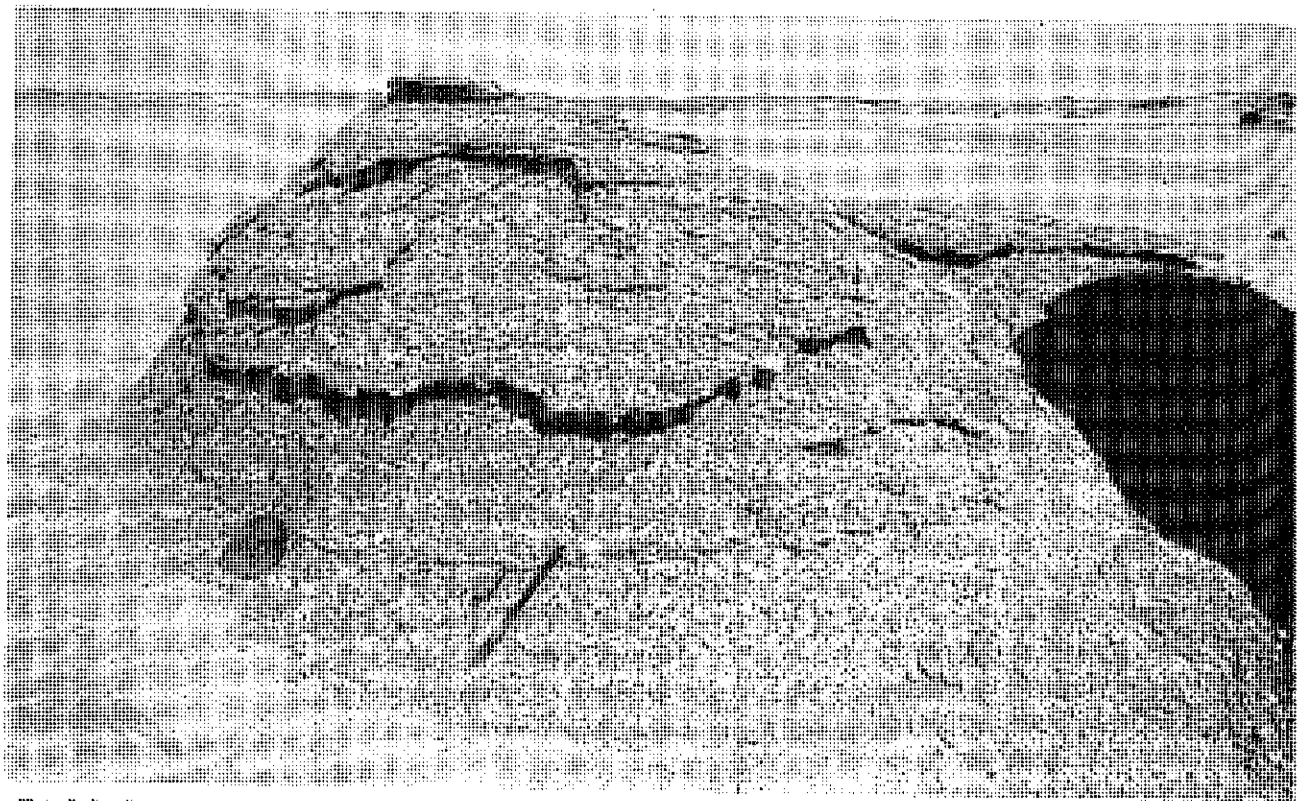


Plate 5. Laminae on granite knob, Sout River.

crystals had suffered swelling and separation of the plates forming the crystal and all had been noticeably discoloured. The red staining emanating from the biotites had spread along boundaries between feldspar and quartz crystals where these boundaries approximately corresponded with the lineation of stringers of biotite crystals. The staining was thus preferentially restricted to lines within the samples, but there was no evidence of separation along these lines. The strong red colours on the surface of the samples could be seen to emanate from a few slightly altered mica crystals. Within three of the samples there was some evidence that the biotite crystals were aligned and clustered, but these groupings were not dense or continuous and it is most unlikely that their arrangement could contribute to the formation of spalling of flakes larger than 1–2 cm². The granites all had a granular texture (hypidiomorphic – granular) with no suggestions of gneissic or schistose structures. Amongst the feldspars (microcline, albite, oligoclase and orthoclase) most crystals were fresh and unaltered. A few, however, showed signs of weak to locally moderate kaolinisation and sericitisation; a few large flakes of sericite were observed. These observations together with a few indications of spherulitic structures, which were probably chlorite, associated with biotite indicates that some slight chemical weathering had occurred. This would no doubt slightly weaken the rock but there was no indication that it had caused rock splitting.

The analysis showed that the red staining was caused by ferric hydroxides. These were mostly limonite but some could be goethite. The composition of the Mirabib granite is approximately: quartz 30%; microcline 15%; oligoclase with some albite 20%; orthoclase 20%; biotite 10%; muscovite <5%. The average mineral grain of quartz and feldspar has a diameter of about 1.5 mm.

Samples taken from the inside of taffoni were also analysed but the results were uniformly uninformative. The rock crystals had suffered no visible chemical alteration and the fine dust from between laminae had approximately the same composition as the granite, with no soluble salts or chemical alteration products being detected.

In the Mirabib area many of the taffoni and cavernously undercut boulders and lips appeared to be suffering vigorous exfoliation. Fresh laminae could be seen separating from the walls and roofs of most cavities and the floors had a fresh-looking litter of fallen flakes. The only site where an indication of the rate of weathering could be obtained was in a very large cave which had been used as a shelter by early men. Occupation layers on the floor of the shelter contain charcoal which has been dated at about 10 000 B.P. (Sandelowsky, 1974). A crude measurement of the volume of fresh rock flakes in the occupation debris suggests a minimum rate of scaling of about 3 cm/1 000 years. Because some of the fallen debris may have been removed by wind or people the possible maximum rate is unknown. The site may also be misleading for the roof and backwall are partly coated with soot which may have sealed the rock surface and reduced weathering rates.

3.2 Laminae on granites from Antarctica

The general nature of weathering crusts and taffoni on granite in the McMurdo Oasis has already been described by Selby (1971b, 1972). These forms are as common there as they are in the Namib and have similar dimensions.

Samples have also been taken from rock spalls and laminae within taffoni in the McMurdo Oasis. The results are no more informative than those obtained from samples from the Namib Desert. Chemical weathering was confined to biotite crystals near the surface of laminae taken from the outside of boulders. The weathering crusts were also composed of ferric hydroxides but in Antarctica these formed a distinct crust – up to 0.5 mm thick – on some samples from the central zone of the valleys. It is notable that the largest taffoni, overhangs and visors occur in those areas where weathering crusts (desert varnish) are most prominent.

3.3 Weathering forms on granites from the central Sahara

The granites of the central Sahara were studied only briefly in the field as specimens for laboratory analysis could not be carried. Conclusions based on field evidence are therefore tentative. The outer surface of the granites was in places covered with a dark blue-black crust which appeared to be totally impervious, but this crust was in many places peeling and revealing fresh rock beneath it. More commonly the rock surface had a dull red-brown colour but there was no evidence on any of the outcrops examined that a crust had formed and the discolouration was superficial only, with no evidence that it had penetrated into the rock between crystal faces.

On the Sahara outcrops laminae were rare. Most boulders had the appearance of being subject to granular disintegration even though broken edges of sheets and boulders had some indications of platy structures in the rock. Hand specimens knocked from outcrops showed strong decomposition and leaching of the biotites, and some feldspars could be easily crumbled between the fingers (Plate 6). Taffoni everywhere were found to be actively growing with fresh quartz crystals falling out of a crumbling matrix of decomposed feldspars. The entrances to taffoni were often in the form of visors and overhangs, but there was no evidence that these apparently more resistant areas of rock were case-hardened or less deeply weathered. The ground around all outcrops consisted of a fine pea-gravel of quartz crystals surrounded by a pale brown silt and fine sand. Fresh feldspar crystals were not observed in this material.

In the central Sahara, then, granite weathering appears to have produced little lamination of the surface of outcrops. By contrast with Antarctica and the Namib the granites are strongly decomposed near the surface (to a depth of 5 to 10 cm). Weathering crusts exist but are exceedingly thin and do not cover all upper surfaces. Taffoni exist but their entrances do not have the sharp edges formed by case-hardened or laminated rock. The dominant exfoliation process seems to be granular rather than laminar.

4 CONCLUSIONS

Evidence from Antarctica clearly supports a secondary, or unloading, hypothesis for the origin of sheeting structures in granites of the Taylor Valley. The evidence from the Namib is more equivocal, but a primary origin seems improbable and the evidence favours a secondary origin.

The cause(s) of laminae in granites of the Namib and Antarctica is still unknown. Lamination is clearly a physical process and does not involve any chemical decomposition of the rock minerals other than possible release of ferric hydroxides from biotites. The investigations reported here throw no light on the relative effectiveness of such physical processes as salt weathering, differential thermal expansion and contraction, stress release, cryogenic weathering or sudden quenching of heated rock by rain – although, of course, some of these

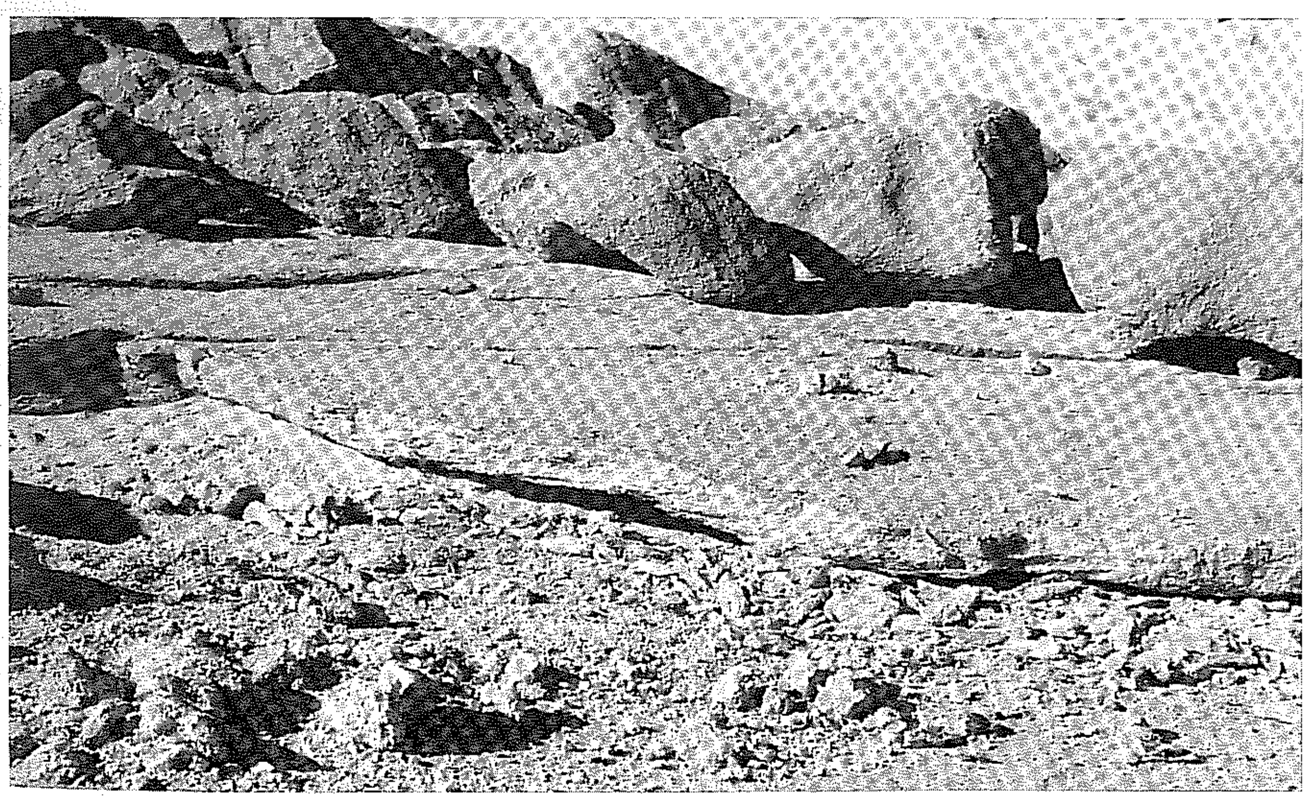


Plate 6. Part of the surface of a large bornhardt near Moulay Hassan, central Sahara. The sheet of granite in the centre has a broken edge revealing decomposed feldspars and leached biotite crystals. Disintegration is largely granular. The boulders have small taffoni formed in their bases. Laminae are not present.

processes are inappropriate for the environments described — (see Schattner, 1961, for a review of these hypotheses). As with so many physical processes their action leaves no unique indicators of their occurrence.

The conclusion of Besler (1972) that the ferric hydroxide coating on rocks of the Namib is not a true, and impervious, desert varnish is supported. Her statement that the reddish-brown patina consists of montmorillonitic weathering products is not supported by the X-ray diffraction analyses.

It would appear from these observations that taffoni and laminae may form both with and without the development of desert varnish. The formation of taffoni in association with chemical weathering is also well established in the central Sahara, but the weak development of laminae there may be caused by chemical weathering. In a traverse through the humid and subhumid regions of central Africa the writer noted that although laminae do form on outcrops of granitic rock they were never as strongly developed as in the Namib and Antarctica. A tentative conclusion is that although laminae can form in all climates the existence of strong chemical weathering on the surface of outcrops reduces the effectiveness of lamination processes. The ubiquitous nature of lamination in granitic rocks suggests that its occurrence may be caused by the inherent properties of the rock — such as in-built stress — rather than by particular weathering processes, although physical processes obviously increase its effectiveness. The in-built stress of rocks needs further investigation.

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