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Form and origin of some bornhardts of the Namib Desert

by

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with 7 figures and 5 photos

Zusammenfassung. Hinweise werden mitgeteilt, die einen früheren Bericht über einige Inselberge in der Namib bestätigen, nämlich daß ihre Glockenbergform verursacht wird durch die Domform des aufgedrungenen Granits. Die Hinweise umfassen: konforme Faltung des unverwitterten kristallinen Schiefers um und über dem Dom, Durchdringen von Pegmatit- und Aplitgängen vom Granit in den Schiefer, Einflüsse von Schieferstücken im Dach des Granits. Abschalungen erhalten die Domform, bis sich kreuzweise Klüfte öffnen, während der Granit Hänge entwickelt, deren Neigungen im Gleichgewicht sind mit der Widerstandsfähigkeit des Gesteins. Die Steuerung der Entstehung und Entwicklung von Namib Bornhardts durch die geologische Struktur ist eindeutig und unterstützt die Meinung, daß Theorien, die eine klimatische Steuerung verlangen, mit Vorsicht betrachtet werden müssen, aber es ist klar, daß Domformen auf viele verschiedene Arten entstehen können.

Summary. Evidence is presented which confirms an earlier report that some bornhardts in the Namib desert owe their dome form to that created during emplacement of the granite. The evidence includes: conformable folding of unweathered schist around and over the domes; penetration of pegmatite and aplite dykes through the granite and into the schist; survival of schist xenoliths in the roofs of the domes. Sheeting of granite perpetuates the dome form until cross joints open when the granite slopes develop inclinations which are in equilibrium with the mass strength of the rock. The control of geological structure on the origin and development of Namib bornhardts is unequivocal and supports the contention that theories invoking climatic controls should be treated with caution, although it is clear that domed landforms can be produced in many different ways.

Résumé. De nouvelles informations confirment des conclusions antérieures selon lesquelles l'aspect en cloche des inselbergs de Namibie résulte de la forme en dôme des granites. Ces données comprennent: plissement conforme des schistes cristallisés, non-altérés, autour et au-dessus du dôme, injection de filons pegmatitiques et aplitiques de granite dans le schiste, influences de fragments de schiste dans le toit du granite. L'écaillement maintient la forme en dôme jusqu'à ce que les fissures s'ouvrent en croix pendant que le granite développe des versants dont la pente est en équilibre avec la résistance de la roche. La régulation de la naissance et de l'évolution des "Namib Bornhardts" par la structure géologique est évidente. En conséquence les théories d'une régulation climatique doivent être considérées avec prudence, mais il est clair que des formes en dôme peuvent apparaître de diverses façons.

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Introduction

Bornhardts were first defined as hills possessing "bare surfaces, dome-like summits, precipitous sides becoming steeper towards the base . . ." (Willis 1936: 117). Most geomorphologists accept the original descriptive definition of bornhardts but inspite of a considerable literature on the subject there is little agreement on the structural controls on their morphology, or upon the significance of climate and weathering in their development. This literature has been extensively reviewed by Birot (1978); Thomas (1978); and Twidale & Bourne (1978).

There is now a substantial body of evidence that massive monolithic domical landforms can be formed as a result of a number of processes and in a variety of climatic and tectonic environments, and several warnings have been published against seeking a single cause for such features, and against assumptions that a single end-form must have been produced by a unique set of controls (White 1945; Cunningham 1969; Selby 1977a). Inspite of such warnings it is widely accepted that domical forms are produced by curved sheeting joints and that the domical forms are initiated as compartments of massive resistant and unweathered rock set in a mass of weathered grus or rotted rock (e.g. Twidale & Bourne 1978: 131). While these contentions may be appropriate to many sites they are not universally valid. It is the purpose of this paper to describe the origin of certain bornhardts in the Namib desert which owe their dome-form to that produced as granite was intruded into the schists and metasediments of the Namib Precambrian basement rocks. This dome-form is initially preserved as the granite domes are exposed by stripping of the surrounding schist and perpetuated by the development of sheet joints. As the granite weathers an orthogonal joint set opens, slopes on the bornhardts come into equilibrium with the mass strength of their rock, and the dome-form is lost.

Bornhardts of the Namib are particulary interesting examples of their type because they can be found at several stages of development in an environment in which their origin is not obscured by an accumulation of weathering products.

Central Namib study area

The central Namib is a rock desert lying north of the Namib erg and divided from it by the canyon of the Kuiseb River (fig. 1). It extends inland from the coast for about 130 km as a gently rising erosional plain which terminates at the base of an inland escarpment whose foot is at an altitude of about 1000 metres. The escarpment may be abrupt, but is more commonly a zone of dissection some 30 km wide forming the edge of the main plateau of southern Africa. The Namib plain is cut across late Precambrian metamorphic rocks which include mica schists, metasediments, granitic gneiss and marble. Into these metamorphic rocks are intruded granites. The geology has been described by Martin (1965) and more recently mapped at a scale of 1:1 million (Geological Survey of the Republic of South Africa and South West Africa/Namibia 1980).

The bornhardts described here fall into two groups. A southern group includes the small domes of Mirabib, Amichab and an unnamed dome near Heinrichsberg.

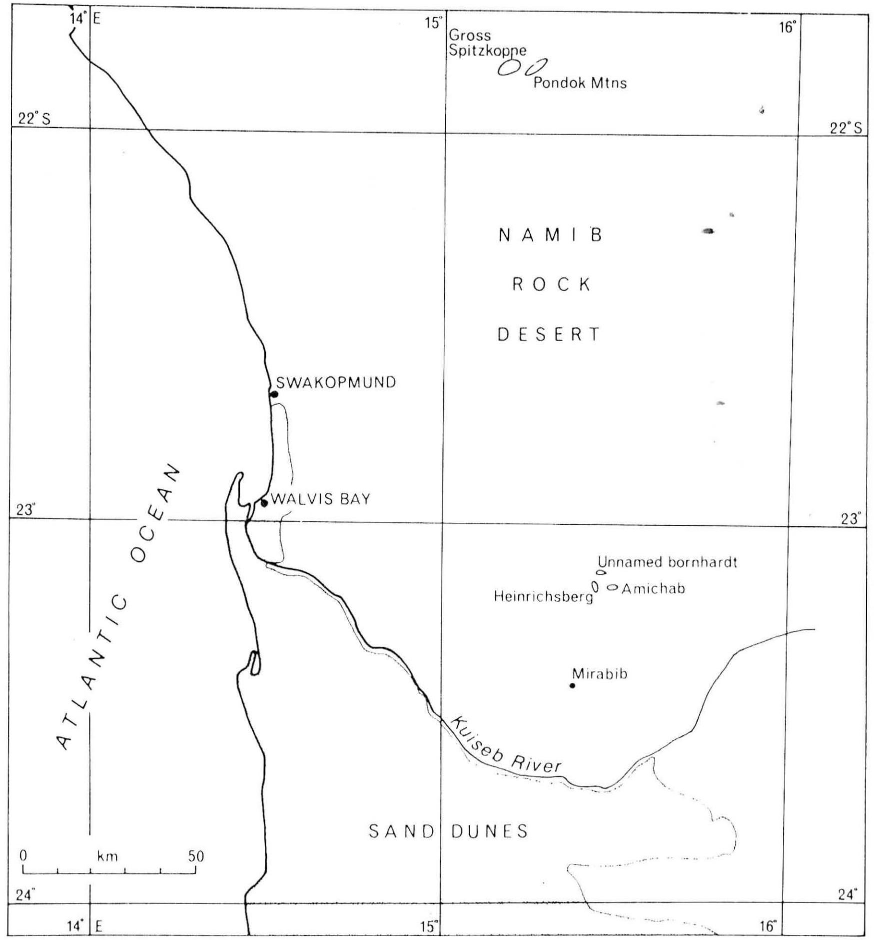

Fig. 1. The central Namib with locations of the bornhardts studied.

This group is composed of Donkerhuk granite of Namibian age (late Precambrian). The granite is generally pale pink to grey porphyritic biotite granite which contains large phenocrysts of orthoclase and microcline feldspar. The approximate composition of the rock is: quartz 20%; plagioclase 45%; orthoclase 22%; mica 13% (Selby 1977b: 175). The northern group contains the very large bornhardt of Gross Spitzkoppe (or Spitzkop) and the adjacent ridge, surmounted by domes, which is locally known as the Pondok Mountains. Gross Spitzkoppe is composed of Erongo Granite of Cretaceous age which has been intruded into Old Granite of the Damara Sequence of late Precambrian age. The Erongo Granite is uniform mineralogically and mechanically undeformed. It is coarse grained with red coloured feldspar crystals. Its approximate composition is: quartz 33%; orthoclase 44%; plagioclase 20%; mica 2–3%. All of the Namib inselbergs described here have been shown by detailed geological mapping to be formed on intrusions whose outcrop coincides with the boundary of the bornhardt. (Frommurze et al. 1942; Union of South Africa, Departement of Mines 1942; Geological Survey 1980).

Some Namib bornhardts have already been described by Selby (1977a) who proposed that they have been exposed by removal of the surrounding schist, without the operation of deep chemical weathering, in a desert environment which has been arid during much of late Cenozoic time. These conclusions are generally supported by the comments of Ollier (1978). Since the observations reported in 1977 a site has been found near Heinrichsberg which shows, unequivocally, that some granite intrusions have a dome shape which is created during emplacement. This verifies the earlier report which was based mostly on aerial reconnaissance.

Method of study

The two bornhardts Mirabib and Amichab have been studied by applying a rock mass strength classification to the rock units exposed along a profile across each inselberg.

The classification uses eight parameters: strength of intact rock as indicated by an 'N' type Schmidt hammer; state of weathering of the rock; spacing of joints or other partings; orientation of the partings; width of the partings; continuity of the partings; gouge or infilling in the partings; movement of water out of the rock mass. Each parameter is assessed according to defined criteria (Selby 1980) and scored on a five–class scale. The strongest possible rocks thus have a score of 100 and the weakest a score of 25 points.

The outcrop surface along the line of profile is divided into units so that each unit has a general uniformity of slope angle, or a uniformity of slope curvature. Segments of domes are, of course, continuously varying in slope angle and definition of unit boundaries is therefore arbitrary.

The rock mass strength classification has been applied to rock slopes in Antarctica, New Zealand and to slopes on bedded rocks in the Namib. Slope units with angles which are adjusted to the mass strength of their rocks have been called "strength equilibrium slopes" and on a graphical plot of mass strength against slope unit angle the data points for such slopes fall within an envelope called a "strength equilibrium envelope" (Selby in prep.) If rock slope units have angles which are not adjusted to their mass strength then the data points will plot outside the envelope.

Mirabib and Amichab

Mirabib is a multiple-domed inselberg rising about 100 m above its pediment, and Amichab is a ridge of mica-schist with a cone-shaped peak of granite at its northern end. This cone rises about 200 m above the pediment. Most of the granite of these two inselbergs has moderate intact strength, is slightly weathered, has no groundwater outflow and no infill in the joints. The dip of the joints is shown diagrammatically in the profile drawings (fig. 2, 3); joint widths vary from less than 1 mm to more than 20 mm; joint continuity is very variable.

The mass strength-slope angle relationships for Mirabib and Amichab are shown in fig. 4. On Mirabib the steep flanks of the domes are strength equilibrium slopes because they have few and widely spaced joints, and consequently a high mass strength rating. The upper surfaces of both the large and small domes have lower angles of slope, but their mass strength rating is as high as that of the flanks, so they have considerably lower slope angles than, theoretically, could be supported by their mass strength. On Amichab the slope units A to I forming the lower part of the east facing slope appear to be the outcrop of sheet structures with a low angle of dip. Unit E is an exception as it results from a steeply dipping cross joint forming the face of the slope unit. As a consequence units A to D and F to I have slope angles which are lower than those which could be supported by their mass strengths. Higher on Amichab units J, K and L are formed in the outcrop of sheet structures which are being broken down by the development of an orthogonal joint set. The presence of these joints cutting across the sheets reduces the mass strength, and their data points plot within the strength equilibrium envelope. On the western face of

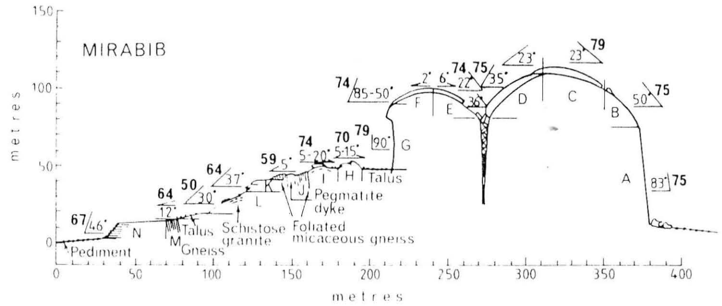

Fig. 2. A profile across the bornhardt Mirabib with characteristic angles of the slope units and rock mass strength ratings given in bold type.

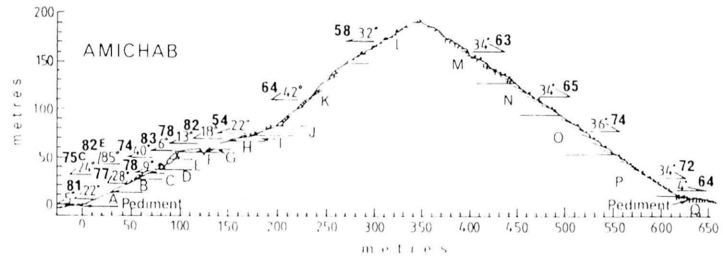

Fig. 3. A profile across Amichab.

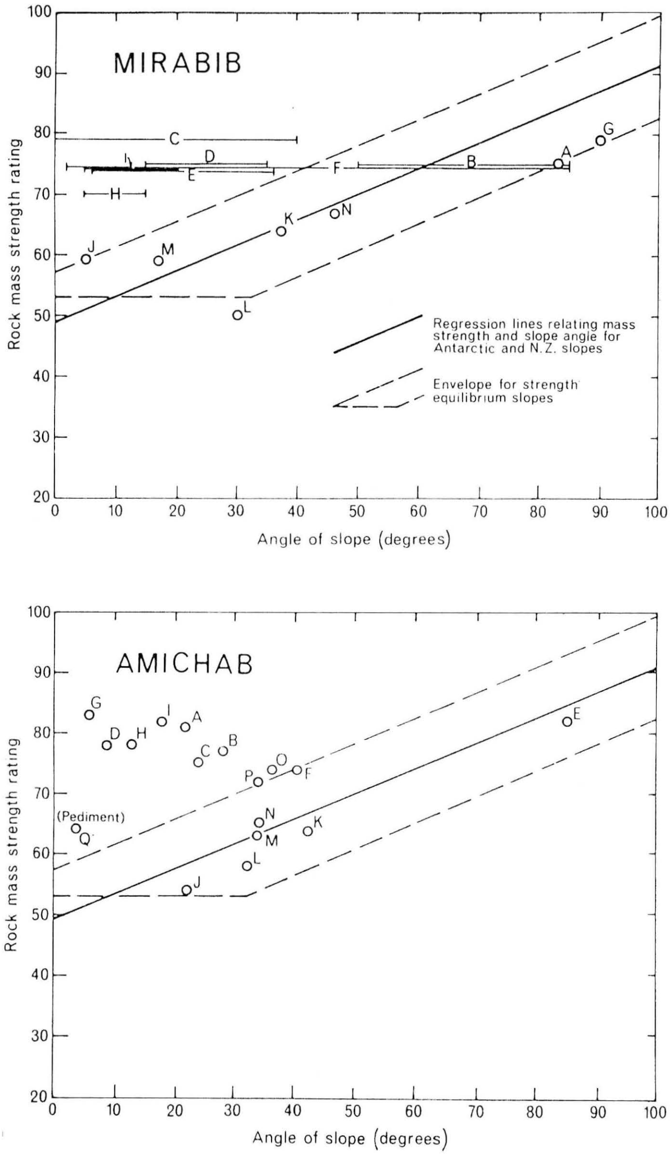

Fig. 4. Relationships between mass strength and slope angle for Mirabib and Amichab.

Amichab units M, N and P are composed of granite in which the joints are closely spaced (300–400 mm) and continuous, hence any controlling influence of sheet structures on slope angles has been lost. Only unit O retains the influence of sheet structure through its widely spaced joints and it is marginally stronger than needed for strength equilibrium with its slope angle. The pediment at the base of the western slopes is composed of gneiss with a joint spacing of only 80 mm. This produces a rock of only moderate strength but because of its low slope angle its data points plot above the strength equilibrium envelope.

Unnamed dome

About 5 km north of Amichab and 3 km north of Heinrichsberg (fig. 1) lies a domical granite outcrop with a vertical relief of about 100 m. This feature has such

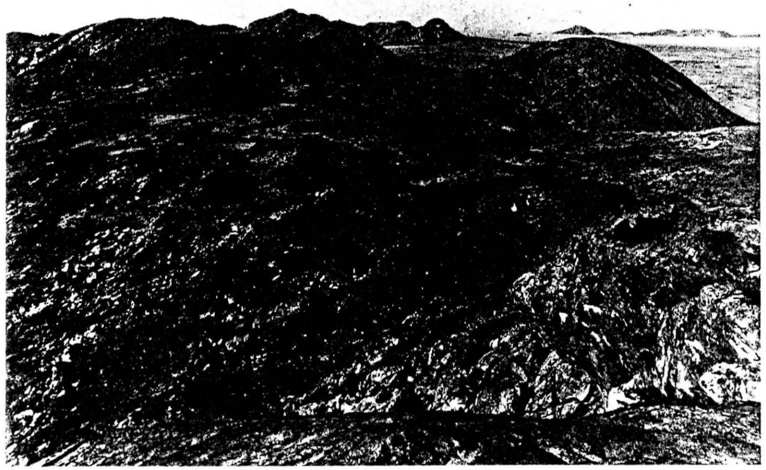

Photo 1. The upper surface of the unnamed bornhardt showing schist lying conformably on the granite.

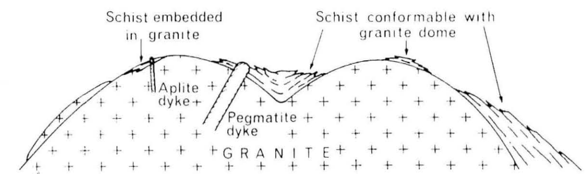

Fig. 5. A diagrammatic cross-section of the unnamed bornhardt, north of Heinrichsberg, showing the various lines of evidence which indicate that granite has been intruded as a dome into the schist.

low angles of curvature that its slopes are everywhere more gentle than its mass strength, theoretically, could support. Its importance, however, lies in the outstanding evidence it presents of a bornhardt owing all of its dome shape to that created during the original intrusion of the granitic magma (photo 1).

The granite which is exposed has a gently sloping upper surface forming two low-angle domes against which the schist lies conformably. The schist lies in contact with the granite on the northern and eastern flank of the bornhardt and dips with the granite surface at angles of up to 28°. Where the two domes intersect along the upper surface of the bornhardt the schist has been warped to form an open synclinal fold: here pegmatite dykes pass through the granite into the schist (fig. 5).

In the upper surface and western flank of the granite, from which the schist has been stripped by erosion, xenolithic masses of schist are embedded. At one site an 80 mm wide aplite dyke passes through the granite and the schist.

It appears that the domical form of the granite was produced at the time of original intrusion. Stripping of the conformably arched and domed schist has exposed part of the upper surface of the granite on its southern and western flanks, but the xenoliths of schist embedded in the upper surface indicate that there has been little loss of granite even though some sheet joints are opening conformably with the main dome on its exposed flanks, and in so doing are preserving the dome form in the granite beneath the sheets.

Gross Spitzkoppe and the Pondok Mountains

Gross Spitzkoppe is a large multi-domed mountain (fig. 6) rising from the main desert plain at an altitude of about 1100 m: the highest dome has a summit altitude of 1728 m. The western part of the mountain has closely spaced joints except in the area of one small dome on its flank. The eastern part of the mountain consists of a main dome (photo 2, fig. 7) separated from a minor dome to the south by an east-west trending joint. On its western side the main dome is composed of massive granite with few joints, but the eastern side is cut into large vertical slices by a set of parallel north-south trending joints (photos 3 and 4). The upper part of the east face of the main dome is also subdivided by a number of vertical east-west trending joints.

The Pondok Mountains are a ridge which is aligned east– west and in structural continuity with Gross Spitzkoppe. Its summits are formed of granite domes which reach altitudes of 1350–1500 m and are thus 250–400 m above the desert plain.

The features of Gross Spitzkoppe and the Pondok Mountains which are of outstanding interest include: (1) the plan-form of the domes; (2) the sheeting joints exposed on the surface of the larger domes; (3) the section through part of the large dome of Gross Spitzkoppe which shows the development of sheeting joints at depth within the dome; (4) the development and opening of an orthogonal joint set in the flanks of the domes; and (5) the development of elongated and rounded boulders, from separated joint blocks, by modern weathering processes.

The influence of joints upon the plan-form of Gross Spitzkoppe and the Pondok Mountains is evident from the map (fig. 6). Domes occur where the linear joints are far apart and areas of lower relief where joints are closely spaced. Alignment of the domes in an east-west direction is controlled by two joint sets which tend to converge towards the east and so cause narrowing of the Pondok domes in that direction. The Pondok domes appear to have attained their present form after the opening of the dominant joints as their individual shapes are confined within the joints. Gross Spitzkoppe, by contrast, was apparently a multi-domed feature whose eastern side was later cut by the development of the north-south trending set of joints which have spacings of 10–30 m (photo 4). The lower dome cut by this set now has a relief and suite of minor landforms dominated by these joints.

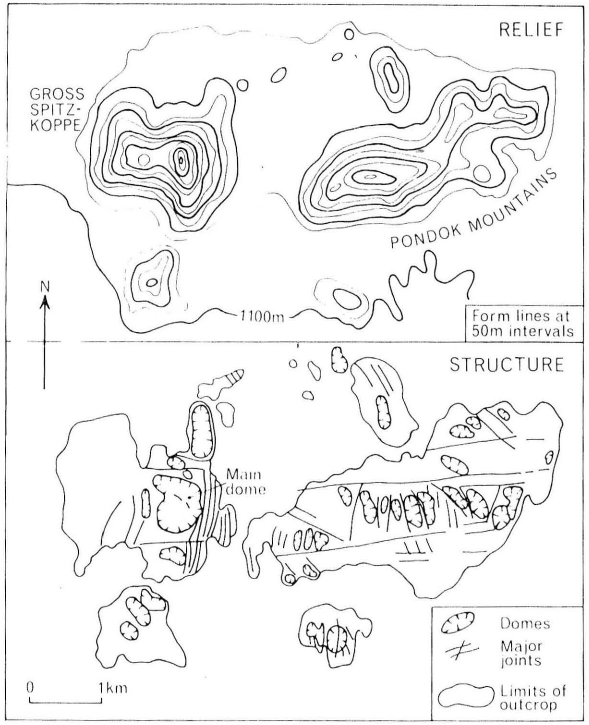

Fig. 6. The relief, domes and dominant joints of Gross Spitzkoppe and the Pondok Mountains.

Nowhere on these mountains have outcrops or residuals of the country rock, into which the granite was intruded, been seen or reported. It is, consequently, not possible to ascertain whether the domes owe their outline to original emplacement forms or to subsequent development of sheeting joints developing on the massive compartments of granite between the major linear joint sets.

All of the large domes have well-developed sheeting joints which are nearly parallel with the dome surface where the sheeting rock units are thin (1–10 m), but have a greater curvature than the dome where the sheeting units are thicker than about 10 m. The exfoliation of thin sheets of rock consequently preserves the form of the domes, but the loss of thick sheets produces a reduction in the slope of the dome and can lead to a loss of the high relief and steep sides which are the characteristic forms of bornhardts.

An outstanding opportunity for observing the development of thick sheeting units is available at the southwestern flank of the main dome of Gross Spitzkoppe. Here major sheeting joints are exposed in a vertical cut across the edge of the dome. An outer sheeting unit has formed with a curvature conformable with that of the present surface, but an inner unit has a downslope segment which is parallel with the ground surface but an upper segment which flattens sharply so that, if the outer sheet is exfoliated, the new form will be that of a small steep-sided dome capping a large dome of lesser curvature (area A, fig. 7). The development of cross joints of an orthogonal set may then destroy the small upper dome and leave a smaller and less curved dome below.

The destruction of sheeting units and small domes as orthogonal joint sets develop is evident at many sites on these mountains (e.g. area B, fig. 7). The large straight and continuous joints may be, and probably are, tectonically controlled, but the small localised joints are not continuous and presumably result from the local release of internal stresses. Destruction of the surface form of the domes can only occur where these local joints have become continuous and sufficiently open for newly developed joint blocks to slide, roll or rotate. At this stage the slope becomes

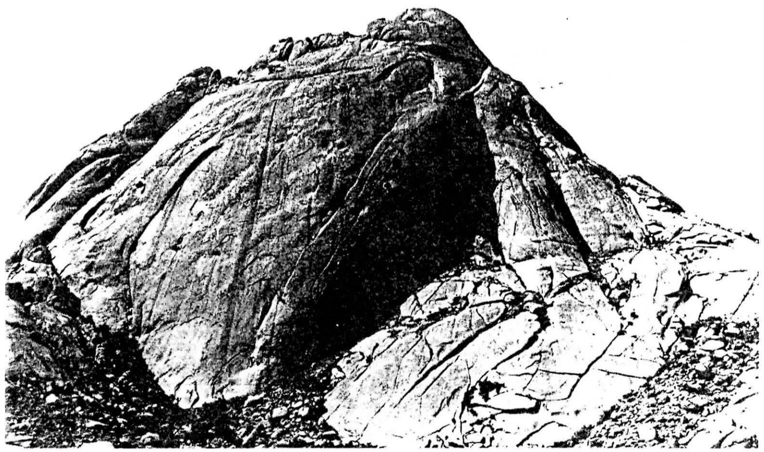

Photo 2. The southwestern face of Gross Spitzkoppe. The section showing the large sheeting joints is in shade.

a massive talus or, of the joints produce a stepped slope profile, it becomes a strength equilibrium slope.

The process of joint block reduction proceeds in the arid environment of the Namib by granular disaggregation of coarse grained rocks. The Erongo Granite is particularly susceptible to this kind of weathering and the surfaces of all joint blocks, and of the domes, are characterised by this process. Its mechanism is still obscure but involves the partial alteration of biotite, the release of ferric hydroxides and loosening of individual quartz and feldspar crystals (SELBY 1977b: 176). No alteration of feldspar crystals was evident in hand specimens. The upper surfaces of the large vertical rock slices forming the eastern edge of Gross Spitzkoppe show the results of this weathering very clearly (photo 5). The upper surfaces of each slice are subdivided by joints which are either parallel to the faces of the slice or cut into them at right angles. The edges of each joint block are rounded by spalling and the ultimate result is the separation of partly rounded blocks from the parent slice. Thus joint blocks of many sizes and shapes are being formed on the faces of the moun-

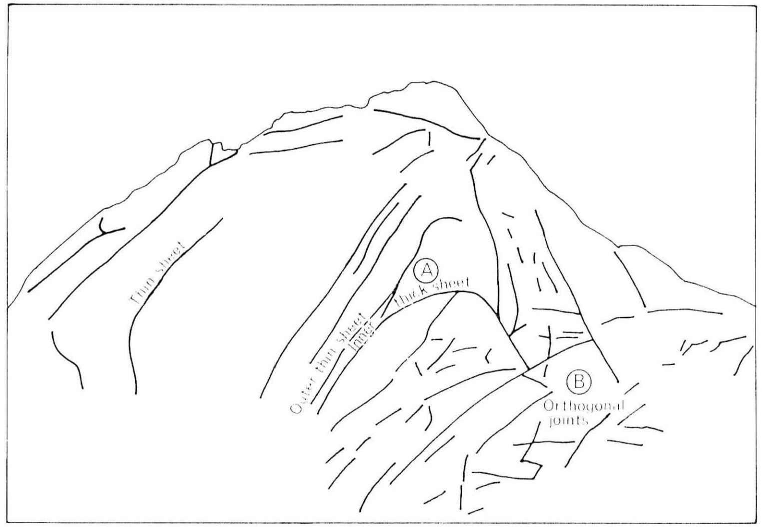

Fig. 7. The main structural features of the southwest face of Gross Spitzkoppe.

tains. Similar weathering forms of crystalline rocks in an arid environment have been reported by MENSCHING (1978: 12, photo 4).

Conclusions

The evidence from Mirabib and Amichab shows that bornhardts may, initially, have slope angles controlled by structure and perpetuated by the opening of sheeting

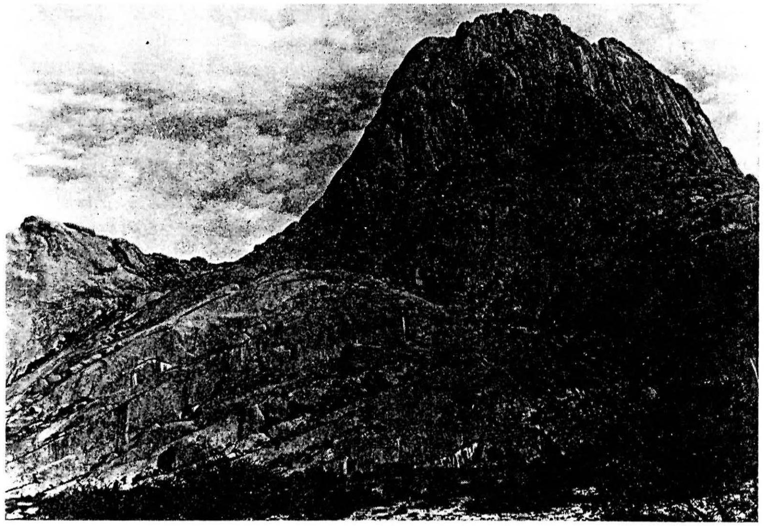

Photo 3. Spitzkoppe from the southeast showing the large north-south trend of joints in the lower domes and the lesser dissection of the upper dome by east-west trending joints.

Photo 4. Detail of the joints, trending away from the camera, cutting the eastern low domes of Gross Spitzkoppe, with weathered unattached joint blocks.

Photo 5. The weathering of granite on Gross Spitzkoppe by joint opening and granular disaggregation to form rounded boulders.

joints. As an orthogonal set of joints open the mass strength of the rock is reduced and slope profiles are adjusted so that the slope angle is in a strength equilibrium with the rock. Studies of inselbergs on metamorphic and sedimentary rocks elsewhere in the Namib (Selby in prep.) have shown that strength equilibrium slopes are widespread and may be universal in the absence of talus deposits. It is probable, therefore, that continued evolution of the granite slopes preserves strength equilibrium so that, in the virtual absence of groundwater and weathering, slope angles are controlled by the joint pattern through its influence on mass strength.

The significance of the finding that some Namib Desert granite domes achieved that form at the time of their emplacement is difficult to evaluate. It does, of course, stress the significance of original structural control, but cannot be compared with assumptions about origins of domes elsewhere because in few other places is similar strong evidence of emplacement forms preserved. Wherever the country-rock above the granite has been removed by erosion or altered by weathering the original form can only be inferred and is never certain. The unequivocal evidence from the Namib cannot be used to infer similar origins for bornhardts elsewhere. It is evident, of course, that some bornhardts cannot owe their form to that created during emplacement and this is the case with examples like Ayres Rock and the Olgas (Twidale 1978) which are formed of sedimentary rocks.

Survival of dome forms clearly owes much to the development of sheeting joints. Where they are concentric with the original dome its form will be preserved, but its dimensions reduced, by exfoliation. Where sheeting joints develop with a curvature producing a less steeply inclined inner dome then the form is reduced and eventually may be lost. A reduction in the steepness of domes is well displayed at Gross Spitzkoppe and at Amichab where outer and upper sheeting joints have a greater radius of curvature than inner and lower sheeting joints. The intersection of sheeting joints of different curvatures can give rise to small domes which rest upon large domes until cross joints open and the smaller domes lose their form.

Evidence for the structural controls on domed landforms which have evolved in an arid or semiarid climate, and in the absence of significant chemical weathering, should provide a clear warning against assuming that deep chemical weathering is necessary to produce any of the characteristic features of bornhardts.

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