ACTA UNIVERSITATIS CAROLINAE
2000 GEOGRAPHICA, XXXV, SUPPLEMENTUM, PAG. 17–38

Granite Landforms of the Central Namib

PIOTR MIGOŃ[1] and ANDREW GOUDIE[2]

[1]Department of Geography, University of Wroclaw, Poland
[2]School of Geography, University of Oxford, United Kingdom

ABSTRACT

The central Namib Desert in Namibia is an area of extreme aridity. It possesses a wide range of granite landforms, that include domes, boulders, pediments, caves, tafoni, alveoles, weathering pits and flakes. Many of these features are of exceptional size. The granites are of two main ages: those of around 500–600 million years old that are associated with the Damaran Orogeny and those that are of early Cretaceous age and are associated with the fragmentation of Gondwanaland and the opening of the South Atlantic. In spite of the steep climatic gradient from the coast to the Great Escarpment, the forms of the major granite landforms show little variation along this gradient. It is also unlikely that there has been deep weathering under prolonged humid conditions, as the area has a history of aridity that may date back to the early Cretaceous. The conclusion is therefore made that the prime control on the granite landforms of the area is lithostructural.

Key words: granite landforms, Central Namib

1. Introduction

Granitic rocks support some of the most spectacular landscapes of the world, including for example the assemblage of 'sugar-loaf' hills in Rio de Janeiro, the domes of the Yosemite Valley in California, or the tor-crowned uplands in south-west Britain, to name just a few. Undoubtedly, landforms of the Central Namib in south-west Africa, including the inselberg of Spitzkoppe, aptly called the 'Matterhorn of Africa', rank among these great granite landscapes of the world. Surprisingly, in spite of this great scenic and potentially scientific value, they are rather poorly covered by the existing literature.

Although the central part of the Namib has already featured in numerous geomorphological studies, some of which have treated selected granite landforms at specific sites in detail (cf. Selby 1977a, 1977b, 1982, Goudie and Migon 1997), such studies have not tended to focus specifically on the full variety of granite morphology. Therefore, in this paper we attempt to fill this gap through providing an overview of granite landforms which occur north of the Namib Sand Sea in the Central Namib, between the Great Escarpment in the east and the Atlantic coast in the west (Figure 1). Moreover, such a systematic treatment may significantly contribute to the ongoing debate on structural versus climatic controls on landform development in granite. This is for two reasons. First, in the central part of the Namib there occur two fundamentally different types of granite, varying in age, composition and emplacement history. Second, these landforms occur along a west-east transect characterised by a very strong climatic gradient, reflected mainly in precipitation.

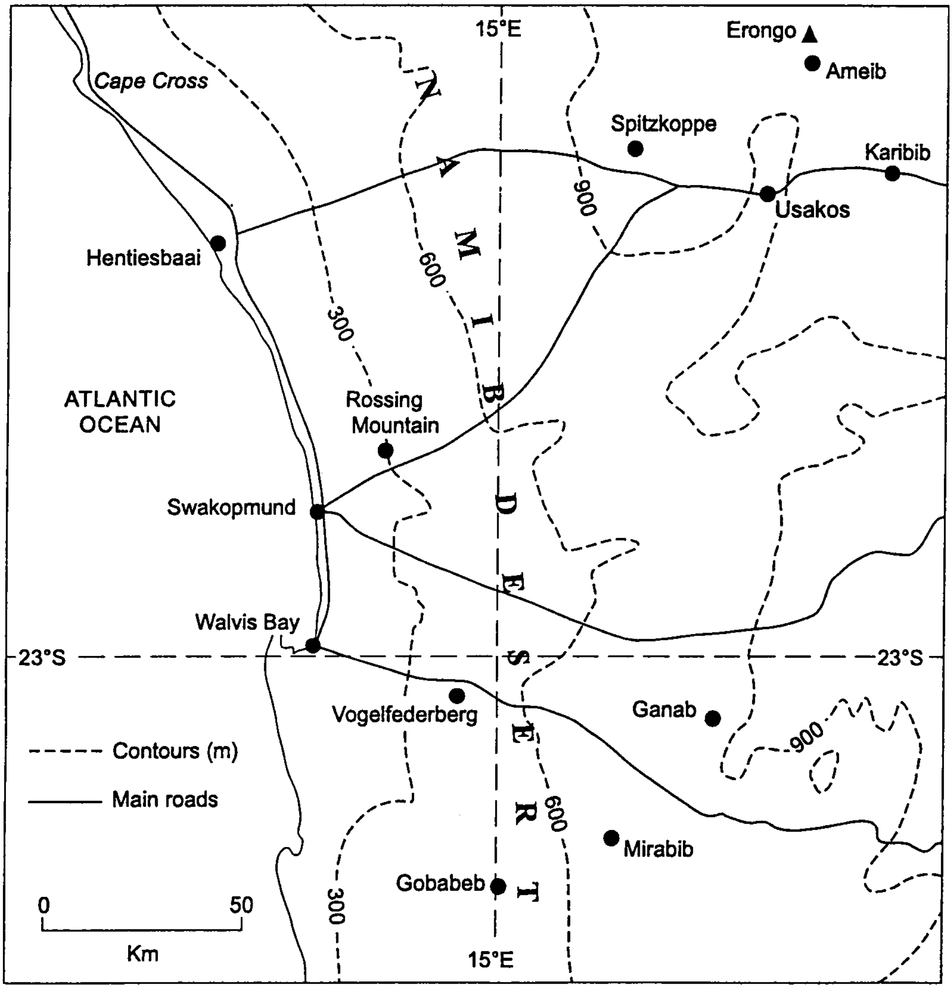

Figure 1: The location of the central Namib Desert.

2. The area

2.1. Location and regional relief

The study area is located in the west-central part of Namibia, in front of the Great Escarpment. This, however, does not form here a single prominent topographic scarp but is composed of a series of mountain massif and ranges (Goudie, Eckardt 1999). The width of the area considered is c. 150 km. In between the escarpment and the coast granite outcrops are quite frequent, as granite is one of the dominant rocks in the Damara Group which underlies this part of Namibia. However, more prominent granite relief occurs at isolated sites only, as otherwise gravel and sand extensively mantle the topographic surface. In this study we will refer to the following granite areas; Erongo, Spitzkoppe and the Rössing Mountain in the northern part, and Mirabib, Gobabeb and Vogelfederberg in the southern one (Figure 1). Of these, Erongo is located in a dry savanna environment, Spitzkoppe is at the margin of the Namib Desert, and the remaining ones are located in a truly desert environment. Detailed topographic characteristics of each area are provided below.

The main feature of regional relief is the occurrence of an extensive rock-cut plain, which slopes gently from the footslope of the Great Escarpment down to the coast, at an average gradient of 10 m per km. Over much of the area the plain is covered by a thin veneer of weathering and alluvial origin. It is drained via numerous episodic streams and a few allochtonous rivers which flow down to the sea only several times a year. Above the plain rise inselbergs, ridges and larger mountain massifs, built of granite, gneiss, quartzite, marble and dolerite. Their height varies from a few tens of meters up to 500-600 m in the case of the Spitzkoppe group. The volcano-plutonic structure of Erongo is even higher and its prominent western, southern and eastern escarpments rise above the rock-cut plain by more than 1 km. However, the Erongo granite does not occupy such a high elevation and forms either the lower slopes of the scarp or the hilly landscape in front of the main scarp.

The long-term geomorphological history of the Central Namib may be traced back to at least the Jurassic, the period of break-up of Gondwanaland (Goudie, Eckardt 1999). After the period of rapid surface lowering at the turn of the Cretaceous, inferred from apatite fission-track analysis (Brown et al. 2000), the mean denudation rate may have been much lower in the Cainozoic, and especially since the Miocene, when aridity was established. Cosmogenic exposure dating performed on three inselbergs in the southern part of the Central Namib, including two referred to in this paper (Cockburn et al. 1999), reveal that their mean denudation rate is of the order of 5 m/m.y. and these rates may have been applicable to the last 10 m.y. This implies that high granite domed inselbergs are durable landforms of long geomorphological history and their relief has probably increased through time.

2.2. Granite geology

There are essentially two main groups of granite in the area. The older group was emplaced in association with the deformational and metamorphic events of the Damara Orogeny and ranges from early syn-tectonic dioritic plutons to late, post-tectonic alaskites and pegmatites (Schreiber 1996). Most of these intrusives date back to around 500-600 million years ago. They include the Salem Granite, a coarse-grained, biotite and K-feldspar rich porphyritic type. These pinkish to grey rocks occur in two north-east trending zones, roughly following the course of the Khan and Swakop rivers. The second group of granites is that associated with the Karoo sequence and known as Cretaceous Intrusive Complexes. They are related to the presence of the Tristan Plume, the fragmentation of Gondwanaland and the opening of the South Atlantic in early Cretaceous times around 130 million years ago (Milner et al. 1995).

2.3. Climatic gradient

The Namib has a very strong gradient of precipitation from the coast to the Great Escarpment. At the coast the mean annual precipitation is under 25 mm whereas at stations near the Great Escarpment the figure is closer to 200 mm. For example, at Walvis Bay the mean annual rainfall is only 15 mm whereas at Ganab (113 km inland) it is 87 mm.

Also significant from the point of view of rock weathering is the role of advective fogs. These result from the cooling of moist oceanic air as it passes over the Benguela Current (Olivier 1995). The amount of fog precipitation rises from the coast, where it averages 34 mm per year (precipitated on 65 days) to a maximum of over 180 mm at 35-60 km inland. It decreases sharply thereafter to only 15 mm in the east of the desert (Lancaster et.al. 1984). Temperatures also show a clear climatic gradient. Mean annual temperatures range from around 17 °C at the coast to 28-33 °C inland. The same is true for humidity. Mean annual relative humidity falls from 87% at Walvis Bay to 50% near Gobabeb and to under 40% on the eastern margin of the desert.

3. Main granite outcrops

3.1. Erongo

Erongo is the largest of the early Cretaceous Damaran Complex Intrusives and its pluton has a mean diameter of 35–40 km. It forms a large mountain mass that rises to some 1000 m above the surrounding plains, attaining a maximum altitude of 2305 m (Huser 1977; Blumel et al. 1979). It is believed to be a central caldera structure consisting of lavas and pyroclastic deposits. It was formed by cauldron subsidence, following which the granitic rocks were passively emplaced by the space provided by the subsidence (Pirajno 1990). For the most part the granites are coarse-grained, biotite-bearing varieties. They are especially well developed on the south side of the complex on Ameib Farm. Here there are large domes, clusters of large boulders (including the famous Bulls' Parties), some of which rest on small pedestals, arches, caves and many runnels and pans.

3.2. Spitzkoppe

The Spitzkoppe group dominates in the northern part of the Central Namib, where it rises above the surrounding plain by 500–600 m, attaining the altitude of 1728 m a.s.l. in the Gross Spitzkoppe. The morphology of the group is very complex and has been described by Selby (1982). It actually consists of two major hills, the big dome of Gross Spitzkoppe and the multi-domed ridge of the Pondok Mountains, separated by a 100 m wide pediment pass. On the flanks granite is more densely jointed, although massive compartments of smaller size do occur within the lower slopes. Moreover, low domes and whalebacks are quite frequent within the pediment surface surrounding the major domes. The prominent inselberg of Klein Spitzkoppe (1584 m a.s.l.) is located 15 km to the west of Gross Spitzkoppe and has relative height of 500 m. On its south-facing pediment there occur more than 10 low granite domes up to 50–70 m high. In contrast to Gross Spitzkoppe, no large domes are present within Klein Spitzkoppe. The granite of Spitzkoppe belongs to the family of Early Cretaceous (137–124 Ma) intrusions, associated with continental break-up and upwelling of the Tristan mantle plume (Milner et al. 1995). Vegetation around the Spitzkoppe is generally sparse, but acacia trees are fairly common along episodic watercourses on the pediment, and tree species such as Aloe dichotoma and Cyphostemma juttae and thorny bushes grow in topographic lows between the smooth faces of granite domes. The Spitzkoppe granites are essentially similar to those of Erongo and details of their composition are provided by Mathias (1962).

3.3. Mirabib

The inselberg of Mirabib (840 m a.s.l.) is located in the south-eastern part of the Central Namib plain, where it rises up to 100 m above its level. It is built by a few granite stocks of Precambrian age, which cut through gneiss and schist. The general morphology of Mirabib and its slope form have been described in detail by Selby (1982) who pointed to the occurrence of closely spaced domes separated by depressions developed on densely jointed granite compartments. Dome slopes are smooth and approach verticality, and the piedmont angle is very sharp; otherwise the slopes are littered with boulders of various size and shape. Vegetation is virtually absent, except a few isolated trees.

3.4. Gobabeb

Granite outcrops around the Desert Ecological Research Station at Gobabeb, c. 100 km south-east from Walvis Bay, are scattered on the northern bank of the episodic Kuiseb river and in an unnamed tributary 5 km to the north. In between, they are totally covered by the sandy-gravelly veneer of the plain. In contrast to the other areas described here, no inselbergs occur in Gobabeb. Instead, granite crops out in the form of numerous boulder-like compartments, rising at most to 3–4 m above the adjacent surface. Granite is very coarse and heavily weathered as shown by the widespread presence of grus and larger flakes. No vegetation is present. Granite outcrops at Gobabeb are referred to in Goudie (1972), Selby (1977b) and Ollier (1978).

3.5. Vogelfederberg

This is an isolated twinned inselberg c. 50 km east of Walvis Bay, rising above the gravel plain to the altitude of 527 m a.s.l.; relative height is 60 m. The group consists of two hills of contrasting morphology. The western one is a classic low-radius dome with smooth slopes and sharp contrast between them and sand-covered pediment. The eastern one takes the form of an elongated ridge, undercut by a big rock shelter on the east side. Lower slopes are covered by weathering debris and windblown sand. Hence no distinct piedmont angle is present. Vogelfederberg granite is coarse grained, of porphyritic structure, and of Precambrian age (Salem Suite). The hills are located amidst an almost bare plain covered by gypsum crust, but Zygophyllum stapffi and Arthraerua leubnitziae dwarf shrubs grow along the moisture-retaining footslope zone.

3.6. Rössing Mountain

This is a group of partly granite hills rising in a horseshoe shape to 669 m a.s.l., located c. 40 km east of Swakopmund, north of Swakopmund-Usakos road. The surrounding plain is at elevation of 350–400 m. The highest hills are on the western side of the group and slope steeply to the west, whilst on the eastern side the lower slope is mantled by a long ramp of mainly windblown sand. The granite of the Rössing Mountain belongs to the granites of the Damaran Orogeny, is predominantly fine grained, and is cut across by coarse grained alaskite veins. Most of the exposed granite mass is densely jointed according to the orthogonal pattern; massive compartments are rare and of small size. Joints and alaskite veins are subject to preferential weathering, resulting in the development of gullies. Flaking is ubiquitous and appears to proceed at a fast rate, therefore slopes are largely vegetation free, but in gullies Euphorbia and Aloe asperipholia are fairly common and occasional fog supports various species of lichens. In all but the wettest years, the surrounding desert is almost completely vegetation free.

4. Granite landforms

4.1. Domes

Many of the granite inselbergs in the Central Namib have a dome form and are therefore called bornhardts (Selby 1977a). Domes may occur in isolation (Vogelfederberg, Photo 1), be superimposed onto one another (Gross Spitzkoppe, Photo 2), or adjacent to each other (the Pondok Mountains – Photo 3, Mirabib). They vary in height, from as little as 10-15 m to as much as 600 m, and also vary in the radius and slope curvature. For example, Vogelfederberg has rather gently inclined slopes (25–30°) which may be walked on, whilst the slopes of Spitzkoppe and the Pondoks are very steep, in sections approaching verticality. In some places smooth slopes of domes descend to the piedmont angle which then is exceptionally well pronounced; in others they disappear beneath talus or orthogonally-jointed granite compartments. Selby (1977a, 1982) provided evidence that at least some dome forms are primary features, dating back to the times of emplacement.

Slope development of domed inselbergs has been outlined by Selby (1982), who argues that initially bornhardts have slope angles controlled by structure and the opening of sheeting joints operates extensively, the splendid example of which is at Mirabib (Photo 4). Steepness of sheeting joint surfaces facilitates sheet removal in a form of rock sliding and rock avalanches, evident from large taluses mantling lower slopes in many places at Erongo, Spitzkoppe and Mirabib (Photo 5). Where the domes are intersected by an orthogonal joint set, joints of the latter one progressively open up, causing slope form to adjust to reduced strength and the decrease in slope angle (Selby 1982). Other processes operating on domes are preferential weathering of sub-horizontal sheeting planes, development of rock shelters and overhang collapse (see section on caves, below).

Dome granite forms are also present in the south-western face of the major escarpment of the Erongo Massif, below volcanic rocks. They form lower, convex segments of slopes, whose height approaches 400–500 m (Photo 6). Although Erongo slopes have not been analysed in any detail, field observations and comparison with the results of Selby's research on domed inselbergs allow us to assume that these slopes are similarly strongly adjusted to the structure of granite and develop slowly through the opening of major sheeting joints.

4.2. Other hills

Not all granite inselbergs and hill clusters in the Central Namib have a rounded domical shape; some are castellated and their slopes have stepped profiles; other are extensively covered by boulders; some of the small ones would resemble tors in that they appear to be built of a number of loose boulders. The Rössing Mountains have hardly any dome compartments (Photo 7), the prominent Klein Spitzkoppe is not a dome, some of the lower hills around Gross Spitzkoppe do not show a domical outline, and at Ameib/Erongo domes and block-strewn hills are present in similar quantities. Except Klein Spitzkoppe, however, these hills are significantly lower than the domes and usually do not exceed 100 m high.

The influence of jointing patterns on the form and development of these hills is obvious. Massive structures delineated by curved sheeting joints are absent; instead an orthogonal joint pattern occurs. Vertical joints are most prominent, usually spaced 2–4 m apart. Bedrock crops out in the summit parts, and slopes are mantled by irregular boulder fields derived from in situ weathering. In contrast to the domes, no evident signs of large slope failures can be identified. At Ameib/Erongo it is possible that the difference in jointing pattern and form can be ascribed to lithological differentiation of composite granite intrusions; domes are built of the light coloured Erongo granite, whilst densely jointed parts are more granodioritic and may belong to the slightly older Ombu magmatic event. However, this cannot be the universal explanation as Klein Spitzkoppe is built of the same granite as Gross Spitzkoppe, yet the form is different.

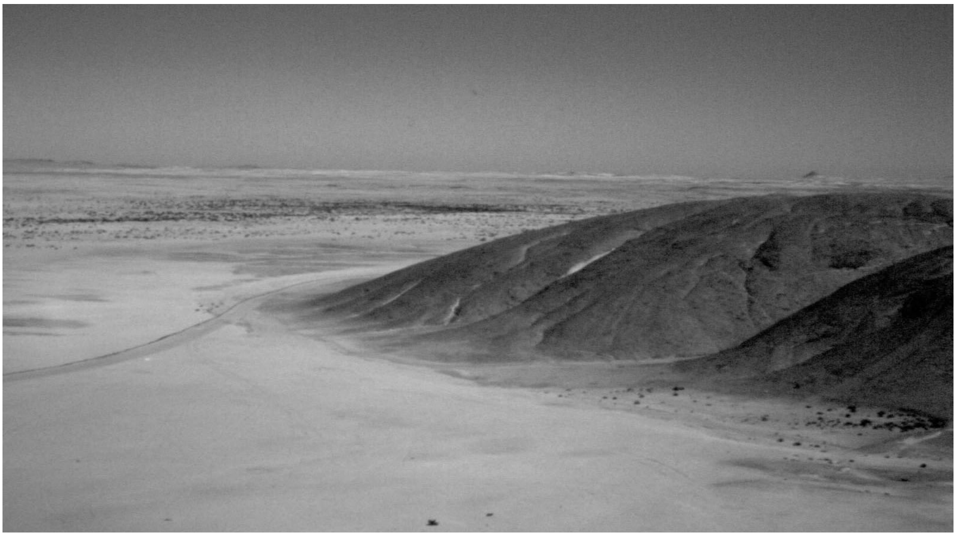

Photo 1: Smooth gently inclined slopes of the Vogelfederberg dome. Note the absence of talus and boulders on the adjacent desert plain.

Photo 2: Main dome of Gross Spitzkoppe (in the middle) surrounded by lower hills, some also related to massive domical structures. A low pediment outcrop with abundant weathering pits is in the foreground.

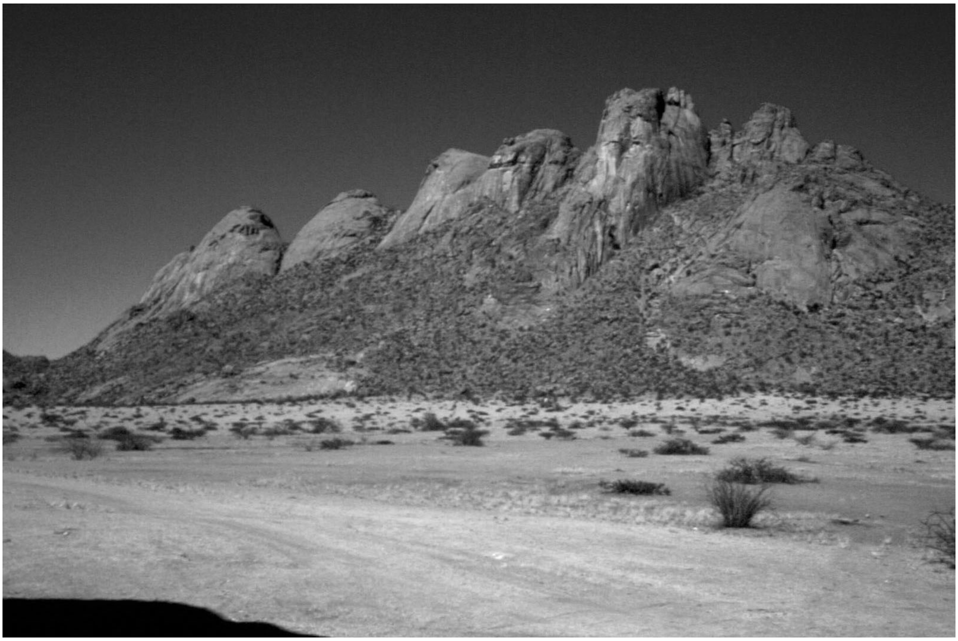

Photo 3: Closely spaced domes of the Pondok Mountains, protruding from orthogonally jointed granite.

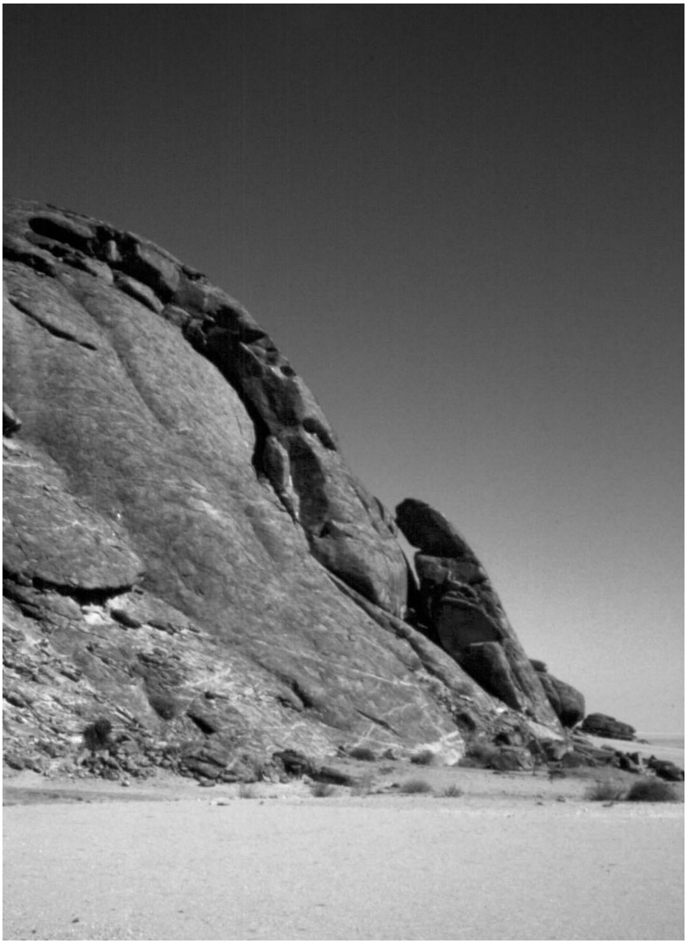

Photo 4: Mega-exfoliation due to opening of sheeting joints at Mirabib. The total height of the slope is about 80 m.

4.3. Boulders

Each block of granite on a hillslope, whether detached by weathering or slope failure, can be classified as a boulder; in this paragraph, however, we want to restrict our discussion to those boulders which occur independently from domes and other hills. In places such as Ameib/Erongo and Spitzkoppe, fairly extensive tracts of lower ground between higher granite elevations are littered with boulders of various sizes (Photo 8). Isolated boulders also occasionally crown these elevations forming picturesque pedestals or rocking stones, often of imposing dimensions (Photo 9). They have rounded shapes, display the presence of a brown protective crust (see below), and may attain 10 m in diameter.

Photo 5: Distinct piedmont angle, only partially mantled by rockslide- and rockfall-derived talus. A dome south of Gross Spitzkoppe.

Photo 6: Marginal slopes of the Erongo volcanic-plutonic structure. Smooth convex slopes in the far distance are built of the massive Erongo granite, those to left are developed in ignimbrites and lava flows.

Photo 7: Slopes of the Rössing Mountains, with prominent vertical jointing. Note the absence of dome-shaped compartments.

Photo 8: Granite landscape at Ameib/Erongo. Co-existence of domes, castellated hills, boulders and granite platforms is seen.

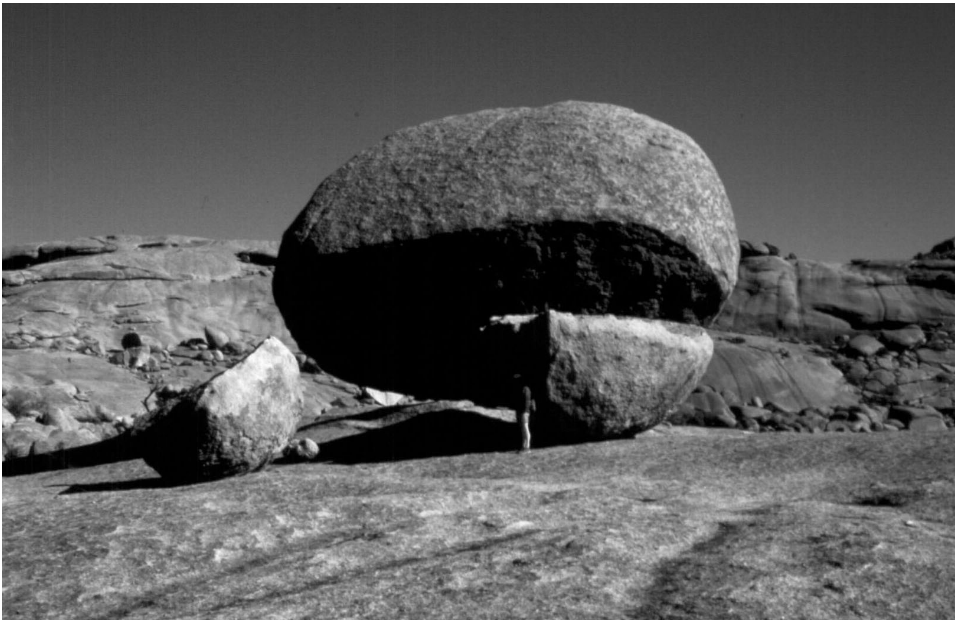

Photo 9: One of big boulders (rocking stones) on a gently inclined rock platform, with clear induced cracking. Note the person for scale.

Photo 10: Heavily tafonised exposed part of a granite boulder at Gobabeb.

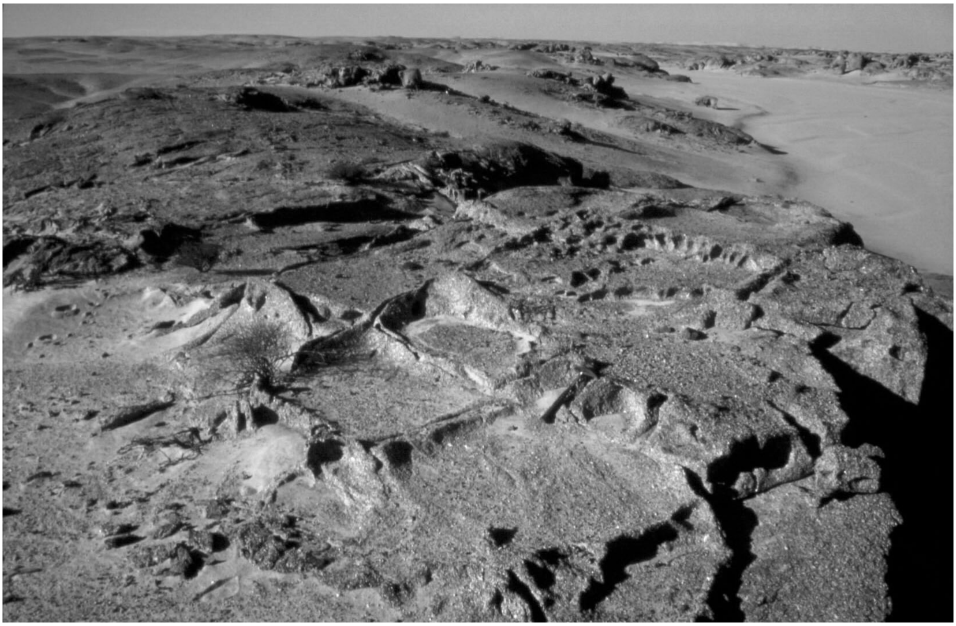

Photo 11: Granite platform at Gobabeb, with raised, case hardened rims along former joints; perhaps the ultimate stage of boulder development.

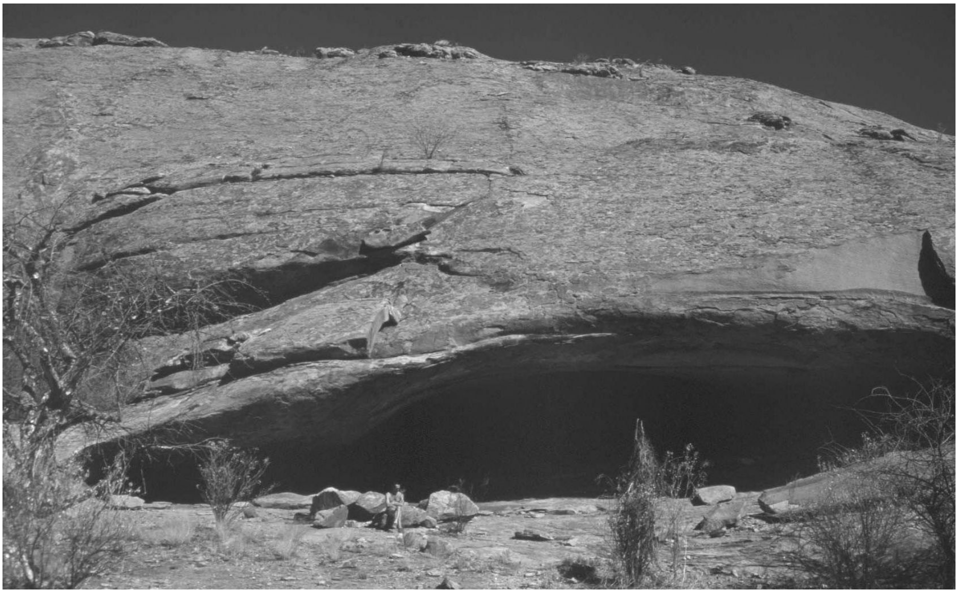

Photo 12: Philip's Cave at Ameib/Erongo. This huge overhang (note the person in front of the entrance) has develop at the intersection of dome surface and sub-horizontal sheeting joint. Big blocks before the entrance testify to rockfalls from above the overhang.

Photo 13: Big tafoni in the summit part of one of the low hills north of Gross Spitzkoppe.

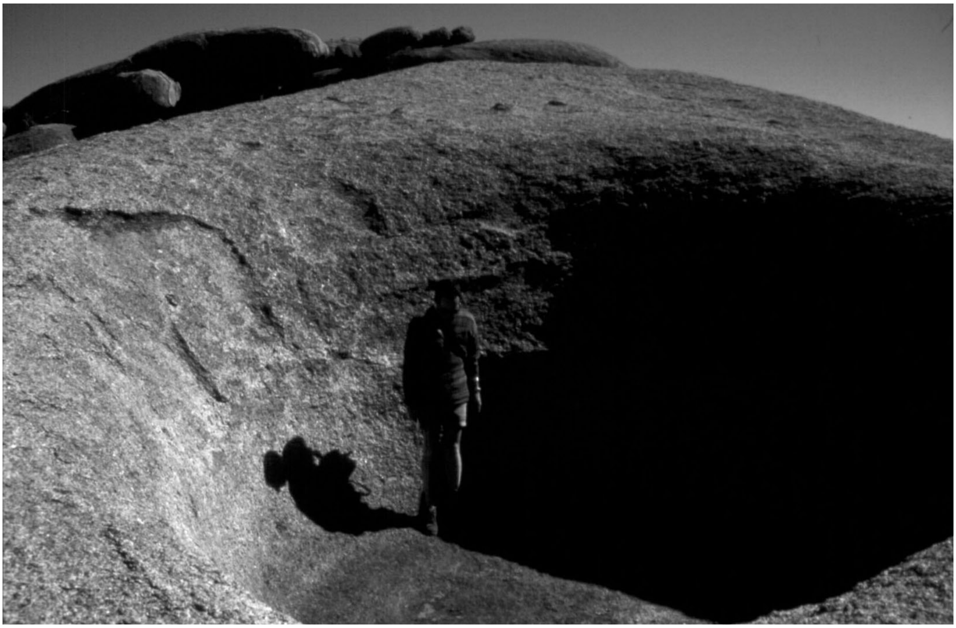

Photo 14: Big weathering pit on the summit of one of the domes, at Ameib/Erongo. Note that the pit is closed and does not have any debris infill.

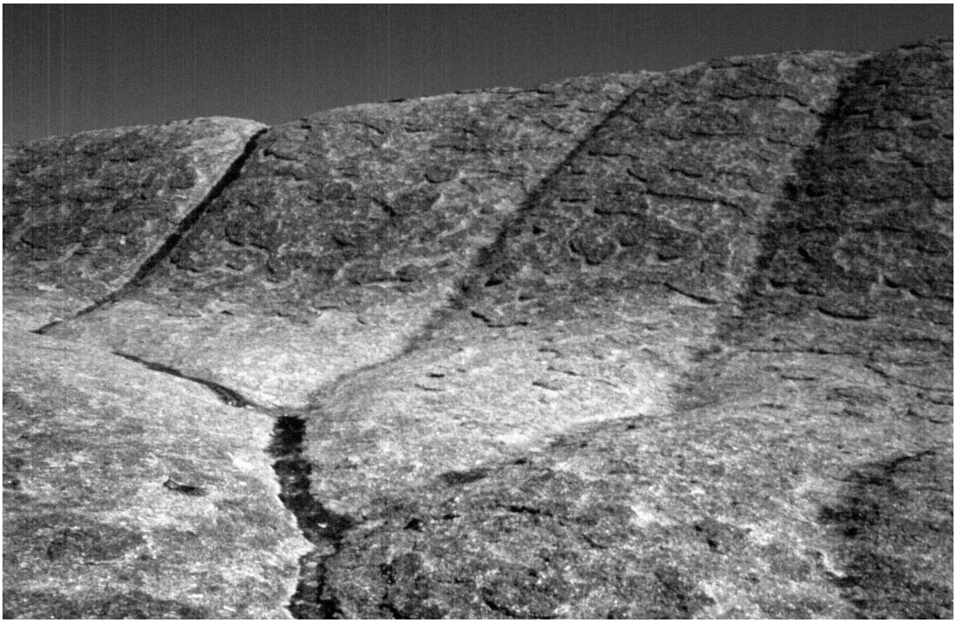

Photo 15: Shallow runnels on a gently sloping dome surface at Ameib/Erongo. The surface in between is covered by a brown crust subjected to flaking and cracking.

The situation at Gobabeb merits special attention. Boulders are irregularly distributed, spaced apart from a few to 20–30 m, and exposed at the surface to various degrees. Those fully exposed are often perfectly rounded, whilst in the case of partial exposure they look like small half-oranges or are just low (<0.5 m) convex elevations on the sandy desert floor. Co-existent with boulders are flat granite surfaces 2–3 m across, with distinctive raised rims. Exposed parts of boulders are subject to a variety of weathering processes, including exfoliation and flaking, splitting, alveolization and development of tafoni (Photo 10). Case hardening is also in operation on boulder surfaces and along joints, and raised rims show this phenomenon. It is likely that granite pavements with raised rims are the final stage of weathering-controlled subaerial boulder evolution (Photo 11).

Some of the outcrops studied do not contain any more extensive boulder fields. At Vogelfederberg, for example, smooth slopes of the dome are surrounded by the sand-and-gravel covered plain (Photo 1).

4.4. Pediments

Rock-cut surfaces covered by a thin veneer of redistributed products of granite weathering slope away from each of the larger hills in the Central Namib. Close to the piedmont angle, the rock-cut surface is occasionally exposed. Pediment surfaces are usually fairly rough, the general slope being interrupted by frequent low elevations ranging from 1–2 to 10–15 m in height. These low hills are particularly common around

Spitzkoppe and the Pondoks. In the marginal part of the Namib, pediment surfaces are locally calcretised; in the hyper-arid west, however, calcrete is replaced by gypsum crusts. The remarkable feature of the pediments is their well-developed linear drainage (Photo 9). It appears that most of the episodic flow on these surfaces is accomplished in shallow channels rather than by laterally extensive sheet floods.

It appears that geological control has been important for pediment origin and development. At a few places, at Mirabib for instance, it has been shown that the pediment is cut across the country rock and the granite itself (Selby 1977a). Around Spitzkoppe, pediments have developed across the older Salem granite or heavily jointed Erongo granite, and the low elevations of massive granite are stocks of massive younger granite. In a similar way, dolerite veins form distinct ridges on the pediments.

4.5. Caves

Caves are landforms which attract little attention in the literature on granite and, if mentioned, are regarded as geomorphological curiosities rather than features of any wider significance. Nevertheless, they are fairly common in the granites of Erongo and Spitzkoppe. Most impressive are the big overhangs in massive granite, of which the Philip's Cave in Ameib/Erongo is the best example (Photo 12). It is 50 m long, up to 10 m deep and the height of the overhang at the entrance exceeds 5 m. It has developed along a major slightly convex-upward sheeting joint plane. The 'Bushman's Paradise' in the Spitzkoppe group and the huge recess at Vogelfederberg have a similar morphology and structural predisposition.

Overhangs are important for slope development of massive domes and dome reduction in that tensional stresses above the overhang accumulate up to the point when the rock strength is exceeded and major rockfall of the roof takes place. Witnesses of this are big unweathered blocks up to 5 m long beneath overhangs and their arched roofs; the example is the fresh rockfall near 'The Giant' at Ameib/Erongo.

Another group of cave-like features are big voids in excess of 10 m long in between rockfall-derived, interlocking boulders on the lower slopes of high domes. Apart from Erongo and Gross Spitzkoppe, they also occur at Mirabib and domes around Klein Spitzkoppe. Some of the boulders involved in the roofs of these caves are up to 10 m long.

4.6. Tafoni and alveoles

Tafonization and alveolisation of granite outcrops is very common in the Central Namib, although the types, dimensions and controlling factors of cavernous weathering features differ from place to place. The biggest tafoni have been found in the Spitzkoppe granite, within the low domes north of the main hill (Photo 13). They attain dimensions of 12 m across, up to 3–4 m deep and up to 3–4 m high. Their inner sides are intensively flaked and the floors are covered by weathering debris. The pale, flaked inner sides of the tafoni stand in marked contrast to the outer surfaces of the outcrops, with their brown crust. Big tafoni also occur on the massive domes of Mirabib. Tafonization also affects granite boulders which then take the form of a hollow boulder. At the final stage of development it is only the crusted outer surface present, whilst the interior is a huge void up to 2.5 m high. Boulder-covered slopes of domes in Gross Spitzkoppe and Klein Spitzkoppe group provide many splendid examples.

A good example of lithological control on tafoni development is observed in the Rössing Mountains. Tafoni are restricted to the rather thin veins of coarse grained alaskite and this is why they cannot attain larger depths; in a few cases it was observed that the back side was built of the jointed fine grained granite, which is not conducive to cavernous weathering. Instead, it appears to release flakes and joint bounded small blocks at a fast rate, as may be inferred from the large talus covering lower slopes. Other interesting effects of tafonization and case hardening have been observed on joint-delineated granite boulders at Gobabeb. Tafoni are preferentially located along the base of boulders, growing inside from one side whilst case hardened surfaces develop on the other ones (Photo 10). As soon as tafoni is large enough, the roof collapses and only case hardened rims remain on the surface.

Alveolization is ubiquitous on granite outcrops at Gobabeb and Vogelsfederberg, but is less common on other granite outcrops.

4.7. Weathering pits

Weathering pits from various places in the Central Namib have already been extensively described by Goudie and Migon (1997). Hence only the main characteristics will be given here. It appears that pits developed in the massive granites of Spitzkoppe and Erongo rank among the biggest features of this kind described so far (Photo 9). More than 50% of the pits investigated were larger than 2 m across, and diameters in excess of 5 m were not uncommon. Most pits were relatively shallow (pan-like) if compared to their diameters (<0.5 m), but at Ameib a closed pit more than 3 m deep and 6 m across has been found (Photo 14). Locally pits can cover up to one third of the total outcrop surface. Although the exact processes involved in the development of pits are poorly known, especially as far as evacuation of debris from apparently closed pits is concerned, there is no doubt that pits play an important part in the reduction of low elevations on the pediment surfaces, in the manner similar to one described by Dzulynski and Kotarba (1979) from semi-arid Mongolia.

Abundance of weathering pits in massive granites of Spitzkoppe and Erongo can be contrasted with their scarcity in other areas reported here. At Vogelfederberg, where granite is similarly massive, there are only a few shallow (<0.2 m) depressions with a diameter approaching 1 m. However, the entire upper surface is subjected to intensive flaking, whilst granite surfaces at Spitzkoppe and Erongo are much less flaked and often carry a few cm thick brown crust. At Mirabib no clear pits have been seen, even though the granite is locally quite massive as well, nor do they occur at Gobabeb and Rössing Mountain.

4.8. Other surface features

Various minor superficial features are present on the granite outcrops in the Central Namib. Most abundant is flaking, which is particularly well-developed in the south--western, hyper-arid part of the study area (Vogelfederberg, Gobabeb). Flakes are usually multiple; under small overhangs more than 10 flakes superimposed onto each other occur. At Spitzkoppe and Erongo small-scale flaking is less common; flakes are thicker (> 2 cm) and often restricted to the thickness of the brown crust.

The brown crust is present only in the wetter part of the Namib (Besler 1979) as at Spitzkoppe and Erongo. It invariably covers surfaces of massive domes, tors and low pediment elevations, and isolated boulders, but not the inner sides of weathering pits. Its thickness may exceed 5 cm. The crust appears to be in a state of decay and shows some degree of cracking (Photo 15). Locally, rectangular and hexagonal crack patterns are present. In the more arid part the brown crust seems to disappear and is replaced by blackish case hardening.

Shallow runnels, apparently used by running water, dissect the smooth slopes of topographic domes (Photo 12). They can be as long as 10–15 m (Ameib) and 15–20 cm wide. Both dendritic and parallel patterns are observed. A black algal crust covers the floors of the runnels. Some of these runnels are clearly lithologically controlled, such as at Vogelfederberg, where they follow the sinuous pattern of pegmatite veins. They have been found at each large outcrop, except Gobabeb where the size of the boulders is not sufficient for micro-catchments to develop, and the Rössing Mountain, where no domes are present.

5. Present-day granite weathering

The presence of tafoni, alveoles, caves, flakes, pits and crusts indicates that weathering has played an important role in the modification of granite surfaces. It is, however, difficult to ascertain the importance of specific weathering processes. None the less, in spite of the degree of aridity that the area experiences, there are two circumstances that may promote surface weathering: fog and salt. Fogs occur with considerable frequency in the coastal zone, causing rock surfaces on domes like Vogelfederberg, to be moistened on many days in the year. This can facilitate superficial chemical weathering and cycles of salt crystallisation. In addition, the area is characterised by the widespread occurrence of halite and gypsum crusts. Both field monitoring with rock blocks (Goudie et al. 1997) and laboratory simulations (Goudie, Parker 1998) suggest that the coastal portion of the central Namib is an highly aggressive weathering environment (see also Lageat 1994; Bulley 1986). However, studies further inland, at Mirabib, showed no evidence of salt attack.

6. Granite landforms – recent or inherited?

Much of the discussion on the geomorphology of the Namib has focused on the possibility of inheritance in the present-day landscape. In this context granite landforms, and particularly inselbergs, are no exception.

Hövermann (1978) argued that deep chemical weathering was playing the major part in the formation of granite inselbergs and the domes are most resistant compartments excavated from the saprolite. Apparently, he transferred to the Namib the model of two-stage origin of bornhardts, as outlined earlier in the humid tropics (cf. Thomas 1965). The validity of this concept was, however, doubted by Selby (1977a) and Ollier (1978), who pointed to the total absence of any deep regolith in the Namib. Later on, Selby (1982) provided the geomechanical context for the analysis of the inselbergs in the Namib and, using the rock mass strength approach, demonstrated that their slopes are adjusted to the geological structure and there is no necessity to invoke deep weathering as being antecedent to bornhardt formation.

The rounded boulders have also been regarded as witnesses of selective subsurface weathering (Hövermann 1978). However, at Ameib, where boulders are most abundant, there are no signs of former selective deep weathering, which would have produced corestones, then exposed as rounded boulders. Features of large boulder fields such as those around Gobabeb do not support such a two-stage hypothesis either. In the absence of any deeper soils, not to mention saprolitic cover, the co-existence of boulders at various stages of exposure and development is best explained by the continuous excavation and destruction of more massive, structurally-predisposed compartments as the surface is lowered.

Smaller landforms such as weathering pits also seem to be developing at present, as inferred from widespread flaking of their floors and sides, low Schmidt hammer reading values, and fine detritus within the pits (Goudie, Migon 1997). Similarly, grus-covered floors of tafoni and extensive flaking of their back sides are clear indicators of recent development.

It appears that the only superficial feature of granite outcrops in the study area which no longer forms is the brown crusting, so well developed at Erongo and Spitzkoppe. It probably formed under a former, more humid climate and predates the extensive development of weathering pits. Unfortunately, the age of the crust, and hence the age of pit initiation, remains unknown.

In summary, it appears that most of the granite landforms and landscapes described here are actively evolving today and no unequivocal signs of relief inheritance in the form of 'relief generations' can be identified in the Central Namib. Large domes and debris-veneered hills are subjected to continuous exposure and adjustment to structure as the surrounding country rock is worn down, and the massiveness of granite, especially of Mesozoic granite, aids their survival and increase relative relief. However, their slopes are active features as shown by big rockfall-derived talus. Low elevations on pediments and boulders, once exposed, are reduced to rock-cut platforms by the variety of currently active weathering processes, including pit and tafoni development, flaking and granular disintegration. Possibly, long-term climatic stability and strong lithostructural control, the issues discussed in the next paragraph, explain no identifiable alterations in the geomorphic development of granite landscapes in the Late Cainozoic.

7. Climatic versus lithostructural control

The role of lithological and structural control appears dominant in the development of the variety of granite landforms in the Central Namib, and clearly outweighs the influence of climate, past or present. The evidence to support this statement includes the following facts. None of the large and medium-size landforms is restricted to particular, climate-defined part of the Central Namib, and actually they occur at both east and west climatic extremities of the study area. Distribution patterns of major landforms show distinct sympathy to the differences in structure and lithology. Topographic domes and big boulders are present where there occur massive granite compartments, the form of which can often be traced back to the time of emplacement. Domes and block-strewn hills frequently co-exist, in relation to contrasting jointing patterns. Hill height and form are usually adjusted to the pattern of sheeting joints, and the evolution of slopes proceeds towards the development of strength-equilibrium (Selby 1982). Among the small-scale landforms, large pits and tafoni are evidently restricted to massive coarse Mesozoic granites. It is only some minor surface features whose distribution appears to be influenced by climatic factors. Weathering pits tend to disappear if aridity increases, as do brown crusts. On the other hand, flaking and alveolization become more pronounced towards the coast.

Long-term climatic stability of the Central Namib may have aided to the manifestation of structure. There is some evidence that the central Namib has been a zone of considerable climatic stability during the period since the emplacement of the early Cretaceous Intrusive Complexes. There is certainly no convincing evidence for any prolonged phase of great humidity of the type that would be required for deep weathering and saprolite development. It is conceivable that aridity may have been the dominant climatic condition since the time of continental fragmentation itself, for aeolianites of the Etjo Formation are interdigitated with the early Cretaceous Etendeka Lavas (Miller et al. 1994). Moreover, the aeolianite of the Tsondab Sandstone Erg, which underlies much of the current Namib Sand Sea, dates back to at least the lower Miocene and overlies wind-sculptured rocks of Late Proterozoic age (Senut et al. 1994). Aridity was intensified with the establishment of the Benguela Current in the Miocene (Siesser 1980). Evidence for humid phases in the Pleistocene is limited and equivocal, and although there are various lake, pond and tufa deposits, Heine (1998) has argued that the offshore Benguela Current has been relatively stable during the Late Quaternary, thereby helping to maintain arid conditions. Ward et al. (l983:182) have therefore concluded that "A review of the Late Mesozoic – Cenozoic geology leads us to conclude that the Namib tract, which dates back to the Cretaceous, has not experienced climates significantly more humid than semi-arid for any length of time during the last 80 million years."

8. Conclusions

The central Namib displays a remarkable diversity of striking granite landforms, and some of these have exceptional dimensions: domes 600 m high, boulders more than10 m across, pits over 5 m in diameter and tafoni that exceed 5 m in height. A contributory factor to this is the massiveness of the granites associated with the Cretaceous Intrusive Complexes. Structure appears to be the dominant control of the distribution and development of the major forms, and influences the shape, dimensions and slope evolution of the major domes.

In spite of the aridity, the central Namib displays a full range of granite features, such as bornhardts, pits and runnels, many of which have often been seen as characteristic of humid climatic regimes. Moreover, despite the strong climatic gradient of the area, there is no corresponding zonation of major granite landforms, though for some of the small ones there is. Pits tend to disappear towards the coast, alveoles become more common there, and the surface crusts are less well developed and of a different kind.

The area shows little evidence of prolonged humid climatic conditions over the last 130 million years and no signs of deep weathering. Erosion and weathering under long-continued conditions of aridity and semi-aridity have served to reveal the profound importance of rock structure.

In addition, although some climatic influence on the distribution of some minor weathering forms can be recognised, none of the large and medium-sized landform types is restricted to a particular climate-defined tract of the central Namib. It is apparent, therefore, that the predominant control on landform characteristics is structure rather than climate. The pattern and spacing of joints, the mode of emplacement and texture are crucial factors.

Acknowledgements

Piotr Migon is grateful to the Royal Society, for covering his travel expenses while he held a fellowship at the University of Oxford. All the plates in this paper are by Piotr Migon.

References

BESLER H. (l979): Feldversuche zur aktuellen Granitverwitterung und Rindenbildung in der Namib (Sudwestafrika, Namibia). Stuttgarter Geographische Studien, 93, 95–106, Stuttgart.

BLUMEL W-D., EMMERMANN R., HUSER K. (1979): Der Erongo. Geowissenschaftliche Beschreibung und Deutung eines sudwestafrikanischer Vulkankomplex. Scientific Research Series, South West African Scientific Society, 16, 140 pp.

BULLEY B. G. (1986): The engineering geology of Swakopmund. Communications of the Geological Survey of South West Africa/Namibia 2, 7–12.

BROWN R. W., GALLAGHER K., GLEADOW A. J. W., SUMMERFIELD M. A. (2000): Morphotectonic evolution of the South Atlantic margins of Africa and South America. In: Summerfield, M. A. (ed.), Geomorphology and Global Tectonics, John Wiley & Sons, 255–281, Chichester.

COCKBURN H. A. P., SEIDL M. A., SUMMERFIELD M. A. (1999): Quantifying denudation rates on inselbergs in the central Namib Desert using in-situ produced cosmogenic ^{10}Be and ^{26}Al. Geology 27, 399–402.

DZULYNSKI S., KOTARBA A. (1979): Solution pans and their bearing on the development of pediment and tors in granite. Z. Geomorph. N. F. 23, 172–191.

GOUDIE A. S. (1972): Climate, weathering, crust formation, dunes and fluvial features of the Central Namib desert, near Gobabeb, South West Africa. Madoqua 1, 15–31.

GOUDIE A. S., ECKARDT F. (1999): The evolution of the morphological framework of the Central Namib Desert, Namibia, since the Early Cretaceous. Geogr. Ann. 81A, 443–458.

GOUDIE A. S., MIGON P. (1997): Weathering pits in the Spitzkoppe area, Central Namib Desert. Z. Geomorph. N. F. 41, 417–444.

GOUDIE A. S., PARKER A. G. (1998): Experimental simulation of rapid rock disintegration by sodium chloride in a foggy coastal desert. Journal of Arid Environments 29, 129–138.

GOUDIE A. S., VILES H. A., PARKER A. G. (1997): Monitoring of rapid salt weathering in the central Namib desert using limestone blocks. Journal of Arid Environments 37, 581–598.

HEINE K. (1998): Climate change over the past 135 000 years in the Namib Desert (Namibia) derived from proxy data. Palaeoecology of Africa 25, 171–198.

HÖVERMANN J. (1978): Formen und Formung in der Pränamib (Flächen-Namib). Z. Geomorph. N. F., Suppl.-Bd. 30, 55–73.
HUSER K. (1977): Namibrand und Erongo. Karlsruher Geographische Hefte 9, 214 pp.
LAGEAT Y. (1994): Le desert du Namib central. Annales de Geographie 103, 339–360.
LANCASTER J., LANCASTRER N., SEELY M. K. (1984): Climate of the Central Namib Desert. Madoqua 14, 5–61.
MATHIAS M. (1962): A disharmonious granite: the Spitzkop granite, South West Africa. Transactions of the Geological Society of South Africa 65, 281–292.
MILLER S. C., DUNCAN A. R., EWART A., MARSH J. S. (1994): Promotion of the Etendeka Formation to Group status: a new integrated stratigraphy. Communications of the Geological Survey of Namibia 9, 5–11.
MILNER S. C., LE ROEX A. P., O'CONNOR J. M. (1995): Age of Mesozoic igneous rocks in northwestern Namibia and their relationship to continental breakup. J. Geol. Soc. London 152, 97–104.
OLIVIER J. (l995): Spatial distribution of fog in the Namib. Journal of Arid Environments 29, 129–138.
OLLIER C. D. (1978): Inselbergs of the Namib Desert. Processes and history. Z. Geomorph. N. F., Suppl.-Bd. 31, 161–176.
PIRAJNO F. (1990): Geology, geochemistry and mineralisation of the Erongo Volcanic Complex, Namibia. South African Journal of Geology 93, 485–504.
SCHREIBER U. M. (1996): The geology of the Walvis Bay area. Windhoek: Geological Survey of Namibia, 50pp.
SELBY M. J. (1977a): Bornhardts of the Namib Desert. Z. Geomorph. N. F. 21, 1–13.
SELBY M. J. (1977b): On the origin of sheeting and laminae in granitic rocks: evidence from Antarctica, the Namib Desert and the central Sahara. Madoqua 10, 171–179.
SELBY M. J. (1982): Form and origin of some bornhardts of the Namib Desert. Z. Geomorph. N. F. 26, 1–15.
SENUT B., PICKFORD M., WARD J. (1994): Biostratigraphie de eolianites neogenes du sud de la Sperrgebiet (Desert de Namib, Namibie). Comptes Rendus de l'Academie des Sciences de Paris, 318, 1001–1007.
SIESSER W. G. (1980): Late Miocene origin of the Benguela upwelling system off northern Namibia. Science 208, 283–285.
THOMAS M. F. (1965): Some aspects of the geomorphology of domes and tors in Nigeria. Z. Geomorph. N. F. 9, 63–82.
WARD J. D., SEELY M. K., LANCASTER N., (1983): On the antiquity of the Namib. South African Journal of Science 79, 175–183.

POVRCHOVÉ TVARY NA GRANITECH V CENTRÁLNÍ NAMIBII

Résumé

Centrální Namibijská poušť v Namibii je extrémně aridní oblastí. Vyskytuje se v ní mnoho typů granitových povrchových tvarů, které zahrnují dómy, balvany, pedimenty, jeskyně, tafoni, dutiny, zvětrávací jámy a šupiny. Mnohé z těchto tvarů mají mimořádné rozměry: dómy vysoké 600 m, balvany s průměrem přes 10 m, jámy s průměrem přes 5 m a tafoni s výškou nad 5 m. Granity jsou dvojího stáří: 1) z období Damaranské orogeneze (500–600 milionů let), 2) z období rané křídy, spojené s fragmentací Gondwany a otvíráním jižního Atlantiku.

Podstatným faktorem výrazné rozmanitosti nápadných granitových tvarů je masivnost granitů spojená s intruzivními komplexy křídového stáří. Geologická struktura je dominantním faktorem, který určuje výskyt a vývoj hlavních povrchových tvarů o ovlivňuje podobu, rozměry a vývoj svahů velkých dómů. Přes strmý klimatický gradient od pobřeží Atlantického oceánu k masivu Great Escarpment vzhled hlavních granitových útvarů vykazuje malé změny podél tohoto gradientu. Je také nepravděpodobné, že zde probíhalo hluboké zvětrávání v dlouhodobě humidních podmínkách, protože historii aridity této oblasti lze dokumentovat již od rané křídy. Proto lze vyslovit závěr, že rozhodujícími faktory při vzniku povrchových tvarů této oblasti jsou litologické a strukturní vlastnosti granitů.