Popups on Moon Rock, Augrabies Falls National Park

C. PLUG and I. PLUG

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Naturally occuring popups (or A-tents) occur mainly on outcrops of horizontally compressed, sheeted granite. They consist of two slabs of surface rock pushed up to form a tent-like structure, or a surface sheet pushed up into an arc. Although popups have been studied in several countries, none have so far been described in South Africa. A survey of Moon Rock, a granite dome in the Augrabies Falls National Park, led to the discovery of 14 of these structures, including both angular and arched forms. The dimensions and orientations of the high, angular forms support the hypothesis that they constitute a stress release phenomenon, but the characteristics of the low, thin plated forms suggest that these are erosional features. The structures are eventually destroyed by the movements, as yet largely unexplained, of surrounding rock slabs, and by the gradual abrasion of the edges of the popped up slabs as a result of slight movements caused by daily heating and cooling of the surface sheet.

Key words: popups, A-tents, minor granite landforms, Augrabies.

C. Plug, Theo van Wijk Building 5-46, University of South Africa, P.O. Box 392, Pretoria 0003, Republic of South Africa; I. Plug, Transvaal Museum, Paul Kruger Street, Pretoria 0002, Republic of South Africa.

Introduction

Granite is a common and widely distributed lithology in South Africa, as in many other countries. A number of characteristic landforms are associated with this rock type, for example "castle koppies" (tors) consisting of quadrangular blocks, and granite domes or "inselbergs". The latter are now generally known as bornhardts, after the German explorer who first studied them in East Africa a century ago, although the flatter varieties are also referred to as "whalebacks" (Twidale 1982). Moon Rock, a prominent feature in the Augrabies Falls National Park (Northern Cape), is a typical example (Fig. 1).

The surfaces of bornhardts often display a variety of features that are characteristic of granite surfaces, although these features may also occur on other rock types. These so-called "minor granite landforms" include rock slabs of various sizes and thicknesses, a variety of basins, pans and other weathering hollows, water-worn surface channels, and flared (overhanging) slopes. Most enigmatic of all, however, are the so-called "popups" or "A-tents". Angular popups consist of two roughly rectangular flat plates of rock, continuous with the surface sheet along their outer edges, but standing some distance above the surface where they lean against each other in the middle of the feature, forming a triangular cavity between the two plates and the underlying surface (Fig. 2). Arched popups are so called because their plates are slightly curved convex upward, and do not always have visible fractures at the apex (crestal fracture) or at the base (terminal fractures) (Fig. 3). Twidale & Sved (1978) suggested that the arched forms develop into angular forms through the formation of crestal and terminal fractures.

Popups have been reported from several countries, including Australia, the USA, Malaysia, Canada and Guyana (Twidale 1982). They usually occur on granite, but have also been found on sandstone and lime-

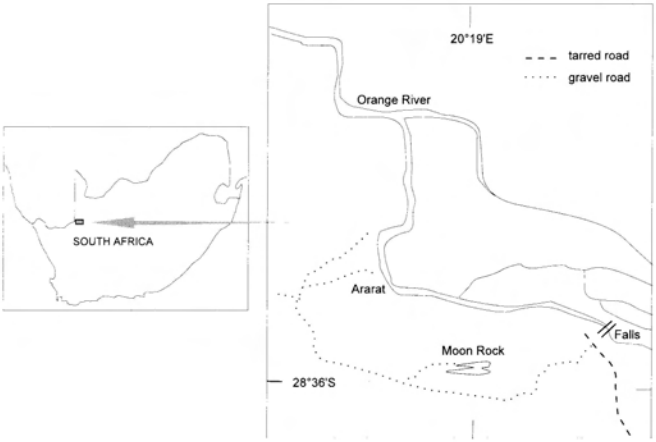

Fig. 1. Location map showing position of Moon Rock.

stone. Although they usually occur naturally, some have formed on the floors of rock quarries.

Some years ago Twidale (1988), in a review of granite landscapes in South Africa, noted that no popups had as yet been reported in this country and a literature search indicates that none have been described since. The main purpose of this article is to report on the occurrence of a number of popups in the Augrabies Waterfall National Park, and more specifically on Moon Rock. A study of 14 of these structures has yielded information that largely supports, but in some respects modifies or expands, current ideas on their formation and eventual fate.

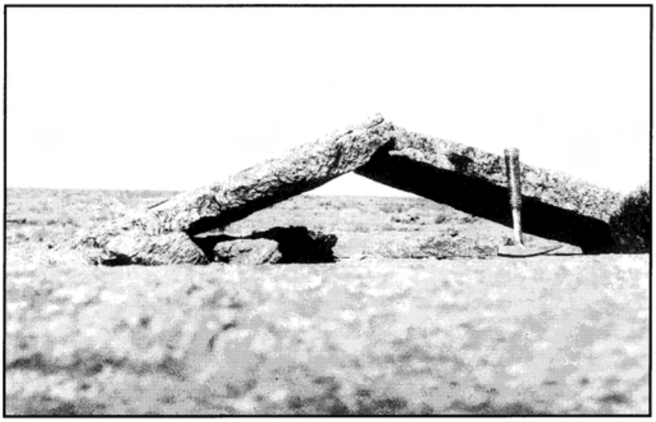

Fig. 2. A typical angular, thick plated popup (number 5) on Moon Rock.

Moon Rock and its setting

Moon Rock and the surrounding rock domes, including those at Ararat and in the area around the Augrabies Falls, are outcrops of Augrabies granite, a poorly foliated, medium to coarse grained biotite-hornblende-granite (Praekelt, 1989). This granite intrusion of about 9 km × 13 km forms part of the 1000–1200 Ma Namaqua Metamorphic Province (e.g., Geringer *et al.* 1990).

Two distinct sets of near-vertical main joints, one running north-south and the other east-west, are developed in the granites of the Augrabies area. For some 10 km downstream of the falls the course of the Orange River is controlled by these joints, as indicated by its rectangular flow pattern along the north-south and east-west directions (Slabbert & Malherbe 1983).

Moon Rock and other nearby granite domes and platforms some tens to hundreds of meters in size are delineated by these joints. They stand out above the surrounding landscape because they are more resistant to weathering, as the blocks on which they are formed have fewer fractures than the surrounding granite, which weathers mainly through the action of water entering fractures. As long as granite remains dry it is very resistant to chemical weathering. Hence most weathering, including the formation of bornhardts, occurs under a moisture retaining soil cover, with the domes emerging as the overlying soil is eroded away (Twidale 1993).

Moon Rock comprises two east-west trending elongated domes joined in the middle, rising about 30 m above the surrounding landscape (Fig. 4). The northern dome is the main one and contains most of the features described in this article. It is about 700 m long and up to about 100 m wide. The steepest slopes are on the northern side, which is practically vertical in places. The slope from the crest to the western extremity is quite gentle (about 4° on average). Towards the east the dome slopes down more steeply (about 9° on average), ending in the bed of a small ephemeral stream that runs northwards towards the Orange River, about 1 km away.

Most granite domes, including Moon Rock, have well developed sheet-joints. These consist of narrow sheet fractures near the surface that divide massive, relatively homogeneous rock such as granite into sheets or lenses. The sheets, which may vary in thickness from a few centimeters to a few meters, are generally parallel to the rock surface. Hence they curve with the dome, which as a result seems to be composed of layers somewhat like those of an onion (Holzhausen 1989). Such exfoliation is a necessary condition for the formation of popups, as the latter are formed by plates or

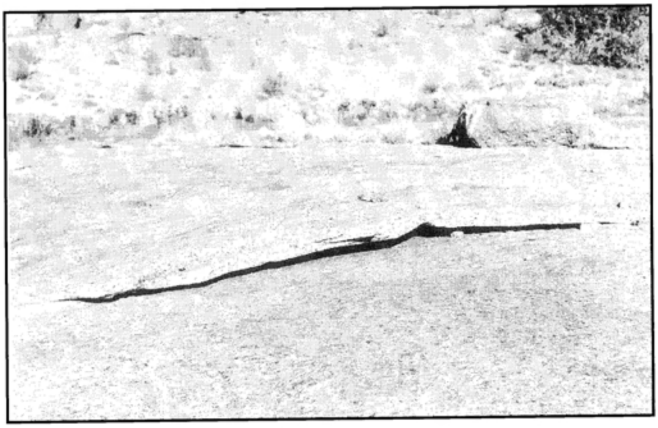
Fig. 3. An arched popup (number 7).

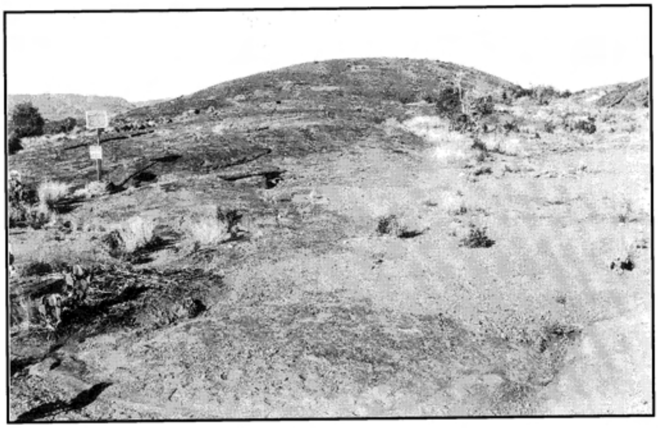
Fig. 4. The northern dome of Moon Rock, seen from its western extremity. Twelve of the 14 popups described in this article are situated on this dome.

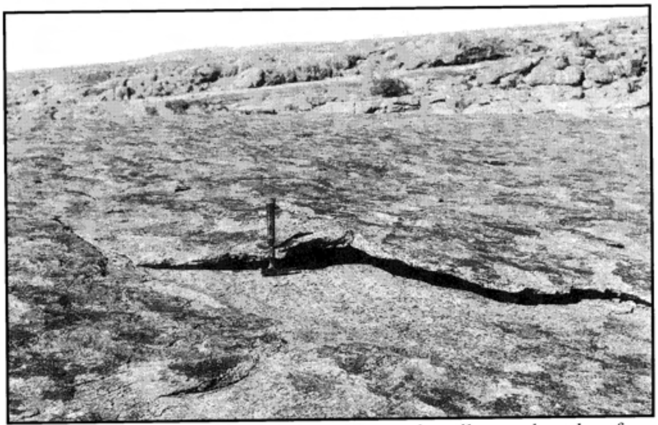
Fig. 5. A typical low, thin plated popup on a heavily weathered surface (number 6).

Table 1

Measurements of 14 popup structures on Moon Rock. All lengths are in meters. L1 and L2: mean length of plates, crest to terminal fracture; W: mean width of plates; t: mean thickness of plates; Exp: calculated expansion of sheet into popup space; E(%): expansion as a percentage of L1 + L2; Aspect (direction of downslope): clockwise from north; Slope: angle between the rock surface under the popup and the horizontal; Orient: direction of the crestal fracture relative to north, with positive angles eastwards

No	L_1	L_2	W	height	t	Exp	E(%)	Aspect	Slope	Orient	
1	0.85	1.07	1.5	0.40	0.12	0.077	4.0	280°	5°	-24°	
2	1.03	2.18	3.4	0.91	0.19	0.499	15.5	210°	15°	-7°	
3	1.69	2.26	1.7	0.33	0.09	0.027	0.7	356°	18°	4°	Group I
4	1.60	1.65	2.3	0.70	0.11	0.218	6.7	168°	15°	16°	
5	1.05	1.20	1.5	0.35	0.08	0.062	2.8	152°	3°	-10°	
6	0.97	1.63	1.5	0.10	0.07	-0.003	-0.1	287°	7°	-7°	
7	1.40	1.88	1.2	0.08	0.08	-0.004	-0.1	100°	12°	-72°	
8	0.60	[a]	1.1	0.06	0.09			95°	14°	45°	
9	0.45	0.88	1.0	0.04	0.03	-0.002	-0.1	344°	10°	-68°	Group II
10	0.74	0.76	0.7	0.04	0.04	-0.002	-0.1	209°	7°	62°	
11	0.81	1.10	1.1	0.05	0.04	-0.002	-0.1	180°	31°	16°	
12	3.80	[a]	4.0	0.16	0.15			330°	6°	-15°	
13	2.40	3.30	2.9	0.12	0.12	-0.005	-0.1	292°	3°	26°	Group III
14	1.80	1.95	1.3	0.09	0.13	-0.008	-0.2	214°	4°	8°	

[a] No terminal fracture present

arches of rock that form part of the outer surface sheet of the granite dome.

Description of the popups on Moon Rock

A brief survey of Moon Rock during a visit to the Park in September 1996 led to the identification of 14 popups, which were subsequently measured, photographed and described. Their characteristics are summariaed in Table 1. Numbers 1 to 5 (which will be referred to as Group I) are fairly similar. Their plates are flat, so that they are angular rather than arched; all are quite high (0.33–0.91 m); the plates are fairly thick (80–190 mm); and the upper surfaces of the plates are reasonably fresh. Numbers 6 to 11 (Group II) form a second homogeneous category (Fig. 5). Their plates are generally smaller and thinner (30–90 mm) than those in Group I, the top surfaces are uneven owing to heavy weathering and are covered by a brown to black patina, the structures are all quite low (0.04–0.10 m), and some are arched (one plate of numbers 7 and 9, and both plates of numbers 8 and 11). The remaining three structures form a third category (Group III). They are thick plated, angular and relatively fresh looking like those of Group I, but are quite low like those of Group II.

The plates are usually irregular in width, with pieces broken away especially near the crest. Some of these pieces are still lying where they fell, and were probably broken off when the structures were pushed up.

Most of the structures are asymmetrical. The length ratio of the longer to the shorter plate varies from 1.03 to 2.12 with a median value of 1.34.

The two terminal fractures of each structure are more or less parallel. More specifically, the difference in direction between them varies from zero to 32°. Similarly, the crestal fracture is more or less parallel to the terminal fractures, except in structure number 2, the plates of which are triangular.

The popups on Moon Rock, like those elsewhere, are not confined to a particular side of the dome but occur on surfaces with widely different aspects (i.e., surfaces sloping in different directions). The steepness of the slopes on which they are found range from 3° to 18° for 13 of the 14, but structure number 11 occurs on a much steeper slope of 31°.

Analysis of popup geometry

The shape of the high angular structures in Group I suggests that the combined lengths of the two plates exceeds the length of the open space in the sheet below them. This is difficult to ascertain by direct measurements, as the fractures are in most cases too irregular to achieve the required accuracy. However, geometric analysis of an idealiaed structure (Fig. 6) allows one to determine the extent to which the surrounding sheet has expanded into (or contracted away from) the opening under the popup.

Before the structure arose, the plates occupied a space with length $L_1 + L_2$ (see Fig. 6). The present length of the same space can be calculated from the dimensions of the structure, namely:

$$L_1.\mathrm{Cos}\,A_1 + t.\mathrm{Sin}\,A_1 + L_2.\mathrm{Cos}\,A_2 + t.\mathrm{Sin}\,A_2$$

with $\mathrm{Sin}\,A_1 = h/L_1$ and
$\mathrm{Sin}\,A_2 = h/L_2$.

Subtracting the result from $L_1 + L_2$ provides the amount of expansion (or contraction) of the adjacent sheet. When the structure is symmetrical, that is, when the plates are of equal length, the above expression reduces to the simpler form derived earlier by Twidale and Sved (1978).

As indicated in Table 1, popups numbers 1 to 5 (Group I) appear to have been pushed up through expansion of the adjacent sheet by various amounts. The geometry of structures 6 to 14, on the other hand, suggests that the adjacent sheet did not expand, and may even have contracted by a few millimeters after the popups were formed. These findings are in line with those of Twidale and Sved (1978), who reported that the openings of thick slabbed popups had been reduced by 3% to 4% owing to expansion of the surrounding sheet, whereas thin slabbed ones reflect some contraction.

The excessive steepness of structure number 2 (Fig. 7), however, has a secondary cause. On its upslope side the sheet is fractured into a series of slabs that have all been displaced down the slope (towards the popup) by small

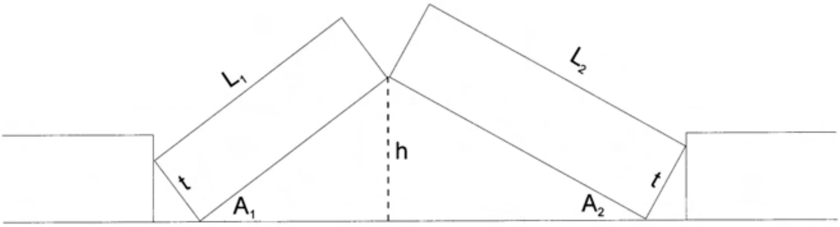

Fig. 6. Model of an angular popup, used to calculate the extent to which the adjacent sheet has expanded into the space originally occupied by the two plates.

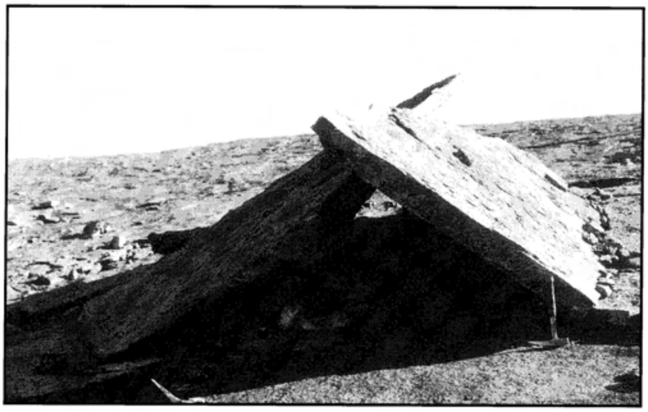

Fig. 7. Popup number 2, the steepest structure encountered. Its twisted appearance results from the fact that the crestal fracture is not parallel to the terminal fractures, resulting in triangular plates.

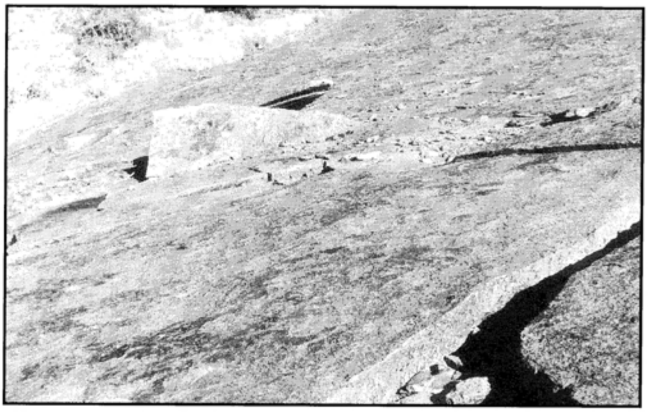

Fig. 8. The sheet upslope of popup number 2 is fractured and the resulting slabs have moved down the slope, pushing the structure up higher than it would otherwise have been.

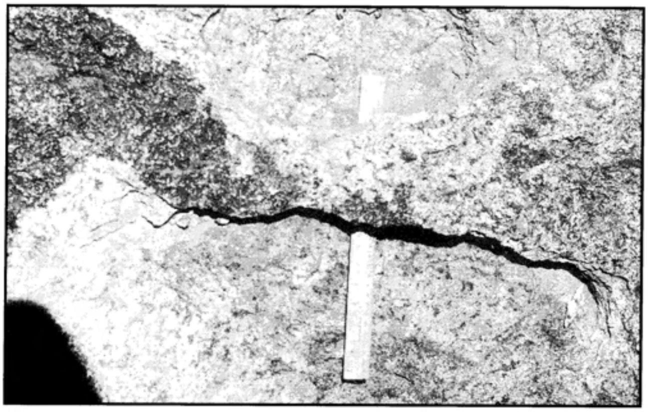

Fig. 9. A small, unfractured arch formed by the erosion of a thin layer of rock just below the hardened surface.

distances (Fig. 8). As a result the base of the structure has been pushed in by at least 0.3 m and perhaps by as much as 0.6 m. Without this extra push its height would have been comparable to that of the other structures in Group I.

The origin of popups

The underlying cause of sheet structures, and hence of popups, is horizontal compressive stress (Roorda 1995). Sheeted rock masses are in a state of high compression parallel to the rock surface, as shown by rockbursts, arched sheets, expansion of quarried blocks, and direct stress measurements. Such stress is usually anisotropic, that is, stronger in one direction than in others. Measurements in granite quarries in the USA have yielded principal stresses (i.e., in the direction of maximum stress) of 9 to 380 MPa, with values about half as large in the horizontal direction perpendicular to the principal stresses (Holzhausen 1989).

The stress causing sheet fractures, particularly at some depth beneath the surface, is the result of tectonic forces acting over fairly large areas. This stress is usually directional. It may be added to by the release of pressure as overlying material is gradually removed by erosion (Holzhausen 1989). Near the rock surface two other factors may add additional stress components. First, daily heating and cooling of the rock surface causes the horizontal stress to fluctuate about a mean value. Assuming a coefficient of thermal expansion of 8 x 10^{-6}/°C and a Young's modulus of 5 x 10^{10} Pa (Holzhausen 1989), a daily temperature fluctuation of 30°C (not unreasonable in the sun at Augrabies) will cause a fluctuation of about 12 MPa in the compressive stress, acting equally in all horizontal directions. The magnitude of the temperature fluctuations and of the resulting stress decline rapidly with depth and are insignificant at depths of more than about a meter.

Second, chemical weathering may produce changes in volume that result in stress. Such changes may explain the spheroidal weathering of granite boulders, during which chemically weathered curved plates of rock split off from the unweathered interior of the boulder (Holzhausen 1989).

The horizontal stresses in some parts of rock sheets can be released by popups. However, below the surface this is prevented by the weight of additional material resting on the sheet. Popups are therefore essentially a surface phenomenon.

Even on the surface, however, a thick horizontal sheet may be prevented by its own weight from popping up spontaneously. A disturbance, or a deviation of the sheet from a flat plane is needed to trigger the event. On bornhardts the most obvious enabling condition is their typically slightly curved form, parallel to the dome surface. Other triggers may be some upward displacement of the surface sheet owing to the growth of sheet fractures lower down, or earthquakes. Once the small amount of required vertical movement has been achieved, the sheet will arch up rapidly and may fracture to form an angular popup. Thus, some high multilayered popups have arisen in quarries, sometimes overnight (Roorda 1995).

The orientations of popups provide important clues to the nature of the stresses in the granite sheets on Moon Rock. Consider first the five structures in Group I, which evidence significant encroachment by (and hence stress release in) the adjacent rock sheet. The crestal fractures of these structures are all oriented approximately north-south, or more specifically in the direction 356° ± 20°. As the crestal fractures should develop approximately perpendicular to the line of principal compressive stress, the stress that produced these five structures acted in an east-west direction, parallel to the main axis of the dome and in line with one of the sets of main joints in the area. This suggests that the stress is the result of tectonic forces that affect Moon Rock. A search for angular popups on neighbouring domes may reveal whether this stress is present over a wider area.

The orientations of the structures in Group II (numbers 6 to 11) are differently distributed. The six crests point in widely different directions, among which no pattern is discernable. Considering also that no expansion of the sheet into the popup space took place in these cases, it would appear that other causes are at work. Two considerations suggest that volume changes as a result of chemical weathering may play a role. First, the upper surface of the sheets in which these popups occur is heavily weathered and the plates of two of them (numbers 9 and 10) are somewhat friable, as crystals can be scratched off with a knife blade. Second, there occur on these weathered surfaces a number of small arches that are the result of chemical weathering. One of these is shown in Fig. 9. It was formed by the weathering and erosion of a thin layer of rock just below the hardened surface. There are no crestal or terminal fractures and the layer forming the arch is flat rather than curved, hence it is not a popup. Similar and larger arches occur on another heavily weathered surface at Ararat, just over 2 km away. The largest of these is an arched popup without crestal or terminal fractures formed by an 80 mm thich sheet and covering an opening of about 2.5 m long, with a maximum height of 0.14 m. These arches represent a seemingly continuous series of structures between the small flat arches caused by weathering and erosion on the one hand, and thin plated popups on the other.

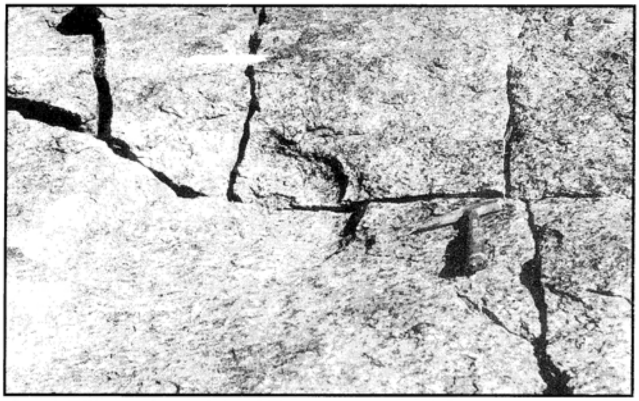

Fig. 10. A small, shallow weathering hollow on Moon Rock, traversed by a vertical fracture. The slabs on the furthest side of the fracture have been displaced to the left by some 50 mm, probably by the release of compressive stress. The fracture occurred after the hollow had already attained more or less its present form.

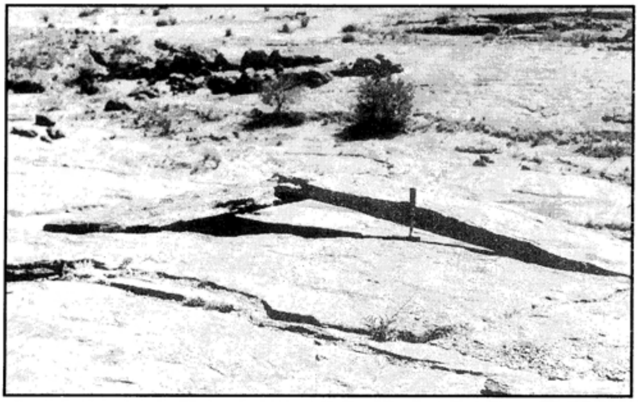

Fig. 11. Popup number 3, the height of which was monitored to determine the effect of daily variations in temperature.

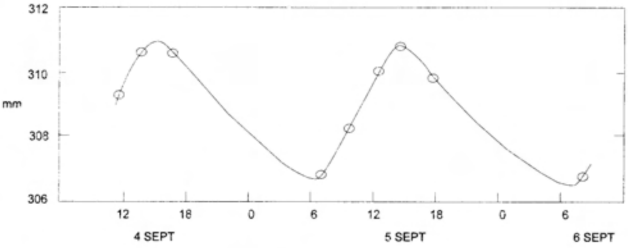

Fig. 12. The height of popup number 3, measured repeatedly over a period of two days, showing a small diurnal variation.

Displaced slabs and the destruction of popups

As surface phenomena popups are subject to various destructive influences. The most important of these appears to be fracturing of the sheet in which the structure is situated and movement of the resulting slabs.

Displaced slabs have proved difficult to explain (Twidale & Sved 1978; Twidale 1982; 1993). The movements of the slabs that are squashing structure number 2 (Fig. 8) are an example. These movements occurred down a slope of only 15°. Yet in other places on Moon Rock similar slabs remain stable on much steeper slopes, in one case at an angle of 29°. The displacement of slabs on Moon Rock most often amounts to only some tens of centimeters or less. However, Twidale (1982: 322-325) found some large slabs to be displaced by several meters on Little Wudinna Hill, on the Eyre Peninsula of Southern Australia.

The gaps between adjacent displaced slabs vary in width from a few millimeters upwards. This suggests that the movements are gradual, or occur in tiny steps. Furthermore, the fact that many gaps are wider at one end than at the other indicates that the movement of some slabs involves rotation. Also, the movement did not always proceed straight down the steepest local slope, and some slabs are displaced on surfaces that are nearly horizontal.

Twidale and Sved (1978) suggested the action of tree roots as a possible cause, but there are no trees or soil on most of Moon Rock. Earthquakes might cause such movements, but should dislodge the slabs on the steepest slopes first. Furthermore, the Augrabies area is virtually aseismic.

The initial motion of at least some of the slabs probably results from the expansion of the rock when its compressive stress is released by a popup or by local disintegration. The force required to push even large slabs apart is insignificant compared to the rock's force of expansion. This movement is unlikely to exceed some tens of millimeters. The displacement illustrated in Fig. 10 may be an example.

Subsequent displacement may result from daily or seasonal heat expansion of the sheets relative to the more sheltered underlying rock, combined with a coefficient of static friction that is lower in some directions than in others. Such an anisotropic coefficient of static friction is to be expected from the characteristics of sheet fractures as observed by Holzhausen (1989).

Movements of slabs, whatever their cause, will eventually destroy popups by either squashing the structures (as is happening to number 2), creating an increased space into which they can collapse, or pushing them down steep slopes to be smashed at the bottom of the dome. The latter fate awaits popup number 3 (Fig. 11). Slabs to the south and east of this structure have been displaced downslope by some 60 mm, pushing the eastern base of the structure in front of them.

Weathering of popups by expansion and contraction

Since diurnal changes in temperature contribute to the horizontal compressive stress in rock sheets, they may also affect the heights of popups. Structure number 3 was monitored for a period of two days to test this idea. The results, presented in Fig. 12, show a small but consistent daily variation in the structure's height, presumably as a result of changes in temperature. On 5 September the variation amounted to 4.1 mm. Calculations show that less than half of this (1.7 mm) is due to the expansion of the two plates of the popup itself, as a result of a temperature change of 19°C on that day. The rest must be due to the thermal expansion of the sheet a few meters on either side of the structure.

These small daily movements of the plates will gradually wear down the edges of the plates at the structure's crest and bases, contributing to its eventual destruction.

Conclusion

This preliminary study of popups and related phenomena on Moon Rock has established that popups do occur in South Africa and have some of the same characteristics as those studied in other countries. However, we have not yet encountered them in any other granite area in South Africa.

It has also been shown that the study of these structures can contribute to a better understanding of the processes that occur during the life histories of granite domes. In this respect a more detailed study of popups and other minor granite landforms that occur on Moon Rock and elsewhere in the Augrabies Falls National Park is bound to prove rewarding.

In terms of the geological time scale popups are transient phenomena. They form only once the outermost sheet of a bornhardt starts breaking up and disappear before the remnants of that sheet have been completely removed by erosion. In terms of the human life span, however, the structures are quite old, as only one natural popup is as yet known to have originated during living memory (Twidale 1993). Unfortunately the regular presence of tourists on Moon Rock is likely to shorten the lifetime of the structures. Some of them may perhaps be brought to the attention of visitors, while at the same time affording them some protection against trampling.

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