ORIGIN OF MINOR SANDSTONE LANDFORMS

With 4 figures and 7 plates

C. R. TWIDALE

Zusammenfassung: Die Entstehung von Kleinformen in Sandstein

Geländebeobachtungen in Sandsteingebieten von Südafrika und Australien erweisen, daß steilhängige Geländeformen zwar subaerischer Entstehung sind, daß jedoch im sanftgeneigten Gelände Rillen („gutters"), kessel- und ringförmige Felsformen („gnammas" und „rock doughnuts") an der Verwitterungsbasisfläche unter Bodenbedeckung gebildet wurden. Der Angriff der Bodenfeuchtigkeit erklärt ebenfalls die Pilzfelsen und andere residuelle Blockbildungen, während die Bienenkorb-Felsen großenteils exogener Entstehung sein dürften.

INTRODUCTION

Although sandstone occupies about 15% of the continental areas, the landforms developed on that rock type have not received commensurate attention in the geomorphological literature. Compared with karst and granite, and notwithstanding MICHEL-MAINGUET'S (1972) outstanding contribution, many aspects of sandstone geomorphology remain neglected. Sheet structure (BRADLEY, 1963) and inselbergs and associated forms (see e.g. OLLIER and TUDDENHAM, 1962; BREMER, 1965; TWIDALE, 1978a; TWIDALE and BOURNE, 1978) all of which are analogous with features developed on granite, have been discussed, but by and large the origin of minor sandstone forms has received only incidental and cursory attention.

In this short article it is argued that though many minor sandstone forms developed on steep slopes are of epigene or exogene origin, others, and particularly those found on gentle slopes are, like their congeners in granitic environments, initiated by moisture attack at the weathering front. They are subsurface forms. The paper is based on field observations in several parts of Australia, but particularly in Lesotho and in the Republic of South Africa, at the margins of the Drakensberg (Fig. 1).

GENERAL SETTING

The Drakensberg massif is a high plateau that in the east attains 3482 metres altitude and exceeds 2900 metres at both its northern and southern margins. It is capped by the Drakensberg Volcanics, of Triassic-Jurassic age and some 1400 metres thick in northern Lesotho. Tholeiitic basalts dominate the volcanic suite though there are many associated doleritic sills and dykes that are thought to have been feeders for the lava flows.

The basalts overlie Stormberg Group sediments deposited in the Karroo Basin. The uppermost of the three lithostratigraphic units of the Stormberg sediments comprises the Clarens Formation (formerly and evocatively known as the Cave Sandstone) which consists of white to cream very fine- to fine-grained sandstones with occasional clay lenses. They are mostly massive though in places cross-bedded. They are flat-lying and as they are deeply eroded characteristically give rise to plateau, mesa and butte forms with struc-

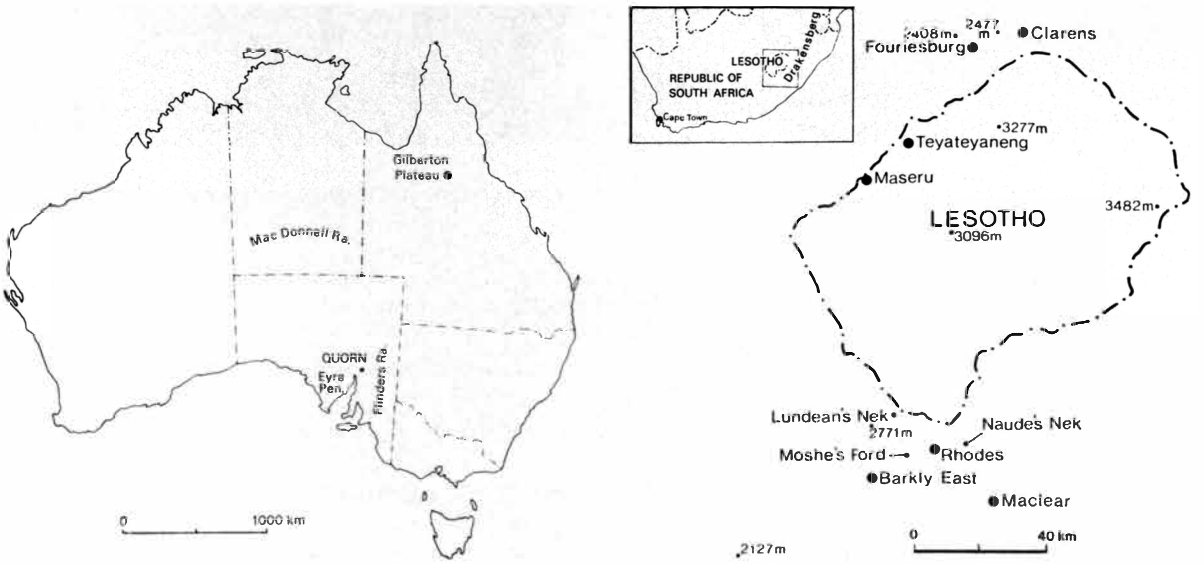
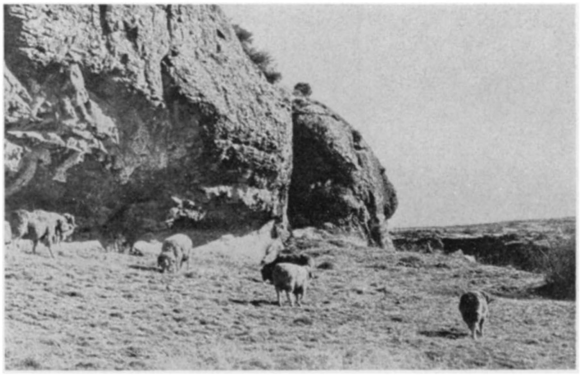


Fig. 1: Location maps of Australian and South African places and features referred to in text



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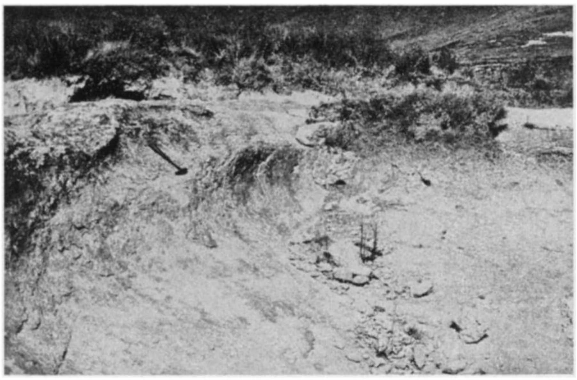

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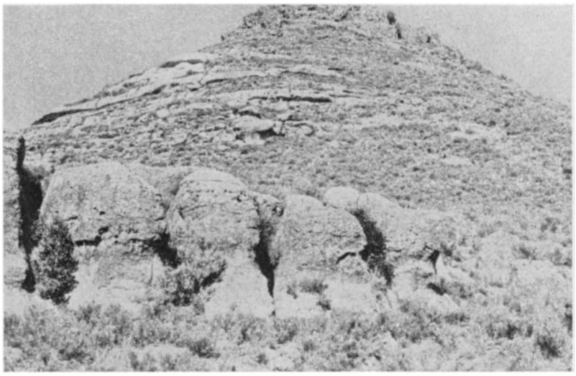

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Plate 1: Cliff in Clarens Formation sandstone in Caledon Valley east of Fouriesburg, showing cavernous weathering at base of bluff and well-developed grooves or *Rille* (C. R. TWIDALE)

Plate 2: Basal sapping of sandstone cliff followed by soil erosion of 1–2 m has caused these cliff foot caverns to develop in a sandstone bluff located some 30 km southeast of Lundean's Nek (C. R. TWIDALE)

Plate 3: Tension scars with underlying sandstone exposed on debris slope 2–3 km east of Lundean's Nek (C. R. TWIDALE)

Plate 5: Sandstone platforms with shallow rivulets and gutters, near Clarens (C. R. TWIDALE)

Plate 6: Flared sandstone cliff with regolith *in situ* in middle distance. West of Lundean's Nek (C. R. TWIDALE)

Plate 7: Sandstone bluff near Lundean's Nek, with joint clefts widened at depth and with flares (A & B) developed on the cliff face. The caprock in the distance is basalt (C. R. TWIDALE)

tural benches well-developed in the valley side slopes. It is on these benches, and associated platforms and cliffs, that are developed the minor features discussed here.

STEEP SLOPE FORMS

The cliffs bordering benches and platforms are typically overhanging due in part to the induration, by silica and to a lesser degree iron, of the upper zone of each major sandstone stratum within the Clarens Formation. Also, caves and shelters have developed low down on the cliff face due in some measure to moisture percolating through the strata and tending to seep out above the indurated bedding planes, in part to sapping by moisture in soil and debris accumulated at the base of the cliff (Pl. 1). In addition, vertical grooves or *Rille* (Pl. 2) eroded by water either pouring over the cliff edge and scouring the channels, or seeping over the edge and adhering to steep, even overhanging slopes by surface tension, are commonly developed.

Thus, so far as steep slope forms are concerned the present writer is in agreement with Klaer (1957) in separating the steep slope forms from those of gentle inclines, and in postulating that they are largely formed subaerially.

FORMS OF GENTLE SLOPES

Most of the gentle slopes are platforms rather than benches, for the latter have been modified and rendered slightly steeper by erosion. Many of these platforms, and indeed slopes up to 15°–16° inclination, carry a soil cover, with a vegetation of coarse tussocky, grasses, and up to one metre thick. The sandstone bedrock is exposed as a result of erosion, particularly at the outer edges of the platforms, and as a result of slippage, which develops particularly on steeper slopes.

Some of the erosion is natural, but much has been accelerated or induced by man's activities. The causes of accelerated soil erosion are many and varied but the deforestation resulting from the grazing of domesticated animals and the search for domestic fuel over many centuries (Van der Merwe, 1979), and the trampling and compaction of soil by animals and man, are two important factors. The significance of trampling and compaction is indicated by the many linear zones of soil erosion.

The slippages are due to water running along the interface between soils and sandstone. The basal soil becomes a liquid mud and the whole mass slides downslope, causing lobes to develop at the lower margin of the mass movement and leaving at the upper extremity tension cracks and scars in which the underlying sandstone platforms are exposed (Pl. 3).

But whether due to slippage or to erosion the sandstone platforms are uneven due to the development of saucer-shaped depressions, some of which have developed into steep-sided, flat-floored pans (Pl. 4) and others into hemispherical hollows or pits (Wentworth, 1944; Twidale and Corbin, 1963). At a few sites, and notably Moshe's Ford, between Rhodes and Barkly East (Fig. 1) the pans are bordered by raised rims or rock doughnuts (Pl. 4) and are similar to forms described from granitic areas in central Texas and Eyre Peninsula (Blank, 1951; Twidale and Bourne, 1977). Both platforms and some of the isolated blocks of sandstone standing upon them display polygonal cracking.

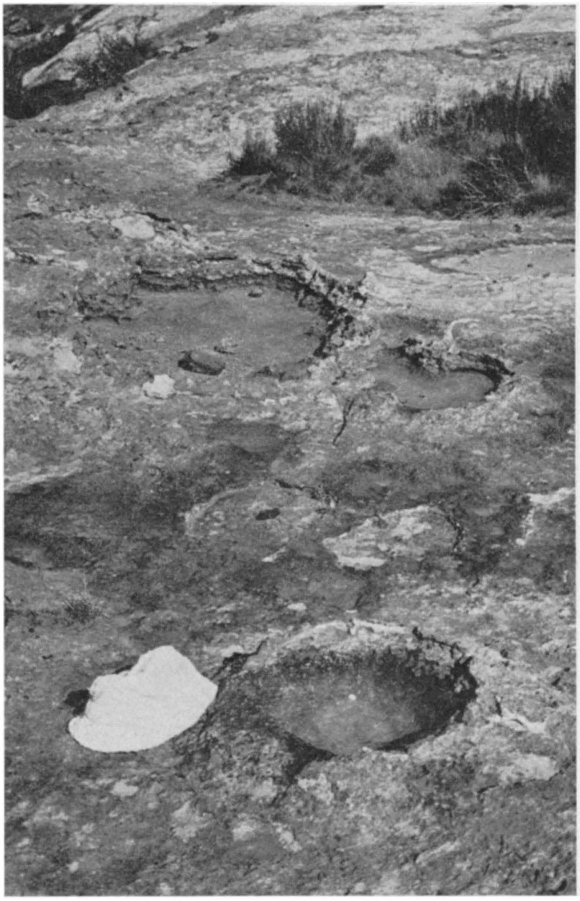
Plate 4: Flat-floored pans with raised indurated rims (rock doughnuts) on sandstone platform near Moshe's Ford, between Rhodes and Barkly East (C. R. Twidale)

There are obvious morphological comparisons to be made with minor granite forms (Wilhelmy, 1958; Twidale, 1971, 1976; Twidale and Foale, 1972, pp. 40–50). Genetically also there is convincing evidence that these minor forms of the sandstone platforms, like their granitic congeners (Twidale, 1971, 1976; Boyé and Fritsch, 1973; Twidale and Bourne, 1975) are initiated in the subsurface as a result of differential moisture attack at the weathering front.

In many places rivulets of water have eroded shallow winding gutters in the platforms (Pl. 5), and both gutters and streams can be traced beneath the soil cover both up- and downslope. Seepages or sheets of water also emerge from soil onto the platforms. This demonstrates the reality of flows at the soil-rock interface, and also the fact that channels are eroded by running water beneath the soil cover.

Some platforms are bordered by low cliffs in which soil and sandstone are juxtaposed, and in many places the junction between the two materials takes the form of a concave slope in sandstone, a flared slope (Pl. 6). Similar flared slopes in sandstone, and associated narrow platforms, have been described from near Quorn in the southern Flinders Ranges (VERRALL, 1975). Such flared slopes are widely and well, in places spectacularly well, developed in granitic rocks. Using various lines of evidence and argument it has been shown that the concavities are exposed weathering fronts initiated in the subsurface by moisture weathering and exposed as a result of the removal of the weathered debris (TWIDALE, 1962, 1967, 1968). Platforms are merely gently sloping lateral extensions of the flared slopes and are also exposed weathering fronts (TWIDALE, 1978b). The exposure of flares and platforms, particularly minor forms, is demonstrably of recent date. Those small sandstone flares and platforms previously referred to from the Flinders Ranges have been exposed within the last 60 years as a result of anthropogenic land clearance, and many other minor flares are of equal or greater recency.

It is envisaged that moisture in soils developed and accumulated on structural benches causes the disintegration of the rock with which it comes into contact, so that the weathering front is lowered and at the same time advances laterally. The vertical marginal front becomes flared (Fig. 2), but the basal one becomes both sloping and irregular: sloping because moisture is more plentiful at the outer edges of the benches than on the inner margins, so that weathering is deeper there and a sloping platform develops (Fig. 2); irregular because the soil moisture preferentially attacks weaknesses such as joints and cracks, and because the sloping bedrock surface induces linear flow and hence linear erosion. For these reasons the weathering front takes on a grooved and dimpled aspect due to the development of gutters and shallow depressions. With further flow, or with water standing in depressions, the forms are enlarged and regularised to form *Rille* and various types of gnamma.

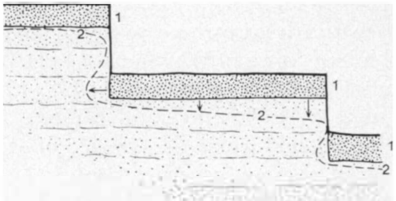

Fig. 2: Development of sloping platforms and flared slopes as a result of soil moisture attack on structural benches

The groundwaters are charged not only with silica derived from the solution of the constituents of the Clarens Formation sandstone but also with iron originating both in the sandstone and in the overlying volcanic rocks. This iron precipitates out and forms thin coatings in for example the floors of gnammas, and also indurates the rock marginal to some, causing these zones to be more resistant to further disintegration so that as the general level of the platforms is lowered these narrow zones marginal to the gnammas remain upstanding and come to form rock doughnuts. In origin these features are similar to the coastal doughnuts in sandstone described from South Island, New Zealand (TWIDALE, 1976, p. 377) but different from the gneissic forms investigated on Eyre Peninsula (TWIDALE and BOURNE, 1977).

Precipitation of salts from circulating groundwaters may also cause the polygonal cracking observed on many surfaces. Such precipitation would cause a space problem, and compression in the near surface layers causing them to arch and fracture.

The crux of this argument is that groundwaters aggressively attack the sandstone, to produce the well-developed though limited suite of forms described here. Silica is of course soluble in the range of temperatures found at and near the earth's surface. It is a common and significant component of the solutes found in river waters the world over (DAVIS, 1964). Nevertheless the forms are so widely developed that some special factor must be operative, as it is in other areas where massive sandstone is intricately weathered. For instance the outcrops adjacent to the flared blocks and boulders described from the southern Flinders Ranges are limestone and the groundwaters are therefore alkaline. That such waters are particularly effective on quartzite or sandstone materials is demonstrated on the Brachina pediment, in the western piedmont of the Flinders. The pediment mantle comprises cobbles and small boulders of quartzite and limestone set in a matrix of calcareous silt. The groundwaters are alkaline and in fact many of the coarse mantle fragments carry a coating of lime. But many of the quartzite boulders and cobbles have been weathered by the alkaline waters so that they have been planed off flush with the present surface, which has been lowered recently as a result of anthropogenically accelerated erosion by a matter of 15–20 cm, whereas the limestone cobbles are marginally etched or at most have developed boss and shield forms (Fig. 3).

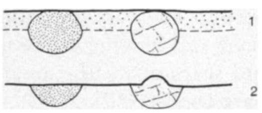

Fig. 3: Development of planed boulders (quartzite) and shield and boss forms (limestone) by soil moisture weathering

But despite being derived in part from basalts, neither the groundwaters nor the soils of the Clarens Formation are alkaline. There seems no reason why iron should endow groundwaters with particularly aggressive qualities. Two possible reasons for the marked etching of the sandstone in this region can be suggested. First, the soils of the Drakensberg region are very wet in spring and early summer when the snows of the high country melt. Thus there is a heavy flow through of water, a constant renewal of weathering agents. Second and more important the soils are rich in humus and chelation (see e.g. BIRKELAND, 1974, pp. 64 et seq.) could contribute significantly to the weathering of the local bedrock.

Thus, in summary the field evidence argues that, contrary to the conclusion reached by KLAER (1957) the gentle slope forms are not of subaerial, but rather of subsurface origin. They certainly are modified after exposure, but they are initiated beneath the soil cover at the weathering front.

BLOCKS, MUSHROOM ROCKS AND BEEHIVES

In many places in the Lundean's Nek and Teyateyaneng areas isolated blocks and rounded boulder stand above the level of the gently sloping platforms. They are not erratics for they remain in structural continuity with the country rock.

Their flanks are flared indicating that they are joint blocks that for some unknown reason have resisted subsurface moisture attack and have become positive relief features with the stripping of the regolith. The flared margins developed when the blocks were completely or largely submerged in the soil cover. In a cliff at Lundean's Nek the first stage of this process of isolation and flaring can be observed. The blocks are separated by vertical joints that are noticeably wider at depth than near the surface (Pl. 7). The narrow joint clefts are flared. The cliff face is also flared with a major concavity coincident with the joint cleft and another smaller basal flare indicating recent soil erosion of the order of 30–40 cm.

There seems no obvious or necessary connection between these features and mushroom rocks such as that located some 25 km southeast of Lundean's Nek Police Station. The narrow stem appears to be developed in somewhat finer bedded, though still massive, sandstone so that the feature may reasonably be ascribed to exogene forces exploiting a structural weakness. However a few metres away, (Fig. 4) a low platform bounded by flared slopes stands at the same level as the top of the stem, suggesting that the latter may be due to concentrated soil moisture weathering at a time when the soil and land surface stood perhaps 50–60 cm higher than at present.

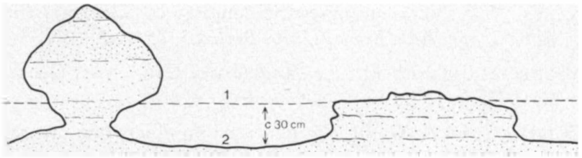

Fig. 4: Mushroom rock, and flared platforms some 25 km southwest of Lundean's Nek

Yet other blocks, particularly those located on spurs, remain essentially angular though many have rounded upper slopes. They stand in orderly arrangement, and are joint blocks that have been but little modified by weathering. They are beehives (TWIDALE, 1956) examples of which have been observed in the Gilberton Plateau of north Queensland, and in the western MacDonnell Ranges of central Australia. These beehives do not display basal steepening as do the joint blocks. This suggests that the widening of joints may have been achieved largely by subaerial processes. On the other hand, the widening of joints on the upper parts of the joint blocks can be equally well explained in terms of soil moisture attack of short duration, causing rounding of the upper slopes and so producing the typical beehive shape. The location of the forms near cliffs and on spurs, where erosion is active, may account for the brevity of the subsurface activity.

CONCLUSION

Though steep slope forms developed on sandstone are mainly of exogene origin those of the more gently inclined platforms and benches are fundamentally due to moisture attack at the weathering front. In suggesting such a subsurface origin, contrasts are drawn with the general view of such forms developed by KLAER (1957) and with the explanations offered for rock doughnuts in granite (BLANK, 1951; TWIDALE and BOURNE, 1977). However, it is more important to emphasise the many similarities, both morphological and genetic between minor forms developed on sandstone and on granitic rocks.

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DIE AGRO-ÖKOLOGISCHE TROCKENGRENZE

Neu-Definition und Dynamik der Trockengrenze des Regenfeldbaus in den zentralen Great Plains von Nord-Amerika*)

Mit 1 Abbildung und 1 Tabelle

HANS-JOACHIM SPÄTH

Summary: The agro-ecological dry boundary. Re-definition and mobility of the dry boundary of non-irrigated agriculture in the central Great Plains of North America

In all semi-arid regions agricultural land use is stimulating the process of desertification. Therefore, a new approach to dryland use must be found. It should be an approach both ecologically sound and practically feasable. Such an approach mainly deals with the search for a new definition of the dry boundary of non-irrigated agriculture.

FALKNER'S (1938) definition of the dry boundary of non-irrigated agriculture is based on mean values of temperature and precipitation. It does not take into consideration actual land use patterns and problems. Furthermore it cannot be used as a planning tool in resource management, in soil and moisture conservation, or in reclamation programs for moisture-deficit zones damaged by wind erosion.

Taking reclamation and conservation aspects as well as longterm ecological stability into consideration the dry boundary is adjacent to places where soil erosion can just be effectively controlled. The complete absence of destructive soil erosion is the principal criterion of the new ecological definition of the dry boundary of non-irrigated agriculture. According to this definition this new boundary will be called „agro-ecological dry boundary".

The relationships ‚soil / soil moisture', ‚available moisture / grain yield', ‚grain yield / straw yield', ‚minimum straw requirement / wind erosion control', ‚tillage / remaining residue rate' are integrated into the equation for determining the location of the agro-ecological dry boundary. The equation reads

$$F_{opt} = \frac{100 \cdot Re_{min}}{b \cdot d \cdot (100\text{-}Ti)} - \frac{a + b \cdot c}{b \cdot d}$$

where F_{opt} = optimized moisture supply; Re_{min} = minimum residue rate for effective erosion control required at planting time; Ti = residue loss due to tillage between harvest and planting time in % of prell-tillage residue rate a = Y-intercept and b = slope of local grain/straw yield–regression equation; c = Y-intercept and d = slope of local available moisture/grain yield–regression equation.

By means of this formula the agro-ecological dry boundary can be localized for the various soils, cropping systems, and years (= moisture supply conditions). Due to its character this formula can be used as a guide for planning local and regional land use patterns and practices. There is no regional limitation to its applicability.

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