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Bornhardts, Boulders and Inselbergs

Bornhardts, Bloques e Inselbergs

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Bornhardts are steep-sided domical hills. The profiles are associated with sheet fractures, and their plan form with steeply dipping fractures of orthogonal or rhomboidal systems. They are well developed in massive rocks, especially, but not only, in granite, and they occur in various climatic settings. They are found in multicyclic landscapes. They occur in massifs as well as in isolation, as inselbergs; in either setting they meet the adjacent plain or valley floor in a piedmont angle or nick. They may be the basic form from which are derived nubbins and castle koppies. Bornhardts are upstanding for various reasons. For example, some are tectonic forms, while others are exposed stocks. Such causations have only local validity. Two competing hypotheses find favour as general explanations. Some workers conclude that bornhardts are remnants of circumdenudation, monadnocks de position or Fernlinge, residuals shaped by and remaining after scarp retreat. Others consider that bornhardts are structural forms, Härtlinge, or monadnocks de dureté, which have evolved in two stages and are etch forms. The rock compartments on which they are based resisted subsurface weathering either because of their composition or because of their low fracture density. They are comparable to corestone boulders, with the important difference that whereas corestones are detached, bornhardts remain in physical continuity with the main mass of country rock.

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INTRODUCTION

Bornhardts are bald, domical hills (Pl. 1). Some occur in isolation, as inselbergs, or island mountains, but many are found in ordered groups within massifs (Pl.2). They were first recorded in the scientific literature by Darwin, from the Rio de Janeiro area, in 1846, but are named after Wilhelm Bornhardt, who bequeathed to us splendid descriptions and perceptive comments on the forms in an inselberg setting from what is now Tanzania (BORNHARDT, 1900; WILLIS, 1934). Why, when and how have they formed, why are they domical, and why do some stand in isolation?

BORNHARDT CHARACTERISTICS

Bornhardts are found in a variety of topographic contexts, in all major climatic settings, and in a variety of lithologies, though they are best developed, preserved and displayed in granitic rocks, in shield lands, and in arid or savanna climates. They meet the adjacent plains or valley floors in an abrupt break of slope called the piedmont angle or nick, and occur in multicyclic landscapes. In plan, they are defined by steeply dipping fracturesand their convex-upward profiles are associated with sheet fractures (KING, 1949a; BIROT, 1950; TWIDALE, 1982 a and b).

Bornhardts are spectacular, even dramatic, landscape features (see e. g. VAN DER POST, 1962, pp.181-182) and they have long engaged the interest of geologists and geomorphologists. They have been explained in various ways. All of the interpretations advanced in explanation of bornhardts, however, are based either in environment or in structure.

PREVIOUS EXPLANATIONS

Some early workers saw bornhardt inselbergs are literal as well as littoral features (e.g. albeit briefly, BORNHARDT, 1900), and many bornhardts are found in coastal settings as for example in the Rio de Janeiro area, and at several sites along the south coast of Australia. But it was soon realised that such coastal connections are coincidental rather than essential, for not only do many bornhardts stand above and beyond the reach of any feasible sealevel, but there is also no evidence of oceanic contacts during the likely period of formation, either in the recent or distant past, or indeed, in some instances, at any time. Thus, the domes of the high Sierra Nevada in California, are developed in granitic rocks emplaced during the Cretaceous(e.g. BATEMAN and WAHRHAFTIG, 1966; HUBER, 1987) and standing as they do thousands of metres high in the relief, surely cannot have been touched by the sea after the exposure of the host masses. Similarly Ayers Rock formed in the later Cretaceous and Cainozoic times (TWIDALE, 1978a; HARRIS and TWIDALE, 1991), but there is no evidence of marine incursions into the region since the Early Cretaceous, and even then not into the immediate vicinity of the residual (FRAKES et al., 1988).

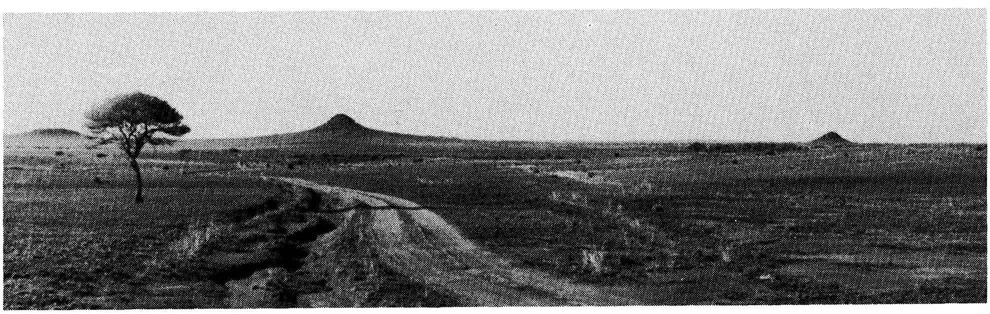
Bornhardts are well developed and preserved in arid and semiarid lands, and this convinced many workers that there is a genetic connection between landform and climatically induced processes. Inselbergs and inselberg landscapes were at one time attributed to differential aeolian planation at the regional scale (PASSARGE, 1904a, 1904b, 1924; see also KEYES, 1912; JUTSON, 1914), but the concept never achieved widespread acceptance and soon faded as evidence accumulated pointing to

Pl. 1. Bald, domical residuals or bornhardts, central Namibia.

Pl. 2. Bornhardts arranged on adjacent fracture defined blocks, in the Kamiesberge of Namaqualand, South Africa.

the erosional dominance of rivers, even in arid and semiarid lands (e.g. JUTSON, 1934; PEEL, 1941). Many interpret bornhardt inselbergs as remnants of circumdenudation, as the final residuals surviving after long distance scarp retreat, Fernlinge or monadnocks de position (KING, 1942, 1949a). King (1957) suggested that scarp recession is dominant wherever the land surface is shaped by running water, butmost workers consider that the process operates optimally in semiarid and savanna conditions. The mechanism is certainly operative in appropriate structural conditions, namely, where there is a resistant caprock; and it is significant that this situation is commonplace in southern Africa, where King developed the concept. Recession of scarps is also assisted by aridity or by semiarid conditions, where the importance of what moisture there is, is enhanced, and where scarp foot weathering becomes a dominant factor in shaping slope morphology and in determining slope behaviour (TWIDALE, 1967; TWIDALE and MILNES 1983). So important is this factor that scarp retreat can be envisaged even in non-caprock situations, as for instance in granitic terrains, for it can be argued that in arid or semiarid conditions, and in a dissected landscape, water gravitates to the water table, leaving the higher zones high, dry and stable (see e.g. BARTON, 1916); whereas at and below the water table, the bedrock is in contact with water and is altered, rendering it susceptible to erosion. Surface wash is also concentrated in the piedmont zone. Thus, lower slopes are steepened and the upper undermined, leading to scarp retreat (TWIDALE and MILNES, 1983; TWIDALE, 1983). Thus the scarp retreat hypothesis is theoretically feasible, and is now, as in the past, the most favoured explanation of inselberg and bornhardt formation (e.g. KING, 1949a,1953; PUGH, 1956; OLLIER and TUDDENHAM, 1962; SELBY 1970).

For other workers, however, bornhardts are structural forms (sensu lato): Härtlingeor monadnocks de dureté . A few isolated granite residuals are demonstrably upthrust along faults and are tectonic forms. The Pic Parana, in southeastern Brazil, is a well documented example (BARBIER, 1957) and some of the pitonsof French Guyana are evidently of the same genre (CHOUBERT, 1949). But, far more commonly the fractures that define bornhardts are joints, with no



Pl. 3. The Pinnacles, a small group of inselbergs near Broken Hill, western New South Wales.

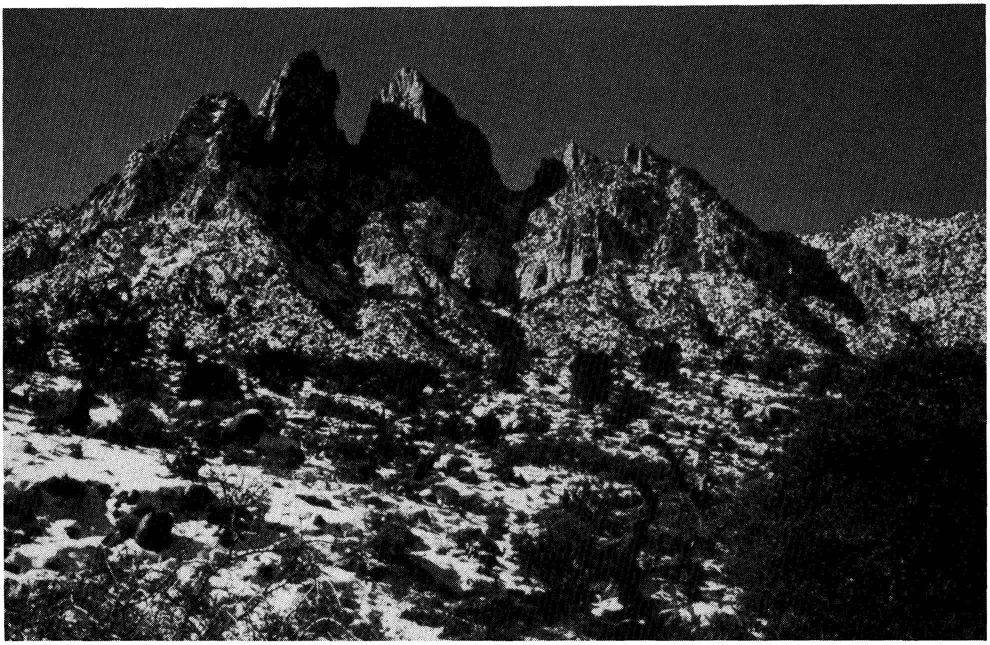
demonstrated differential movement, so that though locally valid, this tectonic explanation has no general application. Evidently some bornhardts are upstanding because they are developed in a different type of rock which is, implicitly, more resistant to weathering and erosion than that which underlies the adjacent plains or valleys. Thus, some of the bornhardts of French Guyana are formed in a leucogranite which is more resistant than the biotite-rich rocks in which the plains are eroded (HURAULT, 1963). The Pinnacles (Pl.3), near Broken Hill, in western New South Wales, are buttressed by discrete blocks of vein quartz which render the masses more resistant than the biotite-rich schists that have been worn down to form thesurrounding plains. Some domical forms are merely exposed stocks, or batholithic protuberances, which are more resistant than the host rock. Several examples have been cited from Mozambique and Zimbabwe (HOLMES and WRAY,1912; DU TOIT, 1939, p.61) and in central Namibia a rounded boss of granite (Pl.4a) stands above the weaker schist into which it is intrusive (see TWIDALE, 1982a 1982b). In the Musgrave Ranges of central Australia, Mitchell Knob and associated bald domical masses (Pl.4b) may be intrusive into a metamorphic complex, though the smooth continuation of the upper convexities into basal overhangs gives the appearance of large discrete globules or bubbles of granite (cf BRAJNIKOV, 1953; BARBEAU and GÈZE, 1957). Whatever the method of emplacement of these crystalline masses, however, the bornhardts based on them merely constitute a special case of lithological contrast.

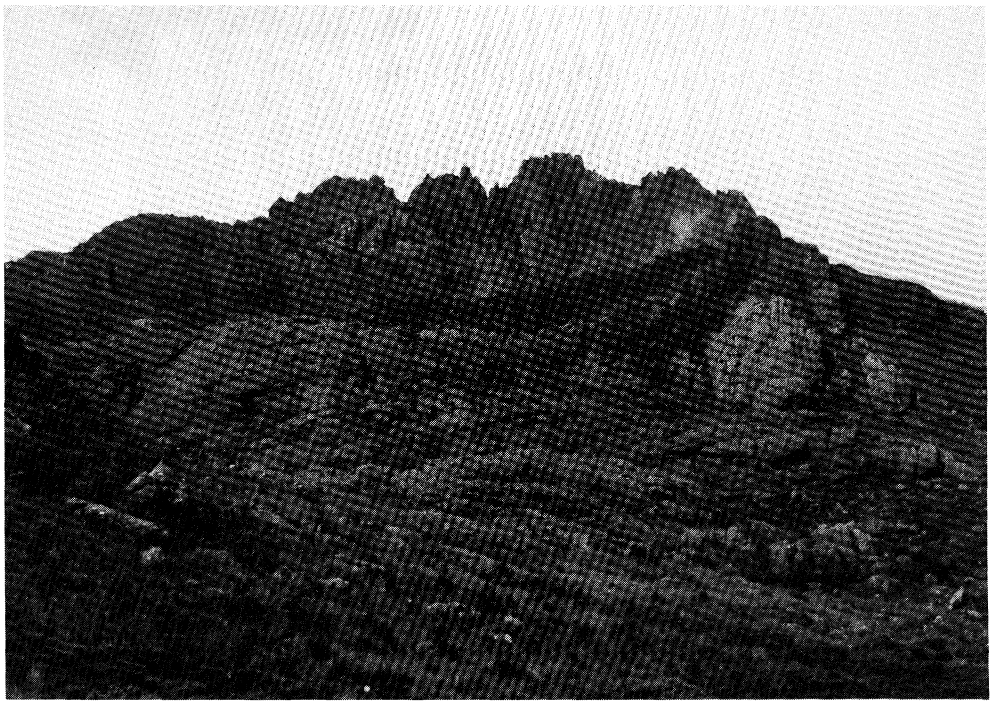
Many bornhardts, however, appear to be of the same rock type that underlies the adjacent plains. For these, a majority of bornhardts, appeal has been made to variations in fracture density (e.g. LE CONTE, 1873), with the suggestion that the upstanding hills are developed on massive, compact compartments, and the plains eroded in rock characterised by numerous open fractures. Some early workers, and notably MENNELL (1904), argued that water could more readily penetrate into compartments of high fracture density, with the result that these were eroded to leave the compact masses in relief. They considered that the differential weathering took place at the surface, after exposure. The exploitation of prominent vertical fractures to give acicular forms and turrets, as in the eastern Sierra Nevada of California (for instance in Unicorn peak and around Mt Whitney), the Organ Mountains of New Mexico (see SEAGER, 1981), in southern Greenland (SOEN, 1965) and, in syenite, in the Agulhas Negras of southeastern Brazil, sustain this interpretation, for frost shattering, initially perhaps below the surface but overwhelmingly under epigene conditions, is responsible (Pl.5).

Other investigators, however, envisaged that the fracture controlled differential weathering took place beneath the surface, at the base of the regolithic veneer (e.g. LINTON, 1955; WILHELMY, 1958; GODARD, 1977). The concept involving the exploitation of fracture density, but allowing also for the differential weathering of different rock types, was earliest and most succinctly expressed by Falconer:

"A plane surface of granite and gneiss subjected to long-continued weathering at base level would be decomposed to unequal depths, mainly according to the composition and texture of the various rocks. When

Pl. 4. (a) This stock of granite in central Namibia is upstanding because of the preferential weathering of biotite schists into which it is intruded.
(b) These ovoid masses of granite in the Musgrave Ranges of central Australia are intruded or injected into a gneissic host rock: the most prominent is called Mitchell Knob.





Pl. 5. (a) Acicular granitic peaks in the Organ Mountains, New Mexico.
(b) Vertical fractures have been exploited to give numerous low turrets on the crest of part of the syenitic Agulhas Negras, southeastern Brazil.

elevation and erosion ensued, the weathered crust would be removed, and an irregular surface would be produced from which the more resistant rocks would project." (FALCONER, 1911, p. 246).

In some instances isolated residuals are left in relief, but where large masses of resistant rock are affected, weathering exploits steeply inclined fractures, subdividing the massif into rows or ordered domes, as in the granitic Everard Ranges, the dacitic Gawler Ranges and the conglomeratic Olgas complex, all in the arid interior of Australia, and in the granitic and gneissic Kamiesberge of Namaqualand, in Cape Province, South Africa. The essential feature of Falconer's concept is that bornhardts evolve in two major stages (Fig.1). First, shallow groundwaters cause structurally controlled differential subsurface weathering of the rock mass at a regional scale, and so create an irregular weathering front (MABBUTT, 1961), leaving the more resistant compartments protruding into the base of the regolith. Second, various agents, including wind, glaciers and waves, but most commonly rivers, effect the erosional stripping of the regolithic veneer to expose the projecting compartments, rounded as a result of the preferential weathering of corners and edges, upstanding as bornhardts. In reality, the 'first' stage involves interactions of groundwaters with bedrock at the weathering front, and the exploitation of structures and textures inherited from earlier magmatic, thermal, tectonic and diagenetic phases, so that etch features can be regarded as multiphase rather than two stage (TWIDALE and VIDAL ROMANI, 1994); but Falconer's point is well taken for it is subsurface weathering and later exposure of the weathereing front that in an immediate sense produce etch forms.

COMPARISON WITH BOULDERS

The two stage concept used to explain many bornhardts had earlier been introduced

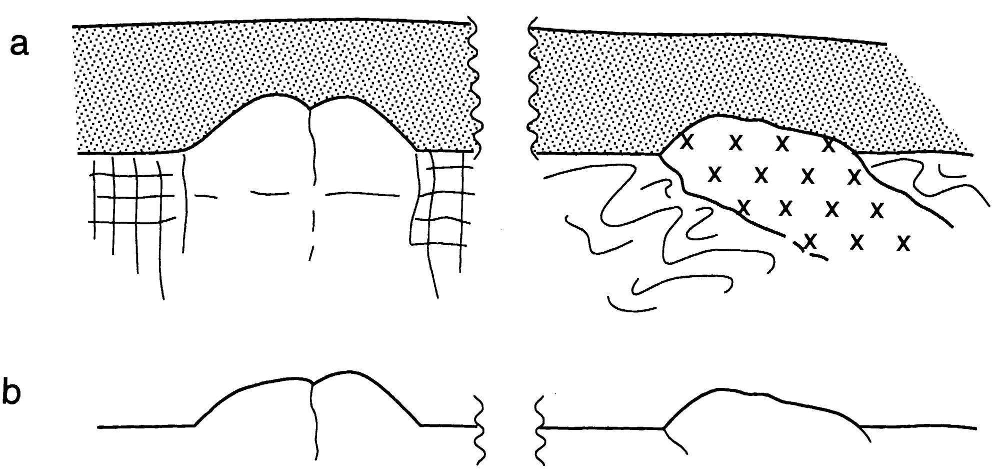
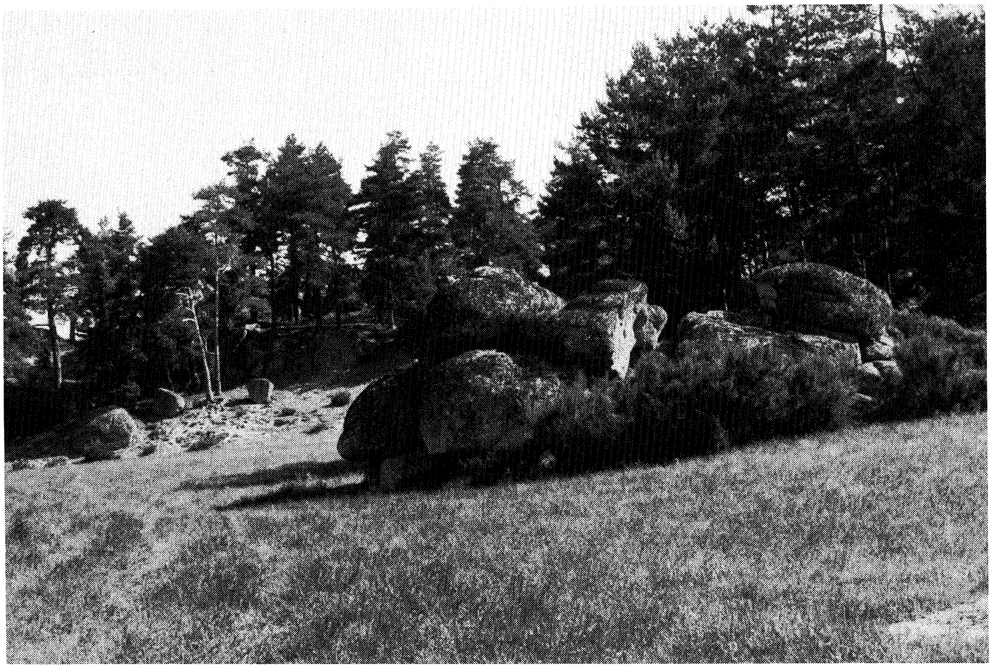
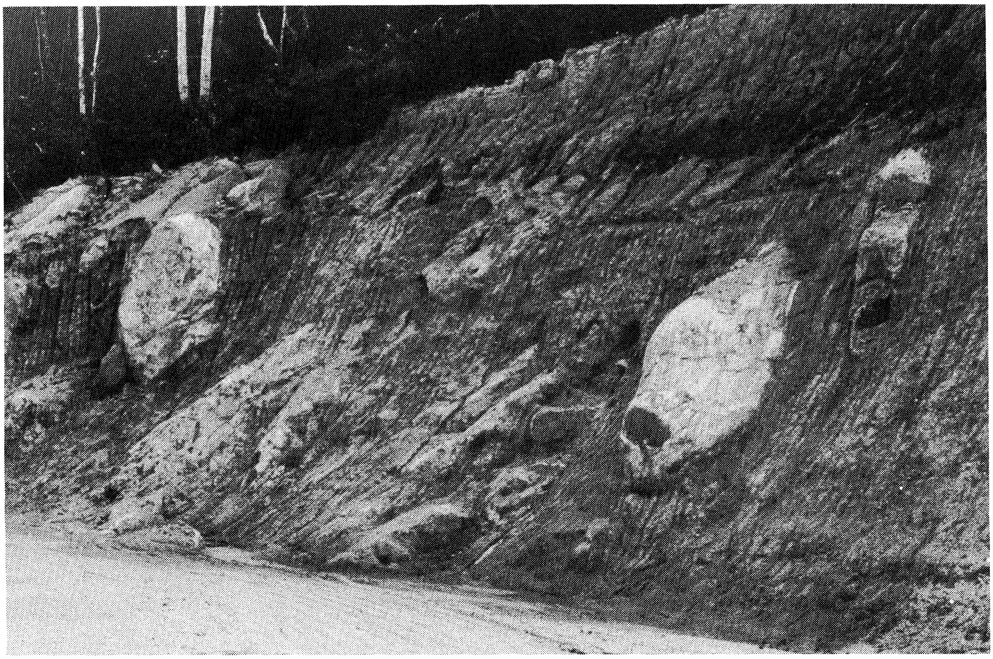


Fig. 1. The two stage evolution of bornhardts and inselbergs.In (a) a regolith of uneven thickness has developed on structurally differentiated country rock, and in (b) removal of he regolith has exposed previously developed projections of bedrock into the base of the regolith as bornhardts.





Pl. 6. (a) Granite corestones and boulders near Chazeirollettes, near Aumont, southern Massif Central, France.
(b) Granite corestones, Selangor, West Malaysia.

to account for boulders. More than two centuries ago, Hassenfratz gave an explanatory account of a granite exposure he had noted near Aumont, in the southern Massif Central (Pl.6a). He noted boulders strewn over the surface, and corestones still embedded in the weathered granite or grus. He interpreted the assemblage as an evolutionary sequence, and wrote:

"... on aperçoit tous les intermédiaires entre un bloc de granit dur contenu et enchassé dans la masse totale du granit friable et un bloc entièrement dégagé." (HASSENFRATZ, 1791, p. 101).

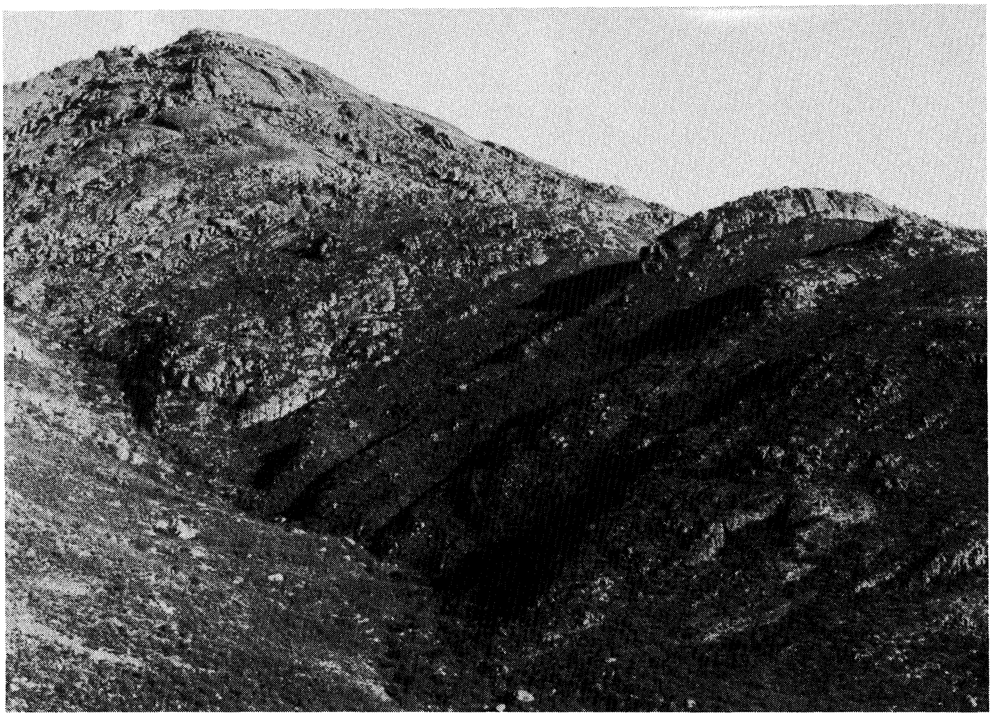
The number of exposures, from all parts of the world, in which corestones are contained in a matrix of grus (Pl.6b), leaves little doubt that most granite boulders have formed in this manner. Most are derived from joint blocks defined by fractures of orthogonal systems. Some are due to the disintegration of sheet fractures, either below the surface, or, and perhaps more commonly, after exposure, and to the subsequent subaerial rounding of the resultant blocks, but mostoriginated as corestones, and are two stage forms. Weathering also exploits foliation, producing domical hills with ribbed slopes, each "rib" consisting of numerous penitent rocks, monkstones, *Büssersteine* or tombstones (Pl.7).

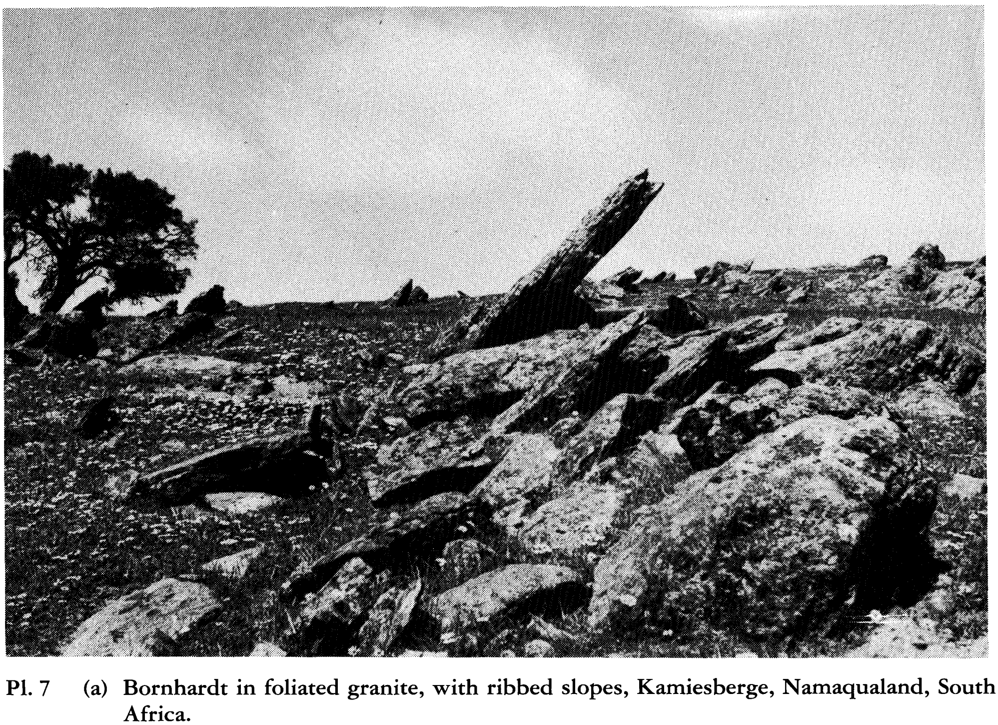
Corestones, however, are isolated and no longer in physical continuity withthe parent mass, and though Brajnikov (1953) has suggested that some of the morrosof Brazil have become detached, bornhardts are more properly compared to the rock pillars exposed at Murphy Haystacks, on the northwest coast of Eyre Peninsula (TWIDALE and CAMPBELL, 1984). These pillars, most of them with flared sidewalls, stand4-5 m above the surrounding hill crest, and despite the weathering of vertical fracture zones remain in substantial contiguity with the underlying granite (Pl.8). Bornhardts are very large pillars rather than large boulders.

EVIDENCE AND ARGUMENT

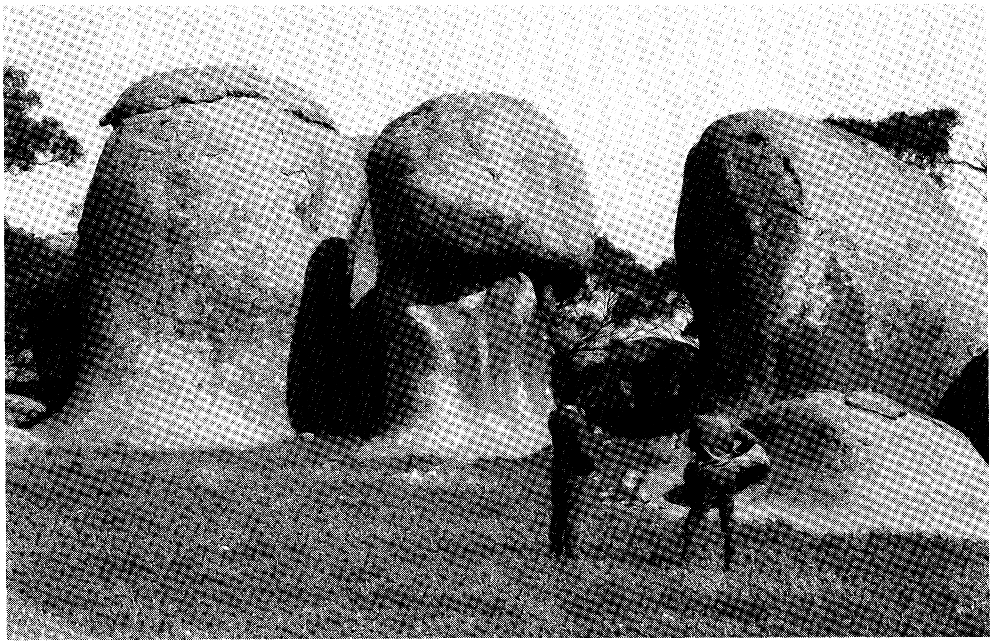
Several of the hypotheses outlined have local or specific application, but only two have found favour as general explanations, that is, as hypotheses that have the capacity to account not necessarily for all, but certainly for most, bornhardts; these are the scarp retreat and the two stage hypotheses. Various lines of evidence and argument can be adduced wherewith to test the field data against the deducible consequences of the two major hypotheses (TWIDALE, 1982a and b).

If bornhardts are two stage forms, and assuming that the same processes and mechanisms that operated in the past are still active, then besides those that have been subjected to both stages and are exposed, there ought to be some that have passed through only the first stage, that have been formed by differential weathering beneath the surface but are not yet exposed. There ought to be nascent bornhardt masses projecting into the regolith but not yet naturally exposed by stripping of the regolith. There are. Of some, like that exposed in the Vredefort Brick Pit, Orange Free State, South Africa (Pl.9a), there is no indication at the natural surface: the incipientbornhardt came to light only during excavation. Others were minimally exposed as a small platform or low large radius dome which on excavation proved to be the crest of a bornhardt, as at Ebaka, Cameroun

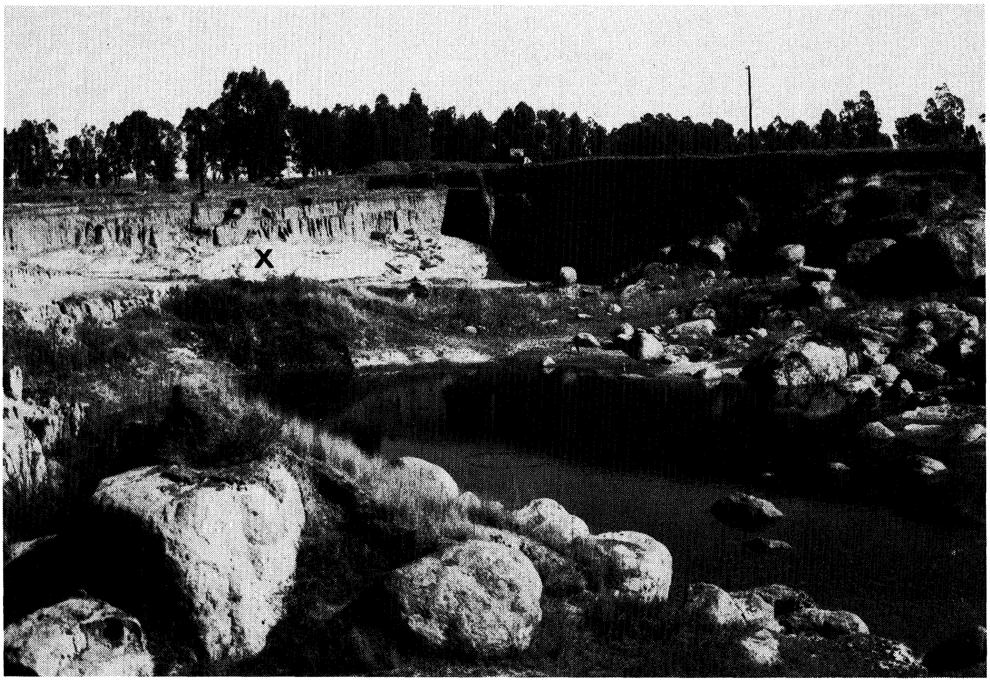




Pl. 7 (a) Bornhardt in foliated granite, with ribbed slopes, Kamiesberge, Namaqualand, South Africa.
(b) Penitent rocks in eastern Mt Lofty Ranges, South Australia.



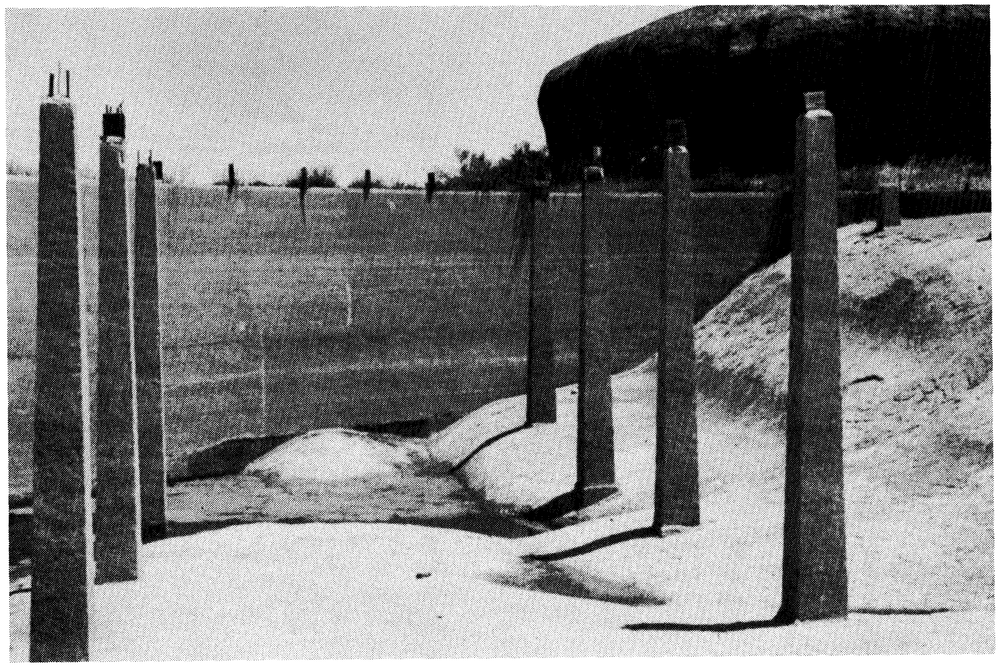
Pl. 8. Granite pillars, Murphy Haystacks, west coast of Eyre Peninsula, South Australia.



Pl. 9. (a) Part of nascent dome (X) exposed in Vredefort Brick Pit, Orange Free State, South Africa.
(b) Incipient bornhardt exposed by excavation at Elkington Rock, north of Minnipa, Eyre Peninsula, South Australia.

(BOYÉ and FRITSCH, 1973); adjacent to the Leeukop, near Vredefort; at Midrand (the former Halfway), in the central Traansvaal, South Africa; at Calca Quarry, northwest coast of Eyre Peninsula, and at Elkington Rock, near Minnipa, northwestern Eyre Peninsula (Pl.9b). In these examples the thickness of regolith increases in all directions away from the platform; and similar situations have been demonstrated by augering at other platforms on Eyre Peninsula.

A subsurface initiation of bornhardts, the host mass, is consistent with the irrefutable evidence that several minor forms commonly associated with bornhardts, such forms as pitting, basins, Rillen, and flared slopes, are also initiated in the subsurface, at the weathering front (TWIDALE 1962; BOYÉ and FRITSCH, 1973; TWIDALE and BOURNE, 1975a,1976). Not all minor forms originate at the weathering front. Some, including some basins and flutings, indubitably develop wholly under the influence of epigene processes (e.g. LAGEAT et al., 1994). Others, though initiated at the weathering front, largely develop, or they diversify, after exposure, as exemplified by tafoni and rock basins respectively. Some, like rock doughnuts and rock levees, are due to the unequal weathering of exposed and covered surfaces (e.g. Twidale, 1988) and others, namely plinths, owe their existence to protection by overlying blocks. Yet others, like displaced blocks, owe their origin to gravity



Pl. 10. Flared slope, and incipient flared slope exposed in reservoir, at Yarwondutta Rock, near Minnipa, Eyre Peninsula, South Australia.

(TWIDALE et al., 1991) and a suite of forms, in which A-tents are prominent, are associated with the release of compressive stress (TWIDALE and SVED, 1978). But many minor granite forms are initiated at the base of the regolith, at the weathering front.

Though they are perhaps a special case, flared slopes unquestionably form at the weathering front, in the scarp foot zone (Pl.10), for they have been uncovered from beneath a regolithic veneer in situin excavations at several sites (TWIDALE, 1962, 1982a). These concavities represent an undermining of the bases of rocky slopes and they well illustrate, albeit in extreme form, the mechanism responsible for the piedmont angle or nick, the abrupt break of slope between hill and plain which is particularly pronounced in arid and semiarid lands (e.g. HILLS, 1955). Scarp foot weathering induces erosion of the basalsectors of hillslopes, the steepening of scarps and hence a sharp transition from hill to plain (PEEL, 1941; TWIDALE, 1967). In some terrains, and especially those developed in granitic or other well jointed rocks, structural factors play an important role, and induce truly angular nicks, but the abrupt change from hill to plain is also well represented in plateau areas, for example where the hill-plain junction is developed in one rock type. The basal sapping responsible for the piedmont angle undoubtedly takes placein the shallow subsurface, but may also evolve at depth, as water gravitates along slopes on the weathering front to the bases of projections, where it may well sit and circulate above the impermeable mass of fresh rock.

Some bornhardts are upstanding because they are of a rock type different and more resistant than that worn down to form plains, and this has been demonstrated in a number of cases. It has been suggested that others are upstanding by virtue not of lithological contrasts but of their being massive, i.e. because of variations in fracture density. If this were so, there ought to be evidence of such variations. There is. The evidence is not plentiful, for suitably positioned excavations are required, but the presence of rocks subdivided by numerous fractures located immediately adjacent to compactor massive compartments (Pl.11) has been described from Ucontitchie Hill, on northwestern Eyre Peninsula, near Garies in Namaqualand, around Blackingstone Rock, on eastern Dartmoor, and at Kolar, near Bangalore, in peninsular India (e.g. JONES, 1859; TWIDALE,1964, 1982a; BÜDEL, 1977, pp.108-109).

It might be argued that such evidence is irrelevant because the relevant contrast in fracture density is not that between the present bornhardt and the compartment beneath the present plain, but rather between the bornhardt and the adjacent compartments, located at the same level as the bornhardts, that have been eroded. The point is well taken, but BLÈS (1986) has shown that near surface fracture densities provide a reliable guide to fracture density and pattern at depth, and extrapolating vertically upwards rather than in depth, it can be suggested that they also provide a guide to conditions in the eroded compartments, so that the evidence cited is germane to the discussion (TWIDALE, 1987).

Variations in fracture density have been explained in terms of strain distribution in

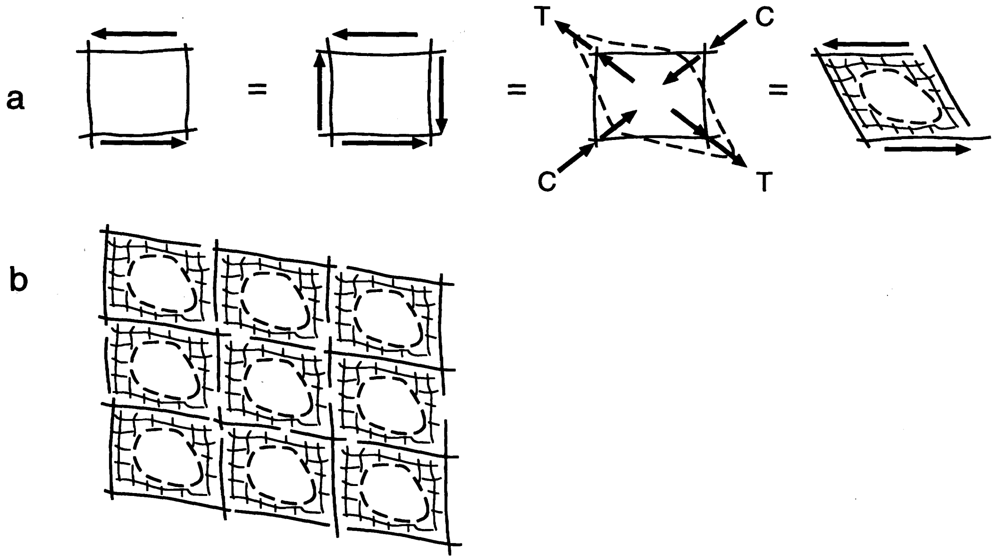


Fig. 2. Development of stressed core or incipient residual within a fracture- defined block by shearing and fracture propagation. In (a) a single orthogonal block is repeatedly sheared, and in (b) several such blocks are depicted.

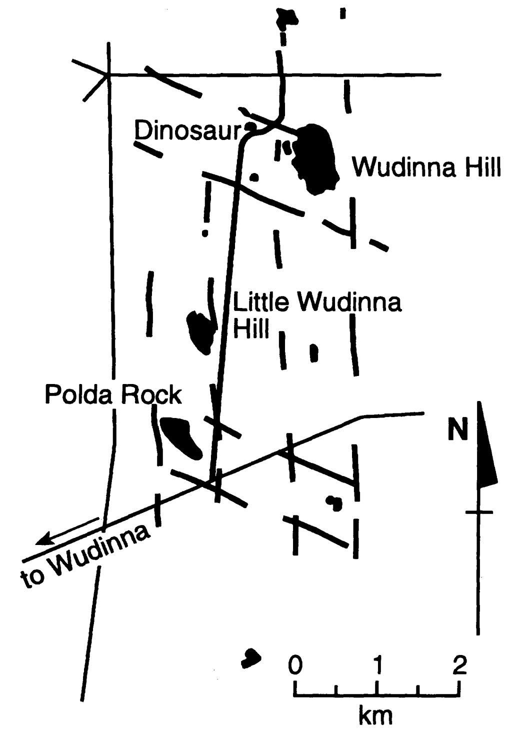


Fig. 3. Plan pattern of granite outcrops north of Wudinna, Eyre Peninsula, South Australia.

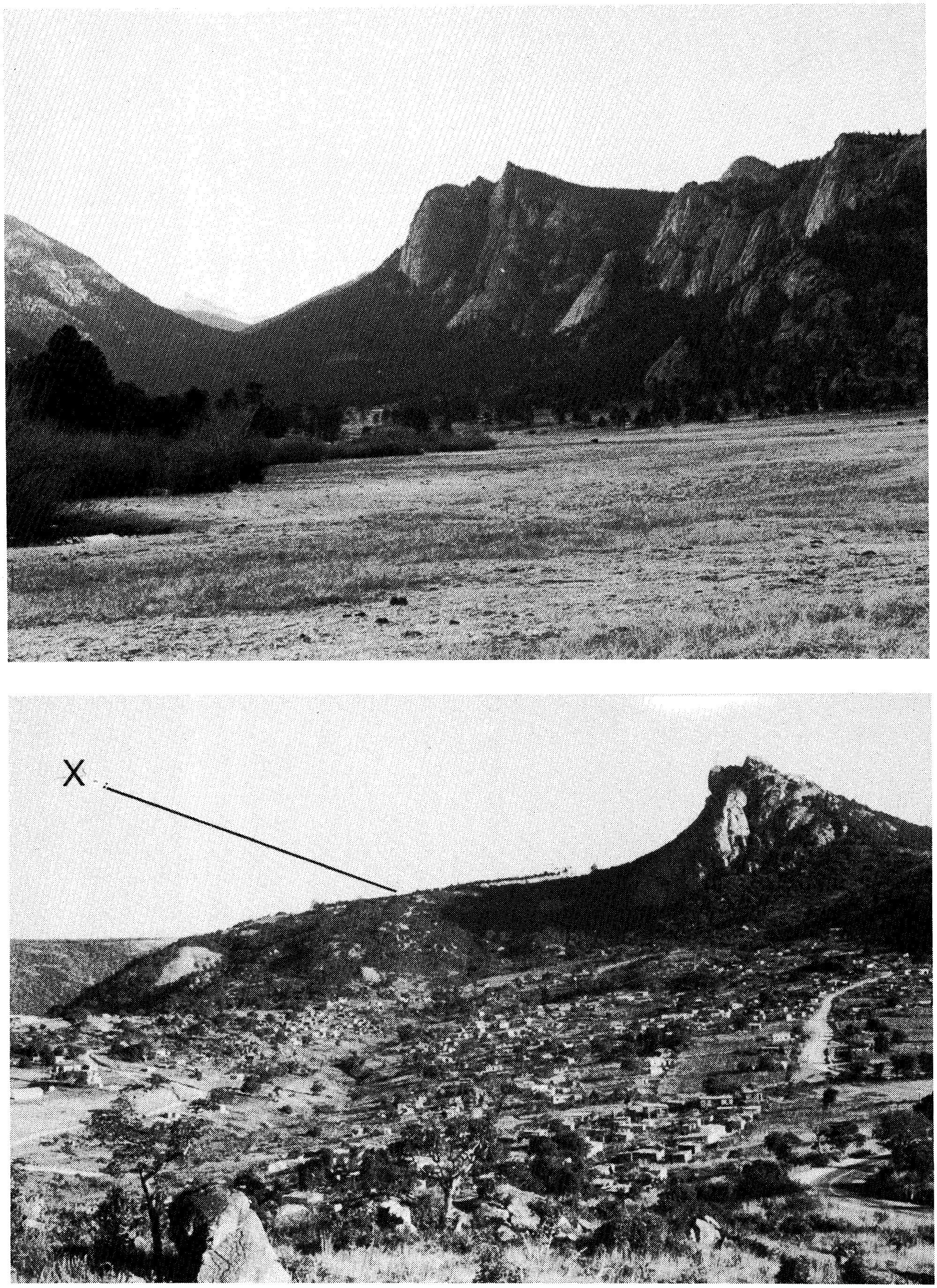
antiforms and synforms (LAMEGO, 1938), and as a consequence of shearing (TWIDALE, 1980a). The second mechanism in particular (Fig.2), implies that bornhardts ought to be in compression along one horizonal axis and in tension along the other horizontal axis normal to the first; there is some evidence, at present sparse, that this is so. In these terms also (Fig.2), bornhardts ought to be disposed in plan patterns, in alignments, rather than scattered randomly in the landscape. They are, for not only in massifs, but also in inselberg landscapes, the residuals stand in ordered rows (e.g. Fig.3).In some areas, such as the Kamiesberge of Namaqualand, that the fractures defining major compartments are faults is demonstrated by displacements, slickensides, recrystallisation, and so on. Also, a genetic relationship between bornhardts and implied compressive stress is consistent with the characteristic occurrence on and within bornhardts of sheet fractures and structures, and the common development on the residuals of a suite of forms associated with stress and strain (MERRILL, 1897; TWIDALE, 1964, 1973, 1982a; TWIDALE et al., 1995).

The occurrence of bornhardts in multicyclic landscapes, is implicit in FALCONER'S (1911) two stage concept, and has been noted by BORNHARDT (1900), WILLIS (1936), JESSEN (1936) and KING (1949a). Planation surfaces can be interpreted as implying stability and time for deep (differential) subsurface weathering, and multicyclicity implies deep erosion and exposure of the differentiated weathering front , including residual hills. Thus it is no coincidence that in Zimbabwe, for example, about 80% of the bornhardts and other inselbergs of that country occur on surfaces eroded below the early Cainozoic African planation surface (WHITLOW, 1978-9; LISTER 1987), and that the bornhardt massif that is the Gawler Ranges occurs below the level of an etch surface of Early Cretaceous age (CAMPBELL and TWIDALE, 1991). The association between multiple planations and bornhardts can be linked to crustal stress, for a multicyclic landscape implies not only time for the differential weathering essential to the two stage concept, but also profound erosion and the possible exposure of the deeper zones of compression found below the neutral plane in antiformal structures.

Turning to some of the implications of the scarp retreat hypothesis, if bornhardt inselbergs are the last remnants of circumdenudation, they ought to be preserved on major divides. They are not. Evidence from several parts of the world shows that bornhardts are found adjacent to rivers and valleys , as in parts of Nigeria (THOMAS, 1966), and in the Yosemite of the Sierra Nevada in California (HUBER, 1987); partly exposed in the sides of relatively narrow valleys as in the Thompson Valley near Estes, Colorado, and of the Witrivier in the eastern Transvaal (Pl.12); and even in the floors of valleys, as near Malmesbury, north of Cape Town (Pl.13).

If bornhardts are the last remnants of circumdenudation, none ought to be older than the duration of a geomorphic cycle operating in a region of continental or subcontinental extent, i.e. about 33 my (SCHUMM, 1963). No inselberg that has not been exhumed ought to be older than Oligocene. Some are. The Humps, in the southern Yilgarn of Western Australia, are at least of Eocene age (FAIRBRIDGE and FINKL, 1978; TWIDALE, 1986). The

Pl.. 11. Reservoir at Uncontitchie Hill, Eyre Peninsula, South Australia, showing contrast between fracture density beneath the plains, as indicated by the diameters of the boulders exposed in excavation, and that of the adjacent residual.



Pl. 12. Granite domes exposed in valley side slopes (a) Near Estes, Colorado, USA, and (b) near Witrivier, eastern Transvaal, South Africa. In (b) X indicates King's African planation surface, of essentially Paleogene age.

Pl. 13. Granitic dome exposed in valley floor near Malmesbury, north of Cape Town, Cape Province, South Africa.

Pl. 14. Stepped northwestern slope of Yarwondutta Rock, near Minnipa, Eyre Peninsula, South Australia.

summit bevels of Ayers Rock and the Olgas complex are probably of latest Cretaceous (Maastrichtian) age, though the steep bounding slopes are Cainozoic features (TWIDALE and HARRIS, 1977; TWIDALE, 1978a; HARRIS and TWIDALE, 1991). The Gawler Ranges massif was an upstanding topographic feature during the Eocene, and probably dates back to the Early Cretaceous (CAMPBELL and TWIDALE, 1991).

If bornhardts are due to scarp recession, there ought to be some bounding slopes that are distant from major partingswhereas in reality most are located close to fracture zones: there has been a certain amount of wearing back of slopes, for example in the Gawler and Everard ranges, butnot much. It is asking much, and perhaps too much, of coincidence that slopes should have stabilised on or near fractures, and moreover stabilised long enough for flared slopes and scarp foot depressions to have developed (see e.g PUGH, 1956; CLAYTON,1956; TWIDALE, 1962).

Stepped inselbergs provide crucial evidence concerning the reality, as opposed to the theory, of scarp recession in granitic terrains. Stepped inselbergs are residuals

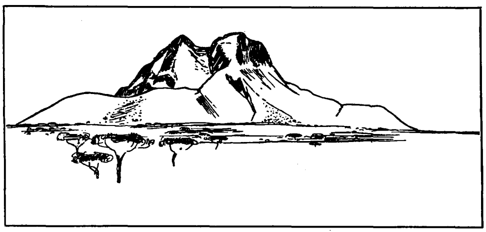


Fig. 4. Inselberg with distinct bevel or shoulder, the Bongoberg, Angola. (After Jessen, 1936).

the bounding slopes of which display alternations of scarp and platform, step and tread. Such forms, developed at various scales (Fig.4) are quite widely distributed (see e.g. JESSEN, 1936; TWIDALE and BOURNE, 1975b; TWIDALE, 1882a) The northwestern slope of Yarwondutta Rock, near Minnipa, northwestern Eyre Peninsula, provides a clear, compact example (Pl. 14). The steps are, in fact, flared slopes (see above, and TWIDALE, 1962). Exposures of contemporary flared weathering fronts confirm that the shoulder marking the upper limit of the concavity represents the former hill-plain junction. Extrapolating this conclusion to the stepped slope, the exposed flared slopes denote alternations of subsurface scarp foot weathering and erosion, though whether this took the form of lowering of the entire plains or simply a phased erosion of the plains surrounding the residuals is not known.The stepped morphology implies some recession of the steep slopes, but this is due not to gullying, as supposed by KING (1949b), but to subsurface (moisture) weathering; and the recession amounts to at most a few tens of metres and not the scores or even hundreds of kilometres demanded by King's theory, andmore importantly, by inselberg landscapes. Evidently the landscape slate is not wiped clean during each phase or cycle of erosion, for Yarwondutta Rock has survived at least two such alternations of weathering and erosion (TWIDALE, 1982c). Retardation of recession due to diminution of the contributing catchment (TWIDALE 1978b) may account for this in some measure. On the other hand, reinforcement or positive feedback effects (TWIDALE et al., 1974) tend to perpetuate and enhance relief.

KING (1966) pointed out that in many

areas the height of the bornhardts above the plains far exceeds the depth of weathering below them, and suggested that this was inconsistent with the requirements of the two stage theory. But stepped forms imply that some bornhardts, at any rate, have evolved not in a single alternation of subsurface weathering and erosion, but in several (TWIDALE and BOURNE, 1975b; see also TWIDALE, 1978a), so that the discrepancy between height of residual and thickness of regolith in any one area is not critical.

RELATED FORMS

The value of a principle or hypothesis lies in the number of features it explains. The scarp retreat explanation of bornhardts is refuted by much field evidence and leaves other aspects unexplained. The two stage hypothesis on the other hand accounts for the field evidence, local, regional and global. It is also capable of accommodating related forms and features.

Thus, in these terms, block- and boulder-strewn nubbins (or knolls) and the castellated forms known as castle koppies are simply variants of bornhardts TWIDALE, 1981a). Nubbins (Pl.15a) are prominent in the humid and seasonally humid (monsoonal) tropics. They commonly occur in ordered groups. Though some blocks and boulders reflect epigene weathering of exposed sheet structures, some break down undoubtedly takes place beneath the surface (Pl.16) and most nubbins are best interpreted as due to rapid disintegration in the upper part of the regolith of the outer one or two shells or sheet structures, so that the inner domical core, which can be seen in many of the forms, is all but covered by blocks and boulders (Fig. 5a; Pl.15b). Such intense weathering can be explained in terms of the abundant rainfall and high ambient temperatures of the humid tropics.Nubbins that occur outside these regions reflect either climatic change, as in the American Southwest (OBERLANDER, 1972) or locally abundant subsurface moisture, as may be the case in valleys and basins underlain by well fractured granites in parts of Namaqualand (Pl.15c), and north of Alice Springs, in the Macdonnell Ranges of central Australia.

Castellated forms or castle koppies (Pl.17a), most commonly occur in isolation, as in Zimbabwe, and on many of the Hercynian massifs of western Europe. In the Traba Massif of Galicia, and in the Sierra Gerês of northern Portugal (e.g. the Corga das Negras), however, they are closely spaced and stand in ordered, fracture-controlled groups(Pl. 17b) They are best explained as the innermost cores of bornhardts, the crests of which were exposed and thus relatively dry and stable, but the buried flanks of which were weathered in the subsurface, causing a reduction in the mass by lateral centripetal migration of the weathering front (Fig.5b). That such marginal subsurface weathering has taken place is indicated by the presence of flared segments on some of the bounding slopes (Pl.17c)This marginal weathering may have taken place either over a long period, as in Zimbabwe, or intensely and rapidly, as for example in cold, or formerly cold, areas such as the moors of southwestern England, the Pyrenees, and the uplands of northern Portugal and southern Galicia (Pl.17d), where frost action and ground ice were and are active in the upper or near surface zone of the

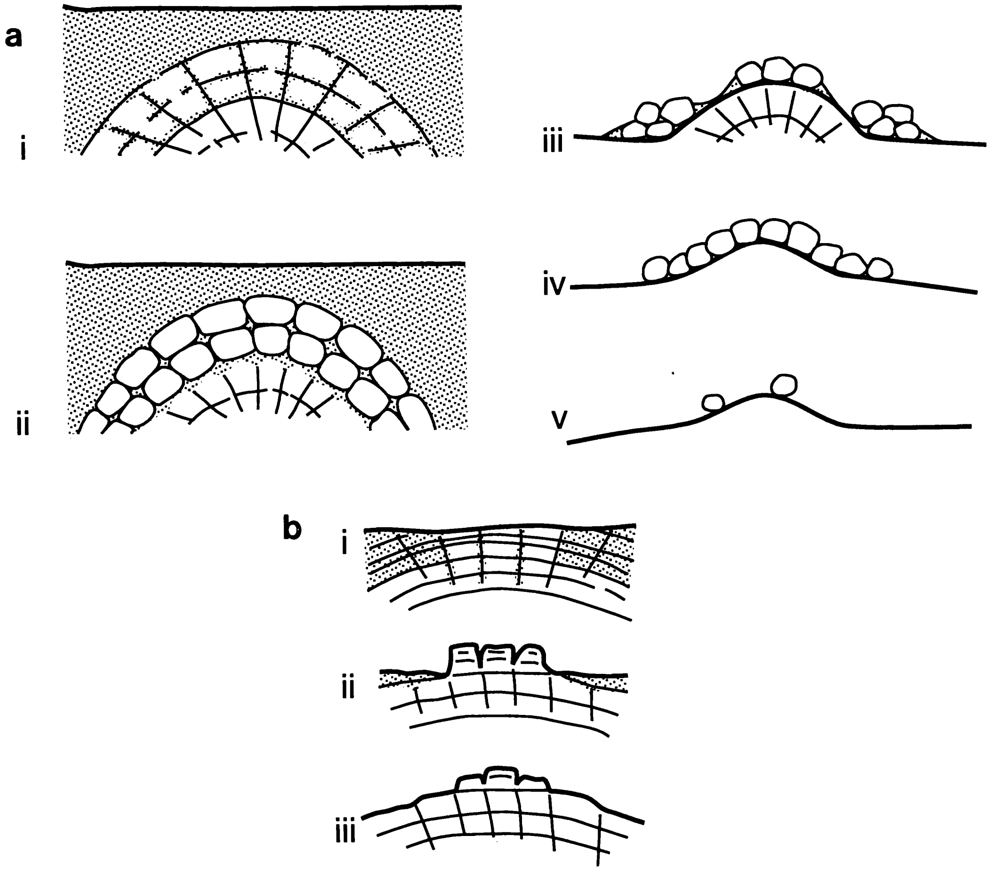
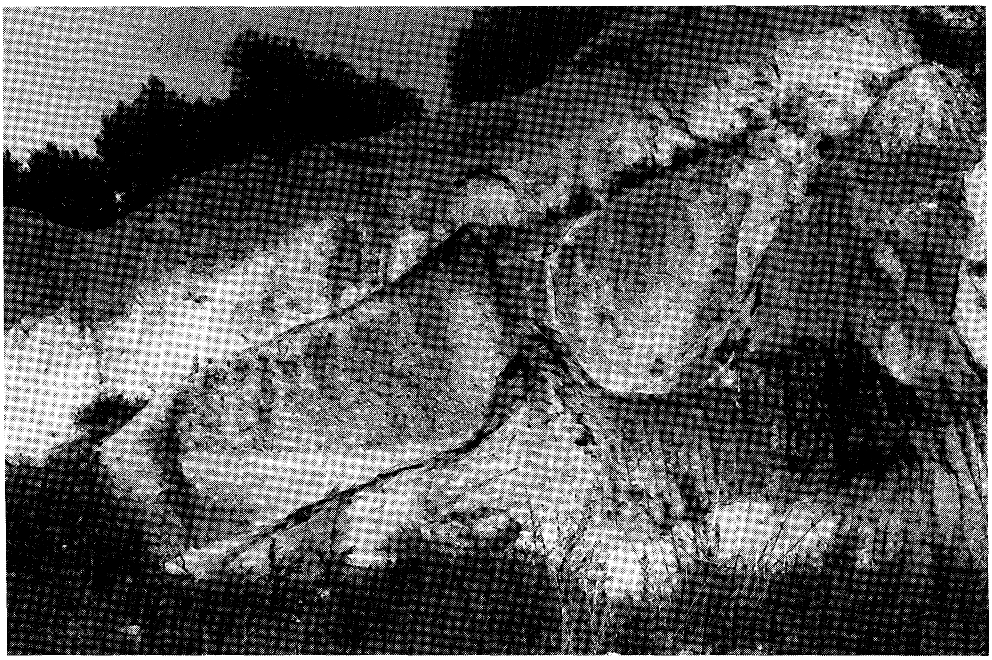


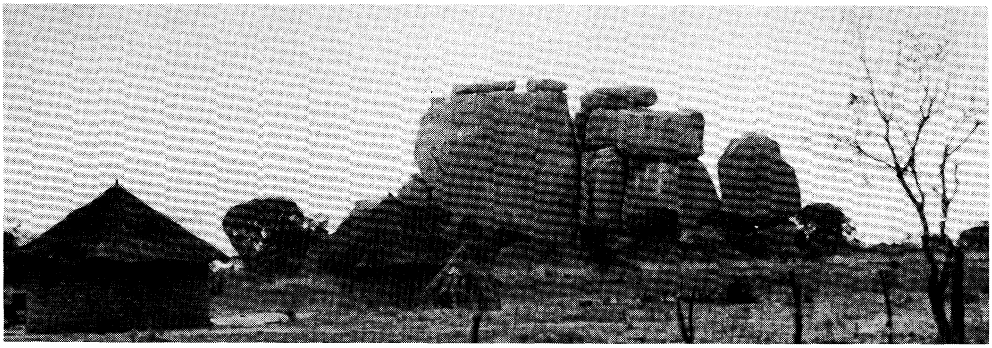
Fig. 5. Sequential development of (a) nubbin (b) castle koppie.

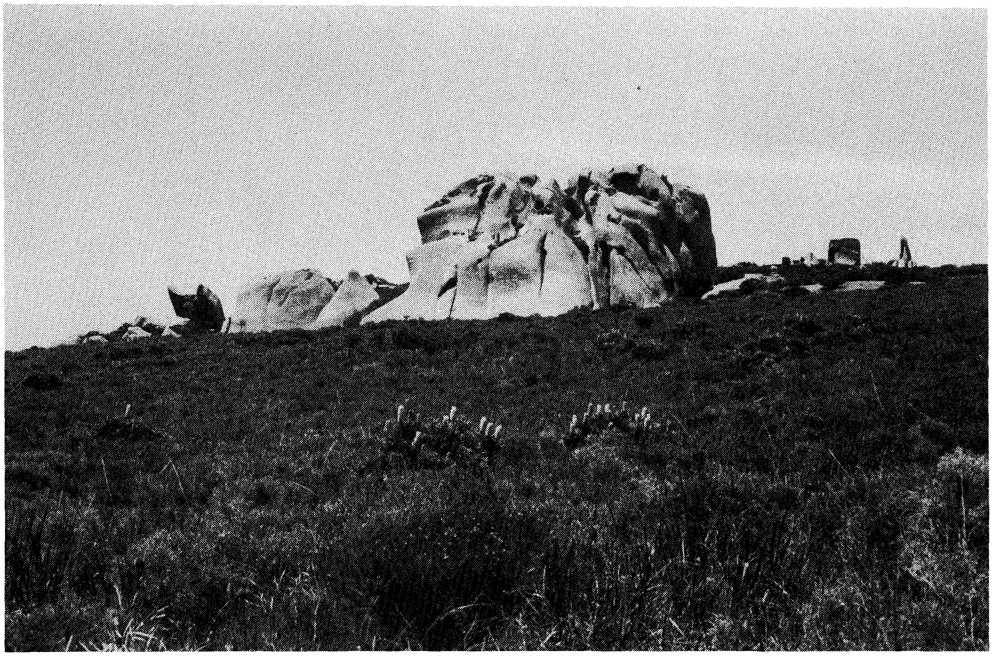
Pl. 15 (a) Granite nubbin, western Pilbara of Western Australia.
(b) Degraded nubbin, Devils Marbles, central Australia, showing residual blocks on dome.

Pl. 15 (c) Granite nubbin, Namaqualand, South Africa.

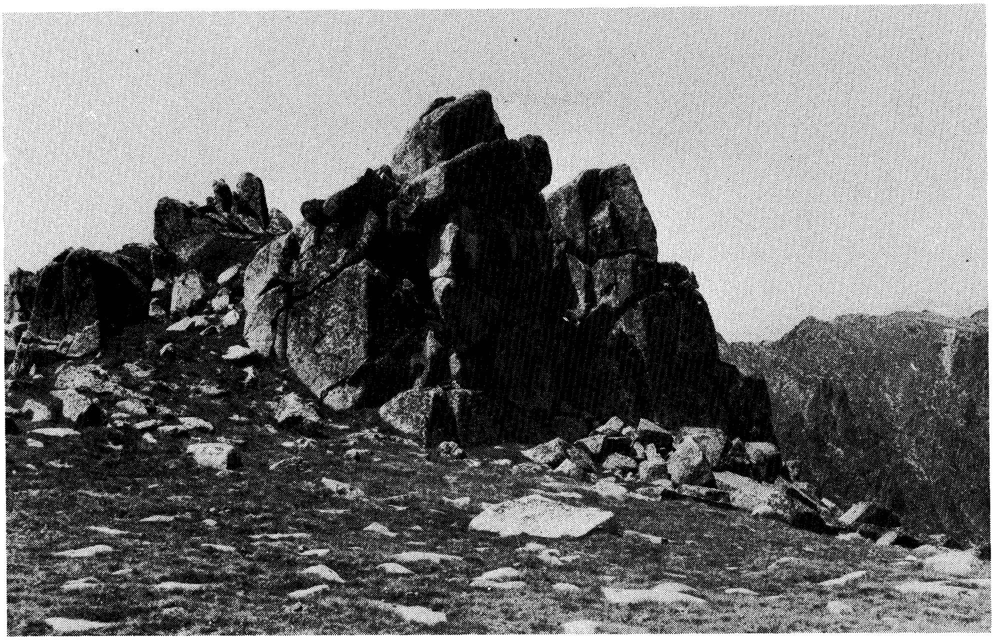


Pl. 16. Section at Paarl Quarry, near Cape Town, South Africa, showing sheet structure already disintegrated beneath the natural land surface.





Pl. 17. (a) Castle koppie, central Zimbabwe. (b) Castle koppies in the Traba Massif of Galicia.



Pl. 17. (c) Castle koppie in central Pyrenees.

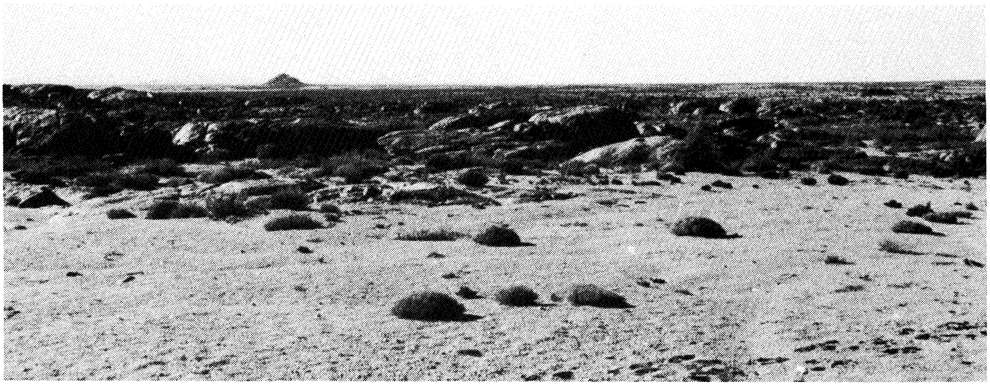
regolith. In any event the rock mass was reduced to a small size to give what French workers appropriately call inselbergs de poches. As with nubbins, local conditons may produce koppies in anomalous situations, as with the Devils Marbles, located in the core of an anticlinal valley in the arid interior of Australia (TWIDALE, 1980).

INSELBERGS

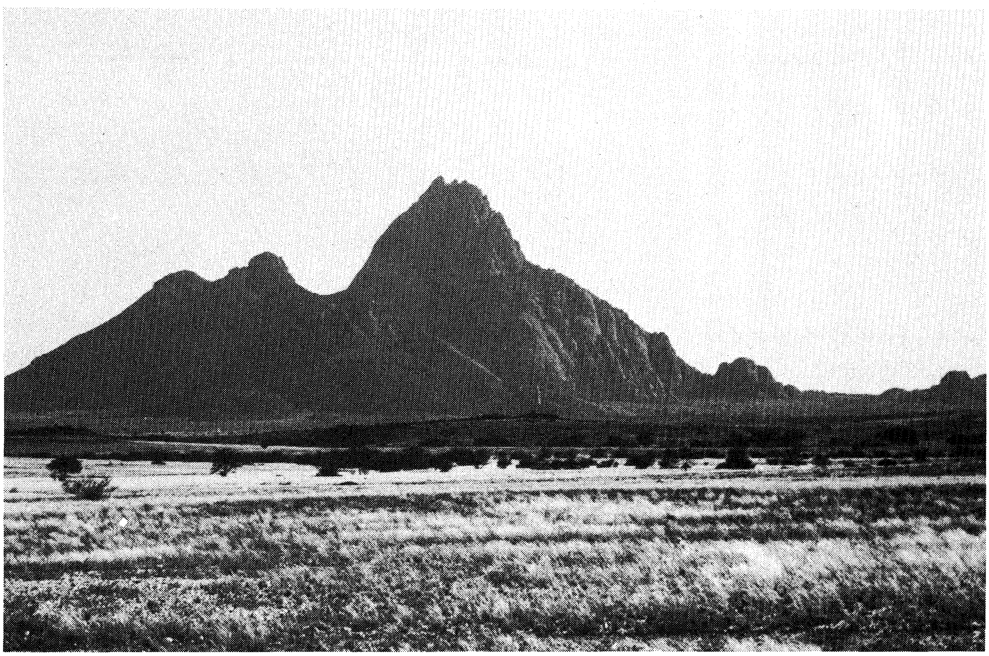
Though bornhardts occur within massifs, they find their most dramatic expression in isolation, in inselberg landscapes (Pl.18); and it is ironic that these comparatively small forms have given their name to entire landscapes.

The most characteristic inselberg landscapes are found in the tropical shield lands. The reason is that the shield lands are stable, so that whatever the climatic conditions, there has been time for subsurface weathering to reduce all but the most resistant compartments to regolith. Most of the surviving resistant masses have been reduced to small size, and only especially durable, originally extensive or recently uplifted massifs, have survived as inselbergs (Pl.19). In weaker lithologies such as limestone, extreme etch planation is more readily and rapidly achieved (as on the Nullarbor Plain - TWIDALE, 1990) but in granitic rocks featureless plains argue duration of weathering, and antiquity of landform.

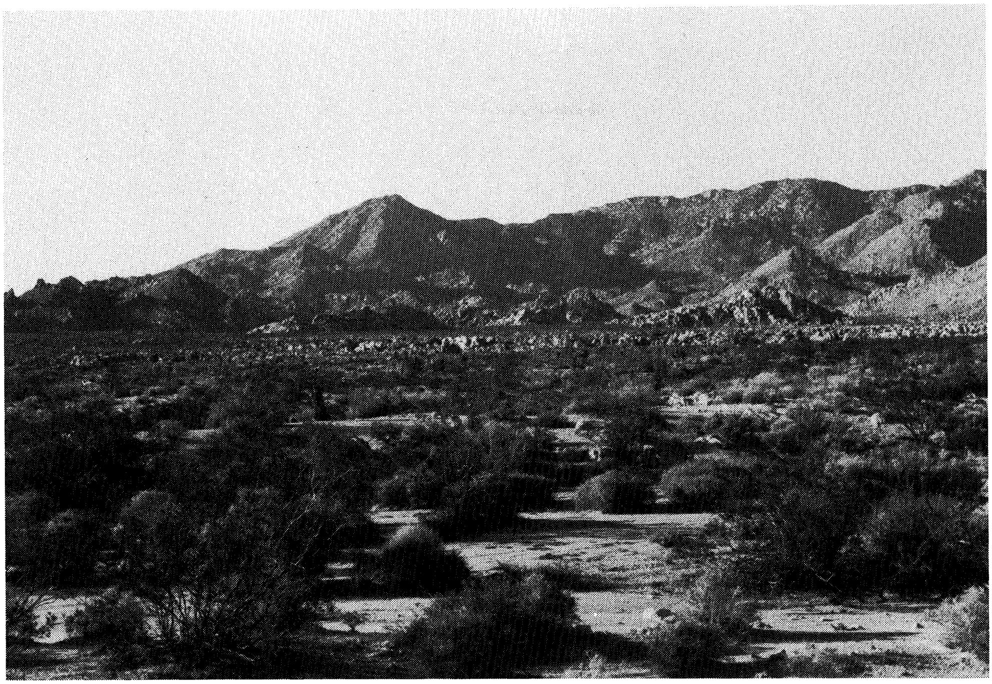
Many, perhaps most, inselbergs are

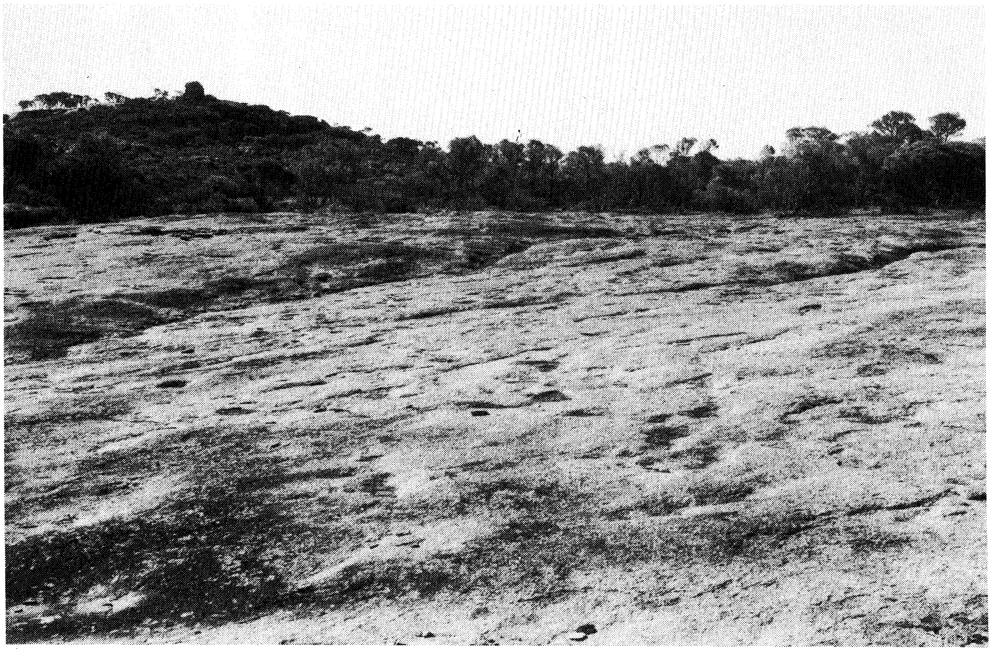


Pl. 18. Inselberg landscape in granite, Namaqualand, South Africa.

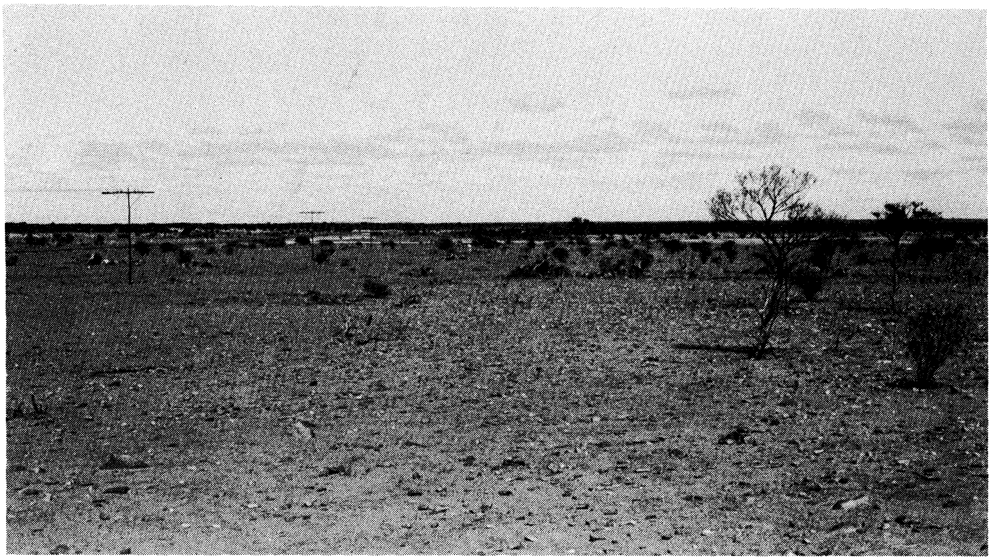


Pl. 19. The Groot Spitzkoppe, central Namibia.

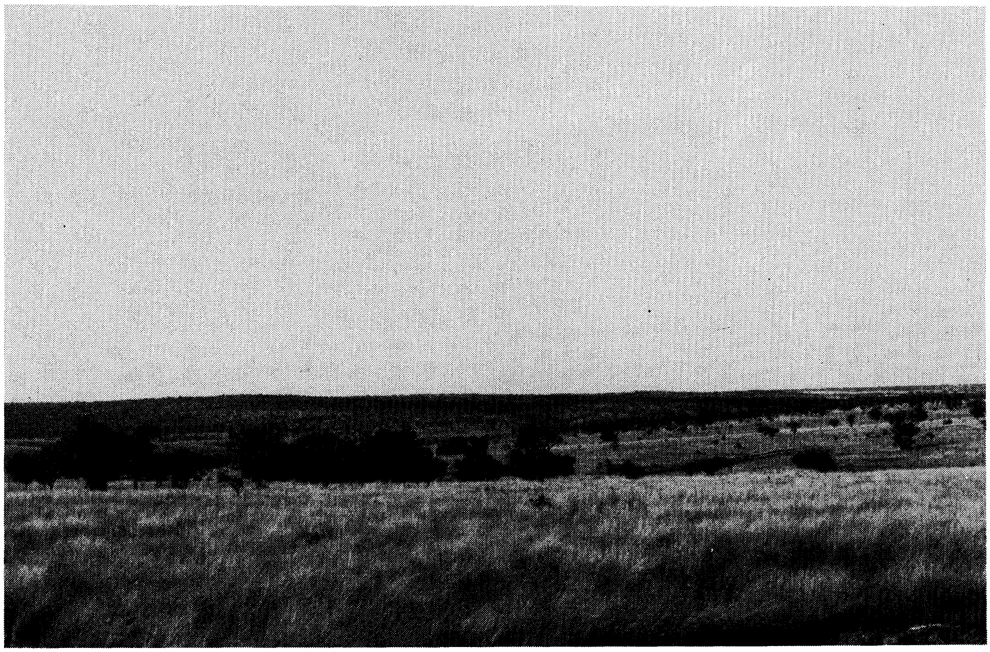




Pl. 20 (a) Mantled pediment in granite, occurring just below the surface, beneath a thin regolith, as exposed in river bluff, Granite Mountains, southern California, USA.
(b) Part of the rock platform or pediment extending from the base of Corrobinnie Hill, northern Eyre Peninsula, South Australia.



Pl. 21. Part of the Meekatharra Plain, a virtually featureless plain eroded in granitic rocks in central Western Australia.



Pl. 22. Rolling planation surface in granite, northern Transvaal, South Africa.

fringed by pediments. Some are mantled (TWIDALE, 1981), and carry a thin regolith, consisting mainly of weathered bedrock in situ (Pl.20a). The regolith has been stripped from others to expose a rock pediment or platform (Pl. 20b). As is well known, KING (1942) believed that pediments have coalesced to form pediplains, but even in his type areas the required multiconcave upward morphology is not evident (TWIDALE, 1983).

Some of the extensive, featureless plains of inselberg landscapes are also etch forms; certainly extraordinarily flatgranite plains like the Bushmanland Surface (Pl.18) and the Meekatharra Plain of the interior of Western Australia (Pl. 21) are of this type. Where the regolith has not been completely stripped, plains of low relief, and of broadly rolling morphology (Pl. 22 - see also BIROT et al., 1974), have been eroded in grus, as for example in the southern Yilgarn of Western Australia, and on Eyre Peninsula, in South Australia, where, however, the surface is protected by a carapace of calcrete.

CONCLUSION

On balance, the evidence suggests that most bornhardts have developed in two stages, the first involving structurally controlled subsurface weathering, the second the stripping of the regolith to expose the irregular weathering front of which bornhardts are a prominent feature. Some inselbergs are tectonic, but most are structural and etch features.The rate of weathering doubtless varies according to the physical, chemical and biotic character of the shallow groundwaters (and atmospheric climate may well influence these), but the end products are everywhere similar. As groundwaters are ubiquitous, similar forms develop the world over. In like manner, though the mineralogy of the bedrock influences the rate of development, similar physical characteristics in the bedrock lead to similar weathering forms regardless of petrological classification. Hence the lithological azonality of many landforms. The nature of the agencies responsible for stripping of the regolith has varied both spatially and temporally, but preeminently it is rivers and running water that have exposed etch forms (TWIDALE, 1990).

The two stage or etch hypothesis accounts not only for the typical site and regional features of bornhardts, boulders and inselbergs but also for their global characteristics. It is true that any theory that fits all the facts is bound to be wrong, if only because some of the data are flawed, but the two stage or etch concept is nevertheless a powerful tool in the interpretation not only of granitic terrains but of landscapes generally.

REFERENCES CITED

BARBEAU J. and GÈZE B., 1957. Les coupoles granitiques et rhyolitiques de la région de Fort-Lamy (Tchad). *C. R. Som. et Bull. Soc Géol. de France* 7, 341-351.

BARBIER R., 1957. Aménagement hydroelectriques dans le sud du Brésil. C. R. *C. R. Som. et Bull. Soc Géol. de France* 6, 877-892.

BARTON D. C., 1916. Notes on the disintegration of granite in Egypt. *Jour. of Geol.* 24, 382-393.

BATEMAN P. C. and Wahrhaftig C., 1966. Geology of the Sierra Nevada. pp.107-172 in *Geology of Northern California* (Edited E.H.Bailey) California Division of Mines and Geology Bulletin 190.

BIROT P., 1958. Les domes crystallins. Centre National de Recherches Scientifiques *Mem. et Doc.* 7-34.

BIROT P., GODARD A., PETIT, M. and TERS M., 1974. Contribution à l'étude des surfaces d'aplanissement et d'érosion differentielle dans le Transvaal septentrional et oriental (Afrique du Sud). *Rev. de Géog. Phys. et Géol. Dyn.* 16, 421-554,

BLÈS J. L., 1986. Fracturation profonde des massifs rocheux granitiques. Documents du Bureau de Recherches Géologiques et Minières 102.

BORNHARDT W., 1900. *Zur Oberflächengestaltung und Geologie Deutsch Ostafrikas.* Reimer, Berlin. 595p.

BOYÉ M. and FRITSCH P., 1973. Dégagement artificiel d'un dome crystallin au Sud-Cameroun. *Trav. et Doc. de Géogr. Trop.* 8, 69-94.

BRAJNIKOV B., 1953. Les pains-de-sucre de Brésil: sont ils enracinés? *C. R. Som. et Bull. Soc Géol. de France* 6, 267-269.

BÜDEL J., 1977. *Klima-Morphologie.* Borntraeger, Berlin. 304 p.

CAMPBELL E. M. and TWIDALE C. R., 1991. The evolution of bornhardts in silicic volcanic rocks, Gawler Ranges, South Australia. *Aust. Jour. of Earth Sci.* 38, 79-93.

CHOUBERT B., 1949. *Géologie et petrographie de la Guyane Francaise.* Office de la Recherche Scientifique de l'Outre-Mer, Paris.120p.

CLAYTON R. W., 1956. Linear depressions (Bergfussniederungen) in savannah landscapes. *Geog. Stud.* 3, 102-126.

DARWIN C., 1846. *Geological Observations in South America.* Smith, Elder, London. 279p.

FAIRBRIDGE R. W. and FINKL C. W., 1978. Geomorphic analysis of the rifted cratonic margins of Western Australia. *Zeits. für Geom.* 22, 369-389.

FALCONER J. D., 1911. The Geology and Geography of Northern Nigeria. Macmillan, London. 295p.

FRAKES L. A., BURGER D., APTHORPE M., WISEMAN J., DETTMAN J., ALLEY N., FLINT R., GRAVESTOCK D., LUDBROOK N., BACKHOUSE J., SKWARKO S., SCHEIBNEROVA V., MCMINN A., MOORE P. S., BOLTON B. R., DOUGLAS J. G., CHRIST R., WADE M., MOLNAR R. E., MCGOWRAN B., BALME B. E. and DAY R. A., 1988. Australian Cretaceous shorelines stage by stage. *Palaeogeo., Palaeoclim., Palaeoecol.* 59, 31-48.

GODARD A., 1977. *Pays et Paysages du Granit.* Presses Universitaires de France, Paris. 232p.

HARRIS W. K. and TWIDALE C. R., 1991. Revised age for Ayers Rock and the Olgas. *Trans. of the R. Soc. of South Aust.* 115, 109.

HASSENFRATZ J.-H., 1791. Sur l'arrangement de plusieurs gros blocs de différentes pierres que l'on observe dans les montagnes. *Ann. de Chim.* 1, 95-107.

HILLS E. S., 1955. Die landoberfläche Australiens. *Die Erde* 7, 195-205.

HOLMES A. and WRAY D. A., 1912. Outlines of the geology of Mozambique. *Geol. Mag.* 9, 412-417.

HUBER N. K., 1987. The geologic story of Yosemite National Park. United States *Geol. Surv. Bull.* 1595.

HURAULT J., 1963. Recherches sur les inselbergs granitiques nus en Guyane Francaise. *Rev. de Géom. Dyn.* 14, 49-61.

JESSEN O., 1936. *Reisen und Forschungen in Angola.* Reimer, Berlin. 397p.

JONES T. R.,1859. Notes on some granite tors. *Geol.* 2, 301-312.

JUTSON J. T., 1914. An outline of the physiographical geology (physiography) of Western Australia. *Geol. Surv. of West. Aust.Bull.* 61.

JUTSON J. T., 1934. The physiography (geomorphology) of Western Australia. *Geol. Surv. of West. Aust.Bull* 95.

KEYES C. R., 1912. Deflative scheme of the geographic cycle in an arid climate. *Geol Soc of America Bull.* 23, 537-562.

KING L. C., 1942. *South African Scenery.* Oliver and Boyd, Edinburgh. 308p.

KING L. C., 1949a. A theory of bornhardts. *Geog J* 12, 83-87.

KING L. C., 1949b. The pediment landform: some current problems. *Geol Mag* **86**, 245-250.

KING L. C., 1953. Canons of landscape evolution. *Geol Soc of America Bull* 64, 721-752.

KING L. C., 1957. The uniformitarian nature of hillslopes. *Trans of the Geol Soc of Edinburgh* 17, 81-102.

KING L. C., 1966. The origin of bornhardts. *Zeit für Geom* **10**, 97-98.

LAGEAT Y., SELLIER D. and TWIDALE C. R., 1994. Megalithes et méteorisation de granite en Bretagne littorale, France du nord-ouest. *Géog Phy. et Quaternaire* **48**, 107-113..

LAMEGO A. R.,1938. Escarpas do Rio de Janeiro. Departamento Nacional da Produção Mineral (Brasil), *Serie Geologia y Mineria Boletin* 93.

LE CONTE J. N., 1873. On some of the ancient glaciers of the Sierras. *Amer J of Sc and Arts* 5, 325-342.

LINTON D. L., 1955. The problem of tors. *Geog J* 121, 470-487.

MABBUTT J. A., 1961. 'Basal surface' or 'weathering front'. *Proceedings of the Geol Assoc* (London) 72, 357-358.

LISTER L. A., 1987. The erosion surfaces of Zimbabwe. *Zimbabwe Geol Surv Bull* **90**.

MENNELL F. P., 1904. Some aspects of the Matopos. 1. Geological and physical features. *Proce of the Rhodesian Science Assoc* 4, 72-76.

MERRILL G. P., 1897. *Treatise on Rocks, Rock-weathering and Soils.* Macmillan, New York. 411p.

OBERLANDER T. M., 1972. Morphogenesis of granitic boulder slopes in the Mojave Desert, California. J. *of Geol* **80**, 1-20.

OLLIER C. D. and TUDDENHAM W. G., 1962. Inselbergs of central Australia. *Zeits für Geom* **5**, 257-276.

PASSARGE S., 1904a. Das Inselberglandschaften in tropischen Afrika. *Naturwiss Woch* **3**, 657-665.

PASSARGE S., 1904b. Rumpfläche ind Inselberge. *Zeits, Deuts. Geol Gesel* 56, 195-203.

PASSARGE S., 1924. Das Problem afrikanischer Inselberglandschaften. *Petermanns Mitteilungen* 70, 66-70, 117-120.

PEEL R. F., 1941. Denudational landforms of the central Libyan Desert. *J. .of Geom* 4, 3-23.

POST L. VAN DER, 1962. *The Lost World of the Kalahari.* Penguin, Harmonsworth, 253 p.

PUGH J. C., 1956. Fringing pediments and marginal depressions in the inselberg landscape of Nigeria. *Trans and Papers of the Inst of Brit Geogr* 22, 15-31.

SCHUMM S. A., 1963. Disparity between present rates of denudation and orogeny. *United States Geol Surv. Prof. Paper* 454.

SEAGER W. R., 1981. Geology of the Organ Mountains and southern San Andreas Mountains, New Mexico. *New Mexico Bureau of Mines and Mineral Resources Memoir* 36.

SELBY M. J., 1970. Bornhardts of the Namib Desert. *Zeits für Geom* **21**, 1-13.

SOEN OEN ING, 1965. Sheeting and exfoliation in the granites of Sermasoq, south Greenland. *Medelesser om Gronland* 179(6).

THOMAS M. F., 1966. Some geomorphological implications of deep weathering patterns in crystalline rocks in Nigeria. *Trans of the Institute of British Geogr* 40, 173-191.

TOIT A. L. du, 1939. *Geology of South Africa.* Oliver and Boyd, Edinburgh. 611p.

TWIDALE C. R., 1962. Steepened margins of inselbergs from north-western Eyre Peninsula, South Australia. *Zeits für Geom* 6, 51-69.

TWIDALE C. R., 1964. Contribution to the general theory of domed inselbergs. Conclusions derived from observations in South Australia. *Trans and Papers of the Inst of British Geogr* 34, 91-113.

TWIDALE C. R., 1967. Origin of the piedmont angle as evidenced in South Australia. *J of Geol* 75, 393-411.

TWIDALE C. R., 1973. On the origin of sheet jointing. *Rock Mechanics* 3, 163-187.

TWIDALE C. R., 1978a. On the origin of Ayers Rock, central Australia. *Zeits für Geom Supplement-Band* 31, 177-206.

TWIDALE C. R., 1978b. On the origin of pediments in different structural settings. *Amer. J Science* 278, 1138-1176.

TWIDALE C. R., 1980a. Origin of bornhardts. *J Geol Soc of Australia*. 27, 195-208.

TWIDALE C. R., 1980b. The Devil's Marbles, central Australia. *Trans of the Royal Soc of South Australia* 104, 41-49.

TWIDALE C. R., 1981a. Granite inselbergs: domed, block-strewn and castellated. *Geogr J* 147, 54-71.

TWIDALE C. R., 1981b. Origins and environments of pediments. *J Geol Soc of Australia* **28**, 423-434.

TWIDALE C. R., 1982a. *Granite Landforms.* Elsevier, Amsterdam. 372p.

TWIDALE C. R., 1982b. The evolution of bornhardts. *Amer Scien* **70**, 268-276.

TWIDALE C. R. 1982c. Les inselbergs à gradins et leur signification: l'exemple de l'Australia. *Ann de Géogr* 91, 657-678.

TWIDALE C. R., 1983. Pediments, peneplains and ultiplains. *Rev de Géom Dyn* 32, 1-35.

TWIDALE C. R., 1986. A recently formed A-tent on Mt Wudinna, Eyre Peninsula, South Australia. *Rev de Géom Dyn* 35, 21-24.

TWIDALE C. R., 1987. Review of J. L. Blès (1986). Progress in Physical Geography 11, 464.

TWIDALE C. R., 1988. Granite landscapes. pp. 198-230 in *The Geomorphology of Southern Africa*. (Edited B. P. Moon and G. F. Dardis) Southern Publishers, Johannesburg.

TWIDALE C. R., 1990. The origin and implications of some erosional landforms. *J. of Geol* 98, 343-364.

TWIDALE C. R. and BOURNE J. A., 1975a. The subsurface initiation of some minor granite landforms. *J. Geol Soc of Australia* 22, 477-484.

TWIDALE C. R. and BOURNE J. A., 1975b. Episodic exposure of inselbergs. *Geol Soc of America Bull* 86, 1473-1481.

TWIDALE C. R. and BOURNE J. A., 1976. Origin and significance of pitting on granite rocks. *Zeits für Geom* 20, 405-416.

TWIDALE C. R., BOURNE J. A. and SMITH D. M., 1974. Reinforcement and stabilisation mechanisms in landform development. *Rev. Géom Dyn* 23, 115-125.

TWIDALE C. R. and CAMPBELL E. M., 1984. Murphy Haystacks, Eyre Peninsula, South Australia. *Trans. Royal Soc. of South Australia* 108, 95-103.

TWIDALE C. R. and HARRIS W. K., 1977. On the age of Ayers Rock and the Olgas, central Australia. *Trans. Royal Soc. of South Australia* 101, 45-50.

TWIDALE C. R. and MILNES A. R., 1983. Aspects of the distribution and disintegration of duricrusts in arid Australia. *Geologie en Mijnbouw* 62, 373-382.

TWIDALE C. R., SCHUBERT C. and CAMPBELL E. M., 1991. Dislodged blocks. *Rev. de Géom Dyn.* 40, 119-129.

TWIDALE C. R. and SVED G., 1978. Minor granite forms associated with the release of compressive stress. *Aust. Geogl. Stud.* 16, 161-174.

TWIDALE C. R. and VIDAL ROMANI J. R., 1994. The multistage development of etch forms. *Geomorphology.* 11, 107-124..

VIDAL ROMANI J. R., TWIDALE C. R., CAMPBELL E. M. and CENTENO J. D., 1995. Pruebas morfológicas y estructurales sobre el origen de las fracturas de descamación. *Cuad. Lab. Xeol. Laxe.* 20, 307-346.

WHITLOW J. R., 1978-9. Bornhardt terrain on granitic rocks in Zimbabwe: a preliminary assessment. *Zambian Geographical Journal* 33-34,75-93.

WILHELMY H., 1958. Klimamorphologie der Massengesteine. Westerman, Braunsweig. 238p.

WILLIS B., 1934. Inselbergs. *Assoc. of Amer. Geograph. Annals* 24, 123-129.

WILLIS B., 1936. *East African plateaus and rift valleys. Studies in Comparative Seismology,* Carnegie Institute, Washington D. C., Publication 470.

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