BORNHARDTS AND ASSOCIATED FRACTURE PATTERNS

Rowl. C TWIDALE [a, b]

[a] School of Earth and Environmental Sciences, Geology and Geophysics, University of Adelaide, Adelaide 5005, South Australia, Australia. E-mail: rowl.twidale@adelaide.edu.au
[b] Instituto Universitario de Xeolóxia Isidro Parga Pondal, Campus de Zapateira s/n, A Coruña 15071, Galicia, Spain.

ABSTRACT

Bornhardts are bald domical hills. In plan they are defined by systems of steeply-dipping fractures, in profile by arcuate-upward sets. They occur in multicyclic landscapes. They have formed through much of geological time, for some date from the Late Archaean and are represented in most subsequent periods. They have been explained as due to tectonism, or structure or environment, but most workers interpret them either as the last remnants surviving long-distance scarp retreat (*monadnocks de position*), or as two-stage or etch forms which have survived because of their massive structure (*monadnocks de résistance*).

The field evidence suggests that though bornhardts originate in various ways, on balance most appear to be of etch origin. They were initiated at the base of the regolith by differential structurally-controlled subsurface weathering. Many have been exposed in stages. Differential weathering is based in variations in fracture density which is attributed to shearing and fracture propagation. Similarly recurrent shear stresses are responsible for the arcuate fractures characteristic of bornhardts.

Keywords: *Bornhardt, etch form, weathering front, episodic exposure, sheet fracture.*

RESUMEN: *Bornhardts y diseños de fractura asociados.* Los bornhardt son colinas dómicas descubiertas. En planta se ven delimitadas por planos de fractura con fuerte buzamiento, en perfil por otros planos convexos. Se asocian a paisajes multicíclicos. Se han formado a lo largo de los tiempos geológicos ya desde el Arqueano tardío. Han sido interpretados bien por tectonismo, bien por estructura o bien por razones ambientales, pero muchos investigadores las entienden como los últimos restos que han sobrevivido a un retroceso de escarpes prolongado en el tiempo (monadnocks de posición), o como formas de corrosión química o de dos etapas que han sobrevivido a la degradación química/física debido a la estructura masiva de la roca en ese punto (monadnocks de resistencia). Las variaciones en la densidad de fracturación se atribuyen a cizalla y a propagación de fracturas. La fracturación arqueada se relaciona igualmente con tensiones corticales antiguas o activas en el momento actual. Aunque los bornhardt se pueden originar de varias formas, cuando se consideran todas las posibles muchos parecen ser formas de dos etapas iniciadas en la base del regolito por meteorización subsuperficial controlada por las diferencias en la estructura. Muchos bornhardts han sido expuestos en varias etapas. Las razones para el desarrollo de los residuales no deben unirse o ser confundidas con el desarrollo de los superficies que habitualmente los rodean. La evolución de estas últimas es independiente de origen, irrelevante para entender el origen de los bornhardts.

Palabras clave: *Bornhardt, formas de denudación química, frente de meteorización, exposición episódica, fractura laminar.*

INTRODUCTION

Bald domical hills are known as bornhardts. The term is eponymous for they were named in honour of the German explorer-scientist who worked in central Africa just over a century ago (Bornhardt 1900, Willis 1934). Although South American landscapes feature prominently in the investigation of granitic terrains in general, and of bornhardts in particular, general theories concerning the origin of the forms have been based mainly in evidence from Africa and in lesser degree the Americas and Australia. Both orthogonal and sheet fractures are in some way linked to bornhardts (e.g. King 1949, Birot 1958) but their origin, relationship and the role of sheet fractures in particular remain controversial. Some have argued that the rounded form of bornhardts is an expression of the convex-upward fractures that are characteristic of the residuals. Others consider that the rounded form is due to preferential weathering and erosion, and that this shape is simulated by developing fractures. Thus, some interpret morphology as consequent on structure, others structure as consequent on morphology. The possible origins of bornhardts and of the fractures with which they are so closely associated are discussed with reference to field evidence from various parts of the world.

BORNHARDT CHARACTERISTICS

The term bornhardt is applied to bald domical hills, whether standing in isolation as inselbergs, as components of massifs, or as occurrences within broader uplands (Fig. 1). Bornhardts are the basic form from which other types of inselberg, and notably nubbins (or knolls) and castle koppies, are derived (Twidale 1981). In plan, bornhardts are delineated by steeply-dipping orthogonal or rhomboidal fractures, and in profile by arcuate (most commonly, though not everywhere, convex-upward) sheet fractures. Where steeply-dipping fractures are prominent and closely-spaced, turreted forms tend to develop, as in the Organ Mountains of New Mexico (Seager 1981) and in the Agulhas Negras Mountains, WNW of Rio de Janeiro (Fig. 2a). Bornhardts are developed in massive rocks, notably in granite, but also in dacite and norite, sandstone, conglo-

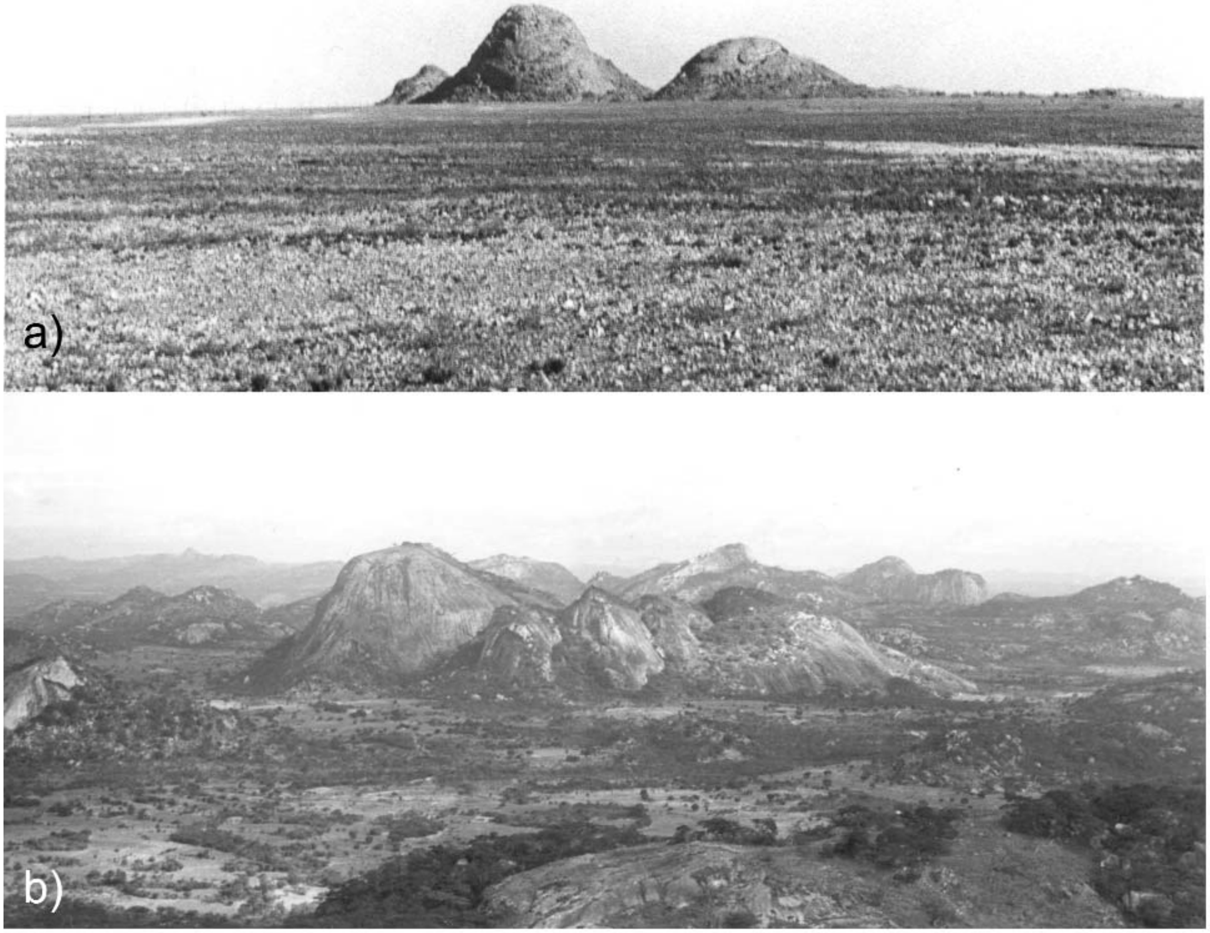


Figure 1: a) Typical bornhardts inselbergs in central Namibia. b) Field of bornhardts, relief amplitude about 400 m, near Mtoro, NNE of Harare, Zimbabwe (L.A. Lister).

merate and limestone. Though spectacularly displayed in arid and semi-arid lands, they are reported from a wide range of climatic environments (Wilhelmy 1958, Twidale and Bourne 1978). They are found in various topographic settings but consistently occur in multicyclic landscapes (Jessen 1936, King 1949).

Exhumed bornhardts range in age from latest Archaean (in the Pilbara Craton of Western Australia: see Twidale 1986) through Neoproterozoic (Williams 1969, Williams and Schmidt 1997) to Middle and Late Pleistocene (Twidale and Campbell 1984). Many date from the Late Jurassic or Early Cretaceous (e.g. Willis 1936, Twidale 1986) just prior to the series of the world-wide marine transgressions characteristic of that period. Such resurrected forms demonstrate that, however bornhardts have evolved, the mechanisms and processes responsible for them have been active through much of geological time.

PREVIOUS THEORIES OF ORIGIN

TECTONICS AND STRUCTURE

Some workers have suggested that bornhardts are upfaulted blocks (Passarge 1895, Lamego 1938, Choubert 1949, 1974, Birot 1958). The Pic Paraná, in southeastern Brazil, is clearly of this origin (Barbier 1957). The fracture-related steep slopes that define most residuals, however, are joint-controlled.

Some bornhardt inselbergs are upstanding by virtue of their composition for they are developed in rock that is different from, and implicitly more resistant to, weathering and erosion than the materials in which the surrounding plains are shaped (e.g. Herrmann 1957, Thorp 1969, Selby 1977). The nature of the postulated mineralogical weakness varies. Lamego (1938) attributed the western face of the Pão de Assuçar (Fig. 2 b) in part to the occurrence of biotite gneiss that is more readily weathered than the lenticular gneiss of which most of the residual is composed, causing the slope to be undermined and steepened. More generally Birot (1950) and Hurault (1963) claimed that biotite is vulnerable to moisture attack and argued that upstanding bornhardt masses are free of, or low in, that mineral, whereas Brook (1978) suggested that some bornhardts are shaped preferentially in granitic rocks rich in potash feldspars.

Many bornhardt masses in the older cratons like those of the Yilgarn and Pilbara regions of Western Australia are buttressed and thereby strengthened by swarms of

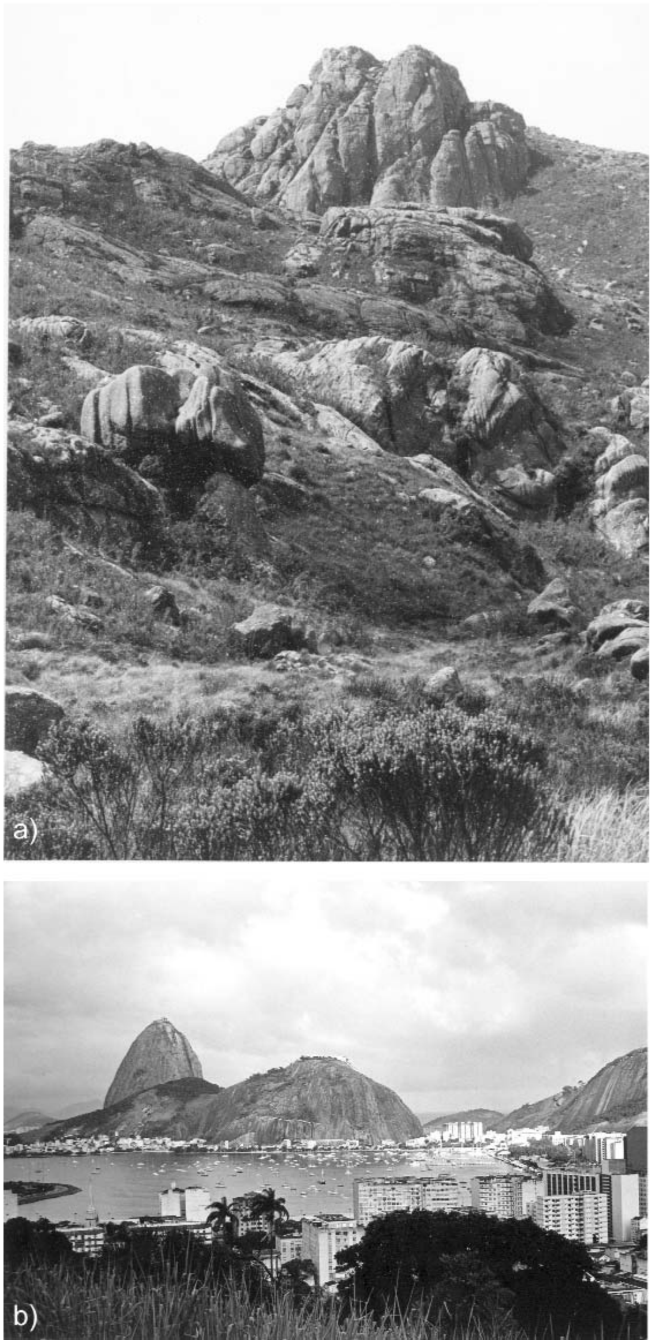


Figure 2: a) Peaks of the Agulhas Negras, a syenitic massif WNW of Rio de Janeiro. b) General view of the Pão de Assuçar (Rio de Janeiro), the crest of which stands 404 m above sea level.

quartz and aplite sills and veins. Other residuals have been interpreted as stocks or minor apophyses projecting from the margins of batholiths or other igneous emplacements (Fig. 3) into hosts of different and implicitly weaker composition (Holmes and Wray 1912, du Toit 1937, Worth 1953, Twidale 1982a, p. 131). But most bornhardts appear to be of the same composition and texture as the rocks beneath the adjacent plains. This applies to the granitic rocks exposed in the domes of northwestern Eyre Peninsula, South Australia, and also in the Pilbara Craton, where the buttressed gneisses revealed in the upland appear identical to those exposed in piedmont platforms; and to sedimentary bornhardts such as Uluru (Ayers Rock) and Kata Tjuta (The Olgas) in central Australia (e.g. Twidale 1978a).

Fractures are avenues of weathering and in particular water penetration. Variations in fracture density (or number of fractures per unit area) and hence of resistance to weathering and erosion could account for topographic differences. Contrasts in fracture density between bornhardt and adjacent plain (Fig. 4a) have been observed at several sites (Jones 1859, Twidale 1964, 1982a, p. 132, Büdel, 1977, p. 109). Contrasted fracture density could develop as a result of recurrent shearing and fracture propagation (e.g. Weissenberg 1947, Gifkins 1965, Fig. 4b). Spatial variations in density, with uplands developed on massive compartments, were cited by Le Conte (1873) in explanation of the domes of the Yosemite region of central California, and by Mennell (1904) concerning the topography of the Matopos of southern Zimbabwe. It may be argued that such contrasts are irrelevant to the problem, that what is significant is not the fracture density of the present piedmont, but rather the spacing or closeness of open fractures in the rock mass that formerly stood at the same level as the present bornhardt, but which has been eroded. Blès (1986), however, has shown statistically that there is a high probability that the fracture density at the present land surface is indicative of density at depth. By extension, if surface density can be projected downwards it can surely be taken as indicating the character of the once higher compartment that has now disappeared (Twidale 1987a).

Bornhardts in Brazilian metamorphic (and especially gneissic) terrains have been construed as developing on the massive compressional cores of antiforms (Fig. 5) or in compressional zones resulting from metasomatic alteration (Lamego 1938, Brajnikov 1953, Valverde 1968). Brajnikov envisaged the compressed cores 'floating' in a matrix of weathered rock, rather like huge corestones, but the model does not find support in deep excavations either in Brazil (e.g. Barbier 1957) or elsewhere (e.g. Moye 1958). The bornhardt masses appear to be physically contiguous with the underlying pluton.

Whatever the precise reason for their being upstanding, bornhardts are in these various terms interpreted as *Härtlinge, monadnocks de dureté or de résistance*, that is, as structural forms sensu lato.

Figure 3: Bornhardt developed on stock of Donkahoek Granite intrusive into schist, central Namibia.

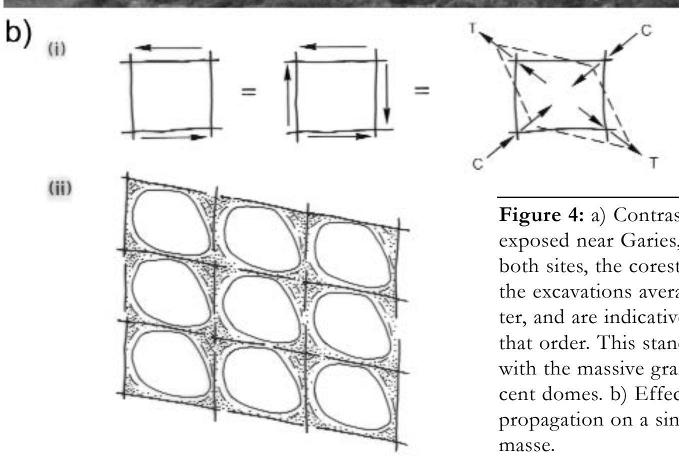


Figure 4: a) Contrasted fracture density as exposed near Garies, in Namaqualand. At both sites, the corestone boulders exposed in the excavations average a metre or so diameter, and are indicative of fracture spacing of that order. This stands in marked contrast with the massive granite exposed in the adjacent domes. b) Effect of shear and fracture propagation on a single joint block and en masse.

ENVIRONMENTS OF FORMATION

Bornhardt (1900, p. 34) entertained the possibility that inselbergs were literally island mountains and had been shaped by waves, for the inselberg landscapes of his type area in what is now Tanzania are exhumed from beneath a cover of Cretaceous marine strata (Willis 1936). But he almost immediately abandoned the idea. Domical hills, standing either in isolation or in ordered groups, quite commonly occur in coastal and insular settings but no evidence has been adduced to suggest that marine processes alone can produce such rounded forms. Bornhardts are well known from inland sites (e.g. the Yilgarn and Pilbara cratons) which evidently have never been inundated by the sea, and certainly not during the Phanerozoic (BMR Palaeogeographic Group 1992). As with bornhardts from cold climates, the occurrence of the domical forms in coastal settings is fortuitous rather than essential.

Agassiz (1865) considered that the granitic domes of the Rio de Janeiro area were gigantic roches moutonnées and thus of glacial origin. Le Conte (1873) reached similar conclusions concerning the domes of the Yosemite. But there is no evidence that the Rio area has been glaciated in recent geological times, and as with the suggested littoral or marine origin of bornhardts, the glacial context of domes found, for example, in the Yosemite and northern Norway (Matthes 1930, Kieslinger 1960, Bateman and Wahrhaftig 1966, Huber 1987) is coincidental rather than essential. Glaciers do not produce domical forms but acting as bulldozers, and like wind-driven waves breaking on the coast, are capable of stripping regoliths, to expose previously prepared bedrock forms. Glaciers have merely revealed and slightly modified pre-existing domical masses from beneath regolithic covers (e.g. Boyé 1950, Bird 1967, Twidale 1990, Lidmar-Bergström 1997).

Inselbergs and bornhardts were briefly considered to be typical desert forms (e.g. Passarge 1895) for they are presently well displayed in arid lands. And this despite their early recognition in the humid tropics (Darwin 1876) and the attraction such features held for later investigators (e.g. Freise 1933-35, 1936-38, 1943, Birot 1958). Considerable erosional power at one time was attributed to wind and sand blasting (Keyes 1912, Jutson 1914). However, even in deserts most erosional forms are due to running water: both desert plains and any associated residuals long have been construed as resulting from river work, past or present (e.g. Bornhardt 1900, Falconer 1911, Thiele and Wilson 1915, Bain 1923, Peel 1941).

SCARP RETREAT

An abrupt transition from hill to plain is

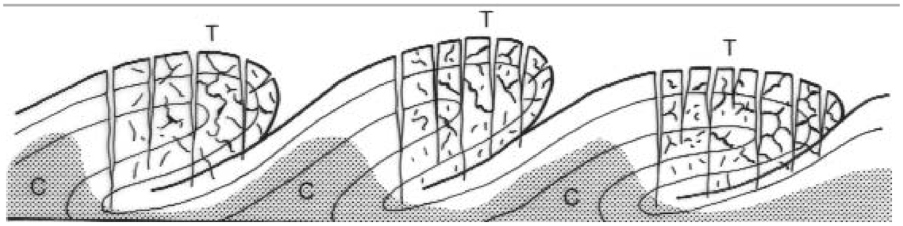


Figure 5: Section through bornhardts of the Rio de Janeiro region. C - compressive core. T - tensional zone (after Lamego 1938).

one of the most distinctive features of desert landscapes (e.g. Hills 1955, Van der Post 1958, p. 183). Known as the piedmont angle, it is due to moisture-related weathering, in most instances exploiting structure, but basically concentrated in the scarp-foot zone (Peel 1941, Twidale 1967, 1978b). This is also the basic mechanism which drives scarp recession. Dry granite remains fresh and stable. Granite in contact with moisture however is soon rotted (see Caillère and Henin 1950, Loughnan 1969, p. 61). Thus in a dissected landscape granite exposed high on a slope is dry and stable and acts as a caprock, by contrast with that exposed below which is weathered and is eroded. This induces first, the steepening of the slope to a maximum inclination commensurate with stability, leading to the undermining and collapse of higher slope elements; and second, the maintenance of scarps of essentially constant inclination and morphology during backwearing (Peel 1941, Twidale and Milnes 1983). The scarp retreat mechanism was appreciated by such early workers as Fisher (1866) but was used as the basis of a model of landscape evolution (King 1942, 1962), and also has been applied in explanation of bornhardts (Holmes, 1918; King, 1949, 1966). For some workers (e.g. Ollier and Tuddenham 1961, Selby 1977) isolated bornhardts are the last remnants remaining after long-distance scarp recession. They are *Fernlinge*, or *monadnocks de position* (Figure 6a).

SUBSURFACE PREPARATION: THE COMPOSITE TWO-STAGE HYPOTHESIS

A hypothesis combining structural aspects with a different but ubiquitous environmental factor, namely the differential weathering and erosion of compartments of contrasted fracture density in the shallow subsurface (Fig. 6b), is due to Falconer (1911). First variations in fracture density can be attributed to recurrent shearing and fracture propagation (Fig. 4b), resulting in the production of massive compressed and resistant cores surrounded by fractured rocks.

Second, several workers (Hassenfratz 1791, MacCulloch 1814, Logan 1849) earlier had concluded that many boulders are of two-stage or etch origin. Basing their deductions on field observations (Fig. 7a), they argued that boulders had formed as a result of fracture-controlled subsurface weathering which converted cubic or quadrangular blocks into rounded corestones. The weathered material was then evacuated, leaving the corestones exposed as boulders. That the corestones are in situ and not transported by rivers or glaciers is demonstrated by the presence at many sites of intrusive veins (Fig. 7b). It was but a short step to regard such corestone boulders as miniature bornhardts and to interpret the latter also as two-stage forms; though as mentioned bornhardts appear to differ from corestones in that they have 'roots'.

Observations in South America concerning the depth and nature of rock weathering, and particularly in granite terrains, were critical to the development of ideas concerning both corestones and bornhardts. Several travellers and scientists, (e.g. Humboldt and Bonpland 1852-3, p. 482, Branner 1896) reported weathering to depths of several tens of metres and more, and many recorded the occurrence of corestones (or 'boulders of decomposition' or some similar name) set in a matrix of grus or weathered granitic material. Though Darwin (1876, p. 428) thought in terms of submarine weathering, the deep and intense weathering noted around Rio de Janeiro was attributed to water, to '…warm rains falling on a heated soil…' (Agassiz 1865, p. 390) under epigene conditions.

But it was Falconer who formally applied the two-stage concept developed in regard to corestones boulders to inselbergs in general and granitic bornhardts in particular. He specifically cited a two-stage or etch origin in explanation of the inselberg landscapes of northern Nigeria:

"*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 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. Those rocks which had offered the greatest resistance to chemical weathering beneath the surface would upon exposure naturally assume that configuration of surface which afforded the least scope for the activity of the agents of denudation. In this way would arise the characteristic domes and turtlebacks* ..." (Falconer 1911, p. 246).

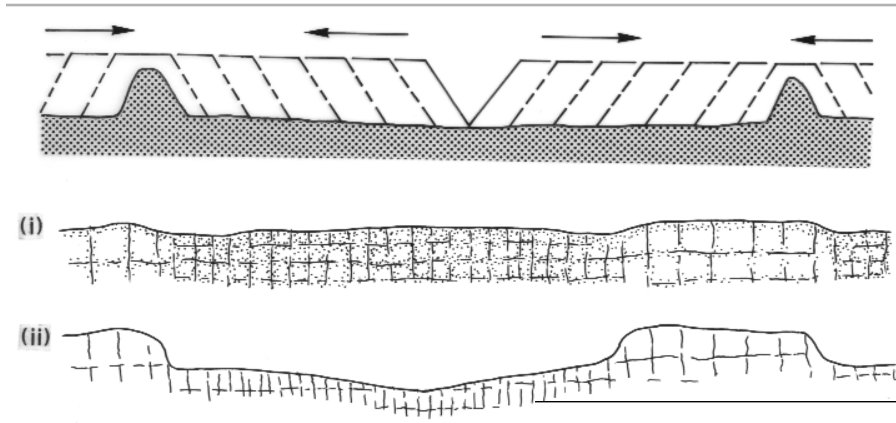


Figure 6: a) Inselbergs resulting from long-distance scarp retreat. b) (i) and (ii) Stages in the etch or two-stage origin of bornhardts.

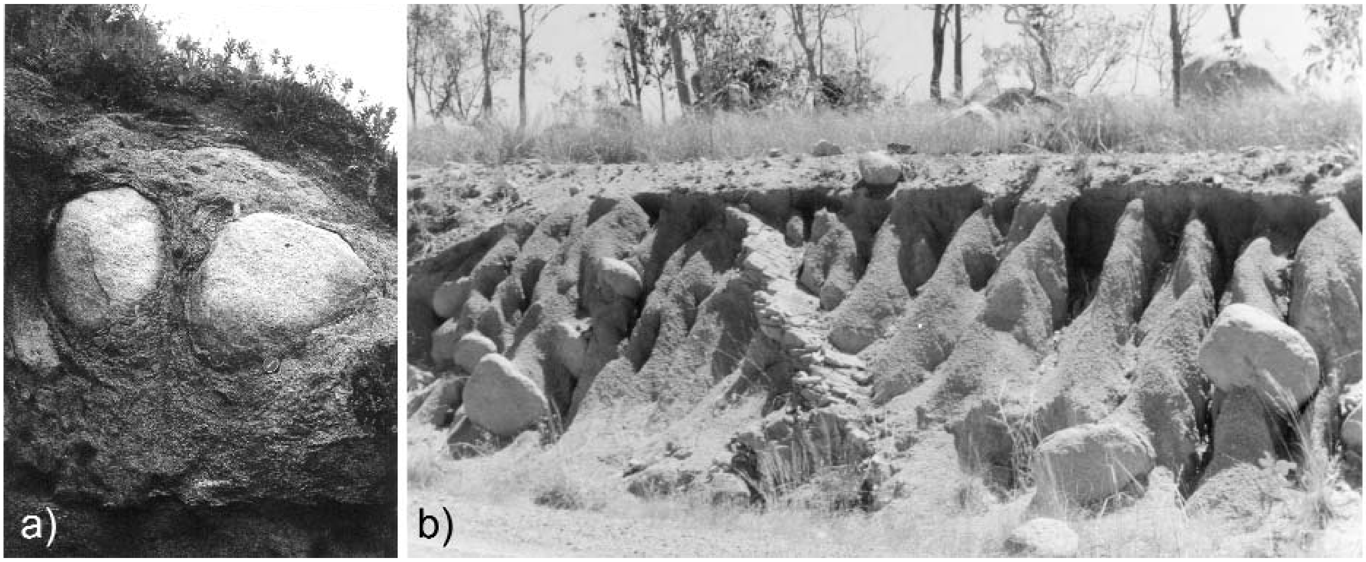


Figure 7: a) Corestones with marginal lamination (onion-skin, spheroidal, weathering) set in matrix of grus and exposed in road cutting (1979) in the foothills of the Agulhas Negras, NNW of Rio de Janeiro, southeastern Brazil. b) Corestones, boulders and intrusive sill exposed in road cutting near Pine Creek, Northern Territory, Australia.

Falconer's rounded 'configuration of surface' which affords the least scope for weathering, and hence erosion, can be construed simply as due to preferential weathering of the corners and edges of rock compartments, as deduced many years ago in explanation of corestones (e.g. MacCulloch 1814, Beche 1839, p. 450, Logan 1849); or to weathering guided by pre-existing sheet fractures (see below).

The two-stage interpretation carries several significant implications (Twidale 1987b, 2002). For example, etch forms have two ages, one of which relates to the period of differential weathering of bedrock at the base of the regolith; which is also known as the weathering front (Mabbutt 1961). The second pertains to the period of exposure of that front as part of the land surface. In some areas an etch surface signals the previous existence of a planation surface of which no other evidence now exists (e.g. Campbell and Twidale 1991, Twidale 2000).

TESTS OF THE COMPETING HYPOTHESES

Both the scarp retreat and the two-stage or etch hypothesis of bornhardt formation are plausible. What are the deducible consequences of the two competing hypotheses and how compatible are they with the field evidence?

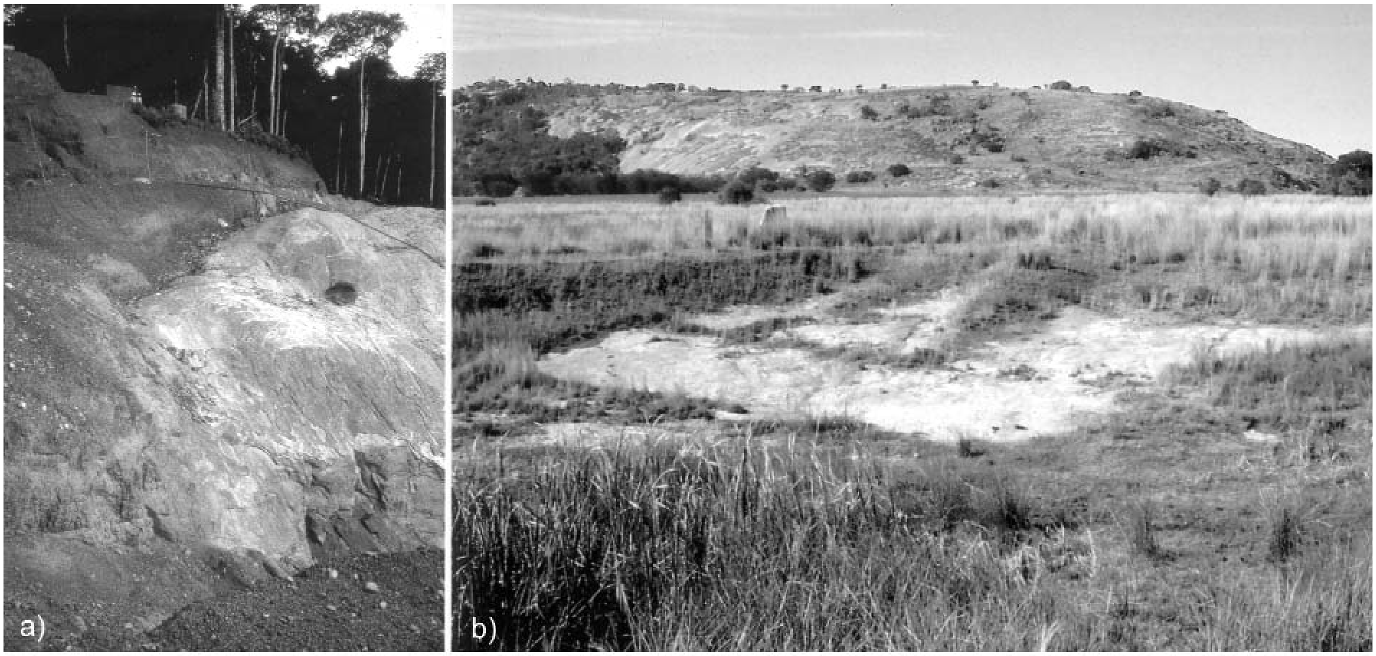
a) Rock masses with convex-upward surfaces have been exposed in artificial excavations in Cameroon (West Africa), southern Africa, and Eyre Peninsula (Boyé and Fritsch 1973, Twidale 1982a, Vidal Romani and Twidale 1998). The occurrence of similar features with the crest just exposed as a rock platform has been established by excavation at several sites in southern Africa and southern Australia (Figs. 8a and 8b). Such features are incompatible with a wholly epigene origin, for the regolithic cover is in situ and not transported.

b) Bornhardts are in process of exposure in valley-side slopes, as for example Rocky Mountain National Park, near Estes, Colorado (Fig. 8c), and Witrivier in Mpumalanga Province in northeastern South Africa. These occurrences, interpreted as par-tly exposed domical rock masses shaped beneath the land surface at the weathering front, are incompatible in terms of epigene scarp recession.

c) Stepped inselbergs (Figure 9a) are interpreted as having been exposed episodically by the differential weathering and erosion of the surrounding plains (Bremer 1975, Twidale and Bourne 1975; Twidale 1982a, 1982b, 1982c, Bourne and Twidale 2000). That the steps preserved on the flanks of the residuals were once hill-plain junctions is indicated by breaks of slope and particularly by flared slopes (Fig. 9b), almost all of which are of subsurface origin (Twidale 1962, Twidale and Bourne 1998). Residuals such as Uluru and the Pão de As-suçar, though not stepped, nevertheless show evidence of episodic exposure in the form of tafoni, breaks of slope and flared sidewalls located in irregular but essentially horizontal zones at various elevations on the uplands (Fig. 9c, Twidale 1978a). Such episodic exposure negates the objection to subsurface initiation of bornhardts voiced by King (1966) and based on his observation that in any particular area the height of bornhardts exceeds the depth of weathering (Twidale and Bourne 1975).

A stepped morphology implies that bornhardts have been subjected to repeated phases of concentrated marginal subsurface weathering followed by erosion and the exposure of the resultant concave or flared scarp-foot zones. In this way the residuals have stood higher in the local relief through time, not because of localised uplift, which is rarely in evidence, but because of the more rapid weathering and erosion of the surrounding plains which receive wash from the adjacent upland as well as direct rainfall and runoff.

d) If bornhardt inselbergs were remnants of circumdenudation they ought to be located on major divides. Many are, but some are not (e.g. Jeje 1973). More telling is the occurrence of some exposed in



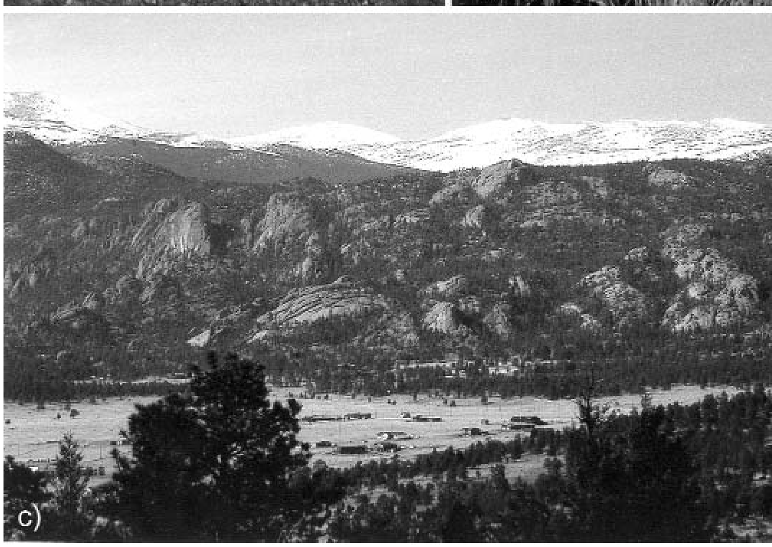


Figure 8: a) Granite dome exposed at Ebaka, Cameroon, West Africa (M. Boyé). b) Bevelled bornhardt in granite-gneiss in the Leeukop, near Potchefstroom, Free State, RSA. The crest of another, but still mainly covered, domical rock mass is exposed in the foreground. c) Bornhardts partly exposed in valley walls near Estes, Colorado.

valley floors (Fig. 10).

Thus, on balance, the field evidence sustains a two-stage or etch origin of bornhardts.

FRACTURE SYSTEMS AND SETS

Bornhardts are closely associated with massive rocks subdivided first, by essentially orthogonal fracture systems which strongly influence the plan form of the residuals and second, by arcuate fracture sets which are associated with their convex-upward profiles. What is the origin of these fractures and what does this imply concerning the development of bornhardts?

ORTHOGONAL SYSTEMS WITH STEEPLY-DIPPING COMPONENTS

The plan form of bornhardts is related to steeply-dipping fractures of orthogonal, or in some instances rhomboidal, systems. Orthogonal and rhomboidal systems are produced by shearing (e.g. Merrill 1897, p. 245, Dekalb 1990, see Fig. 4b). Given the lateral migration of plates through time, the heterogeneous character of the continental masses, the ubiquitous presence of lineament systems (e.g. Vening Meinesz 1947), such shearing, with conjugate sets, is inevitable.

SHEET FRACTURES

Until recently the arcuate fractures characteristic of bornhardts commonly have been referred to as offloading or pressure release joints (and similar names). This terminology carries implications which are at least questionable, and possibly misleading. The genetically neutral yet descriptively evocative term 'sheet fracture' is preferred.

Sheet fractures delineate thick arcuate slabs of rock known as sheet structures (Fig. 11), 'thick' being arbitrarily defined as at least 0.5 m, and up to 10 m, though more commonly in the range 1-2 m. Such fractures extend to depths of several hundreds of metres below the land surface (e.g. Dale 1923). Sheet fractures are found in a wide range of lithologies and in many and varied climatic settings. They transect orthogonal fractures, bedding, and cross-bedding, foliation, flow structures and rift and grain (Dale 1923, Cameron 1945, Bradley 1963). In individual hills the fractures steepen toward the margins of the host residuals. At some sites, sheet structures appear to thicken with depth, but this is at best a generalisation for sheets of varied thicknesses frequently are intercalated. They appear to increase in radius with depth (Fig. 11). They are most commonly aligned roughly parallel with the land surface and are exposed in uplands, sheet fractures most frequently are convex-upward but they demonstrably ex-tend as synforms beneath valleys (e.g. Tolman and Robertson 1969, Campbell and Twidale 1991), thus in toto forming structural undulations beneath the landscape (Dale 1923, p. 35).

Explanations advanced for sheet fractures and structures can be classified as exogenetic or endogenetic (Twidale 1973). Of the former group of hypotheses, only pressure release or offloading (Gilbert 1904) is plausible. The suggestion that the slabs are due to temperature changes, for example, fails to account for their occurrence at depth. Similarly, apart from the theory involving lateral compression (e.g. Merrill 1897, Dale 1923), various endogenetic hypotheses including plutonic injection and metasomatic expansion are unacceptable as general explanations because they fail to account for the field evidence. For instance, sheet structures are well developed in massive sedimentary and volcanic rocks as well as granite and other plutonic rocks (e.g. Bradley 1963, Campbell and Twidale 1991).

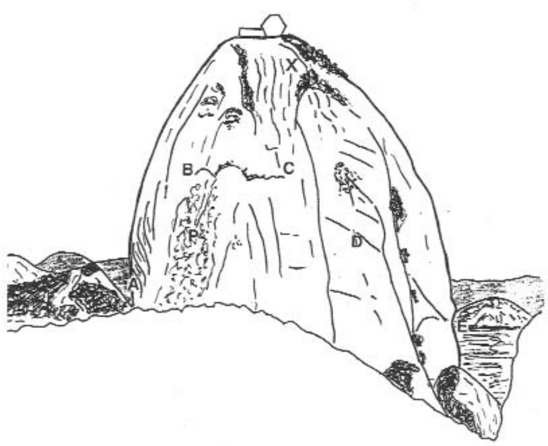


Figure 9: a) Stepped northwestern slope of Yarwondutta Rock, near Minnipa, northwestern Eyre Peninsula, South Australia. b) Concave-upward or flared weathering front and slope exposed in reservoir at Yarwondutta Rock. c) Sketch showing flared and weathered side-walls of the Pão de Assuçar. A-E indicates suggested former junction of rock and soil, as indicated by flared walls, indentations, and pecking (P) or dimpling, which frequently indicate scarp-foot moisture attack (Twidale 1962, Twidale and Bourne 1998b). X is another but higher and earlier flared zone.

CRITIQUE

All fractures are a manifestation of erosional offloading and all disappear at depth under lithostatic pressure (Chapman 1956, see also Richey 1964). The offloading hypothesis, however, implies that sheet fractures are due wholly to offloading, whereas other workers suggest that decrease in lithostatic pressures near the land surface allows other causations to take effect. Strains due to lateral compression, for instance, do not find expression as fractures or folds until lithostatic pressures are sufficiently reduced.

Gilbert's (1904) pressure release hypothesis is plausible in the context of granitic or

Figure 10: Crest of granite dome exposed in valley floor, Malmesbury, north of Cape Town, Western Cape Province.

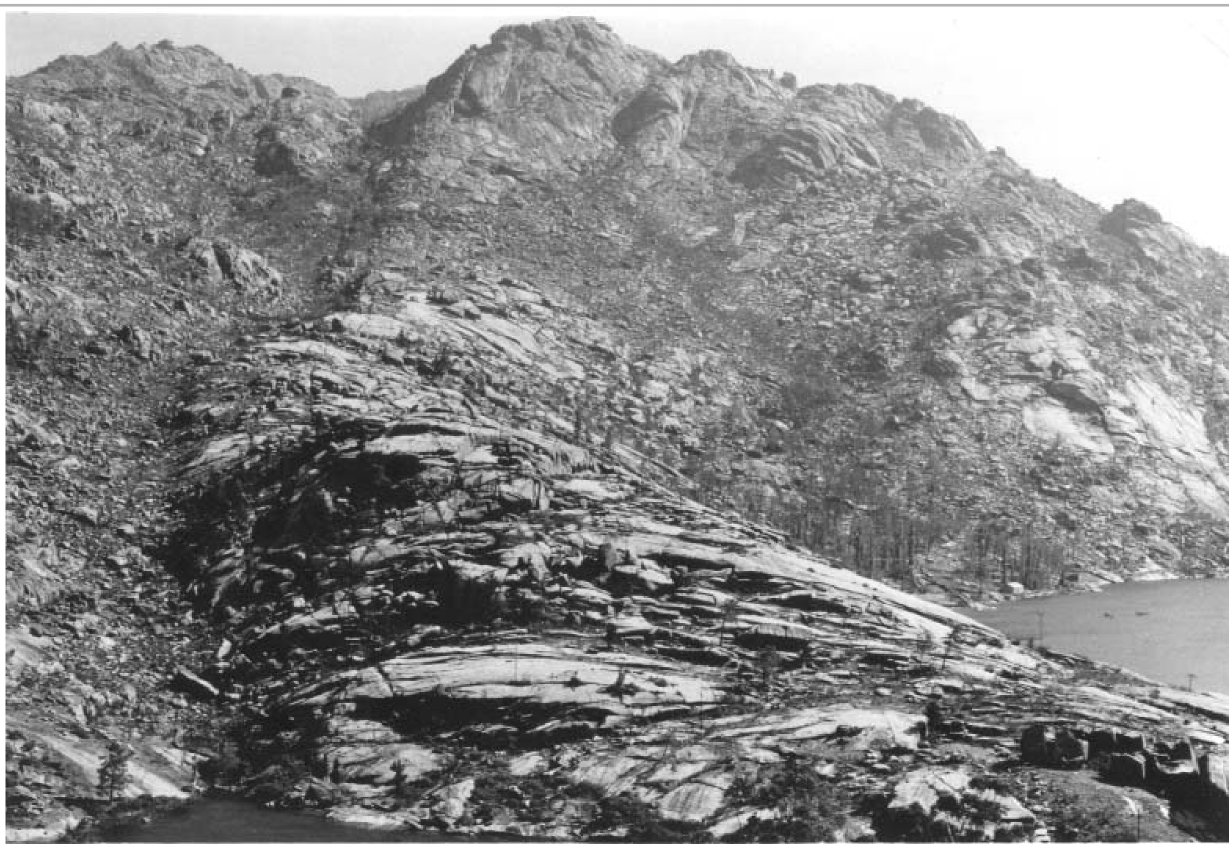


Figure 11: Sheet structures increasing in radius with depth, Pindo area of western Galicia.

other plutonic host rocks. As granites are emplaced at depth, under conditions of high lithostatic pressure, it seems reasonable to suggest that with the erosional stripping of the superincumbent rock, pressures would decrease and the rock expand upwards and outwards. Such radial expansion would result in the formation of tangential partings or sheet fractures. The argument is persuasive. Evidence of relaxation at the granular scale has been noted by Bain (1931) and the parallelism between structure and surface, even on erosional facets of demonstrably recent age (e.g. Lewis 1954, Gage 1966), led many to accept that structure is consequent on surface.

Though the offloading hypothesis has, and has had, many adherents it is nevertheless

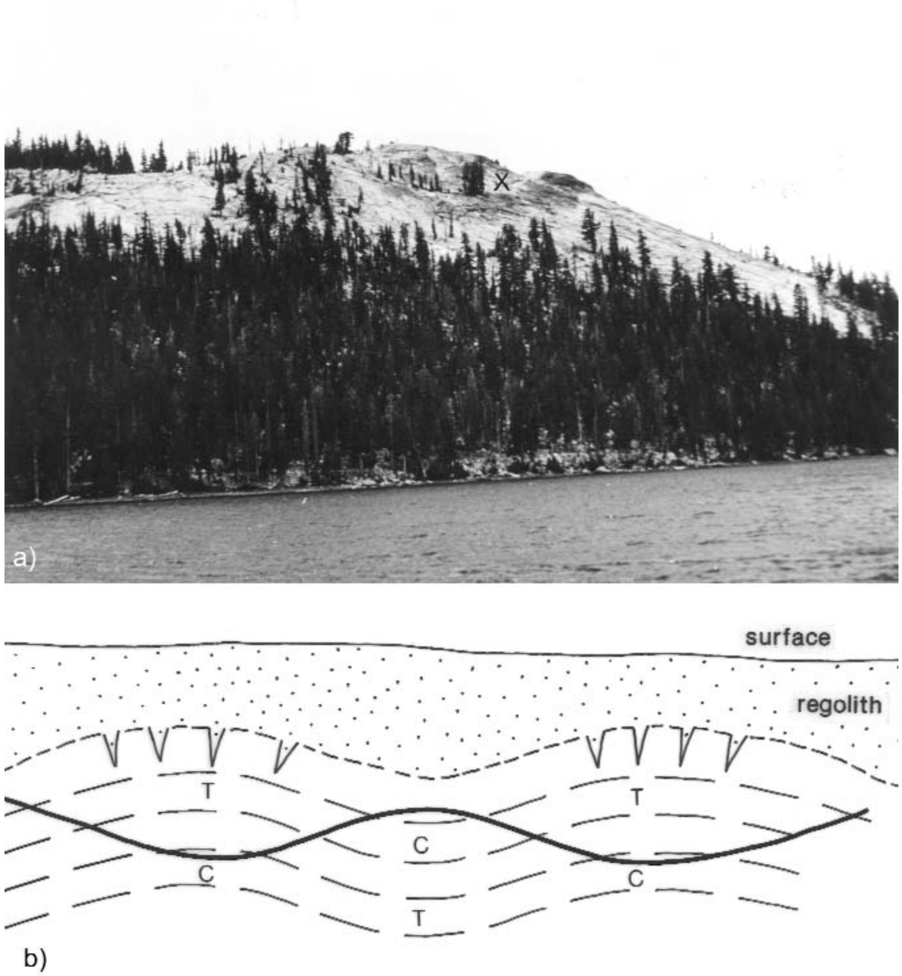


Figure 12: a) Granite dome underlain by synform (X), Tenaya Lake, Yosemite Valley, central California. b) Diagram to illustrate inversion of relief. C - compression. T - tension. I - inversion.

Figure 13: Bornhardt comprising several structural and minor topographic domes, Kamiesberge, Namaqualand.

flawed, and much of the evidence cited in its support is capable of alternative interpretation and many of its implications are not explained by the evidence. For instance, sheet fractures developed in parallel with recent landscape facets can be explained by the re-orientation of principal stress directions following erosion. Similarly, if expansive stress developed during unloading, why were the resultant strains not accommodated along pre-existing zones of weakness? In the Gawler Ranges silicic volcanic province why were expansive stresses not relieved along sets of columnar joints or the ancient (Neoproterozoic) orthogonal fracture systems? In some areas, for example, Dartmoor in southwestern England, there is an inconsistency between the ages of erosional features and the supposedly consequent partings, with the latter older than the former (Twidale 1971, p. 67-68, Gerrard 1974). Though bornhardts most commonly display sheeting that is arcuate-upward and in conformity with topography some such domical hills are shaped in granite subdivided by synformal structures (Fig. 12a). Such structures are difficult to explain by erosional unloading and consequent expansion but are comprehensible in terms of weathering and erosion having exploited tensional zones in rocks deformed by compression (Fig. 12b, Vidal Romani *et al.* 1995, Twidale *et al.* 1996, Twidale and Bourne 2003). And so on - erosional loading does not satisfy much of the evidence and argument.

According to those who favour the Falconer two-stage concept of bornhardt development, arcuate fracture sets are plausibly attributed to the same compressive (torsional) stresses that caused the masses eventually to become bornhardts. Sheet fractures are developed within blocks defined by steeply-dipping fractures of the orthogonal or rhomboidal systems. Frequently a single topographic dome comprises several structural forms each with its set of sheet fractures (Twidale and Bourne 2003, Bourne and Twidale 2005, Fig. 13). This and other indirect evidence suggests that orthogonal and sheet fractures are genetically related and that the rock structures predate and have given rise to bornhardts.

In addition to observed evidence and the direct or measured compressive stress (e.g.

Niles 1872, Isaacson 1957, Moye 1958, Leeman 1962, Coates 1964, Denham *et al.* 1979, Hillis and Reynolds 2000, Twidale and Bourne 2000), many minor forms attributable to compressive stress are associated with bornhardts. Some are of contemporary derivation (e.g. Twidale and Sved 1978, Vidal Romani *et al.* 1995, Twidale *et al.* 1996, Twidale and Bourne 2000, Bourne and Twidale 2005).

Shearing has caused interference or "egg-box" folding and the formation of antiformal and synformal structures defined by sheet fractures (Merrill 1897, Dale 1923, Lamego 1938, MacGregor 1951, Myers and Watkins 1985, Ramsay and Huber 1987, Myers 1993). Gilbert himself considered that some sheet fractures are attributable to regional compressive stress (Gilbert, cited in Dale 1923, p. 29). Hence the obvious alignment of inselbergs in some areas.

The occurrence of sets of sheet structures or synforms with contrasted axis alignments recorded at regional scale by Dale (1923, p. 360) can be understood as resulting either from contrasted stress directions, or from shearing; but they are incongruous in terms of erosional offloading.

In the laboratory, simple triaxial tests show that alternations of compression and decompression of essentially isotropic materials do not cause fracturing, save in special circumstances which are unlikely to obtain in nature (Wolters 1969, Brunner and Scheidegger 1973). On the other hand, sheet fractures have been formed by exposing partly-confined blocks of rock to compression (Holzhausen 1989). This experimental design mimics the field situation of bornhardts, with which sheet fractures are commonly associated, which have evolved as two-stage forms, and which were subjected to compression while projecting from a weathering front beneath a regolithic cover (Fig. 14).

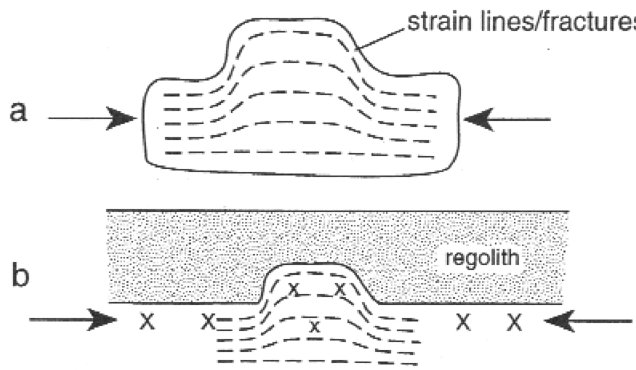


Figure 14: Diagram showing effects of compression on partly confined block (after Holzhausen 1989).

Thus like the bornhardt masses on which they are developed sheet fractures appear to be associated with crustal compression, Though all fractures are an expression of decreased lithostatic pressures, erosional unloading as advocated by Gilbert is incompatible with the field evidence which is more convincingly explained in terms of compressive stress.

INSELBERG LANDSCAPES

Bornhardts occur as components of massifs but most spectacularly in inselberg landscapes with widely separated steep-sided hills protruding above the level of extensive, remarkably flat plains (Fig. 15). Such landscapes imply long-continued subsurface weathering during which all but the most compact cores of sheared blocks have been rotted and eroded.

Inselberg landscapes consist overwhelmingly of plains. It is important not to confuse the genesis of bornhardt residuals with that of the surrounding or adjacent plains. Whatever the mode of origin of the hills the lowering of the plains has been achieved mainly by rivers.

Some bornhardts may be *monadnocks de position*, the penultimate remnants surviving after long-distance scarp recession. On balance, however, the field evidence argues against the residuals being epigene forms and favours a two-stage or etch origin. The resistant masses so formed come increasingly to stand in positive relief as a result of the preferential weathering and erosion of the surrounding or adjacent plains, whether this is due to down- or to backwearing. Once in positive relief granite residuals, whether inselbergs or massifs, shed water (e.g. Jessen 1936, Bremer 1975, Twidale and

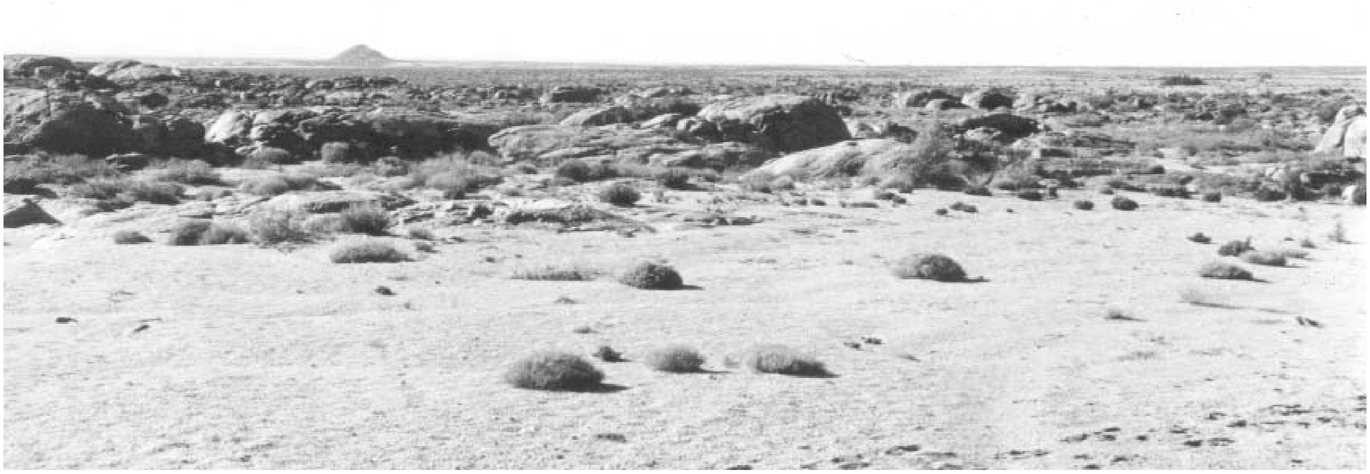


Figure 15: Inselberg landscape in granite, Namaqualand, Northern Cape Province.

Bourne 1975) and remain comparatively dry and stable: an example of a reinforcement or positive feedback effect (e.g. Behrmann 1919, Twidale *et al.* 1974). The adjacent plains, on the other hand, underlain by less resistant (commonly more closely fractured) rock, are even more rapidly weathered by the excess of water they receive.

Several of the bornhardt characteristics previously noted are compatible with the two-stage or etch concept. For example, Jessen and King remarked on their occurrence in multicyclic landscapes. This is consistent with subsurface weathering having taken place beneath one planation surface, and the weathering front, in the form of an incipient bornhardt landscape, being exposed as a consequence of stream rejuvenation and landscape revival following inception of another cycle (see e.g. Lister 1987). Evidence of bornhardts having evolved through the second half of geological time is acceptable, for whether of magmatic or cometary origin there has been water on Earth during that period. That there have been groundwaters to effect subsurface weathering at least since the end of the Archaean is suggested by the existence of partly exhumed bornhardts of end-Archaean or earliest Proterozoic age (Twidale 1986).

A subsurface origin accounts for the climatic azonality of the forms, so that the presence of bornhardts in the humid tropics or the subarctic does not of necessity imply climatic change. In some measure it accommodates their development in a number of lithological settings. It accounts equally well for bornhardts as components of massifs, as in the Gawler Ranges, Zimbawe, and the Kamiesberge of Namaqualand, as those standing in isolation in inselberg landscapes. The concept also implies a genetic link with the orthogonal fracture systems and sheet sets which in turn account for the plan and profile shapes of the forms as well as, in many instances, their massive structure.

CONCLUSIONS

If the value of a principle or hypothesis is the number of things it explains, then the two-stage concept offers the more satisfactory general explanation of bornhardts. Long distance scarp recession is theoretically feasible, more than even King realised, but the field evidence favouring an etch origin is compelling. Moreover, bornhardts and the sheet fractures associated with their characteristic domical form appear to have a common origin.

The landscapes of the Brazilian Shield (Brazil-Guiana Massif) carry remnants of paleosurfaces (e.g. King 1956, 1962, p. 302 et seq., Briceño and Schubert 1990, Demoulin *et al.* 2005) so that conditions were suitable for differential subsurface weathering. Such weathering is known to be deep (e.g. Branner 1896), nascent bornhardts are exposed in hillslopes and inselberg landscapes are reported in multicyclic landscapes (e.g. Journaux 1978). Some bornhardts, including the best known of all, the Pão de Assuçar, appear to have evolved through episodic exposure. Such examples and settings suggest that the two-stage concept based in subsurface weathering of structurally differentiated rocks over long periods may be applicable to the South American situation. But 'for example' does not constitute proof, and until the various possible explanations and any others that may be suggested by the evidence, are tested against South American landscapes, the question remains open.

ACKNOWLEDGEMENTS

The author wishes to thank Professor J. R. Vidal Romani (A Coruña) for translating the Abstract and Professor Jorge Rabassa (Ushuaia) and Dr J. A. Bourne (Adelaide) for constructive comments on the paper in draft stage.

WORKS CITED IN THE TEXT

Agassiz, L. 1865. On the Drift in Brazil, and on decomposed rocks under the Drift. American Journal of Science and Arts 40: 389-390.

Bain, A.D.N. 1923. The formation of inselberge. Geological Magazine 60: 97-107.

Bain, G.W. 1931. Spontaneous rock expansion. The Journal of Geology 39: 715-735.

Barbier, R. 1957. Aménagements hydroélectriques dans le sud du Brésil. Comptes Rendus Sommaire et Bulletin Societé Géologique de France 6: 877-892.

Bateman, P.C. and Wahrhaftig, C. 1966. Geology of the Sierra Nevada. In Bailey, E.H. (ed.) Geology of Northern California, California Division of Mines, Bulletin 190: 107-172.

Beche, H.T. de la 1839. Report on the Geology of Cornwall, Devon and West Somerset. Geological Survey of England and Wales, Longman, Orme, Brown, Green and Longmans, 648 p., London.

Behrmann, W. 1919. Der Vergang der Selbstverstärkung. Gesellschaft für Erdkunde zu Berlin, 153-157.

Bird, J.B. 1967. The Physiography of Arctic Canada. The Johns Hopkins Press, 336 p., Baltimore.

Birot, P. 1950. Notes sur le problème de la désagrégation des roches cristallines. Revue de Géomorphologie Dynamique 1: 271-276.

Birot, P. 1958. Les dômes crystallins. Centre National de la Recherche Scientifique Mémoires et Documents 6: 7-34.

Blès, J.L. 1986. Fracturation profonde des massifs rocheux granitiques. Documents du Bureau de Recherches Géologiques et Minières 102, 316 p.

BMR Palaeogeographic Group 1992. Australia: Evolution of a Continent. Australian Government Publishing Service, Commonwealth of Australia, 96 p., Canberra.

Bornhardt, W. 1900. Zur Oberflachungestaltung und Geologie Deutsch Ostafrikas. Reimer 595 p., Berlin.

Bourne, J.A. and Twidale, C.R. 2000. Stepped landscapes and their significance for general theories of landscape development. South African Journal of Geology 103: 105-119.

Bourne, J.A. and Twidale, C.R. 2005. Penecontemporary tectonic forms in basement areas: evidence derived from quarry exposures on northwestern Eyre Peninsula, South Australia. Geodinamica Acta 18(2): 101-113.

Boyé, M. 1950. Glaciaire et Périglaciaire de l'Ata Sund, nord-oriental Groenland. Hermann, 176 p., Paris.

Boyé, M. and Fritsch, P. 1973. Dégagement artificiel d'un dôme crystallin au Sud-Cameroun. Travaux et Documents de Géographie Tropicale 8: 69-94.

Bradley, W.C. 1963. Large-scale exfoliation in massive sandstones of the Colorado Plateau. Geological Society of America, Bulletin 74: 519-528.

Brajnikov, B. 1953. Les pains-de-sucre du Brésil: sont-ils enracinés? Comptes Rendus Sommaire et Bulletin Societé Géologique de France 6: 267-269.

Branner, J.C. 1896. Decomposition of rocks in Brazil. Geological Society of America, Bulletin 7: 255-314.

Bremer, H. 1975. Intramontane Ebenen, Prozesse der Flächenbildung. Zeitschrift für Geomorphologie, SupplementBand 23: 26-48.

Briceño, H.O. and Schubert, C. 1990. Geomorphology of the Gran Sabana, Guyana Shield, southeastern Venezuela. Geomorphology 3: 125-141.

Brook, G.A. 1978. A new approach to the study of inselberg landscapes. Zeitschrift für Geomorphologie, SupplementBand 31: 138-160.

Brunner, F.K. and Scheidegger, A.E. 1973. Exfoliation. Rock Mechanics 5: 43-62.

Büdel, J. 1977. Klima Geomorphologie. Borntraeger, 304 p., Berlin.

Caillère, S. and Henin, S. 1950. Etude de quelques alterations de la phlogopite à Madagascar. Comptes Rendus de Séances de l'Academie de Sciences 230: 1383-1384, Paris.

Cameron, J. 1945. Structural features of the grey granites of Aberdeenshire. Geological Magazine 82: 189-204.

Campbell, E.M. and Twidale, C.R. 1991. The evolution of bornhardts in silicic volcanic rocks in the Gawler Ranges, South Australia. Australian Journal of Earth Sciences 38: 79-93.

Chapman, C.A. 1956. The control of jointing by topography. The Journal of Geology 66: 552-558.

Choubert, B., 1949. Géologie et Petrographie de la Guyane Française. Office de la Recherche Scientifique Outre-Mer, 120 p., Paris.

Choubert, B. 1974. Le Précambrien des Guyanes. Memoirs Bureau de Recherches Géologiques et Minières 81, 212 p.

Coates, D.F. 1964. Some cases of residual stress effects in engineering work. In Judd, W.R. (ed.) The State of Stress in the Earth's Crust. Elsevier, 679-688, New York.

Dale, T.N. 1923. The commercial granites of New England. United States Geological Survey, Bulletin 738, 488 p.

Darwin, C. R. 1876. Geological Observations on the Volcanic Islands and Parts of South America Visited During the Voyage of H.M.S. Beagle. Second Edition, Smith Elder, 267 p., London.

Dekalb, H.F. 1990. The Twisted Earth. Lytel Eorthe Press, Hilo, 156 p., Hawaii.

Demoulin, A., Zarate, M. and Rabassa, J. 2005. Long-term landscape development: a perspective from the southern Buenos Aires Ranges of east central Argentina. Journal of South American Earth Sciences 19: 193-204.

Denham, D., Alexander, L. T. and Worotnicki, G. 1979. Stresses in the Australian crust: evidence from earthquakes and in-situ stress measurements. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 4: 289-295.

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

Fisher, O. 1866. On the disintegration of a chalk cliff. Geological Magazine 3: 354-356.

Freise, F.W. 1933-5. Braslianische Zuckerhutberge. Zeitschrift für Geomorphologie 8: 49-66.

Friese, F.W. 1936-8. Inselberge und Inselberg-Landschaften im Granit- und Gneisgebiete Brasiliens. Zeitschrift für Geomorphologie 10: 137-168.

Friese, F.W. 1943. Der Ursprung der Brasilianischen Zuckerhutberge. Zeitschrift für Geomorphologie 11: 93-112.

Gage, M. 1966. Franz Josef Glacier. Ice 20: 26-27.

Gerrard, A.J.W. 1974. The geomorphological importance of jointing in the Dartmoor granite. In Brown, E.H., Waters, R.S. (eds) Progress in Geomorphology, Institute of British Geographers, Special Publication 7: 39-51.

Gifkins, R.C. 1965. Intergranular creep fracture. In Osborn, C.J. (ed.) Fracture, Melbourne University Press, 44-61, Melbourne.

Gilbert, G.K. 1904. Domes and dome structures of the High Sierra. Geological Society of America, Bulletin 15: 29-36.

Hassenfratz, J,-H. 1791. Sur l'arrangement de plusieurs gros blocs de différentes pierres que l'on observe dans les montagnes. Annales de Chimie 11: 95-107.

Herrmann, L.A. 1957. Geology of the Stone Mountain-Lithonia district, Georgia. Georgia Geological Survey, Bulletin 61, 139 p.

Hillis, R.R. and Reynolds, S.D. 2000. The Australian stress map. Journal of the Geological Society 157: 915-921 London.

Hills, E.S. 1955. Die Landoberfläche Australiens. Die Erde, 7: 195-205.

Holmes, A. 1918. The Pre-Cambrian and associated rocks of the district of Mozambique. Quarterly Journal of the Geological Society 74: 31-97, London.

Holmes, A. and Wray, D.A. 1912. Outlines of the geology of Mozambique. Geological Magazine 9: 412-417.

Holzhausen, G.R. 1989. Origin of sheet structure. 1. Morphology and boundary conditions. Engineering Geology 27: 225-278.

Huber, N.K. 1987. The geologic story of Yosemite National Park. United States Geological Survey, Bulletin 1595, 64 p.

Humboldt, A. and Bonpland, A.A. von 1852-3. Personal Narrative of Travels to the Equinoctial Regions of America during the years 1799-1804. [Volume 1: Voyage aux regions equinoxiales du Nouveau Continent. First translated and published in 1814 by H.M. Williams]. 3 volumes, translated by Ross T. Bohn. Longman, Hurst, Rees, Orme, and Brown, London.

Hurault, J. 1963. Recherches sur les inselbergs granitiques nus en Guyane Française. Revue de Géomorphologie Dynamique 14: 49-61.

Isaacson, E. de St Q. 1957. Research into the rock burst problem on the Kolar Goldfield. Mine and Quarry Engineering 23: 520-526.

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

Jeje, L.K. 1973. Inselbergs' evolution in a humid tropical environment: the example of south western Nigeria. Zeitschrift für Geomorphologie 17: 194-225.

Jones, T.R. 1859. Notes on some granite tors. The Geologist 2: 301-312.

Journaux, A. 1978. Cuirasses et carapaces au Brésil. Travaux et Documents de Géographie Tropicale 33: 81-95.

Jutson, J.T. 1914. An outline of the physiographical geology (physiography) of Western Australia. Geological Survey of Western Australia, Bulletin 61, 240 p.

Keyes, C.R. 1912. Deflative systems of the geographical cycle in an arid climate. Geological Society of America, Bulletin 23: 537-562.

Kieslinger, A. 1960. Residual stress and relaxation in rocks. 21st. International Geological Congress, Proceedings 18: 270-276, Copenhagen.

King, L.C. 1942. South African Scenery. Oliver, Boyd, 308 p., Edinburgh.

King, L.C. 1949. A theory of bornhardts. Geographical Journal 112: 83-87.

King, L.C. 1956. A geomorphological comparison between Brazil and South Africa. Quarterly Journal of the Geological Society 112: 445-474, London.

King, L.C. 1962. Morphology of the Earth. Oliver, Boyd, 699 p., Edinburgh.

King, L.C. 1966. The origin of bornhardts. Zeitschrift für Geomorphologie 10: 97-98.

Lamego, A.R. 1938. Escarpas do Rio de Janeiro. Departamento Nacional da Produçao Mineral (Brasil). Servicio Geologica y Mineria, Boletin 93, 71 p.

Le Conte, J.N. 1873. On some of the ancient glaciers of the Sierras. American Journal of Science and Arts 5: 325-342.

Leeman, E.F. 1962. Rock bursts in South African gold mines. New Scientist 16: 79-82.

Lewis, W.V. 1954. Pressure release and glacial erosion. Journal of Glaciology 2: 417-422.

Lidmar-Bergström, K. 1997. A long-term perspective on glacial erosion. Earth Surface Processes and Landforms 23: 297-306.

Lister, L.A. 1987. The erosion surfaces of Zimbabwe. Zimbabwe Geological Survey, Bulletin 90, 163 p.

Logan, J.R. 1849. The rocks of Pulo Ubin. Verhandlung Genootschap van Kunsten en Wetenschappen 22: 3-43, Batavia.

Loughnan, F.C. 1969. Chemical Weathering of the Silicate Minerals. Elsevier, 154 p., New York.

Mabbutt, J.A. 1961. 'Basal surface' or 'weathering front'. Proceedings of the Geologists' Association of London 72: 357-358.

MacCulloch, J. 1814. On the granite tors of Cornwall. Transactions of the Geological Society 2: 66-78.

MacGregor, A.M. 1951. Some milestones in the Precambrian of Rhodesia. Transactions of the Geological Society of South Africa 54: 27-71.

Matthes, F.E. 1930. Geologic history of the Yosemite Valley. United States Geological Survey, Professional Paper 160, 137 p.

Mennell, F.P. 1904. Some aspects of the Matopos. 1. Geological and physical features. Proceedings of the Rhodesian Scientific Association 4: 72-76.

Merrill, G.P. 1897. Treatise on Rocks, Weathering and Soils. Macmillan, 411 p., New York.

Moye, D.G. 1958. Rock mechanics in the interpretation and construction of T.1 underground power station, Snowy Mountains, Australia. Symposium on Engineering Geology, AGM/Geological Society of America, St Louis, November 1958, 50 p.

Myers, J.S. 1993. Precambrian history of the West Australian Craton and adjacent orogens. Annual Reviews of Earth and Planetary Science 21: 453-485.

Myers, J.S. and Watkins, K.P. 1985. Origin of granite-greenstone patterns, Yilgarn Block, Western Australia. Geology 13: 778-780.

Niles, W.H. 1872. Some interesting phenomena observed in quarrying. Proceedings of the Boston Natural History Society 14: 80-87; 16: 41-43.

Ollier, C.D. and Tuddenham, W.G. 1961. Inselbergs of central Australia. Zeitschrift für Geomorphologie 5: 257-276.

Passarge, S. 1895. Adamaua. Bericht uber die Expediton des Deutschen Kamerun-Komitees in den Jahren 1893/4. Reimer, 573 p,, Berlin.

Peel, R.F. 1941. Denudation landforms of the central Libyan Desert. Journal of Geomorphology 4: 3-23.

Ramsay, J.G. and Huber, M.I. 1987. The Techniques of Modern Structural Geology. 2. Folds and Fractures. Academic Press, 391 p., London.

Richey, J.E. 1964. Granite. Mine and Quarry Engineering 30: 20-25; 57-61; 121-127; 167-175.

Seager, W.R. 1981. Geology of Organ Mountains and Southern San Andres Mountains, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Memoir 36, 97p.

Selby, M.J., 1977. Bornhardts of the Namib Desert. Zeitschrift für Geomorphologie 21: 1-13.

Thiele, E.L. and Wilson, R.C. 1915. Portuguese East Africa between the Zambesi River and Sabi River: a consideration of the relation of its tectonic and physiographic features. Geographical Journal 45: 16-45.

Thorp, M.B. 1969. Some aspects of the geomorphology of the Air Mountains, southern Sahara. Transactions of the Institute of British Geographers 47: 25-46.

Toit, A.L. du 1937. The Geology of South Africa. Oliver, Boyd, 611 p., Edinburgh.

Tolman, C.F. and Robertson, F. 1969. Exposed Precambrian rocks in southeast Missouri. Contribution to Precambrian Geology 1. Missouri Geological Survey and Water Resources Report of Investigations 44, 68 p.

Twidale, C.R. 1962. Steepened margins of inselbergs from north-western Eyre Peninsula, South Australia. Zeitschrift für Geomorphologie 6: 51-69.

Twidale, C.R. 1964. A contribution to the general theory of domed inselbergs. Conclusions derived from observations in South Australia. Transactions and Papers of the Institute of British Geographers 34: 91-113.

Twidale, C.R. 1967. Origin of the piedmont angle, as evidenced in South Australia. The Journal of Geology 75: 393-411.

Twidale, C.R. 1971. Structural Landforms. Australian National University Press, 247 p., Canberra.

Twidale, C.R. 1973. On the origin of sheet jointing. Rock Mechanics 5: 163-187.

Twidale, C.R. 1978a. On the origin of Ayers Rock, central Australia. Zeitschrift für Geomorphologie SupplementBand 31: 177-206.

Twidale, C.R. 1978b. On the origin of pediments in different structural settings. American Journal of Science 278: 1138-1176.

Twidale, C.R. 1981. Granitic inselbergs: domed, block-strewn and castellated. Geographical Journal, 147: 54-71.

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

Twidale, C.R. 1982b. The evolution of bornhardts. American Scientist 70: 268-276.

Twidale, C.R. 1982c. Les inselbergs à gradins et leur signification: l'exemple de l'Australie. Annales de Géographie 91: 657-678.

Twidale, C.R. 1986. Granite platforms and low domes: newly exposed compartments or degraded remnants. Geografiska Annaler (A) 68: 399-411.

Twidale, C.R. 1987a. Review of Blès 1986. Progress in Physical Geography 11: 464.

Twidale, C.R. 1987b. Etch and intracutaneous forms and their implications. Australian Journal of Earth Sciences 34: 367-386.

Twidale, C.R. 1990. The origin and implications of some erosional landforms. The Journal of Geology 98: 343-364.

Twidale, C.R. 2000. Early Mesozoic (?Triassic) landscapes in Australia: evidence, argument, and implications. The Journal of Geology 10: 537-552.

Twidale, C.R. 2002. The two-stage concept of landform and landscape development involving etching: origin, development and implications of an idea. Earth-Science Reviews 57: 37-74.

Twidale, C.R. and Bourne, J.A. 1975. Episodic exposure of inselbergs. Geological Society of America, Bulletin 86: 1473-1481.

Twidale, C.R. and Bourne, J.A. 1978. Bornhardts. Zeitschrift für Geomorphologie SupplementBand, 31: 111-137.

Twidale, C.R. and Bourne, J.A. 1998. Flared slopes revisited. Physical Geography 19: 110-133.

Twidale, C.R. and Bourne, J.A. 2000. Rock bursts and associated neotectonic forms at Minnipa Hill, northwestern Eyre Peninsula, South Australia. Environmental and Engineering Geoscience 6: 129-140.

Twidale, C.R. and Bourne, J.A. 2003. Active dislocations in granitic terrains of the Gawler and Yilgarn cratons, Australia, and some implications. South African Journal of Geology 106: 71-84.

Twidale, C.R. and Campbell, E.M. 1984. Murphy Haystacks, Eyre Peninsula. South Australia. Transactions of the Royal Society of South Australia 108: 175-183.

Twidale, C.R. and Milnes, A.R. 1983. Slope processes active late in arid scarp retreat. Zeitschrift für Geomorphologie 27: 343-361.

Twidale, C.R. and Sved, G. 1978. Minor granite landforms associated with the release of compressive stress. Australian Geographical Studies 16: 161-174.

Twidale, C.R., Bourne, J.A. and Smith, D.M. 1974. Reinforcement and stabilisation mechanisms in landform development. Revue de Géomorphologie Dynamique 23: 115-125.

Twidale, C.R., Vidal Romani, J.R., Campbell, E.M. and Centeno, J.D. 1996. Sheet fractures: response to erosional offloading or to tectonic stress? Zeitschrift für Geomorphologie SupplementBand 106: 1-24.

Valverde, O. 1968. O Sitio da Cidade. In: Curso de Geografia da Guanabara Fundação. Instituto Brasileiro de Geografia, 3-14, Rio de Janeiro.

Van der Post, L. 1958. The Lost World of the Kalahari. Hogarth Press, 256 p., London.

Vening Meinesz, F.A. 1947. Shear patterns in the Earth's crust. Transactions of the American Geophysical Union 28: 1-61.

Vidal Romani, J.R. and Twidale, C.R. 1998. Formas y Paisajes Graniticos. Serie Monografias 55, Servicio de Publicaciones da Universidade da Coruña, A Coruña, 411 p.

Vidal Romani, J.R., Twidale, C.R., Campbell, E. M. and Centeno, J.de D. 1995. Pruebas morfológicas y estructurales sobre el origen de las fracturas de descamación. Cadernos Laboratorio Xeolóxico de Laxe 20: 347-380.

Weissenberg, K. 1947. Continuum theory of rheological phenomena. Nature 159: 310-311.

Wilhelmy, H. 1958. Klimamorphologie der Massengesteine. Westermanns, 238 p., Braunschsweig.

Williams, G.E. 1969. Characteristics and origin of a Precambrian pediment. The Journal of Geology, 77; 183-207.

Williams, G.E. and Schmidt, P.W. 1997. Palaeomagnetic dating of sub-Torridon Group weathering profiles, NW Scotland: verification of Neoproterozoic palaeosols. Journal of the Geological Society 154: 987-997, London.

Willis, B. 1934. Inselbergs. Association of American Geographers, Annals 24: 123-129.

Willis, B. 1936. East African plateaus and rift valleys. Studies in Comparative Seismology, Washington D.C., Carnegie Institute Publication 470, 358 p.

Wolters, R. 1969. Zur Ursache der enstehung oberflächenparaleller Klüfte. Rock Mechanics, 1: 53-70.

Worth, R.H. 1953. Dartmoor Essays. Spooner, G.M., Russell, R.S. (eds) David and Charles, 523 p., Newton Abbott.

Recibido: 1 de junio, 2006
Aceptado: 2 de octubre, 2006