## Granitic bornhardts: their morphology, characteristics and origins

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**Abstract:** Bornhardts are bald domical hills either standing in isolation as inselbergs ("island mountains"), or forming components of massifs. Though especially well represented in granitic terrains, they are also developed in other lithologies. Their plan form is determined by systems of steeply inclined fractures, while their profiles are associated with convex upward fractures. They meet the adjacent plains or valleys in a piedmont angle or nick. They are climatically azonal. They occur in various topographic settings and consistently in multicyclic landscapes. Epigene forms as old as Cretaceous are known, and exhumed forms ranging from Late Pleistocene to late Archaean in age have been recognised.

Bornhardts have been explained in various ways: as literal and littoral inselbergs, as climatic (savannah) forms, as minor horsts, and so on. Some are upstanding because they are shaped in rock that is compositionally different from, and implicitly more resistant to, weathering and erosion than that which underlies the adjacent plains and valleys. Some are exposed stocks. Such explanations have local validity, but two hypotheses have been suggested as general explanations.

First, bornhardt inselbergs can be construed as remnants of circumdenudation following scarp retreat but much field evidence is not accounted for and some is incompatible with several of the deducible consequences of the hypothesis. Second, bornhardts have been interpreted as two-stage forms, which originated at the weathering front as resistant masses due either to low fracture density or to rock type, and which became landforms as a result of the stripping of the regolith and exposure of weathering front topography. This two-stage model satisfies much of the field evidence and the isolated residuals of shield inselberg landscapes are the last remnants of resistant compartments which have survived long-continued subsurface weathering. According to this hypothesis, topography is consequent upon, and subsequent to, the formation of sheet fractures which are associated with compressional stress. Nubbins (block- and boulder-strewn domes) and castle koppies (small blocky hills) are derived from the weathering of bornhardts.

### **DEFINITION AND HISTORICAL REVIEW**

Of the many new landscapes and landforms discovered by Nineteenth Century European explorers, few created such astonishment as the isolated hills which, seemingly appearing out of nowhere, interrupted the otherwise featureless plains that occupy so much of Africa, Peninsular India, Australia and South America. Even to as erudite and modern a man as Laurens Van Der Post (1958, pp. 181–182) they communicated a sense of mystery.

These isolated residuals were referred to in similar terms by both British and German explorers, but the English "island mount" (Eyre, 1845, I, p. 203; Giles, 1889, I, p. 158) never took hold, and, doubtless because of the major contributions due to the galaxy of German explorer-scientists who were active, mainly in Africa, late last century and early this (e.g. Passarge, 1895, 1904a and b; Bornhardt, 1900; Kaiser, 1926; Jessen, 1936), its German equivalent, *inselberg*, became established in the international technical literature to denote an isolated, steep-sided hill. Similarly, and again logically, the basic inselberg form, the domical hill, or *bornhardt*, was named after Wilhelm Bornhardt who bequeathed to us splendid descriptions and penetrating analyses of these forms as they occur in what is now Tanzania (Bornhardt, 1900; see Willis, 1934).

### CHARACTERISTICS

Bornhardts, and especially bornhardt inselbergs (Fig. 1a), are spectacular forms, and inselberg landscapes (Fig. 1b) are at once intriguing and enigmatic: why are these hills there, surrounded by seemingly limitless featureless plains? Not surprisingly, they have stimulated considerable interest over the years. The most dramatic, the socalled classical, inselberg landscapes are developed, preserved and displayed in arid and semiarid regions of shield lands, in the ancient granitic cores of continents like Africa and Australia, and the

Paper from a GSM Technical Talk presented on 23 November 1998

interior of Brazil (e.g. Bornhardt, 1900; Passarge, 1904a and b, 1928/29; Jessen, 1936; Journaux, 1978). But they are also represented in cold shield areas such as Greenland and Finland (Oen, 1965; Fogelberg, 1985). Inselberg landscapes are well developed in cold climates in orogenic regions, for instance in western Iberia and western Scandinavia, in the cool uplands of the Californian Sierra Nevada, as in the Yosemite Valley and Domeland (Matthes, 1930; Schrepfer, 1933; Huber, 1987), in Mediterranean areas such as the Cape Fold Belt (Fig. 2a) and in the humid tropics, for instance southeastern Brazil (Fig. 2b) and southern Nigeria (see e.g. Darwin, 1846; Falconer, 1911; Birot, 1958;



Figure 1a. Domical hills or bornhardts, eroded in granite gneiss, central Namibia.



Figure 1b. Inselberg landscape in granitic rocks, Namaqualand, northwestern Cape Province, South Africa.



Figure 2a. Paarlberg (Pearl Mountain) a complex granite dome, grey in colour and looking not unlike gigantic pearls set in the landscape, northeast of Cape Town, South Africa.



**Figure 2b.** The Pão de Açucar (Sugarloaf), a tall, steep-sided bornhardt near Rio de Janeiro, southeastern Brazil. The precipitouis flanks are due partly to the exploitation of faults (Brazilian Tourist Bureau).

Kieslinger, 1960). In the latter areas, the form of the land is less readily discernible than in desert or savanna regions, but bornhardts are present; for instance in the rain forests of southern Nigeria, Allison (in Allen, 1980, p. 97) noted "... rocky hills sticking up out of the forests, *inselbergs*, with rounded bare rocks sticking above the two hundred foot tops of the trees".

Bornhardts are domical hills in which bare rock is exposed over most of the surface (Figs. 1 and 2). The slopes of gneissic forms are ribbed (Fig. 2c). They are developed in massive rocks and though orthogonal and sheet fractures are well developed, open partings are few. In plan their shapes are determined by systems of steeply inclined orthogonal or rhomboidal joints and their convexupward profiles are associated with sets of convexupward sheet fractures. The hills are steep-sided and meet the adjacent plains in an abrupt break of slope or piedmont angle which is partly due to steeply dipping fractures but is enhanced by scarpfoot weathering and erosion (e.g. Peel, 1941; Twidale, 1967, 1978a, 1987a).

These domical hills are found in massifs (Fig. 3), or as components of ranges, as well as in isolation. They occur in multicyclic landscapes (Obst, 1923; Jessen, 1936; King, 1949) and many inselbergs and massifs are bevelled (Fig. 4). Numerous bornhardts and inselbergs have been shaped in granitic (and other plutonic, crystalline) rocks, and such residuals have been closely investigated. But domical hills are by no means restricted to such lithological settings, for they are well developed also in arenaceous, rudaceous and carbonate sediments, as well as ancient volcanic rocks (Mainguet, 1972; Sweeting, 1973; Twidale and Bourne, 1978; Jennings, 1985; Campbell and Twidale, 1991). Epigene forms at least as old as Cretaceous have been identified (e.g. Twidale and Bourne, 1975a, 1998) and exhumed bornhardts range in age from latest Archaean to late Pleistocene (Twidale, 1982a, 1986; Twidale and Campbell, 1985), showing that the forms have developed throughout geological time.

### POSSIBLE ORIGINS

### (a) General comments

Any general theory needs to account for the characteristics of granitic bornhardts outlined above, and to apply, in some measure at least to forms developed in other rock types.

Granitic bornhardts have been interpreted in several ways (for reviews see Twidale, 1982a; Vidal Romani and Twidale, 1998) Explanations can broadly be categorised as structural (*sensu lato*), including, upfaulting, compositional variation, magmatic differentiation, and exploitation of variations in fracture density (either surficial or



**Figure 2c.** Bornhardts developed in granite gneiss, northern Namaqualand. The foliation is expressed in faint ridges or ribs, here trending top left to bottom right.



Figure 3a. Part of the same area showing adjoining granitic domes, each developed on a fracture-defined block and with sheet structure well developed.



Figure 3b. Geological sketch of part of the Kamiesberge, Namaqualand, northwest Cape Province, showing fault pattern in relation to bornhardt massifs (drawn from air photographs).

subsurface); or environmental, including marine setting, arid or semiarid environment; or process dominated, in particular, circumdenudation following long-distance scarp retreat, which for some workers at least is associated with savanna or arid climatic regions. Many of these suggestions are locally valid. For instance, Passarge (1895, p. 377) suggested that some inselbergs are horsts, and the Pic Parana, in southeastern Brazil is demonstrably of this character (Barbier, 1957) as are some *pitons*  of French Guyana (Choubert, 1949), but most bornhardts are evidently not defined by recently active faults. Some few bornhardt are exposed stocks (e.g. Holmes and Wray, 1912; Twidale, 1982a, pp. 128–131; Fig. 5) and have been left upstanding by reason of lithology, but most bornhardts are apparently of the same composition as the rock that underlies the adjacent valleys and plains. And so on: some explanations have local or partial application. But only two, those involving scarp



Figure 4. Part of the Everard Ranges, in the northern arid interior of South Australia, showing bevelled granite domes.



Figure 5. This rounded stock of Proterozoic Donkahoek Granite, exposed by erosion of schist into which it was injected, forms a small bornhardt in central Namibia.

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recession (Holmes, 1918; King, 1949) and subsurface exploitation of fracture density (Falconer, 1911), have been considered as general theories.

## (b) Scarp retreat

The suggestion that bornhardts are the last residuals surviving after long-distance scarp recession (King, 1949; Fig. 6a) is widely accepted (e.g. Ollier and Tuddenham, 1962; Selby, 1970). It is plausible, for scarp retreat has undoubtedly occurred in caprock situations and such conditions arguably obtain in granitic terrains, and especially in aridity and semiaridity: granite is not inherently capped but the concentration of groundwaters at shallow depth beneath the surface implies greater weathering and hence susceptibility to erosion there than at the surface (Twidale, 1982a, p. 138). Yet all that is plausible is not necessarily true. Several lines of evidence argue against scarp retreat as a significant mechanism in the development of bornhardts.

1. If bornhardts are associated with scarp retreat they ought to be found mainly on major divides in maturely dissected landscapes. Though some residuals are so situated, others occur in the flanks of narrow valleys and others protrude from valley floors (see Thomas, 1966; Jeje, 1973; Vidal Romani and Twidale, 1998, p. 198; Fig. 7a).

- 2. If bornhardts are the last remnants surviving after long-distance scarp retreat they ought to be no older than the duration of a cycle. In areas of continental extent which include classical shield terrains where bornhardts are well represented, the duration of a cycle has been estimated as about 33 Ma (Schumm, 1963) so that no bornhardt ought to be older than Oligocene. But some (epigene) residuals are demonstrably of Cretaceous age, and are 3-4 times older than they ought to be in terms of theory.
- 3. Several field characteristics are not accounted for by the hypothesis. For example incipient bornhardts occur at shallow depth in the natural subsurface but have been exposed in artificial excavations (Figs. 7b and c). The relationship between bornhardts and multicyclic landscapes and their occurrence in a variety of topographic settings is not explained. The occurrence of stepped inselbergs, especially those with flared sidewalls (Jessen, 1936; Twidale, 1982b) suggest, first, that the wearing back of scarps is limited to a few tens of metres and not the hundreds of kilometres demanded by inselberg



Figure 6a. Bornhardt inselbergs as remnants of denudation following long-distance scarp retreat.



Figure 6b. Bornhardts as two-stage or etch forms.



Figure 7a. Small granite dome exposed in the valley floor of a river near Malmesbury, north of Cape Town, South Africa.



Figure 7b. Granite dome exposed by quarrying, Ebaka, Cameroun (M. Boyé).



Figure 7c. Crest of granite dome (X) exposed near the base of the bevelled Leeukop, near Potchefstroom, South Africa.

landscapes and by King's hypothesis, and, second, that the recession is due to subsurface weathering, not fluvial erosion. Also, they strongly suggest that inselbergs persist through several cycles of weathering and erosion: they persist because even long-continued erosion does not totally reduce land surfaces to baselevel; the slate is not necessarily wiped clean.

## (c) Two-stage development: bornhardts as etch forms

Mennell (1904) attributed the blocks and boulders of the Matopos, in what is now Zimbabwe, to fracture-controlled weathering, implicity at the surface. This undoubtedly occurs but is less common and less effective than the exploitation of fractures by subsurface moisture. Such fracture-controlled differential subsurface weathering and subsequent differential erosion of the weathered granite or grus has long and widely been recognised as responsible for the boulders and core-boulders that are so characteristic of granitic terrains the world over (e.g. Hassenfratz 1791; Scrivenor, 1931; also Twidale, 1978b, 1982a).

Most bornhardts are arguably also two-stage forms (Fig. 6b). They were initiated by differential subsurface weathering, at which stage they were projections of bedrock at the weathering front, or lower limit of effective weathering (Mabbutt, 1961), into the base of the regolith. They were later exposed as bornhardts through the stripping of the That the bornhardt masses were regolith. manifestly less susceptible to subsurface moisturerelated weathering can be attributed to two possible factors. First, they may be developed in a rock which is compositionally or texturally different from that in which the surrounding plains and valleys are eroded. This is true of some residuals but most bornhardts appear to be of the same rock type as that of adjacent compartments. Second, they may be massive in contrast with the high fracture density of surrounding compartments. Such situations can be demonstrated at several sites (e.g. Jones, 1859; Twidale, 1964; 1982a; Büdel, 1977, pp. 108–109) and is, increasingly, accepted as the most common reason for bornhardt development in granitic terrains.

But the question arises whether the present distribution of fracture density constitutes a valid basis for comparison. Fracture density in residuals can be shown to be less than in adjacent compartments, but it can be argued that what is significant is not the density beneath the present plains but the density in the previously existing compartments above the present plains and adjacent to the residuals; for it was these which were differentially weathered and eroded. But, having been eroded, the evidence is no longer available. Blès (1986), however, has shown that surface fracture patterns and densities provide a close and reliable indication of fracture patterns and density at depth, and, reversing the argument, surface conditions can surely be taken as indicative of higher, though now eroded, patterns (Twidale, 1987b)?

Field evidence demonstrates abrupt spatial variations in fracture density, and they are crucial to the two-stage concept. But why are there variations in fracture density? Three mechanisms have been suggested. First, Lamego (1938) suggested that the gneissic terranes of the Rio de Janeiro area had been folded, and that the crests of antiforms, being in tension, had been preferentially weathered and eroded. The deep compressional cores of the same structures, however, were resistant and formed the bases of the well known *morros* (Fig. 8a).

Second, the effects of horizontal shearing on large orthogonal compartments or blocks has been cited (Twidale, 1980). Shearing along steeply inclined fractures would induce compression within the compartments so defined along one horizontal axis and tension on that disposed at right angles to it. Continued or recurrent dislocation would perpetuate the resultant strain patterns and also cause fracture propagation from the margins of the blocks inwards (Fig. 8b). In this way compressed cores would be developed in aligned patterns within fracture defined blocks such as are found in several areas (see e.g. Twidale, 1982a, p. 140). Such a mechanism also seems appropriate to parts of the Kamiesberge of Namagualand, in the northwestern Cape Province, South Africa, where, near Witwater for example, the bornhardt massifs are separated by fault-line valleys in which steeply inclined fault planes are evident (Fig. 3).

### (d) Tectonic: thrusting and compression

A third possible reason for fracture variation is suggested by the thrusting or low angle reverse faulting evidenced in some Iberian granitic masses, has been noted (Vidal Romani and Twidale, 1998, p. 66; Twidale and Vidal Romani, 1999), for example in the Mariz Quarry near Guitiriz, and near Lugo, both in Galicia. Such dislocation causes rupture or imbrication and the formation of sheared margins around large, rounded, commonly ovoid, masses, some of boulder size but others large enough to be counted as bornhardts when exposed (Fig. 8c). They may be detached from the underlying host mass as a result of weathering of sheared zones and may thus be regarded as gigantic floaters (cf. Brajnikof, 1953). This mechanism, involving dislocation along flat-lying, rather than steeply dipping, partings,



Figure 8a. Possible reasons for variations in fracture density according to Lamego.



Figure 8b. Possible reasons for variations in fracture density according to Twidale.



**Figure 8c.** Large boulders and bornhardts formed by shearing along low angle plane of dislocation (after Twidale and Vidal Romani, 1999).

provides another explanation for variation in fracture density.

In his magisterial monograph on the granites of the northeastern United States, Dale (1923) noted the possibility that granitic domes could be developed as a result of a granitic mass being laterally compressed from two contrasted directions. This is analogous to the dome and basin (or "egg box") structures envisaged as evolving in sedimentary terrains as a result of fold interference (Ramsay and Huber, 1987, pp. 494-495). This suggestion is of particular interest in areas like West Malaysia which is in substantial compression from two main directions, namely east-west and NNW-SSE (Gobbett and Tjia, 1973; Tjia, 1978). The resultant landscape would be tectonic. If subjected to subsurface weathering and subsequent erosion the distribution of strain implies that domical forms could develop only as a result of relief inversion.

# (e) Rounding of masses and association with sheet fractures

The convex-upward profiles of bornhardts are associated with sheet fractures and structures (Fig. 9a), but the nature of that association is debatable. In terms of scarp retreat, bornhardts are rounded because of the preferential weathering of corners and edges and sheet fractures developed as a consequence of the rounded shape: they are offloading or pressure release joints in the sense of Gilbert (1904). So widely is this interpretation accepted that the fractures are commonly referred to as offloading or pressure release joints; and this despite the mechanism having been rejected by engineers (Wolters, 1969; Brunner and Scheidegger, 1973).

In terms of the two-stage hypothesis and variations in fracture density related to crustal stress, however, sheet fractures are due to compression and the shape of the residuals is consequent on structure. This point of view found expression about a hundred years ago (e.g. Niles, 1872; Merrill, 1897; Hankar-Urban, 1906), and Gilbert also acknowledged that compression could account for sheeting in and around Stone Mountain, Georgia, USA (in Dale, 1923, p. 29). Evidence pointing to compression being responsible for at least some sheet fractures includes (Twidale, 1964; Vidal Romani *et al.*, 1995; Twidale *et al.*, 1996):

- 1. Inverse relationship between topography and structure, with rounded hills underlain by synformal structures, implying deep erosion and inversion of relief (Fig. 9b).
- 2. Measurements of stress which show that many parts of the continental crust, including

bornhardt terrains, and including West Malaysia (Tjia, 1978) are in substantial compression (e.g. Denham *et al.*, 1979).

- 3. Association of sheeting with minor forms associated with compression e.g. A-tents or popups (e.g. Twidale and Sved, 1978; Wallach *et al.*, 1993), reverse faults, wedges, etc. (Fig. 9c).
- 4. Indications that sheet fractures predate the land surface with which they are related (Twidale, 1971; Gerrard, 1974).

Also, it is pertinent to ask why expansion due to offloading has not been accommodated along pre-existing fractures, and how offloading fractures can develop in rock sequences that have never been deeply buried?

In the laboratory, compression of partly constrained masses produced upwardly convex fractures (Holzhausen, 1989) and this experimental situation may be compared to bedrock protrusions projecting into the base of the regolith being subjected to compressive stress: the crucial evidence of the subsurface origin of many bornhardts is exposed in excavations where domical rock masses, nascent or incipient bornhardts, are seen to be already formed beneath the surface, at the base of, and projecting into, the regolith (e.g. Falconer, 1911; Boyé and Fritsch, 1973; Twidale, 1982a; Vidal Romani and Twidale, 1998). Several minor landforms characteristic of granitic terrains also demonstrably are initiated below the land surface, at the base of the regolith (e.g. Logan, 1849, 1851; Twidale, 1962; Twidale and Bourne, 1975b, 1976).

## (f) Discussion

The two-stage hypothesis is consistent with the azonal distribution of bornhardts, for groundwaters are ubiquitous and only the rate of development may vary with climate; with the occurrence of bornhardts in various topographic settings, for resistant masses can emerge at the surface in uplands as well as plains. It is compatible with their presence in multicyclic landscapes, for the latter imply deep erosion and the exposure of deep compressional zones of antiforms, and also time for deep (differential) erosion). Their development in sedimentary terrains is accommodated in some degree (e.g. Twidale and Bourne, 1978), though not entirely, for other mechanisms may apply in some instances. For example, the Sugarloaf, northwest of Port Augusta, South Australia, is a remnant of circumdenudation following scarp recession (see Twidale et al., 1970, Twidale, 1978a). The classical inselberg landscapes of shield lands become comprehensible in terms of prolonged subsurface weathering to which such regions have been subjected, the great age of some bornhardts is

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Figure 9a. Sheet fractures and structures exposed in the littoral of one of the Pearson Islands, eastern Great Australian Bight.







**Figure 9c.** A-tent, or popup, on lower slopes of Kokerbin Hill, a granite in bornhardt in the southwest of Western Australia. consistent with the suggested mode of development, and the development of bornhardts throughout geological time also becomes understandable for water, and groundwaters, have long been present on Earth.

Many bornhardts (and boulders, and other minor forms) apparently evolve as a result of subsurface weathering, followed by erosion of the regolith and exposure of the topographically differentiated weathering front. Thus they can be regarded as two-stage forms. But in many instances subsurface weathering is guided by fracture patterns or by other structural features which originated long before there was significant contact with groundwaters. Thus the Gawler Ranges, located in the arid interior of South Australia, is a massif of bornhardts exposed during the Early Cretaceous but developed on a mass of MesoProterozoic (ca. 1.582 Ga) ignimbrites. The subsurface weathering to which the bornhardt complex is due was determined by a system of orthogonal and rhomboidal fractures which originated at least 1 Ga and probably 1.4 Ga, yet which eventually effectively determined the size and plan form of the bornhardts (Campbell and Twidale, 1991). The volcanic massif was at least 1.5 km thick (Blissett, 1975). The stresses responsible for the orthogonal fracture system affected the entire mass, but only the uppermost 800 m or so would have been in substantial contact with groundwaters until the Mesozoic (Campbell and Twidale, 1991). For such reasons it has been suggested that many two-stage forms are in reality multistage features (Twidale and Vidal Romani, 1994). Such an approach serves to direct attention to the longer term links between geology and landform evolution.

### **RELATED FORMS**

Pillars can be construed as miniature bornhardts for, unlike corestone-boulders they remain in physical continuity with the bedrock (Fig. 10a). Fracture control of overall size and shape is clearly demonstrated in minor towers or pillars such as Murphy Haystacks (Twidale and Campbell, 1984). Major steeply inclined fractures have in places been exploited by frost or nival action, resulting in steep sided jagged towers of acicular form, in such areas as southern Greenland (Oen, 1965), the Organ Mountains of southern New Mexico (e.g. Seager, 1981), around Mt. Whitney in the eastern Sierra Nevada, California, at Cathedral Rocks in the Yosemite Valley of the same upland, and in The Needles, South Dakota.

Bornhardts can be regarded as a basic form from which are derived two others, the block- or boulder-strewn nubbin (or knoll) and the castellated koppie (Twidale, 1981). Nubbins are due to the subsurface disintegration of the outer shell or shells of rock defined by sheet fractures so that the core dome becomes covered by a mass of blocks and boulders (Fig. 10b and c). Such forms are typical of the humid tropics, especially monsoon lands such as northern Australia and Hong Kong, where the regolith has been largely stripped to expose the core boulders set in a matrix of weathered granite or grus. Massifs and ranges consisting entirely of block- and boulder-strewn hills occur in arid southern California (for instance, in the Mojave Desert and in the ranges inland from San Diego) where they are thought to be inherited from periods of later Tertiary humid climate (Oberlander, 1972). Nubbins are also found in moist niches such as intermontane basins and valleys in such arid regions as the MacDonnell Ranges of central Australia and in parts of Namaqualand, southwestern Africa.

The transformation of bornhardts to nubbins by the disintegration of the outer shells of rock, and their conversion to masses of core-boulders and grus, is crucial to an understanding of the granitic terrains of West Malaysia. There, granitic terrains carry a regolithic cover so thick that only on the steepest hillslopes are faintly convex, bald, smooth rock slopes exposed. This is a function of the prevalent hot humid conditions which are conducive to rapid alteration of rocks in general and granites in particular (see e.g. Caillère and Henin, 1950; Alexander, 1959; also Colman and Dethier, 1986). But sheet structures are developed, as is demonstrated in road cuttings, for example, on Langkawi Island, and Logan (1848, p. 102), Wallace (1869, p. 24), and Scrivenor (1931) among early workers, reported steep rounded bare rock slopes. Logan for example noted that "Amidst the luxuriant forest that always covers granitic hills and mountains, the explorer suddenly finds himself facing a high perpendicular wall of rock, ..." (Logan, 1848, p. 102). These rock faces, commonly slightly convex outward, are undoubtedly exposed sheeting planes. Such exposures suggest the presence beneath the regolithic veneer of incipient bornhardts.

The presence within the regolith of coreboulders, the abundance of which is best appreciated where there have been landslides or where the land has been cleared (Fig. 11), suggests, however, that the hills are incipient nubbins, with the regolith still largely *in situ*. The skyline "tors", blocks, boulders, pinnacles and miniature towers (such as the Batu Gumbar Orang; Ahmad, 1980) that occur on crests such as those of Buki Chemragong and Bukit Panbunga, in Pahang (Ahmad, 1976) and Gunong Gelumut, in Johor (Rajah, 1986) represent



Figure 10a. Granite pillars, Murphy's Haystacks, near Streaky Bay, west coast of Eyre Peninsula, South Australia.



regolith

Figure 10b. Suggested development of nubbin from bornhardt by intense subsurface weathering.

Figure 10c. Nubbin in northwest Queensland.



Figure 11. B o u l d e r s exposed by soil erosion following clearance of vegetation in preparation for plantation arboriculture, near Tampin, West Malaysia.

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**Figure 12a.** Castle koppies Mrewa district of central Zimbabwe.





Figure 12b. Castle koppies Haytor, on Dartmoor, southwestern England.

weathered sectors from which fines have been washed downslope. The bare rock slopes are merely glimpses of the domical cores beneath the weathered outer shells of rock, and boulders are exposed only on the coast and in river channels, and where there has been accelerated soil erosion.

Falconer (1911, p. 247) presaged such an interpretation with his account of what he termed kopjes, but what are here referred to as nubbins, within the walls of Kano, in Hausaland, northern Nigeria:

"Kogon Dutsi, the larger of the two flat-topped hills of diorite, although deeply decomposed, still preserves in its lower part detached boulders or cores of unweathered rock. If the subsequent erosion had continued until the weathered material had been entirely removed, the flattened hill would have been replaced by a typical kopje of loose boulders resting upon a smooth and rounded surface of rock below."

Castle koppies are apparently derived from the marginal subsurface weathering of platforms, which can be regarded as the exposed crests of otherwise covered domes. This results in the rotting of the shallow subterranean bedrock mass, the reduction in the lateral extent of the solid mass and the development of steep bounding slopes. Such castellated forms typically consist of an angular mass constructed of a few large orthogonal blocks in situ, and in toto about as big as a house. They are typically small and are for good reason known also as inselbergs de poche (pocket inselbergs). They are found in two topographic settings. They are well developed in relation to very old palaeosurfaces beneath which there has been prolonged and intense weathering, resulting in the reduction of resistant compartments to very small dimensions (Fig. 12). This is why castellated residuals are so small, for they represent the final resistant cores of resistant compartments. Koppies are also found in areas of present or recent intense frost action where epigene and shallow subsurface action causes reduction and steepening of the solid rock mass. The castle koppies (tors) of Dartmoor (e.g. Linton, 1955), the Bohemian Massif (e.g. Demek, 1964), central and western Iberia (Vidal Romani, 1989) and other Hercynian massifs, and of the high Pyrenees, are typical.

### CONCLUSION

Bornhardts are well represented in granitic terrains in a wide range of, if not all, climatic conditions. Though best known from the oldland plains of shields and cratons, they are also well developed in orogenic regions. They develop in various ways, but most appear to be two-stage forms of etch origin. This hypothesis accounts for the

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field evidence, for the great age-range of the forms, and for their dramatic occurrence in inselberg landscapes. Bornhardts can be regarded as the basic form from which other prominent granitic residuals, namely nubbins and castle kopies have evolved in special (subsurface) weathering environments.

## ACKNOWLEDGEMENTS

The gist of this paper was presented at a meeting of the Geological Society of Malaysia, in Kuala Lumpur, in November, 1998, and thanks are due to the Society for providing that opportunity. Dr. H.J. Tjia offered discerning comments after the lecture, and Dr. Jennie Bourne made valuable criticisms of the paper in draft form, and the author is grateful to both. He also expresses his thanks to officers of the Geological Survey of Malaysia, and particularly Mr. Ibrahim Bin Amnan, for facilitating some of the field studies reported.

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Manuscript received 26 January, 1999