Morphology and origin of three bornhardt inselbergs near Lake Johnston, Western Australia

J A Bourne & C R Twidale

Department of Geology & Geophysics, Adelaide University, Adelaide SA 5005
email: rowl.twidale@adelaide.edu.au

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Abstract

Three domical inselbergs or bornhardts, Disappointment, McDermid and Bank Rocks, located near the Hyden-Norseman road in the south-eastern corner of the Yilgarn Craton, are described and analysed. All are basically similar in origin, being due to differential fracture-controlled subsurface weathering followed by the stripping of the weathered mantle. Disappointment Rock is older and topographically more subdued than either McDermid or Bank Rocks; it is located further from the Lake Johnston valley and has not been as greatly exposed. McDermid and Bank Rocks display spectacular flared slopes, whereas those developed at Disappointment Rock probably remain hidden by the lateritic regolith. All three Rocks display a similar range of minor forms, some due to subsurface weathering, others to weathering after exposure of the rock surface, yet others to contrasted rates of weathering on wet and dry surfaces. Some are due to protection against water attack, others reflect bedrock characteristics, and yet others the effects of gravity. Recent earth movements, as evidenced in neotectonic landforms, have affected all three residuals.

Keywords: Yilgarn Craton, bornhardt, origin, age, palaeodrainage, granitic landforms, Disappointment Rock, McDermid Rock, Bank Rock

Introduction

Like many other cratons, the Yilgarn Block of the south-west of Western Australia is characterised by plains interrupted by ranges or, in areas of granitic outcrop, domical hills or bornhardts. Hyden Rock is well known for the high concave, or flared, slope - Wave Rock - exposed on its northern flank, but most of the other granite hills scattered over the Yilgarn remain undescribed. Yet many features typical of granite outcrops, including some of particular interest, are exposed on them. The purpose of this paper is to give an explanatory account of three bornhardts, Disappointment, McDermid and Bank Rocks. They are located on either side of Lake Johnston, near the south-eastern margin of the Craton (Fig 1). The evolution of the bornhardts, and of the assemblages of minor features developed on them, can be deduced from the regional setting and the local evidence. It is hoped that this account will entice natural scientists to them, for they have much to offer the interested lay person as well as the specialist geologist or geomorphologist.

The evolution of the landscape in that part of the Craton is first reviewed. Some comments on the evolution of bornhardts and of the more common minor forms are presented by way of background, but also with reference to the development of the bornhardts as gross forms. This is followed by an account of the detailed evolution of each of the three bornhardts.

Landscape evolution of the Lake Johnston area

The region under review is underlain by Archaean gneisses and granites with intruded basic dykes and sills (Doepel *et al*. 1972; Gower & Bunting 1976). Following the disappearance of the Late Palaeozoic ice sheets which occupied all or most of what is now southern Australia (BMR Palaeogeographic Group 1992) much of the Lake Johnston area was reduced to low relief and subjected to intense weathering, probably under humid tropical conditions. This resulted in the formation of an iron-rich lateritic regolith (*e.g.* Jutson 1914; Walther 1915; Prider 1966; Maignien 1966; Mulcahy 1973). Remnants of this palaeosol are preserved on higher ground immediately west of Lake Cowan, westwards almost to the Lake Johnston depression, and beyond into the Hyden district. There it is preserved in plateaux, as it is also in the Corrigin and Brookton areas, between Hyden and Perth and, more extensively, in the Darling Range east of Perth.

The ferruginous pisolitic zone of primary or *in situ* laterite is iron-cemented and 0.5-2.0 metres thick. It is overlain by a sandy A-horizon and underlain by pallid and mottled clay-rich kaolinised bedrock. The complete profile is at least 30 metres thick and up to 50 metres in places. Ironstone pisolites ('pea gravel') mixed with clay and derived from the erosion of the primary laterite are widespread on slightly lower slopes. Some valleys associated with the laterite surface carry a fill of silicified debris (including silcrete blocks and boulders) which at some sites, as for example at The Breakaway (Fig 2), give rise to sheer, even overhanging bluffs capped by silcrete.

The major remnants of laterite developed on Precambrian rocks are separated by north-south trending

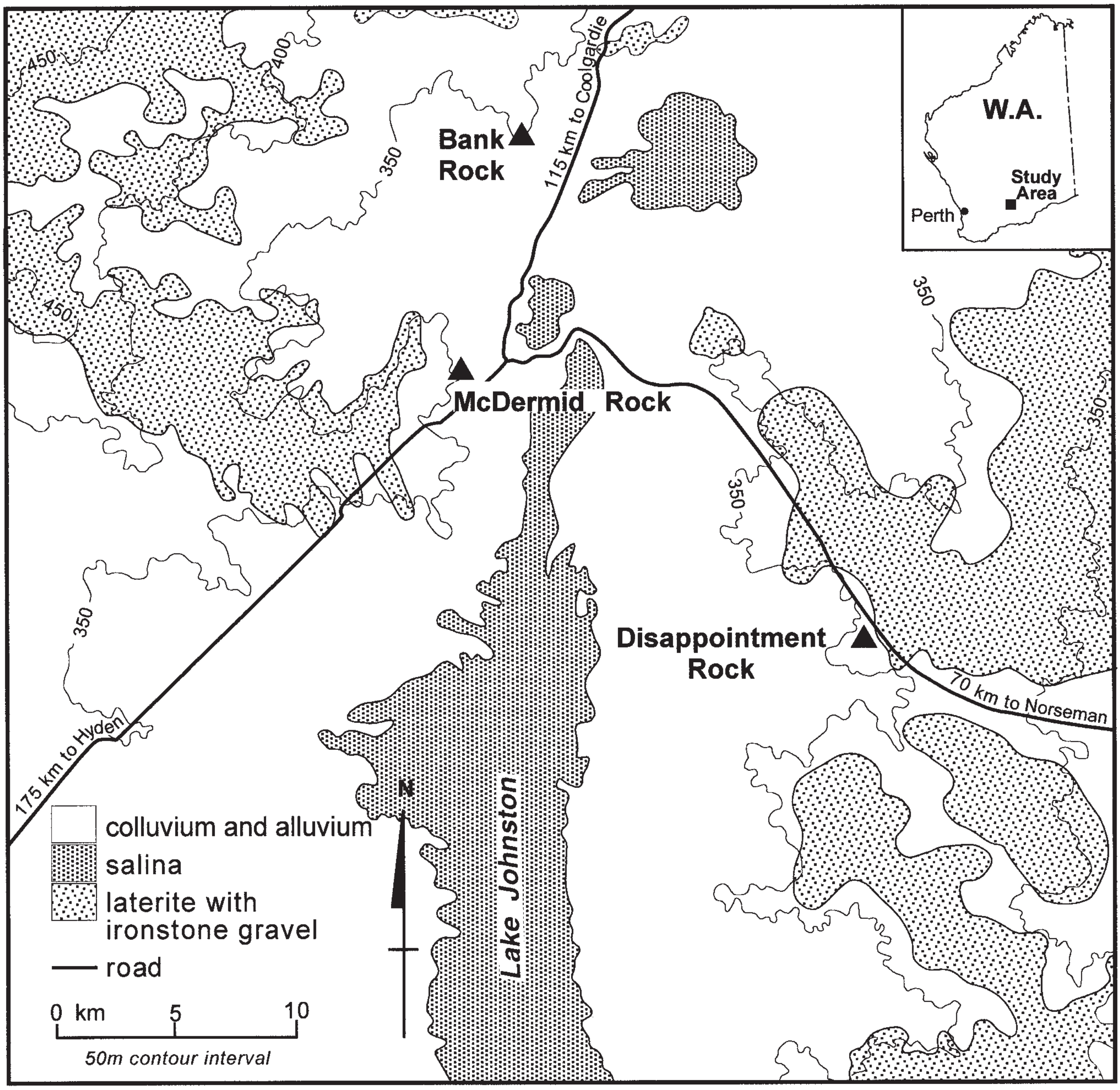

Figure 1. Location map and generalised surficial geology of the Lake Johnston area. The positions of the three inselbergs discussed are shown.

major valleys that are palaeodrainage lines (see *e.g.* Clarke 1994a), which with the onset of aridity in later Cainozoic times were abandoned, blocked and disused. These palaeoriver systems are now occupied by strings of salinas or salt lakes. The Lefroy channel, which embraces Lake Johnston, intervenes between Disappointment Rock on the one hand and McDermid and Bank Rocks on the other.

The palaeochannels have a complex history, for the rivers responsible for their incision originally flowed north and east. The Cowan drainage system, of which the Lefroy arm is tributary, was diverted southwards prior to the Jurassic as a result of the development of the Jarrahwood Upwarp, a south-west to north-east trending rise between what are now Norseman and Kambalda (Clarke 1994a). The valleys became shallow arms of the sea during the Eocene, about 60 million years ago. These estuaries persisted until the Miocene, about 20 million years ago, when aridity set in causing surface drainage to be dismembered. Gypsum and gypsiferous deposits accumulated in the valley floor resulting in the salt pans that are such eye-catching features of the present landscape.

Though it was not diverted southwards, the original Lefroy river probably eroded its channel and created a valley incised below the lateritised plain in the Eocene, about 60 million years ago. The implication is that the lateritic plain is older than the Eocene but it postdates the late Palaeozoic glaciation. It is of later Mesozoic -

Figure 2. The Breakaway is a valley bounded by cliffs, some of them overhanging, as seen here, and eroded in mottled kaolinised granite capped by silcrete. The steepness of the cliffs is due to seepage and sapping at the base of the slope.

later Jurassic and Cretaceous - age (Clarke 1994b; Twidale & Bourne 1998).

Origin and age of bornhardt inselbergs

Terminology

The three granite hills discussed in this paper are all inselbergs, for they each stand in isolation and rise abruptly from the surrounding plains. But all are also essentially domical and for this reason are referred to as domical inselbergs or bornhardts, after the German explorer of that name whose accounts of such features in what is now Tanzania (Bornhardt 1900) prompted Willis (1934) to suggest that his name be given to domical inselbergs.

Morphology

Bornhardts are common throughout the Yilgarn Craton. They are convex-upward hills which display varied radii of curvature and stand at various heights above the surrounding plains. All are domical by definition, but they vary in precise geometry and morphology as well as complexity. Some, like Disappointment Rock, take the form of hemispheres or *meias laranjas* (half oranges), others are elongate domes or turtlebacks, low whalebacks (*dos de baleine*), or asymmetrical elephant rocks (*dos d'elephant*), mostly, as at McDermid and Bank Rocks, with clefts due to the weathering and erosion of fractures. Yet others stand tall in relation to plan diameter to give sugarloafs or turrets, like Quarbabing Hill, some 43 km south-west of Corrigin (and the well-known Sugarloaf of Rio de Janeiro). Taking examples from the south-eastern Yilgarn Craton, some, like Frenchmans Peak, consist of a single dome but most, including Peak Charles, comprise two or more juxtaposed forms. Hyden Rock consists of three domes at once separated and linked by major fracture zones (Twidale & Bourne 1998, 2001), and McDermid Rock, The Humps and Boyagin Rock each include several linked domes. Platforms like Bottle Rock, some 45 km east of Hyden and just north of the Hyden-Norseman road, and several unnamed examples standing flush with the plains around the three residuals discussed here, are regarded as the crests of compartments as yet unexposed. Regardless of their varied areas, elevations, relief amplitude and geometry, however, all these outcrops have many gross characteristics and minor features in common.

The plan outlines of these bornhardts are determined by systems of steeply-dipping, orthogonal fracture systems due to stress and shearing. Their profiles are coincident with sets of sheet fractures which are traditionally attributed to erosional offloading and so are frequently referred to as offloading joints (Gilbert 1904), though in many instances they are more likely due to the same compressional stresses that caused orthogonal fracture systems to develop in the rock (Merrill 1897; Twidale 1964; Vidal Romani *et al.* 1995; Twidale *et al.* 1996).

Origin

The bornhardts are invariably developed on compartments of massive rock, *i.e.* rock with few open partings, and they are upstanding because the scarcity of open fractures offers few avenues for water penetration in what is an impermeable crystalline rock. By contrast, the surrounding plains have been worn down because the granite was well fractured and weathered by contact with water seeping down from the surface. That the granite of the hills is massive is readily demonstrated by walking over the outcrops and noting that the fractures are few and commonly many metres, even tens of metres, apart. It is more difficult to demonstrate rock structure beneath the plains for exposures are few. However, where excavations have been made (dams, tanks) the rock is found to be altered, possibly with corestones, tens of centimetres in diameter, preserved in the weathered granite or grus. The size of the corestones provides a general guide to the original fracture spacing in the bedrock (*e.g.* Twidale 1982a, pp 89 *et seq*). Similarly, boulders (exposed corestones) are frequently found standing in isolation or in small clusters on the plains, and again their dimensions give an indication of fracture density.

Three points need to be made about this interpretation. First, in the study area the evidence is fragmentary and to that extent unsatisfactory, but at some few sites on Dartmoor, south-western England (Jones 1859; Twidale 1982a, p 132), in peninsular India (Büdel 1977, p 109), in Namaqualand, Western Cape Province, South Africa (Vidal Romani & Twidale 1998, p 193) and at Ucontitchie Hill, north-western Eyre Peninsula (Twidale 1964, 1971, pp 52-53) where excavations have been sunk at or near the base of granite hills, fracture contrasts of the kind postulated are observeable.

Second, why are there contrasts in fracture density? The bornhardts are developed on massive blocks. The major fractures are shears from which fractures are propagated by continued dislocation so that the present bornhardts can be viewed as forming the cores of otherwise shattered blocks (Weissenberg 1947; Twidale 1980).

Third, it might be argued that the fracture density beneath the present plains is irrelevant, and that it is the contrast between the granite of the bornhardt and of the rock adjacent to it but now eroded, that is germane to the argument. Blès (1986) has compared fracture density at the surface with that at depth, and found that they are similar at any given site. If surface density is an indicator of density vertically below, is it not reasonable to suggest that it is also an indicator of the density in the rock vertically above, in the compartment that has now been eroded to produce the plain (Twidale 1987)?

Thus the compartments of granitic rocks on which bornhardts are developed resisted weathering and erosion and remain upstanding because they are massive with few open partings. When did this two-stage mechanism, involving differential subsurface weathering and then the stripping of the weathered mantle and exposure of the projecting compartments as bornhardts, take place?

Age

The age of the bornhardts of the south-eastern Yilgan Craton can be deduced from their topographic relationship to the Cretaceous lateritic land surface. Some, like the higher domes of The Humps and Boyagin Rock, stand higher than the local remnants of laterite, and are therefore at least as old as the duricrusted surface. The crests of other bornhardts, such as Waycott Picnic Rock, west of Corrigin, stand at a similar elevation as the laterite preserved on adjacent mesas (in the instance cited, Jingaring Hill) and are construed as Cretaceous platforms, which have however been left high in the relief by subsequent erosion of the surrounding weathered bedrock. Others, however, are more complex with crests higher than the laterite but most of the residual lower.

Granitic bornhardts located on the Gawler Craton, on north-western Eyre Peninsula, South Australia, though domical overall are stepped in detail, with steep slopes or steps separating gently sloping areas, platforms or treads. The steps display flared slopes indicative of former hill-plain junctions, and it has been suggested that the tiered morphology of the residuals is due to their having been exposed in stages. In other words that phases of stability during which subsurface weathering (including the formation of flared forms at the then hill base) alternated with phases of erosion and lowering of the plains around the hills (Twidale & Bourne 1975; Twidale 1982b; Bourne & Twidale 2000). Many of the bornhardts of the Yilgarn Craton are similarly stepped, and the hypothesis of episodic exposure seems compatible with the local evidence.

Such residuals as Boyagin Rock in the Darling Ranges, east of Perth, and King Rocks near Hyden, consist of a smaller dome rising from a larger. These crestal areas stand higher than the local remnants of the lateritised surface and are thus at least of Cretaceous age. The highest crest of bornhardts, like Hyden Rock, may have been exposed as platforms or very low domes in the lateritised plain but they are essentially due to post-Cretaceous erosion of the surrounding areas. Hyden Rock displays two 'treads' lower than the highest crest. They are partly bounded by flared slopes and represent stages in the post Cretaceous lowering of the plains. In general terms the ages of the residuals (in this context, when they were exposed as landforms) can be gauged according to their location within major catchments; Eocene near major palaeochannels, Miocene in headwater reaches and so on (*see* Salama 1997; Twidale *et al.* 1999a), but with variations and phases of exposure according to proximity to major channels, and possibly also the effect of rock barriers or river incision. In addition, besides plains shaped by rivers, weathering at the base of the regolith simultaneously creates another platform at the lower limit of effective weathering, or weathering front (Mabbutt 1961a); what is referred to as double 'planation' (Büdel 1957). The development of the Old and New Plateaux of the Yilgarn Craton (Jutson 1914; see also Mabbutt 1961b) is a good example, with the weathering front later exposed to give the New Plateau, originating at the same time as the Old Plateau was being shaped.

Comparisons

Of the three inselbergs under review, the whole of Disappointment Rock stands higher than the laterite that

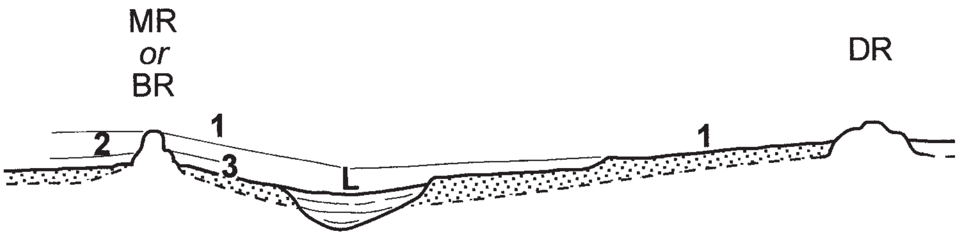

Figure 3. Suggested development of inselbergs in the Lake Johnston area. (L) indicates the Lefroy palaeochannel with Lake Johnston. (1) Cretaceous times with weathered (lateritised) land surface with Disappointment Rock (DR) already exposed and standing as an inselberg on the plain. (2) River incision along Johnston drainage line, stripping of weathered mantle, and exposure of uppermost domes of McDermid (MR) and Bank (BR) Rocks. (3) Further stripping near the valley and exposure of lower levels of McDermid and Bank Rocks, while Disappointment Rock remains basically unchanged.

caps the adjacent plain and which is there exposed in borrow pits (Fig 3). Thus the residual is at least of Cretaceous age. The bornhardt comprises a dome-on-dome form with a distinct break of slope between the two, and the higher dome is the older, in the sense that it was exposed earlier than were the lower slopes.

McDermid and Bank Rocks are more distinctly tiered (Fig 3), with steeper flanks than Disappointment, suggesting that because of their proximity to a major water course subsurface moisture attack was more pronounced. Several minor and possibly localised levels can be detected on each, but on McDermid Rock the upper dome rises from a level of some 355 m, which can tentatively be taken as an old plain level below which a regolith and associated flared slopes and platforms developed. This may have been the lateritic regolith in which case the upper dome is of Cretaceous age and the lower forms are younger, being either a weathering front exposed by the erosion of the regolith or having evolved on the surface so exposed. The convergence of flared slopes on the northern slope suggests localised erosion.

A similar construction can be placed on Bank Rock, where the main dome rises from a gently sloping area at about 380 m bounded by flared slopes. In both instances a regolith some 10-15 m is implied, which is less than the maximum revealed in the deeper valleys but which is comprehensible in terms of having developed on resistant rock masses.

Minor landforms developed on bornhardts

The various minor landforms developed on bornhardts can be classified according to their origin. Some were initiated at the weathering front when the host mass was still below the land surface but was in contact with groundwaters. Some were formed after the exposure of the hill. Others are due to localised contrasts between exposed and regolith-covered areas. Some are an expression of structures in the granitic host rock and yet others are tectonic and are due to earth movements. Yet others owe their existence to protective mechanisms and factors (for reviews *see* Twidale 1982a; Campbell 1997; Vidal Romani & Twidale 1998; Twidale & Vidal Romani 2002).

Subsurface origin

Subsurface moisture attack by way of solution, hydration and hydrolysis preferentially alters mica and feldspar to clay, leaving quartz in micro-relief and producing a rough surface called pitting (Twidale & Bourne 1976). This is a sure sign of relatively recent exposure of the surface through the removal of soil, regolith or slabs of rock.

At a slightly larger scale, small hollows (alveoles, or collectively honeycomb weathering) form at the weathering front. The septa separating alveoles are areas of algal colonisation but whether the plants protect and thus preserve the septa or whether the algae take advantage of a suitable niche is not clear. Pecking denotes a group of slightly larger and more widely separated hollows, again due to localised moisture attack at the weathering front. Neither alveoles nor pecking carries the same implication of recent exposure as pitting.

Chemical reactions at the weathering front may cause concentrations of salts of silicon, iron and manganese. Certainly such concentrations can be seen at exposed fronts (*e.g.* Twidale 1986) but it has been surmised that continued precipitation of such salts could cause space problems and the disruption of the rock surface into small (1-20 cm diameter) plates defined and delimited by fractures. When weathered and enlarged these fractures produce polygonal patterns. Examples of polygonal patterns, which are well displayed at King Rocks, near Hyden, and at Dundas Rocks, about 22 km south of Norseman (Fig 4A), have been noted on recently exposed corestones in the Snowy Mountains. On the other hand, these features may also have formed on exposed surfaces.

Rock basins (or gnammas) are depressions in the bedrock surface and are one of the most common and widely distributed of all granitic forms. Many are initiated as shallow saucer-shaped depressions where moisture has exploited clusters of such susceptible minerals as micas and feldspars, but many form at the intersection of fractures. After exposure they become differentiated according to the structure of the granite and the slope of the surface (Twidale & Corbin 1963). On gentle slopes hemispherical pits form in massive isotropic rock, but shallow flat-floored pans, frequently with overhanging sidewalls, develop in laminated granite which allows more rapid lateral rather than vertical moisture attack. On steep slopes (greater than about 20 °) the basins are asymmetrical with open downslope sides, and are called armchair-shaped hollows. Where pits have penetrated through the base of a slab or sheet structure runoff entering the pit flows through the base, a swirling motion develops and a

A

B

Figure 4. A: Well-developed pattern of polygonal cracking on granite boulder at Dundas Rocks, some 22 km south of Norseman and to the east of the main Esperance road. **B**: Miniature mesas or mogotes on the midslope of King Rocks, near Hyden.

cyclindrical hollow is formed. A particularly large example some 6 m long and 3 m wide and at least 2 m deep is developed on Beswick Rock, near Corrigin. Basins formed along fractures tend to be elongate in plan and when carrying water look like eyes; and for this reason they are known in south-east Asia as 'water eyes' (*e.g.* Tschang 1962).

Water running along the weathering front erodes linear channels in the rock surface. Such channels are known as gutters. Those exploiting fractures are straight and are called *Kluftkarren* or (in the USA) slots. Water running or seeping into the soil or regolith at the margins of an exposed rock mass (whether a dome or bornhardt or a block or boulder) infiltrates into the regolith. It alters the rock with which it is in contact both vertically and laterally. In this way, it creates a concavity just below the land surface. When exposed as a result of the erosion of the regolith and lowering of the plain level, such concavities are known as flared slopes (Twidale 1962). The shoulder between the convex slope above and the concavity below marks the former hill-plain junction. Long-continued subsurface weathering around a block or boulder can eventually produce an hourglass or pedestal rock (Twidale & Campbell 1992).

Sheet structures begin to break down into orthogonal or quadrangular blocks when still beneath the land surface, probably as a result of moisture penetrating along and weathering incipient partings.

Subaerial or epigene origin

After exposure of blocks and boulders, various types of gnammas evolve from saucer-shaped depressions, as described above, and gutters extend and develop. Some new ones are formed below seepages issuing from patches of regolith that may survive on gentler slopes, as for instance on hill crests: decantation flows and gutters. Blocks and boulders are attacked from below partly by moisture persisting in the sheltered parting beneath the block, but mostly by salt crystallisation (exudation, haloclasty) which exerts enough force to rupture even strong rocks like fresh granite (Buckley 1951; Evans 1969). Books of flakes are a manifestation of such salt weathering as is some granular disintegration, but either or both produce alcoves and shelters at the exposed ends of sheet structures and enclosed hollows or tafoni in blocks and boulders, and the outer shell or visor is indurated by iron oxides and silica, possibly related to lichen growth.

Exploitation of the partings defining polygonal cracking (*qv*) to the extent that the residual cores of polygons are widely separated, produces mogotes or miniature mesas, excellent examples of which can be seen at King Rocks, near Hyden (Fig 4B), and at The Granites, Mt Magnet (Twidale *et al.* 1999b).

Contrasts between exposed and covered surfaces

Some granite forms are due to contrasted rates of weathering on exposed and covered rock surfaces, for exposed surfaces are dry and are comparatively stable whereas a rock surface carrying a regolithic cover is longer in contact with moisture and therefore is weathered more rapidly. Both rock doughnuts and rock levees can be explained in this way (Twidale 1993).

Protection – the 'umbrella' effect

A block or boulder shelters the immediate surface on which it rests against rain and hence weathering (Twidale & Bourne 2000a). But water drips on the adjacent surface from the block, augmenting that which falls directly on it, thus causing rapid weathering and hence erosion. Thus a shallow moat is formed around the base of the block. In this way the area beneath the block comes to be higher than its immediate surrounds, forming a plinth on which the perched block or boulder stands.

Petrology

Bornhardts themselves are structural forms, and many minor features are due to the exploitation by agents of weathering and erosion of weaknesses, or contrasts, in the country rock. Fracture patterns give rise *Kluftkarren,* and water eyes. Compositional variations denote differences in susceptibility to weathering and cause the development of micro ridges and depressions, many of them in parallel and forming 'tramlines', as for instance on Kirk Rock and Hyden Rock, some of them irregular as at Boyagin Rock (Twidale & Bourne 2001, p 61). Pitting, as previously mentioned, is due to differential weathering at the crystal scale. Porphyritic texture implies large crystals of one mineral set in a matrix of finer minerals. On Hyden Rock, for example, feldspar phenocrysts have resisted weathering and project to give a pronounced rough surface. The ancient granitic rocks are criss-crossed by veins and sills, most of which were injected along fractures. They vary in composition, some consisting of quartz, others of feldspar, and yet others are a mixture of the two. Some are composed of fine-grained granite or aplite, others of coarse-grained pegmatite. Some aplites are bordered by pegmatite. The veins vary in thickness between a millimetre or so to more than two metres. Some are steeply inclined, others dip gently into the granite.

Tectonic forms

Though the cratons located far from plate boundaries are tectonically stable compared to plate margin locations, no part of the Earth's surface is entirely stable. Earthquakes are frequently recorded in the Australian cratons (*e.g.* Gordon & Lewis 1980; Bowman 1992; Twidale & Bourne 2000b). They result in such tectonic features as fault scarps, A-tents or pop-ups and displaced wedges (Twidale & Sved 1978), related to compressional stress. Orthogonal patterns of fractures and plates develop on sheared surfaces. Shaking gives rise to displaced slabs and blocks and may also contribute to the formation of split rocks, though they are mainly due to gravity. As they are due entirely to earth movements they are called tectonic forms, and as they postdate the Miocene, neotectonic.

Gravity

Gravity is the force behind several of the forms already mentioned. Water infiltrates into soil under gravity and is instrumental in pushing the weathering front further below the land surface. Linear flows of water along the front scour gutters. Also, any blocks and boulders that include a latent steeply-inclined fracture may be split as a result of the fracture being weathered, thus weakening cohesion between the two parts. Gravity eventually causes one or both of the imperfectly supported parts to pull apart and the block or boulder to split in two.

Inselbergs of Lake Johnston area

Not all of these minor forms are found on any one residual, but many are found on almost all. Despite

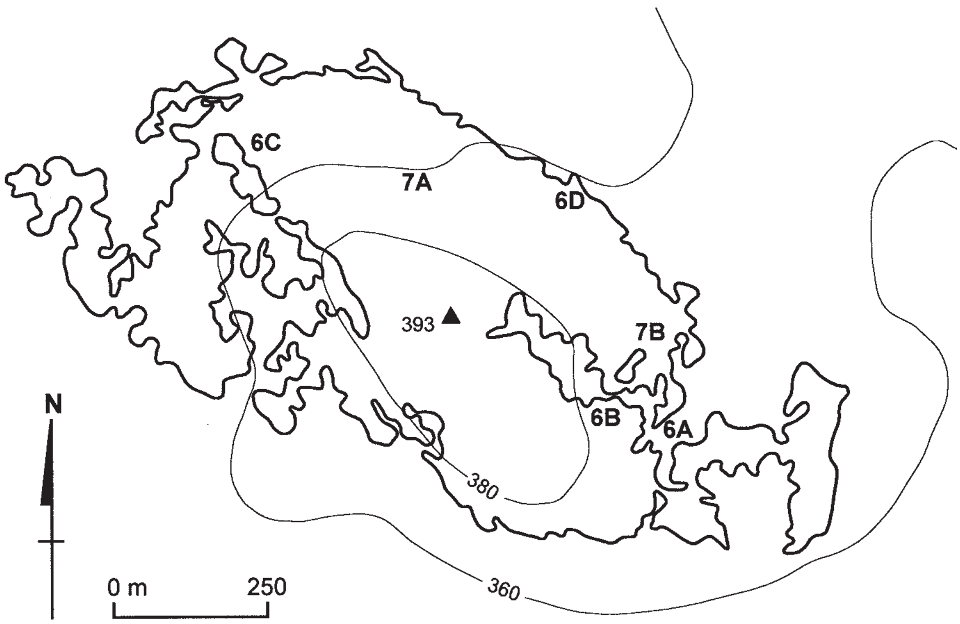

Figure 5. Plan outline of Disappointment Rock. Heavier line indicates outline of granite outcrop; finer lines, contours in metres above sea level; and numbers and letters, positions of landforms shown in Figs 6 and 7. (Drawn from air photographs and topographic map data).

A

B

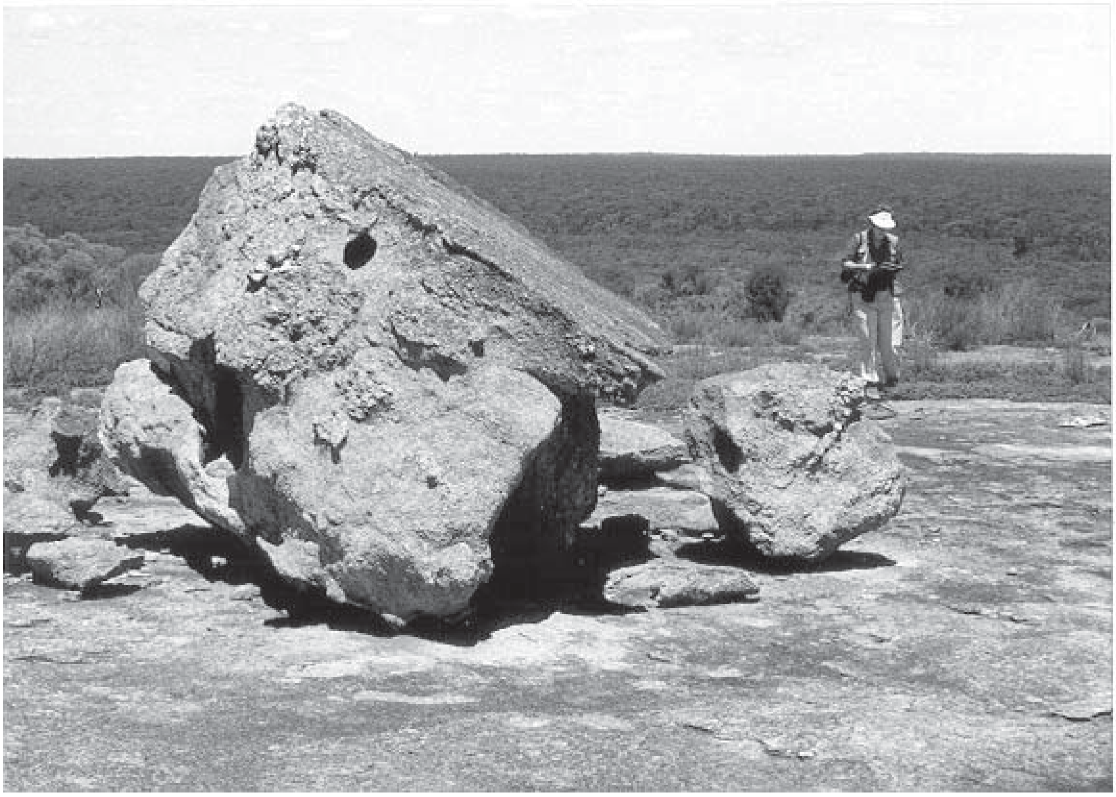

Figure 6. Some notable landforms on Disappointment Rock. **A**: Large A-tent. **B**: Tilted block with indurated surface visible top right. Note the 'window' just below the induration. **C**: The differential weathering and erosion of pegmatitic intrusions result in over-steepened slopes. Here on the western slope of the dome, the linear scarp is related to a moderately steeply dipping sill, and the break of slope to the right is associated with discrete masses of pegmatite. **D**: Low flared slope with rock basins, or gnammas, developed in laminated granite.

C

D

Figure 6. (cont.)

A B

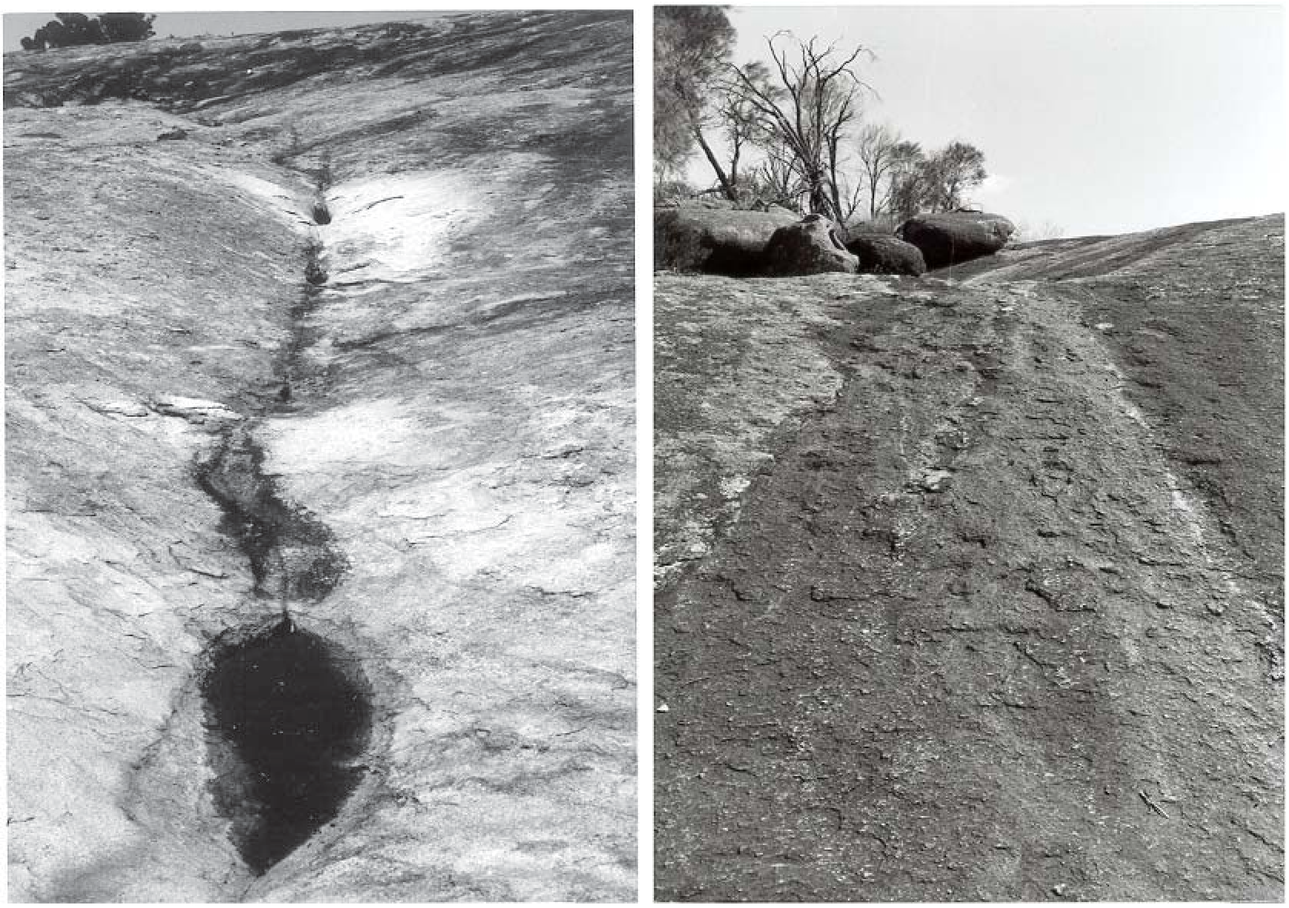

Figure 7. Water weathering and deposition, Disappointment Rock. **A**: Lenticular pits, or water-eyes, developed along a fracture-determined cleft. **B**: Slightly raised (or inverted) algae-coated floor of gutter or *Rille* on flank of inselberg. It drains from a soil-filled and vegetated armchair-shaped hollow (top left).

many common features and attributes every bornhardt is individual, with particular forms of note. This is illustrated by our account of three bornhardt inselbergs, Disappointment, McDermid and Bank Rocks, close to the Lake Johnston palaeochannel, and near the Hyden-Norseman road. A brief account of each is given below with features of special interest highlighted and illustrated. The granite in which they are developed is of Archaean age, *i.e.* more than 2.5 billion years old. The hills rise abruptly from a broadly rolling plain ranging in elevation from about 320 m above sea level in the Lake Johnston valley, to more than 380 m in the sand plain to the east of the valley and 400 m plus to the west (Fig 1).

Disappointment Rock

Disappointment Rock is located about 80 km west of Norseman and stands about 200 m south of the Hyden-Norseman road. Of the three bornhardts under review, this is closest to being characteristic of the standard Yilgarn type, for in plan it forms an irregularly oval whaleback of large radius, with a crest that stands about 393 m above sea level (Fig 5). Rising only 35-40 m above the adjacent plains, relative to its diameter (1.25 km x 0.6 km) its flanks appear gentle and smooth. Its surface is scored by basins and gutters, and blocks and boulders are scattered over the rock surface.

Many small fault scarps, trending 100 º, 40 º or 10 º, are preserved low on the eastern and the western slopes. A large A-tent (trend of crestal fracture 0 º), the largest yet recorded in Western Australia, occurs on the eastern midslope (Fig 6A) and a tilted block is preserved high on the eastern slope (Fig 6B). A good example of a complex (in the sense of including offset sectors) fracture-controlled valley or *Kluftkarren* can be seen to the east of the access track. Along it are developed several of the lenticular basins known as water-eyes (Fig 7A). Here, and on McDermid Rock, pegmatitic sills have been preferentially weathered to produce breaks of slope (Fig 6C) and linear clefts. Notably large (up to 28 cm diameter) phenocrysts of feldspar are exposed in the northern slope, as are good examples of vegetational (tree root) disruption of surficial plates. In addition, however, Aboriginal people tilted and then released slabs in an effort to trap lizards, and some of the displacements evident today may be relic from such activities.

Small flared slopes are exposed in several sectors around the base of the residual but just east of the entry to the Rock they are low but overhanging. They are scored by basins in the walls of which laminated rock typical of the weathering front is exposed, suggesting that the gnammas have formed after the exposure of the flares (Fig 6D). Armchair-shaped hollows with soil and vegetation are well-developed and several of the gutters (or *Rillen*) that drain the dome originate in, or flow through, such depressions. Those that do tend to carry a protective veneer of black algal remains in the channel floors and some are inverted in consequence (Fig 7B). Some gutters have been diverted along fractures and veins resulting in dogleg bends. Large boulders with tafoni occur just to the west of the entry bay and hourglass rocks resulting from subsurface weathering all around blocks and boulders are also found at various sites on the Rock.

McDermid Rock

McDermid Rock which lies west of Lake Johnston, some 100 km from Norseman and about 1.5 km north of the main Hyden-Norseman road, consists of five juxtaposed domes separated from one another by fracture-controlled clefts, *Kluftkarren* (Fig 8). The highest dome stands 373 m above sea level and some 35-40 m above the adjacent plains. In plan, the residual, which extends 1.25 km south-west to north-east and 0.36 km north-west to south-east, is clearly defined by steeply dipping fractures with a south-west to north-east zone forming the south-eastern margin of the upland and with cols developed on roughly north-west to south-east trending fractures separating the four easterly domes. The most westerly dome meets the adjacent dome, the highest, in a NNW-trending fracture. Strong ENE offset, or *en echelon,* trends define the northern flanks of three of the easterly domes. In profile, the dome morphology reflects the development of arcuate-upward sheet fracture sets within the fracture-defined blocks. Pegmatitic and aplitic sills, some of them intersecting, are preferentially weathered to produce linear valleys.

The overall morphology of McDermid Rock is tiered with steep slopes, or steps, many of them concave or flared, separating gently sloping treads. The basal flares on the south-western margin are simple but those on the north-eastern flank of the highest and largest dome are sloping and intersect, suggesting that the erosional

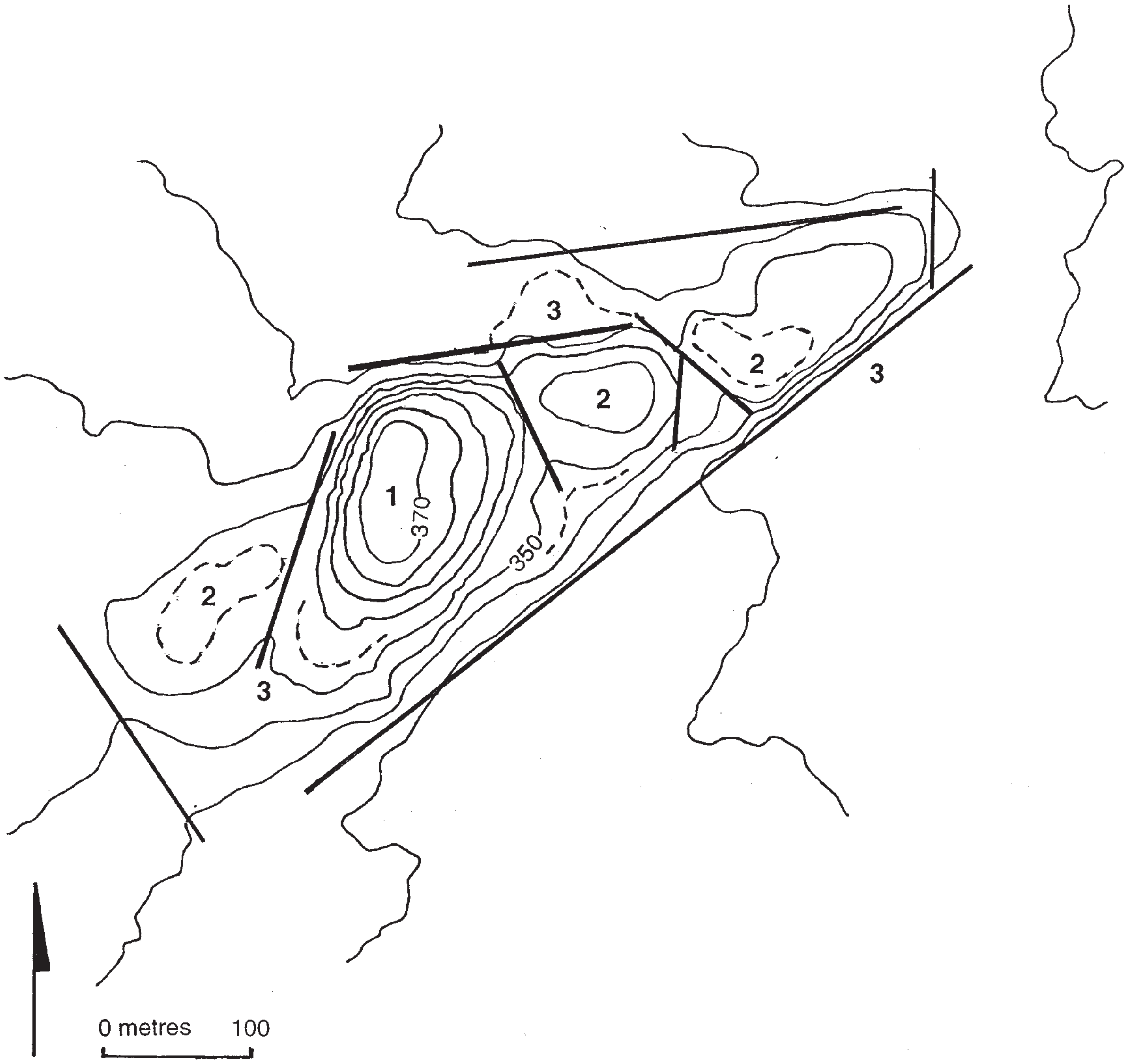

Figure 8. Plan of McDermid Rock showing contours (continuous lines; 4 m intervals) and form-lines (dashed lines), major fractures (heavy lines), and prominent domes, numbered 1-3, with 1 highest and 3 lowest. (Adapted from map drawn by McMullen, Nolan & Partners Surveyors, WA).

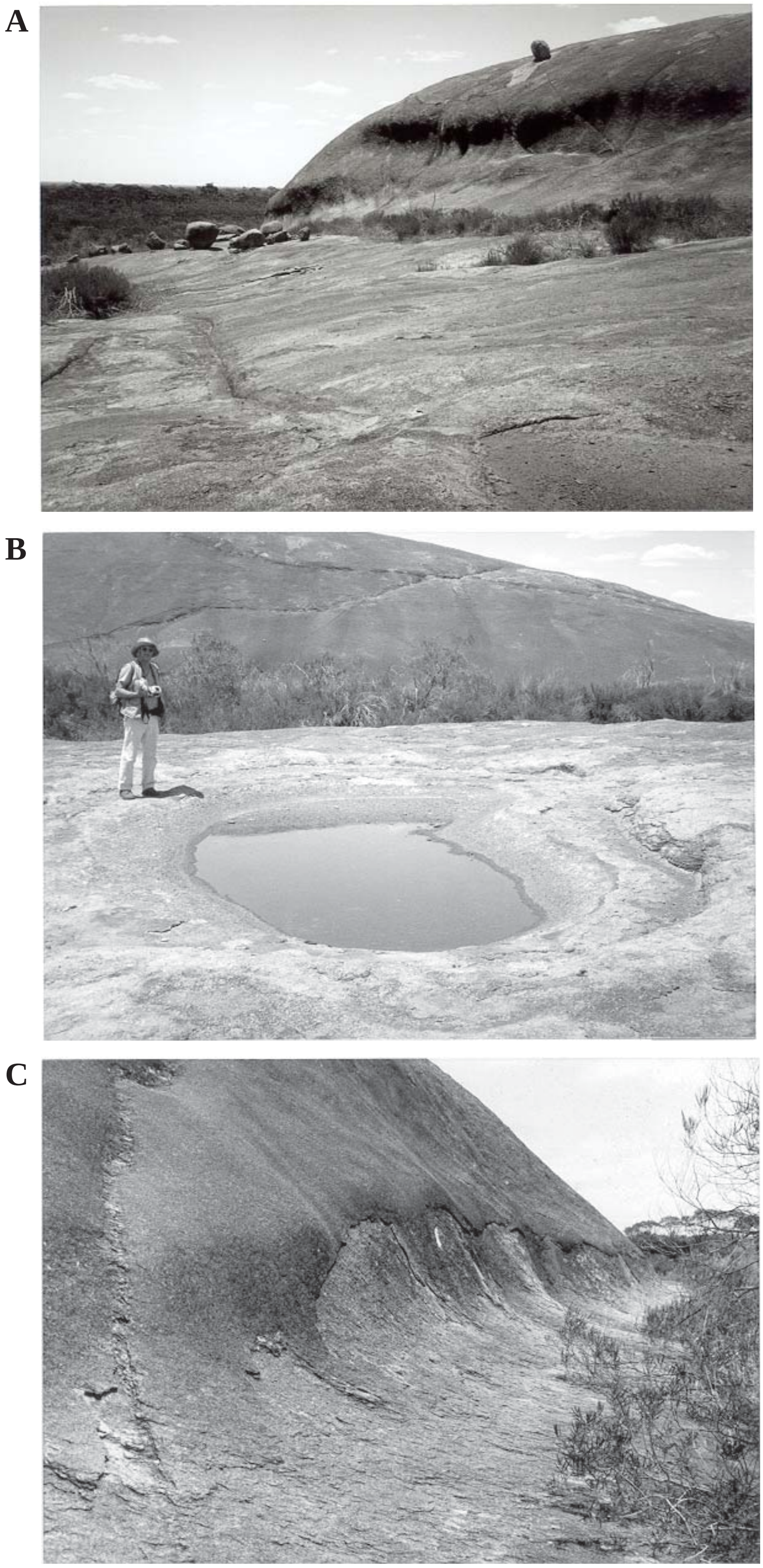

Figure 9. Some notable landforms found on McDermid Rock. **A**: Part of the north-western flank of McDermid Rock showing flared slopes converging to the north-east (right). Note also the perched boulder, and platform with several more perched blocks, some on plinths. **B**: Shallow flat-floored gnamma, or pan, located within a larger diameter pan. Note the intersecting pegmatite and aplite sills on the backing slope. **C**: Flared slope of recent origin is a lighter colour because there has not been enough time for substantial colonisation by algae. It meets an older slope above in a distinct ledge, or break of slope. Note the pegmatite sill exposed on the slope to left of view.

A B

Figure 10. A: Recent fault scarp with splinter on McDermid Rock. **B**: Pecking on northern slope.

chronology of the plain on that side of the residual was more complex than that to the south (Fig 9A). Bearing in mind that the flared forms indicate the former piedmont zone and that the shoulder between the upper convexity and the lower concavity marks the hill-plain junction, it can be suggested that, following the development of the uppermost flared zone the adjacent plain was lowered to the north and another flare formed in relation to this newer, lower, and sloping plain surface.

Features of note include a recent fault scarp (Fig 10A); rock basins or gnammas with distinct basin-in-basin form and spectacular pegmatite sills (Fig 9B); evidence that some gnammas are initiated by the exploitation of clusters of susceptible minerals; curious small depressions or pecking on the steep north-western face (Fig 10B); perched boulders, platforms and multiple flared slopes (Fig 9A), including some that are clearly of relatively recent origin (Fig 9C).

Bank Rock

Bank Rock is located some 10 km north of McDermid Rock and some 2.5 km west of the Coolgardie road. It

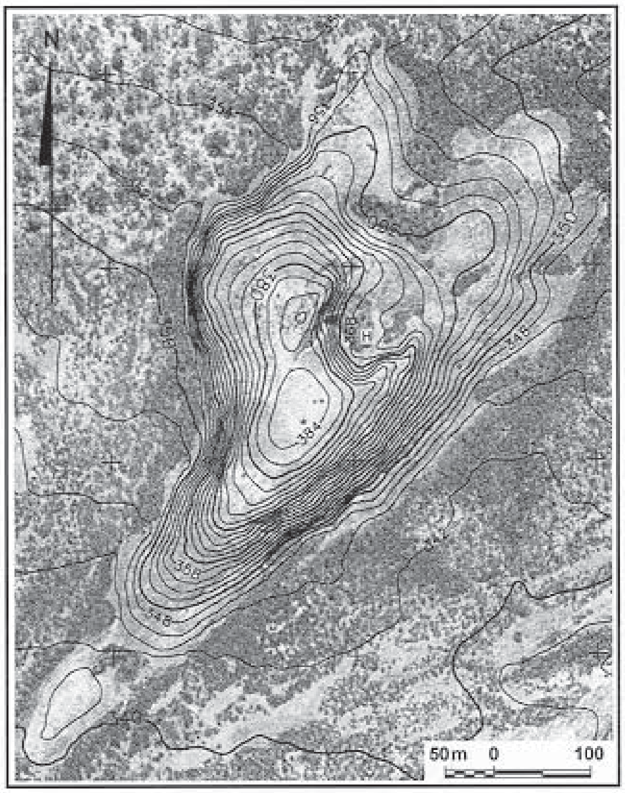

Figure 11. Bank Rock: topography, indicated by two metre form lines, superimposed on vertical aerial photograph. Note that the crosses are part of the form-line plot. (Extract from photo-map drawn by McMullen, Nolan and Partners Surveyors, WA).

A

B

Figure 12. Bank Rock. **A**: Parallel joints, some offset, with quartz injections and water-eye developed; note also pecking on upper slope. **B**: Flared slopes arranged *en echelon* on western side of the residual.

A

B

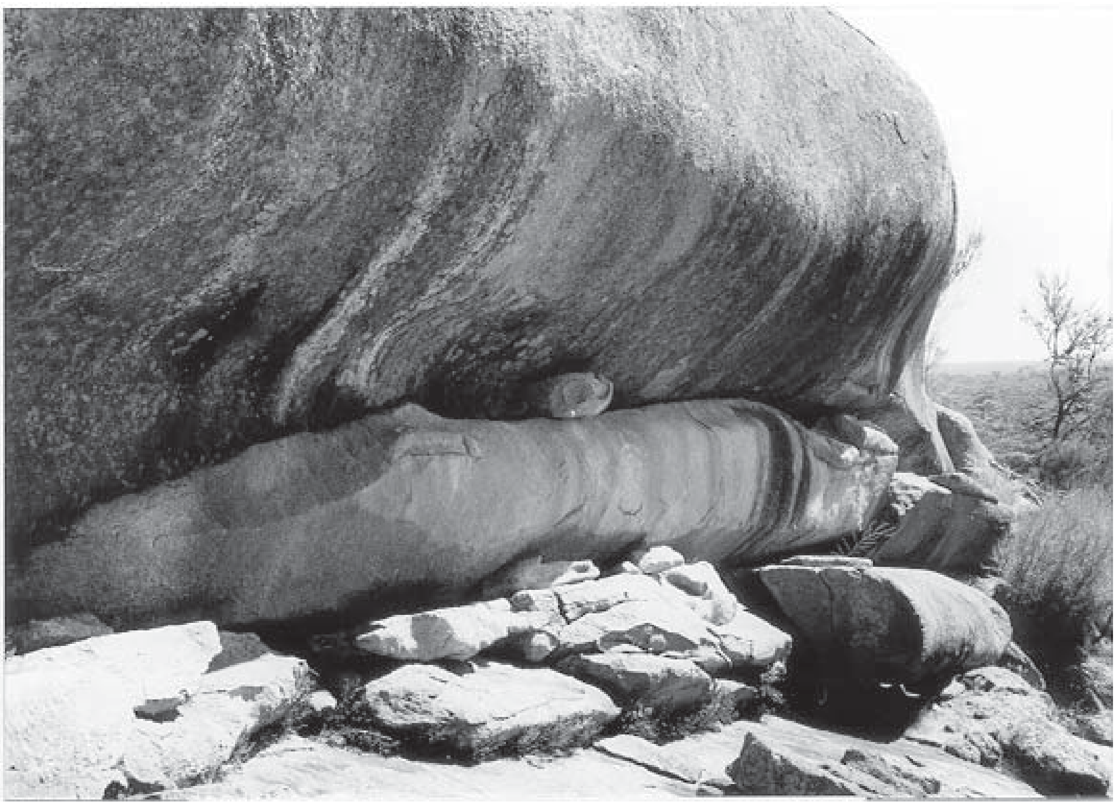

Figure 13. Other notable features found on Bank Rock. **A**: Head of large armchair-shaped hollow (H on Fig 11) with flared sidewalls and large split boulder at its western margin. **B**: Wedge, triangular in cross-section and due to shearing along a sheet fracture. **C**: Broken and disturbed sheet structure just below crest on the western flank; in the foreground is a small perched boulder standing on a plinth. **D**: Face of disturbed slab with slickensides and recrystallisation indicating that the slabs here have split along an old fault plane. **E**: Boulders derived from the breakdown of a sheet structure and with tafoni and alveolar weathering developed. **F**: Elongate A-tent on south-western basal slope.

C

D

Figure 13. (cont).

E

F

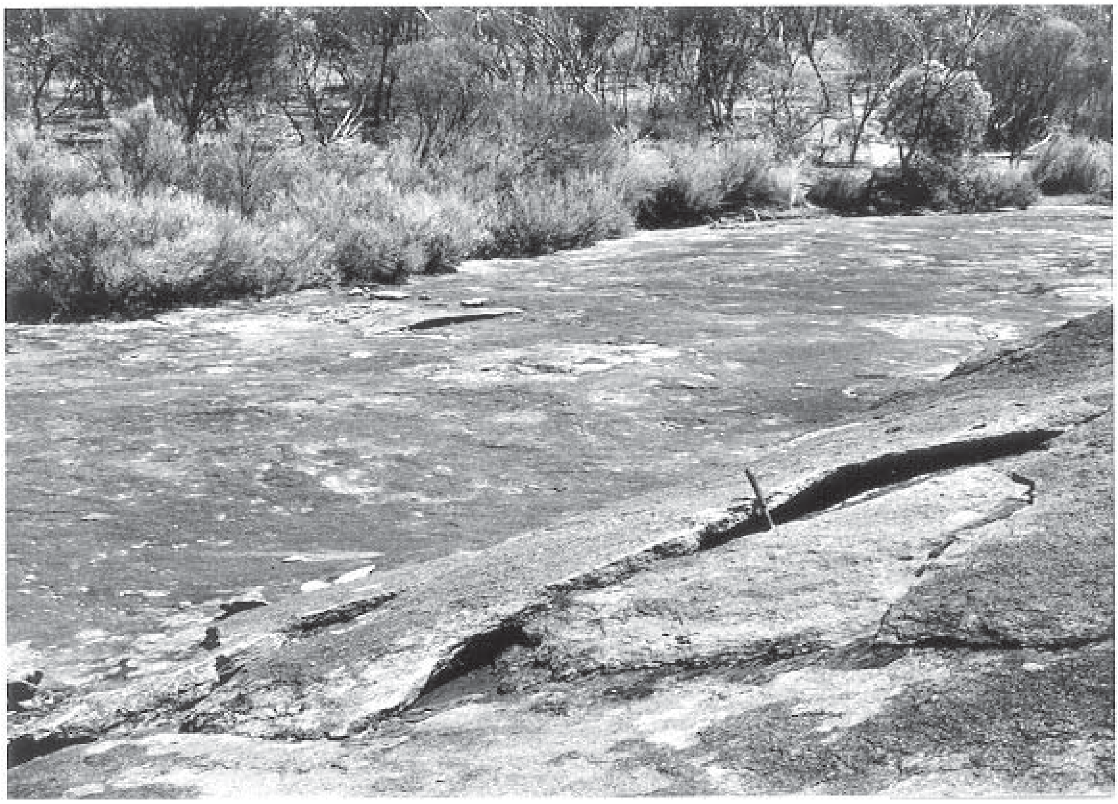

Figure 13. (cont).

(Fig 11) is elongate but triangular in plan form, with a length of some 0.87 km south-west to north-east and 0.4 km at its widest point, from north-west to south-east, at its north-eastern extremity. Like McDermid Rock it is clearly defined by steeply-dipping fractures trending south-west to north-east. Many of the fractures within the upland can be traced long distances (Fig 12A), and many are exploited by weathering to give *Kluftkarren*. The northern and southern flanks are scored by flights of flared forms, most of them inclined. On the eastern flank this geometry can be related to foliation in the bedrock but on the south-western appears to indicate that, as happens at present at some sites, the hill-plain junction was not level, and that, following the formation of the higher zone of flares, the plain was lowered, simultaneously exposing the first-formed concavities and initiating the development of the new lower zone of intense scarp-foot weathering. Closely spaced *en echelon* flared slopes suggest repeated localised lowerings of the hill-plain junction (Fig 12B).

In addition to flights of flares, notable features include a huge armchair-shaped hollow and related collapse and splitting of a large boulder (Fig 13A) and a triangular wedge associated with sheet structure (Fig 13B). Perched and hourglass boulders can be seen at various sites and other minor features of note include a massive aplite sill on the crest of the Rock, disturbed slabs developed in a thick slab or sheet structure (Fig 13C) including an exposure of fault plane with recrystallisation, polishing, fault steps, and slickensides (Fig 13D); tafoni (Fig 13E); and numerous small A-tents (Fig 13F) and perched blocks on plinths. Rather poor remnants of polygonal cracking, including isolated mogotes, are preserved on one sheet structure on the midslope.

Concluding remarks

The relationship of the three bornhardts with the (Cretaceous) palaeosurface and associated palaeosol and the evidence, such as it is, of zones of massive and well-fractured rock, sustain the suggestion that the residuals are essentially two-stage or etch forms (Falconer 1911). No nascent bornhardts have yet been exposed in quarries and other excavations, as they have in Africa and on Eyre Peninsula (*e.g.* Boyé & Fritsch 1973; Twidale 1982a, pp 142-143; Vidal Romani & Twidale 1998, pp 169, 194), but the occurrence of many bornhardts lower in the local landscape than weathered lateritic remnants is consistent with this interpretation (*cf* Lister 1987).

All three are two-stage forms and have been exposed in phases. McDermid Rock is the most obviously stepped with areas of low rolling topography or treads separated by steep flared steps, but sets of multiple flares occur also on the flanks of Bank Rock. At Disappointment Rock, an episodic exposure is suggested by topographic breaks at midslope most of the way round the hill, though the topography cannot be described as obviously stepped.

At Disappointment Rock the dome stands higher than the primary laterite exposed a short distance to the east, so that the bornhardt is at least Cretaceous in age, and the presence of a break of slope between an upper and lower dome suggests that the former may be even older. The age of the crests of McDermid and Bank Rocks is less clear because of their distance from lateritised remnants. They stand closer to the palaeochannel, and their being in wetter sites may account for the more pronounced weathering and resultant greater relief. In particular the contrast between the steeper bounding slopes typical of these two bornhardts and the gentle basal slopes with only a few low flared sections found on Disappointment Rock can be explained in these terms.

Disappointment Rock stands about 15 km from the Lake Johnston valley and has not yet been dissected; the lateritic cover remains essentially in place, and hence any pronounced bedrock concave marginal forms that are developed are not yet exposed. At Disappointment Rock the few, low, flared basal slopes that are revealed can be attributed to a combination of marginal weathering, volume decrease, and compaction, plus runoff and flushing of fines (*cf* Ruxton 1958), leading to localised surface subsidence around the perimeter of the outcrop (*cf* Clayton 1956). On the other hand, McDermid and Bank Rocks stand only some five kilometres from the old channel. The adjacent plains have been dissected and the results of scarp-foot weathering have been exposed. Whereas the exposure of Disappointment Rock appears to have taken place in two major stages, the multiplicity of flared forms and their sloping and intersecting geometries at McDermid and Bank Rocks suggest that many more changes in water table, possibly related to fluctuations in river level, find expression on the lower bornhardts located west of the Lake Johnston valley.

These three quite accessible inselbergs together display a wide range of granite landforms, with excellent examples of several, and uncommon evidence concerning the origin of a few. They also illustrate the evidence and argument that can be used to determine the origin and age of such residuals. In addition, the contrasted gross morphology of Disappointment Rock on the one hand, and McDermid and Bank Rocks on the other highlight the importance of location in relation to water, the major agent of weathering in shaping bornhardts. The upper zones of Disappointment Rock also appear to be sufficiently old to offer the possibility of their having been plant refuges. On the other hand all three bornhardts show clear evidence of recent earth movements: despite their location in crystalline rocks of the shield sectors of the Yilgarn Craton, they are affected by tectonic disturbances.

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