Granite landforms

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Abstract

Fresh granite is low in porosity and permeability, but is highly pervious by virtue of a connected series of orthogonal and sheet fractures. Granite is susceptible to weathering by moisture, leading to the formation of a regolith. The course and rate of weathering are influenced by the structure of the rock, including fractures; mineral composition; texture, especially size of the crystals; and the physical, chemical and biotic nature of the invasive water.

Plains occupy extensive areas of granite outcrops, but positive relief forms – bornhardts, nubbins and castle koppies – have attracted most attention. Minor forms developed on granite are due primarily to weathering, *e.g.* boulders, flared slopes, rock basins, tafoni. Many of them are initiated in the subsurface. Some, like A-tents, are tectonic. Some forms are convergent as they evolve in different ways. Several are not yet satisfactorily explained.

Introduction

The aim of this review is to describe and explain the assemblage of landforms, both major and minor, characteristically developed on granite. None of these landforms is peculiar to granite: each of the forms is developed in a variety of different materials and they all have developed under a wide range of climates (Campbell & Twidale 1995a). Nevertheless, the assemblage of landforms is typical of granite, so much so that it is possible, in many circumstances, to predict from afar the nature of the underlying rock.

Weathering patterns are of primary importance in the development of many granite forms, though others are due principally to tectonic forces (see below). The interaction of granite with the atmosphere and the hydrosphere leads to weathering of the constituent minerals and the formation of a regolith. Weathering, the disintegration or alteration of rocks at and near the Earth's surface, can conveniently be divided into those processes which involve chemical reactions and the formation of new minerals (chemical weathering) and those that involve only physical breakdown of the rock (physical weathering). Most commonly, however, these several processes operate together. The type and rate of weathering of rocks depend on rock characteristics, the physical, chemical and biotic characteristics of the weathering fluids, the nature of reactions at the mineral surface and environmental factors (Colman & Dethier 1986). The base of the regolith, the contact of the regolith with the unweathered bedrock, is called the weathering front (Mabbutt 1961). The weathering front may be irregular, partly due to structural weaknesses of various types and partly as a result of the concentration of moisture.

The rock characteristics which influence the rate of weathering are fracture density, mineral composition and texture. Being composed of interlocking crystals of quartz, feldspar and mica, fresh granite is of low porosity and permeability. Granite is pervious because water penetrates the rock along partings, especially orthogonal joints and sheet fractures. Fractures occur at all scales from microcracks within minerals to partings that can be kilometres in length. Highly fractured rocks are more susceptible to weathering than those in which the fractures are absent, widely spaced or tightly closed. In some instances, even though no fracture is discernible, the crystals may be in strain, leading to a higher susceptibility to weathering (Russell 1935).

The stability of the common silicate minerals is closely related to their order of crystallisation from a silicate melt (Goldich 1938). Minerals that crystallise at the highest temperatures, especially biotite and plagioclase feldspar, are unstable at the Earth's surface and are susceptible to alteration, and granites with a higher than average proportion of these more readily weathered minerals tend to form negative features whereas those with a greater abundance of quartz and potassium minerals, which crystallise at lower temperatures and are more stable, tend to be more resistant (*e.g.* Brook 1978). This variation in suceptibility to weathering is demonstrated at the crystal scale by the occurrence of pitted surfaces where granite is in contact with water. The biotite and plagioclase feldspars are chemically altered, leaving the quartz and potassium feldspars in relief. As the surface is rapidly reduced by flaking, such pitted surfaces are an indicator of recent exposure from beneath the regolith (Twidale & Bourne 1976a).

Variations in crystal size do not produce consistent effects (Twidale 1982). Finer-grained granites tend to be more susceptible to weathering due to the greater surface area to volume ratio of each crystal. However, coarser crystals, especially those that are in strain and hence traversed by an array of microcracks, may be more strongly weathered (Russell 1935; Pope 1995; Hill 1996).

Organisms, especially microorganisms such as bacteria, algae and lichens, significantly affect the rate of weathering of granite. Algae readily colonise rock

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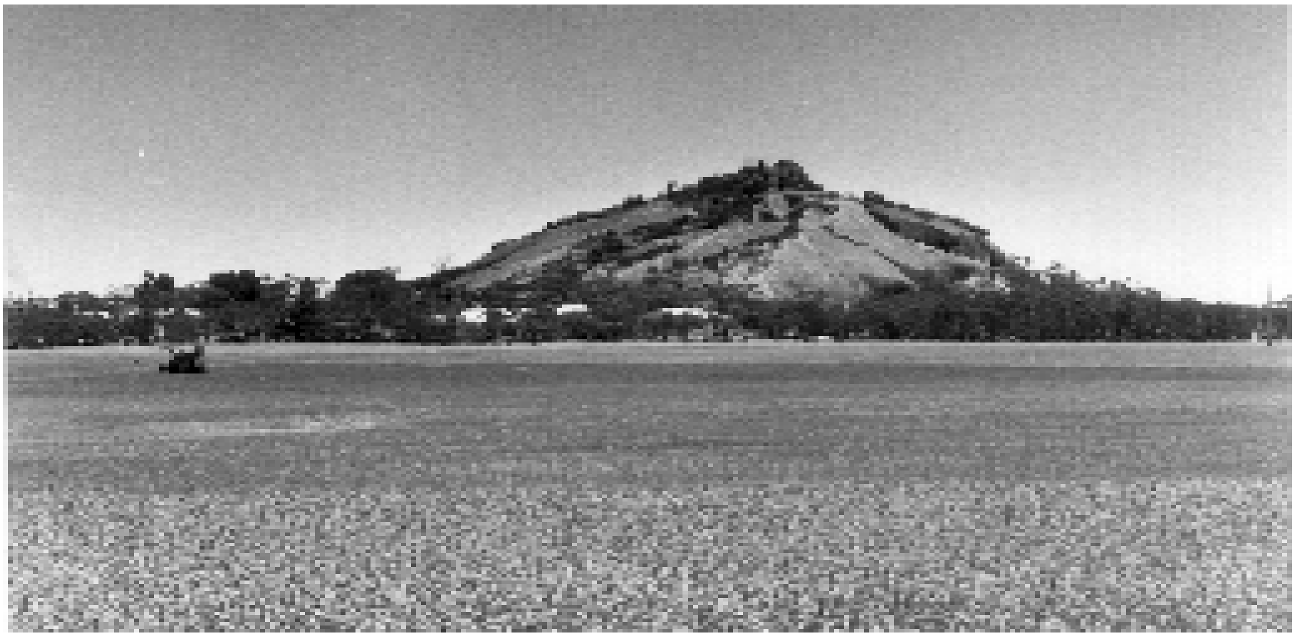

Figure 1. Ucontitchie Hill, Eyre Peninsula, South Australia, is an inselberg which rises abruptly from the surrounding plain. It is also a bornhardt due to the domical profile, a reflection of the sheet fractures essentially parallel to the surface (CR Twidale).

surfaces. Their hyphae penetrate between and within the mineral grains by a combination of physical activity and biochemical reactions (Yatsu 1988). Lichens are characteristic of granite exposures and although in humid environments they protect the surface, in arid environments they contribute to the physical and biochemical weathering of the rock (Fry 1927; Viles 1988). The retention of moisture by plants and soils, especially in fissures and basins, and the humic acids resulting from plant and animal decay also increase weathering.

The thickness of the regolith is a function of the relative rates of weathering and erosion, or the wearing away of the land surface. In most areas erosion is principally by running water. In tectonically stable regions, or those situated far from the sea, which is the ultimate base level of erosion, or those in humid tropical envioronments where weathering proceeds rapidly, or those in arid or semiarid environments where erosion of the regolith may be restricted, great thicknesses of regolith (100 m or more) may develop.

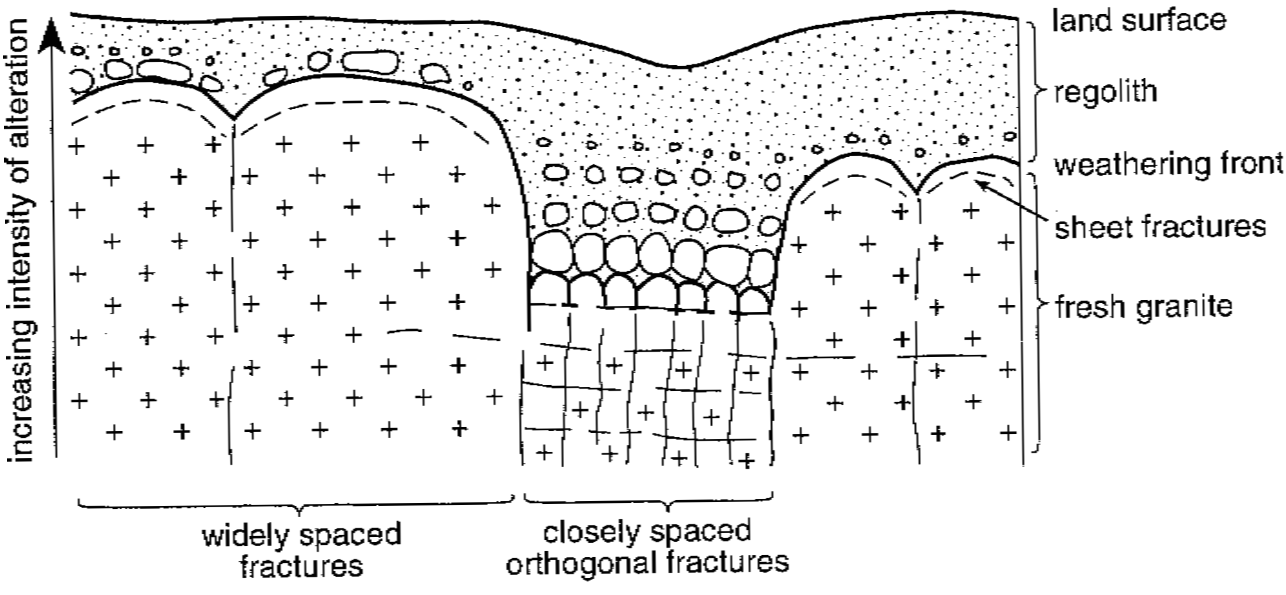

Figure 2. Schematic diagram illustrating the two-stage development of bornhardts. The subsurface exploitation of fractures by weathering is followed by the erosion of the regolith and the exposure of the weathering front. A similar two-stage or etch explanation of boulders is also illustrated (after Twidale 1982).

Major Landforms

Plains are well representative of granite outcrops; they take various forms. Peneplains are gently rolling surfaces, like those on northwest Eyre Peninsula, South Australia, and the southern Yilgarn of Western Australia. Pediments, or rock platforms, are smooth and gently sloping, essentially bare rock surfaces located on the margins of uplands. Mantled pediments carry an *in situ* regolithic veneer. Plains develop in different ways. Some are epigenetic, being formed by subaerial agencies, particularly running water. Etch forms, such as in the plain around Meekatharra, Western Australia, develop as a result of weathering and the formation of a regular weathering front, followed by stripping of the regolith down to the weathering front. Some plains have been buried and later exhumed (Twidale 1982), like that resurrected from beneath a cover of Early Cretaceous strata, found in the north of Western Australia near Port Hedland.

However, it is the positive relief features that have attracted the attention of most geomorphologists. Twidale (1982, 1993) divided the major forms, on the

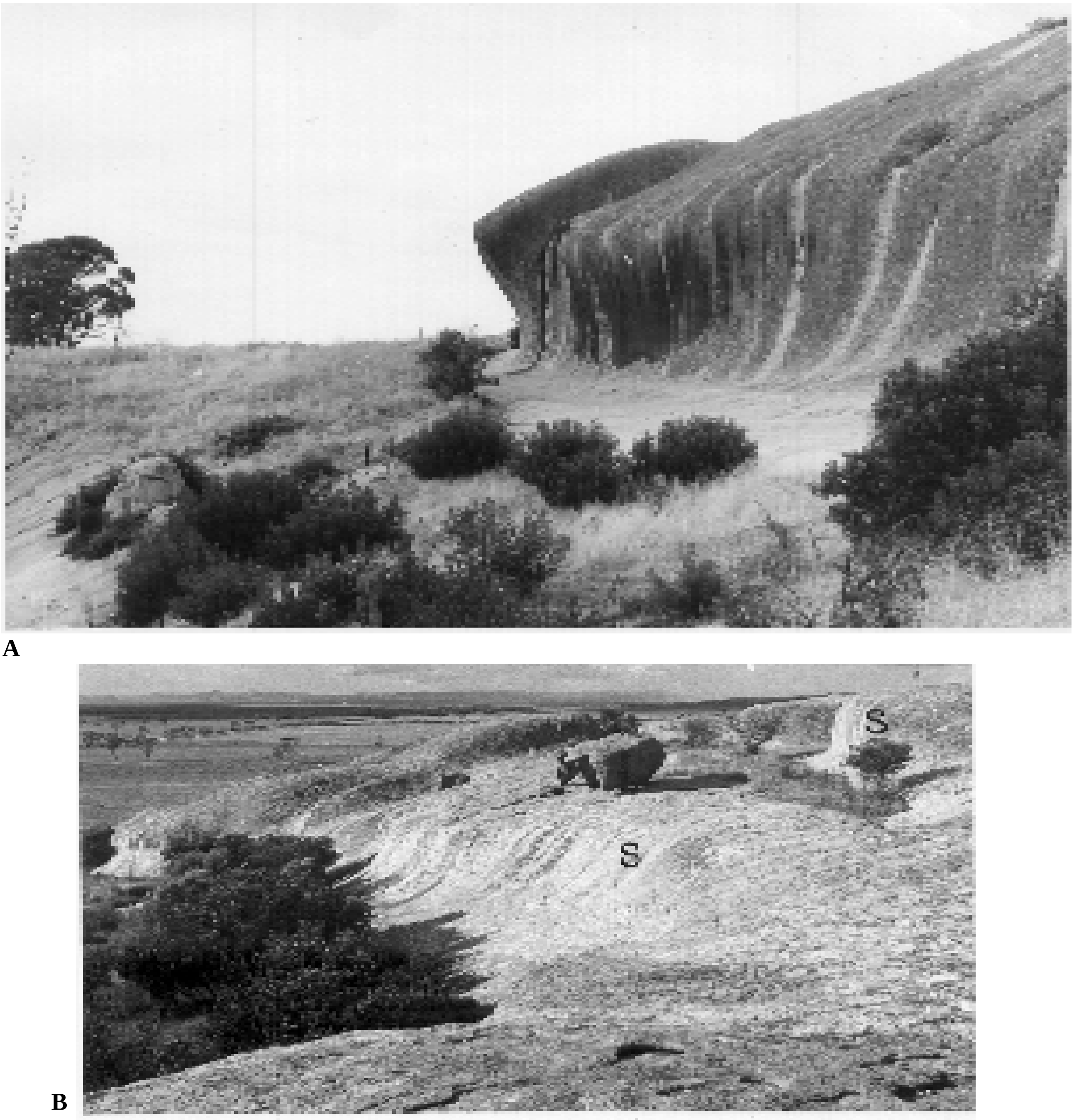

Figure 3. A: Flared slope on Ucontitchie Hill, Eyre Peninsula, South Australia. This prominent overhang is developed on a spur of massive rock, the shoulder of which is 5–6 m above the rock platform. The shoulder marks the level of the land surface prior to the stripping of the weathered material and exposure of the weathering front. **B:** Yarwondutta Rock, Eyre Peninsula, South Australia, showing flared side walls (S) and steps marking stages in exposure of the inselberg from beneath the regolith. The boulder with tafone developed underneath is 2 m high. (CR Twidale).

basis of shape, into inselbergs, bornhardts, nubbins and castle koppies.

Inselbergs are isolated steep-sided island mountains rising abruptly from the adjoining plains (Fig 1). The forms also occur in groups or massifs. The shape of the individual hills varies. Bornhardts are the basic form. They are rounded, domical forms in massive bedrock, bounded by orthogonal fractures giving rise to a circular to square or rectangular plan shape. Sheet fractures, which parallel the surface, are prominent, resulting in a domical profile. Several explanations have been proposed for bornhardts. Some, *e.g.* the Pic Parana in south-eastern Brazil, are upfaulted blocks (Lamego 1938), but most are not fault-defined. Some granite bornhardts, *e.g.* those near Hiltaba in the Gawler Ranges, South Australia, are small plutons that have been exposed as a result of the preferential erosion of the weaker host rocks into which they were injected (Hurault 1963; Campbell & Twidale 1991), though such an explanation cannot apply to those bornhardts shaped in sedimentary rocks. In some instances, the composition of the bornhardts is more resistant to weathering than the rock of the adjacent areas (Hurault 1963; Brook 1978). However, most bornhardts are composed of material of essentially the same composition as that underlying the surrounding plain.

Two explanations proposed to explain bornhardts have been widely accepted. First, bornhardts are considered by many to be the last surviving remnants following long distance scarp retreat (King 1942, 1962). If scarp retreat is a valid explanation, bornhardts ought to be restricted to major drainage divides but this is not so; backwearing of marginal scarps is restricted to a few score metres at most (Twidale & Bourne 1975a) rather than the scores of kilometres demanded by this hypothesis; and, if scarp retreat is involved, no bornhardt should survive through more than one cycle of erosion or, in general terms, for more than about 33 million years. Many are of greater antiquity and the upper parts of some on Eyre Peninsula, South Australia, may be of Mesozoic age, at least 100 million years (Twidale & Bourne 1975a). Also, the scarp retreat hypothesis is unable to explain several aspects of the field evidence (Twidale 1982).

Second, the field evidence points to bornhardts being structural forms developed on compartments of resistant rock with few open fractures whereas the surrounding rock is highly fractured and therefore subject to

A

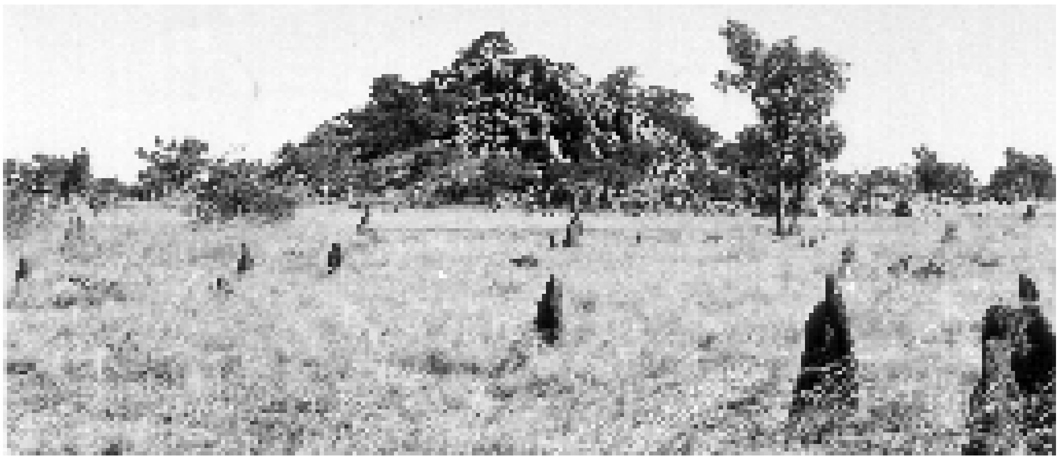

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Figure 4. A: Boulder-strewn surface of a granite nubbin, Naraku, northwest Queensland. Note the termite mounds in the foreground. **B:** Castle koppie, formed of angular joint blocks, near Harare, central Zimbabwe. (CR Twidale).

weathering (Fig 2). According to this theory, bornhardts develop in two stages; differential weathering beneath the surface followed by removal of the regolith to expose the weathering front. They are thus etch forms. The unfractured rocks are resistant to weathering and remain as high points in the landscape, whereas the well-fractured zones are easily weathered and are hence more susceptible to erosion. Once upstanding, bornhardts tend to shed water, which is concentrated in the lower zones where weathering proceeds more rapidly. In support of this hypothesis, numerous examples of convex-upward masses of unweathered granite have been exposed in excavations. Also, in many instances, for example at Ucontitchie Hill in South Australia, the fractures beneath the plain, and evidenced by dam construction, are closer than those widely-spaced fractures on the hill. In addition, the preservation of the outer layers of the bornhardt may be influenced by slight concentrations of iron oxide or silica associated with the weathering front; though lichens and mosses may also concentrate these elements after exposure (Twidale 1982).

The relative rates of weathering and erosion of the bedrock may lead to variations of slope of the exposed bornhardts. For example, flared slopes, as at Wave Rock, southwest Western Australia, and Ucontitchie Hill, Eyre Peninsula, South Australia (Fig 3A), and stepped topography (Fig 3B; Twidale 1982) are expressions of subsurface weathering and stages in exposure, as a consequence of which the bornhardts increase in relative relief as the surrounding plain is lowered.

Bornhardts are the basic major positive relief form from which nubbins and castle koppies are derived (Fig 4). The block- or boulder-strewn nubbins are due to the partial breakdown beneath the surface of sheet structures. Small, steep-sided castle koppies are explained as domes modified by pronounced marginal weathering along vertical fractures and in the subsurface. Alternatively, the presence of strongly-developed near-vertical fractures and pronounced frost action may result in the development of pointed or needle-like forms such as in the Organ Mountains in New Mexico (Seager 1981).

An etch origin similar to that for bornhardts but on a smaller scale is suggested for granite corestones and boulders, which are perhaps the most typical global granite form (Fig 4A). Spherical to ellipsoid corestones of intrinsically fresh rock are set in a matrix of weathered material. As the land surface is lowered the friable weathered material is removed leaving the boulders *in situ* (Hassenfratz 1791). This is the origin of such forms as the Devil's Marbles in central Australia (Twidale 1980). Pillars, such as Murphy Haystacks, Eyre Peninsula (Fig 5), are intermediate forms consisting of attached blocks or towers from which the surrounding regolith has been removed (Twidale & Campbell 1984).

Minor Forms

Minor forms developed on granite outcrops have been classified by Campbell & Twidale (1995b) into those due mainly to weathering and those that are tectonic in origin. Here this classification is generally maintained, although subdivisions are modified. Many of the forms have evolved in different ways *i.e.* they are convergent (Table 1).

In this brief review it is impossible to describe and explain each of these landforms. Rather a selected few will be discussed in order to illustrate the range of factors that are considered to be important in their development.

Rock basins

Rock basins, also known as gnammas, are circular, elliptical or irregular depressions in solid bedrock (Fig 6). Many are initiated at the weathering front which is demonstrated by the presence of shallow saucer-shaped depressions on recently exposed platforms. They commonly form along fractures and especially at fracture intersections. They are etch forms and after

Table I

A classification of minor granite landforms. Those forms in italics are probably convergent.

1. WEATHERING FORMS

a. Initiated at the weathering front
- Pitting
- *Flakes and spalls*
- *Rock basins*
- *Gutters and grooves*
- *Polygonal cracks*
- Flared slopes
- Scarpfoot depressions
- Deep indents
- *Caves*
- *Clefts*
- Pseudobedding
- *Blocks*
- *Boulders*

b. Due to partial exposure
- Rock levées
- Rock doughnuts
- Fonts
- Pedestal rocks
- Plinths

c. Initiated at the surface
- *Rock basins*
- *Gutters and grooves*
- *Tafoni*
- *Flakes and spalls*
- *Blocks*
- *Boulders*

d. Due to crystal strain
- *Clefts*
- *Gutters and grooves*

e. Due to gravitational pressure
- *Rock basins*
- *Tafoni*

f. Due to intrusive veins
- *Clefts*
- Walls

2. CONSTRUCTIONAL FORMS
- Speleothems
- Boxwork pattern of ridges

3. TECTONIC FORMS
- A-tents
- *Blisters*
- Triangular wedges
- Fault scarps
- Orthogonal cracks

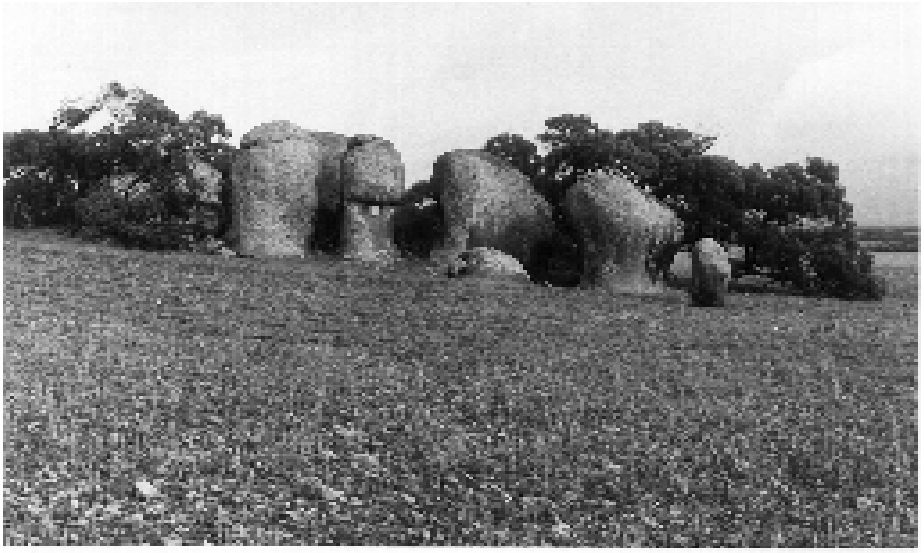


Figure 5. Pillars of granite with flared side walls, Murphy Haystacks, Eyre Peninsula, South Australia (CR Twidale).

exposure develop varied morphologies according to the structure of the granite, the slope of the exposure and the depth of erosion. Flat-floored pans are the most common form, occurring on flattish crests in laminated rock (Fig 7). The laminations allow lateral weathering to outpace vertical weathering, in some cases resulting in overhanging sides. Hemispherical pits occur also on flattish crests but are developed where the granite is homogeneous, especially at depth beneath the superficial laminated zone. Armchair-shaped hollows are modified pans and pits and are restricted to steeper slopes. Cylindrical hollows develop where deep, concentrated weathering and erosion have extended a pit through a sheet allowing throughflow and abrasion of the form (Twidale & Corbin 1963; Twidale & Bourne 1978). On the other hand, some rock basins are formed on exposed surfaces. For instance, a basin formed on the crest of a menhir, or granite monument, at St Uzek, in Brittany, must have developed after exposure when the crest was placed in a roughly horizontal position about 5000 years ago (Lageat *et al.* 1994). Similarly, basins have formed on recently deglaciated surfaces as, for instance, in northern Portugal and southern Galicia (Vidal Romani 1989).

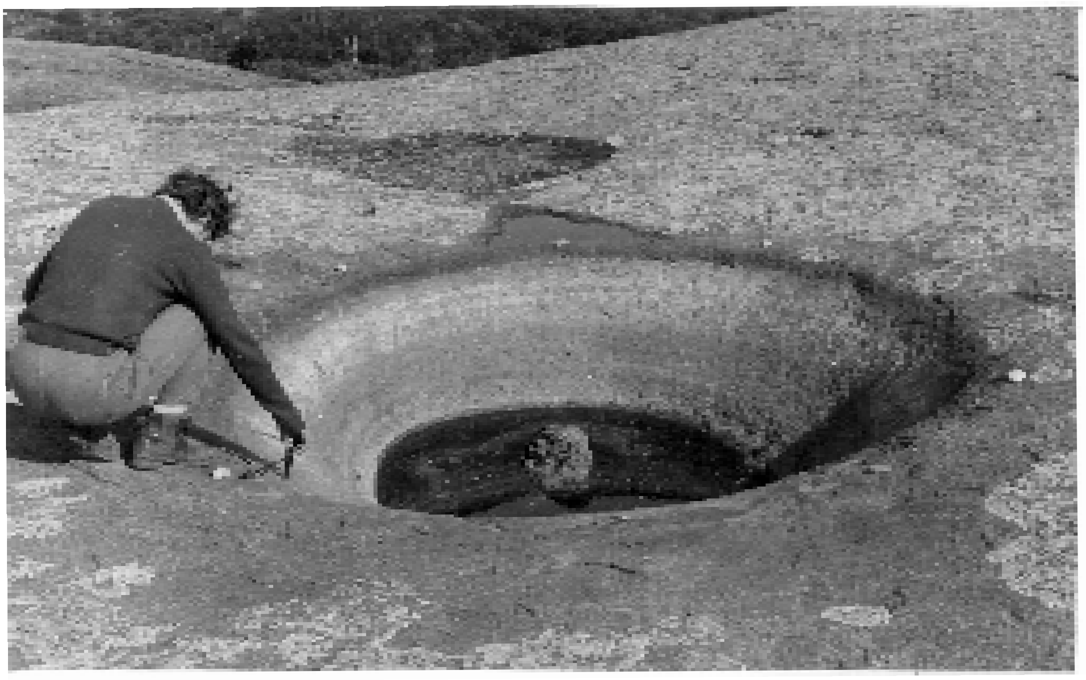
Gutters and grooves

Some gutters and grooves (horizontal Rillen and vertical flutings respectively) are initiated at the weathering front, for, like basins, they are developed on recently exposed bedrock surfaces, as for example at Dumonte Rock on Eyre Peninsula (Fig 8; Twidale & Bourne 1975b). Just as the saucer-shaped precursors of basins are shallow, so the gutters on newly exposed surfaces are shallow and narrow. Epigene gutters can be traced into the subsurface along the weathering front where they may converge and become shallower and wider, presumably as flow filtering between soil particles becomes diffuse, until they fade at a depth of several metres. Equally, however, and spectacularly at the menhir of St Uzek, grooves have formed on the exposed flanks of the erected slab (Lageat *et al.* 1994). Gutters also are found on freshly deglaciated surfaces (Vidal Romani 1989). At Cash Hill, on Eyre Peninsula, gutters have developed on much of the exposed surface but do not extend beneath the regolith nor on the broad bench from which the regolith has apparently been recently stripped, suggesting that some gutters have formed subaerially.

After exposure, incipient gutters are enlarged by running water. Abrasion is evidenced by the development of potholes. In some cases the gutters have become flask-shaped in cross section as a result of the undercutting of side walls by streams and in part a reflection of their development in the laminated surface zone (Fig 9). Some gutters have exploited and follow fractures, but that slope is the prime determinant of the path followed by streams, and also gutters, is demonstrated by the many places where the gutters leave fractures to follow the steepest local slope. There are also instances, *e.g.* on Wudinna Hill, Eyre Peninsula, where elements of the drainage have migrated to new positions suggesting that fractures and slope are not the only factors influential in their development.

Gutters, in many instances, are developed along fractures but the fractures are not apparently present along the entire length of the landform and at some sites, *e.g.* Little Wudinna Hill, on Eyre Peninsula, gutters are paralleled by clefts in which no fractures are discernible; possibly the stresses responsible for fracturing affected the adjacent zones but were insufficient to cause rupture there (*cf* Russell 1935).

Gutters which descend from the summit of Yarwondutta Rock and The Dinosaur, both on Eyre Peninsula, South Australia, on reaching the overhang of the flared slope, bifurcate into two grooves on either side of a central rib (Fig 10). In an immediate sense this is apparently due to the protection afforded by a thin veneer of desiccated algal slime, but why the present channel floors are not similarly protected has not yet been explained.



A

B

Figure 6. A: Rock basin or gnamma, a hemispherical basin or pit developed on homogeneous granite, Pildappa Rock, Eyre Peninsula, South Australia. **B:** A 1 m deep pan developed in laminated granite and with overhanging sides, Yarwondutta Rock, Eyre Peninsula, South Australia (CR Twidale).

Flared slopes

Flared slopes are found in a variety of lithological, climatic and topographic settings. They are particularly well developed in the granite of south-western and southern Australia. Flares are characteristically found around the base of hills but they are also found on higher slopes (Fig 3A,B) and in clefts. Several distinct flares may be present. Many flares are inclined rather than horizontal. On Eyre Peninsula, they are highest and best developed on the southern sides of the hills. Most significantly, flares shaped in bedrock have been exposed by excavation of the *in situ* regolith. Flared slopes evolve in two stages, the first involving subsurface weathering during which the hillslope is undermined. The tectonic

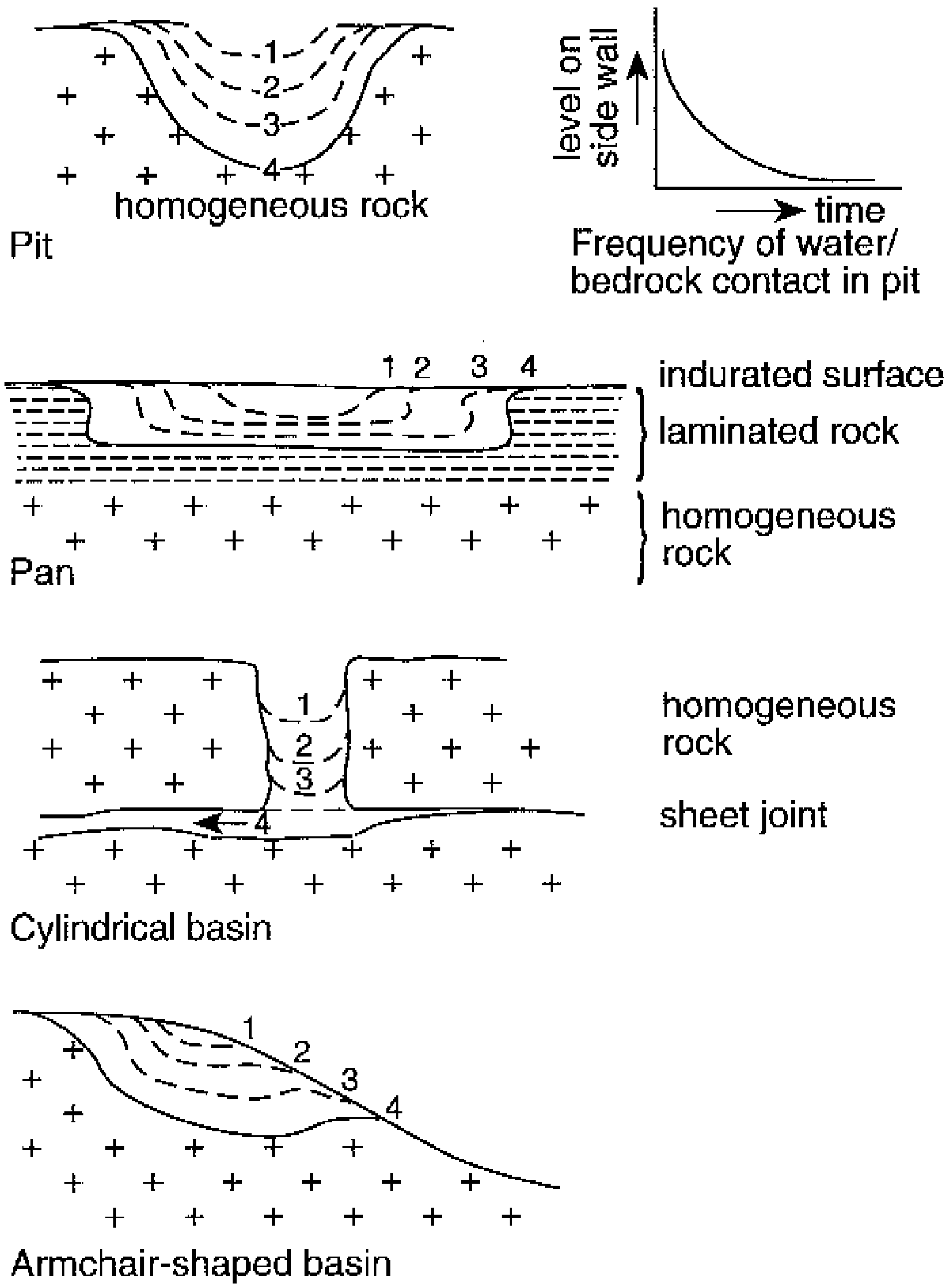


Figure 7. Schematic development of pits, pans, cylindrical gnammas and armchair shaped rock basins (After Twidale 1982).

stability of southern Australia has allowed time for intense scarp foot weathering to develop. The near surface zone dries out in summer, the dry season in southern Australia, but moisture and hence weathering persist at depth. The second stage involves the stripping of the regolith to expose the smooth, concave weathering front (Twidale & Campbell 1993).

Tafoni

Tafoni are hollows formed at the base of boulders and sheets and protected by an outer rim or visor (Fig 11). Some are associated with basal fretting or with flared slopes, suggesting that they too are initiated at the weathering front. Tafoni evolve as inverted saucers and enlarge upward into the rock mass as a result of salt crystallisation, hence the occurrence of tafoni in arid and semiarid lands, in cold and arid Antarctica and also in some coastal areas. The preservation of the outer visor is an integral part of tafone development and is possibly due to concentrations of iron or silica. Tafoni are inevitably self destructive, for their very growth helps destroy the host mass in which they are located (Twidale 1982). They may also result from gravitational forces imposed by a large boulder resting on an outcrop and causing crystal strain at the point or points of contact, eventually leading to rock basins on the outcrop and tafoni on the underside of the boulder (Vidal Romani 1989, 1990).

Figure 8. Dumonte Rock, near Wudinna, Eyre Peninsula, South Australia. The regolith has recently been cleared to make a reservoir, and the former weathering front has been exposed. The gutters continue beneath the former soil level, X–X (CR Twidale).

Figure 9. Undercut side walls of gutters on Wudinna Hill, Eyre Peninsula, South Australia (CR Twidale).

Rock levées and rock doughnuts

Some minor forms are best explained in terms of the partial exposure of the bedrock surface. Rock levées are residual rims bordering shallow channels or gutters scored in bedrock. Rock doughnuts are annular rims encircling basins (Fig 12; Blank 1951a,b; Twidale & Bourne 1977). Protection by organisms and a coating of opaline silica (Whitlow & Shakesby 1988) have been suggested to account for their preservation. They can also be explained by the contrasted behaviour of wet and dry granite (Barton 1916; Twidale 1988). Little weathering takes place in the seasonally dry regolith-free zones adjacent to the gutter or basin though weathering proceeds through all seasons beneath the regolith preserved over most of the surface.

Speleothems

Although the products of granite weathering form important components of sediments, constructional forms are rare in the granite context. Silica released by weathering is, in places, reprecipitated along fractures which are consequently sealed. After weathering of the

Figure 10. Inverted grooves on the flared basal slope of Yarwondutta Rock, Eyre Peninsula, South Australia. The gutters which drain from basins on the hill bifurcate at the top of the flared slope into two grooves. The central rib of each is covered with algal slime (CR Twidale).

Figure 11. Tafoni developed beneath and within sheets 3 m thick at Ucontitchie Hill, Eyre Peninsula, South Australia (CR Twidale).

Figure 12. Rock doughnut, a raised rim encircling a small pan on Waddikee Rock, Eyre Peninsula, South Australia (CR Twidale).

surrounding granite, the silica forms a boxwork pattern of miniature ridges. In some areas silica from water seepages in open fractures is reprecipitated as small (up to 5 mm high) speleothems, most commonly in the form of flowstone, stalagmites or stalactites (Caldcleugh 1829; Vidal Romani & Vilaplana 1984). The stems of the speleothems are composed of opal-A but, curiously, each has a tip of gypsum.

Figure 13. An arched slab of granite 15 cm thick with a crestal fracture and termed an A-tent, on Freeman Hill, western Eyre Peninsula, South Australia (CR Twidale).

A-tents

Tectonic processes are responsible for a small but notable suite of landforms in granite. A-tents, or pop-ups, (Fig 13) involve a permanent expansion, are consistently oriented in a given area and, in some instances as at Quarry Hill (Eyre Peninsula), have been induced by detonation of explosives. They have been attributed to insolation and to erosional unloading but their consistent orientation suggests they are best explained as associated with the release of compressive stress, in natural conditions probably in response to earth tremors (Twidale & Sved 1978).

Conclusion

Many of the landforms developed on granite, both major and minor, are related to the characteristics of the rock, the composition of the penetrating water, and the relative amounts of weathering and erosion. Depositional forms are rare. Tectonic factors are significant in a suite of forms due to the release of compressive stress.

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