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Caves in granitic rocks: types, terminology and origins

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Abstract

Caves or openings of various shapes and sizes are well and widely developed in granitic rocks as well as in other lithological environments. Some are caused by preferential water-related weathering, e.g. hydration, others to sapping, but haloclasty plays a crucial role in the development of tafoni. These are especially well represented in granitic exposures. This can be explained partly because the inherent strength of the crystalline rock permits hollowed blocks, boulders and sheet structures to remain standing. The hollows themselves owe their origin partly to the susceptibility of feldspar and mica to hydration and other forms of water-related alteration, and also to the capacity of haloclasty to rupture and break down the rock. On the other hand, dry granite is relatively stable and, particularly if it is cemented by salts concentrated at and near the surface by lichens and mosses, it forms the crusts or enclosing visors that are an essential part of tafoni morphology.

Key words: cave, niche, shelter, alveole, tafone, hydration, haloclasty

INTRODUCTION

To the layman a cave is ‘an underground hollow with access from the ground surface or from the sea’ (HANKS, 1986, p. 253), a statement that is almost identical to the formal or technical definition of a cave as ‘a natural underground open space, usually with an opening to the surface’ (BATES and JACKSON, 1987, p. 105; unless otherwise stated, all definitions cited in this paper are taken from this source). A cavern is a large cave or a complex of caves. In general parlance, however, any natural shelter or overhang also is referred to as a ‘cave’.

Caves are of various shapes, sizes, and origins.

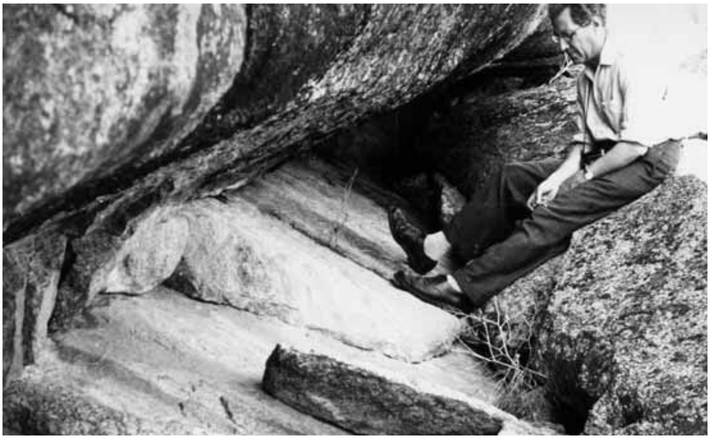
HOLLOWS ASSOCIATED WITH STEEP SLOPES: NICHE, SHELTER, SLOT, ALCOVE, NOTCH

A ‘niche’ is a shallow cave, recess or reentrant produced by weathering and erosion near the base of a rock face or bluff. A ‘shelter’ is a long and deep niche or coalescence of niches. The term ‘alcove’ used both in its geologic and general senses denotes a deep niche formed in a precipitous bluff or wall. ‘Notch’ used in a coastal context is comparable to shelter but in its broader sense the word can denote a small alcove or, and more commonly, a narrow passageway or slot. Niches and shelters are characteristic of faceted slopes, and are typically located where a permeable caprock or regolith is in contact with an impermeable lower formation. Rarely, where the bluff has regressed and simultaneously migrated upslope and been reduced in height as the debris slope extended upwards, the remains of former shelters with indurated walls and ceilings are preserved.

In granitic terrains niches and shelters are a fairly common occurrence. Some are attributable to weathering along sheet fractures to produce sheet tafoni (see below) but others are spaces of roughly triangular cross-section left vacant by the weathering and dislocation of wedges of rock at the exposed ends of sheet structures and generated by shearing along sheet fractures (TWIDALE et al., 1996; figure 1a). Others are caused by the weathering, near the present or former ground level, of obliquely intersecting cross joints or of weaker rocks (figure 1b). In addition they are especially common where the fresh granite underlies either an indurated veneer (figure 1c) or a regolithic duricrust capping such as laterite or silcrete (figure 1d). Thus on plateaux near Cue and at The Granites, near Mt Magnet, both in the central Yilgarn Craton of Western Australia, shelters are frequently formed at the base of the bluff (figures 1e and 1f). They are developed in kaolinitic mottled and pallid zones of the laterite. The location of such shelters varies according to the geometry of the faceted slope for they occur at bluff and debris slope, the extent of which varies spatially and in the long term temporally. Shelters at plain level are referred to as cliff-foot caves.

Niches and shelters are most commonly developed in sedimentary terrains as a result of seepage at the base of a bluff, at the interface of the permeable rock exposed in the rock face and the impermeable detritus accumulated in the so-called debris slope (so-called, because by contrast with talus or scree slopes, the debris from which it takes its name is most commonly discontinuous and/or only a few centimetres thick).

Though developed in Miocene Mannum Limestone, rather than granite, bluffs bounding the Murray Gorge in South Australia display every gradation between slopes consisting wholly of a bluff, to a graded slope comprising upper convexity and lower concave debris slope, distributed according to position with respect to the meandering river (TATE, 1884; TWIDALE, 2000). They provide evidence of how shelters are developed.



(a)

(b)

(c)

Figure 1. (a) Void left by the dislocation of a triangular wedge of rock, eastern flank of Ucontitchie Hill, Eyre Peninsula, South Australia. Scale provided by the late George Sved. (b) Shelter due to ground level weathering, Middle Tor, Dartmoor, south-western England. (c) Shelter high on slope developed beneath indurated crust, but in massive granite, Kokerbin Hill, southwestern Yilgarn Craton, Western Australia.

(d)

(e)

(f)

Figure 1. (d) Shelter in kaolinised zone developed beneath local silcrete (possibly a stream deposit in predominantly lateritic carapace), The Breakaway, between Hyden and Norseman, Yilgarn Craton. (e) Shelters developed high on the slope at the base of bluffs in weathered (lateritised) granite near Cue, northern Yilgarn Craton, and (f) near plain level at The Granites, Mt Magnet, central Yilgarn Craton.

The Limestone is a calcarenite that consists of some 65% $CaCO^3$ and is more susceptible to water attack than is granite. The outer shell of the limestone is cavernous and is riddled with tubes and hollows. Where debris slopes are developed the junction between bedrock and detritus is marked by numerous niches which in the past have merged to form shelters. From about 3000 years ago and up to perhaps the end of the Nineteenth Century the shelters were occasionally occupied by Indigenous/Aboriginal Australians (e.g. HALE and TINDALE, 1930; MULVANEY et al., 1964). Archaeological excavations have revealed steepened bedrock slopes the risers of which display niches comparable to those developed at the back of modern shelters. The shelters were occupied periodically and the stepped morphology of the buried bedrock slope is related to the rates of aggradation of the shelter floor. This varies according to whether the particular shelter was deserted, when natural relatively slow accumulation of debris derived from particles and fragments falling from the shelter walls and ceiling allowed time for backwall niches to develop and steps to form. When the site was occupied, however, natural accumulation was augmented by the ash from fires, shells and other debris (the midden), the rate of accretion increased and bedrock risers developed (TWIDALE, 1964). Given that these events took place in a time span of hundreds of years it is clear that the backwall niches, presently developing and evidenced on risers in the excavation, develop quite rapidly considered in geological terms.

Shelters are optimally developed in limestone terrains in the humid tropics. Here some swamp slots or cliff-foot caves extend many metres beneath the walls of karst towers and cupolas and extend also to depths of several metres. They are critical to the development of towers from domical hills (NEWSON, cited in SCRIVENOR, 1928, p. 189; PATON, 1964; JENNINGS, 1976; TWIDALE, 2006).

Thus niches are caused by weathering and flushing of groundwaters at the permeable-impermeable interface. They increase in size and coalesce to form small shelters. Thereafter the elongate hollows are enlarged by the granular disintegration of the walls and ceilings as a result of water seeping through the permeable country rock and dissolving the cement that binds the calcite and silica fragments. Similar processes are responsible at suitable sites in granitic terrains, only at a slower rate, reflecting the greater stability of mica, feldspar and quartz as compared with calcium carbonate.

ALVEOLES (OR HONEYCOMB WEATHERING)

‘Alveole’ is preferred to the term ‘honeycomb’ because whereas the latter implies geometric regularity and depth, the former have a random plan distribution and involves shallow penetration. Alveoles are small hollows developed on exposed bare and essentially fresh rock surfaces. They are typically a few centimetres diameter and a couple of centimetres deep. They are well and widely developed in arid and semi-arid coastal zones as well as inland sites (see MUSTOE, 1982, p. 108). They are best developed on sandstone, shale, and basic crystalline rocks such as dolerite, as well as on limestone and basalt. They are not as well developed in fresh granite. Some with well-defined septa have been noted in humid tropical north Queensland, in the monsoonal north of Western Australia and on The Humps near Hyden in the southwest of Western Australia (figure 2a). Others are developed in weathered granitic rocks where fractures are indurated and the enclosed corestones have fallen away. But alveoles are rare in fresh granite. Irregular and ill-defined small hollows in which fresh rock is exposed attest the activity of haloclasty but the margins are diffuse and the intervening septa that delimit and define alveoles are not developed, by contrast with adjacent sandstone, dolerite and, though more rarely, phytokarstic outcrops of calcarenite.

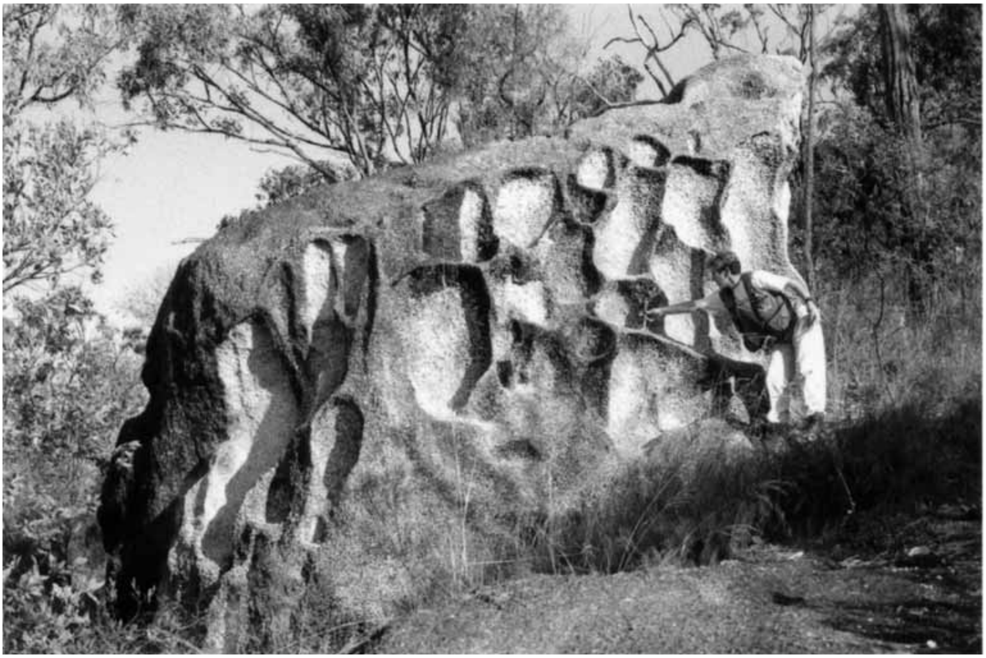


Figure 2. (a) Alveoles in granite, Emu Rock, near Mareeba, north Queensland.

Alveoles have been attributed to wind, frost, and salt weathering but there is now general agreement that they are due in part at least, and probably in large measure, to salt precipitation and associated processes (e.g. WELLMAN and WILSON, 1965; WINKLER, 1975, 1981; BRADLEY et al., 1978; YOUNG, 1987). Many coastal occurrences retain efflorescences of halite in the hollows, and the forces exerted by crystallising salts are sufficient to rupture rocks (WINKLER and SINGER, 1972; see also TWIDALE and BOURNE, 2008).

At most sites the alveoles are randomly distributed with no patterns suggestive, for instance, of the control of weathering by fractures or fissures. The rock of the intervening ribs or septa apparently is of the same composition as that in which the hollows are shaped (MUSTOE, 1982). Though the nature of the rock weathered and eroded cannot of course be ascertained, it is difficult to conceive of a petrologic or lithologic structure or texture that is developed in the varied types of rock in which tafoni occur and that would plausibly explain their distribution. Some septa are covered by green algae (MUSTOE, 1982) and it is tempting to ascribe these separating walls to the protective action of the biota. But is the algal coating cause or effect?

Two scenarios can be envisaged. First, the algae covered the entire rock surface but the veneer was breached where salt settled and started to crystallise, causing disintegration of the rock and destruction of the algal coat in those areas. The algae persist on the dry non-saline areas between haloclastic hollows. Second, the rock surface was randomly broken where salt began to crystallise and the algae colonised the relatively stable spaces between. The septa were reduced in area as the hollows were enlarged, so that some rock faces eventually became devoid both of alveoles and algae

Evidence from the development of alveoles on natural rocks incorporated in human constructions of known date demonstrates that they form in a matter of decades (e.g. BARTRUM, 1936; GRISEZ, 1960; GILL et al., 1981; MUSTOE, 1982). Some workers regard alveoles as small or incipient tafoni (see e.g. the title of the GILL et al., 1981 reference, and the entry in BATES and JACKSON, 1987, p. 671), and in some instances this appears to be the case; though not in granite (figure 2b). But at Cape Cassini on the north coast of Kangaroo Island, for instance, alveoles are well-developed on benches (exposed bedding planes) that comprise fracture-controlled blocks of flat-lying, fine-grained Proterozoic sandstone. All stages of surface lowering are developed in a sequence beginning with isolated alveoles set into the original surface, to surfaces with a few alveoles remaining, to fresh rock surfaces bounded by iron-indurated rims but devoid of alveoles (figure 2c). In sandstone, at least, the effect of the development of numerous alveoles has been to eliminate the layer of rock in which they are formed. Such alveoles have not coalesced to form tafoni. Evidently the protection afforded by algae colonising the septa is not enduring. The neat stripping of sandstone layers by alveolar weathering may be facilitated by bedding. Certainly no such systematic lowering has been noted on granitic or doleritic surfaces affected by the mechanism.

Figure 2. (b) Alveoles in argillite, Beda Valley, southern Arcoona Plateau, South Australia. Note the hollows that may be due to the coalescence of alveoles.

Figure 2. (c) Alveoles in sandstone, Cape Cassini, north coast of Kangaroo Island, South Australia. Note the two levels, the higher riddled with alveoles, the slightly lower almost clean presumably as a result of the coalescence of hollows but with a second generation beginning to develop.

That some rock basins are initiated on pods of minerals susceptible to weathering at the site is suggested by field evidence (e.g. BOURNE and TWIDALE, 2002). Similar exploitation of weak minerals has been adduced in explanation of 'pitting' (TWIDALE and BOURNE, 1976) and could also account for the initiation of alveoles (and also for the initiation of tafoni, for hollows of irregular shape and varied dimensions and referred to as pecking – TWIDALE and BOURNE, 2001, see below – occur on flared slopes). Even so the distribution of some is puzzling both at the local and regional scales. For instance, at Hallett Cove, on the coast south of Adelaide, South Australia, thin beds of fine-grained sandstone interbedded and folded with phyllitic mudstone display alveoles, though the intervening argillitic rocks do not. Regionally, the absence of well-defined alveoles in granite on arid and semiarid coasts implies that granite may be too tough to allow rapid disintegration under attack by either haloclasty or hydration, or that algae cannot readily gain a foothold or that colonisation is outpaced by granite disintegration. Also, the occurrence of well-defined alveoles in granite in seasonally humid northern Australia argues against a haloclastic origin, for salts are flushed through the system in such environments. This suggests either that the alveoles are inherited from a former drier climatic phase, or that hydration has been the dominant process in their formation. But if inherited, and given the known rapidity of chemical weathering in the tropics, how have (admittedly few) granitic alveoles survived? Also if hydration is so effective, why are such forms not more common in the monsoonal north of Australia and in similar environments elsewhere?

TAFONI

The most common cavernous forms developed in granitic rocks are 'tafoni' (singular 'tafone'). Tafone is an Italian word meaning variously an aperture or cavity or (in Corsica) window. Tafoni are well developed in dry regions and on coasts in aridity or semi-aridity. They have been compared to alveoles and 'up to 10 cm deep' but this is misleading. Of course, tafoni are initially small and at some early stage of development (pecking?) must be less than the stipulated limit, but recognisable tafoni are characteristically much larger. Many are large enough to provide shelter for a family or a class of students. They are best defined as hollows developed on the undersides of blocks, boulders or sheet structures, most frequently in granitic host rocks (figures 3a and 3b). They extend upwards into the rock mass and in most instances are more-or-less enclosed by a tough crust or visor of the country rock (granite). Some blocks and boulders are hollowed to such an extent that only a relatively thin shell remains. That large and deep tafoni survive attests not only to the inherent strength of the fresh crystalline rock (e.g. DALE, 1923, p. 11; KESSLER et al., 1940) but also to that of the case hardened zones (figure 3a). The physical weakness of argillaceous rocks explains why, though they are susceptible to weathering, tafoni infrequently develop in such lithological environments.


(a)


(b)

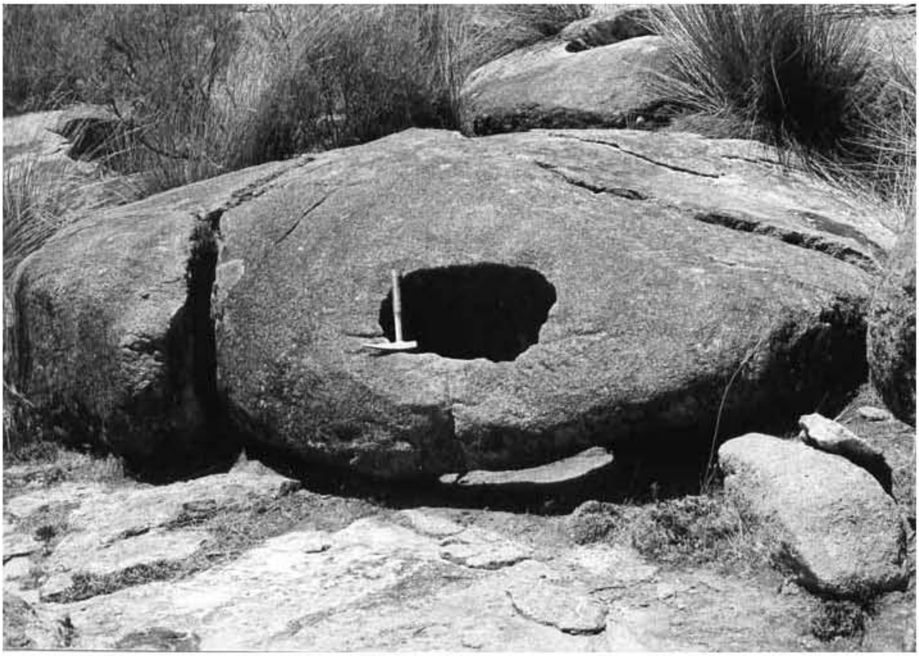
Figure 3. (a) Tafoni developed in boulders on Yarwondutta Rock, near Minnipa, Eyre Peninsula. Note considerable mass of granite that remains, in each instance more than half the original mass. The larger boulder amounts to over 20 m3, the smaller some 8 m3. Each block is supported by legs of which the total area in contact with the underlying platform is approximately 110 cm2. Some of the supporting rock is laminated but all is indurated on the outer face. (b) Tafoni in massive sheet structure, Pearson Islands, eastern Great Australian Bight.

In some tafoni the walls display mamillation (figure 3c) and also books of flakes (figure 3d) which become detached at the touch, and flakes and fragments of flakes are scattered on the floor. Clearly these tafoni are still active and are extending. Eventually the visor is breached from the inside at some sites to produce the apertures that have given the forms their generic name (figure 3e). In other examples, however, and in some areas at adjacent sites, the walls are solid with at most a few loose crystals or fragments. What determines the activity or stability of the interior surfaces is not known. Whether the hollows are associated with initial centres of seepage and salt precipitation is not known, but books of laminae are well developed even, or perhaps most obviously, on the intervening rises of projections. Tafoni are favoured dens for kangaroos and wallabies and their droppings (excrement) encourage plant growth and the development of siliceous speleothems – at some tafoni sites as well as shelters and crevices there are veritable forests of tiny centimetre-high speleothems (VIDAL ROMANI et al., 2003).


(c)

(d)


Figure 3. (c) Mamillated ceiling of tafone, Remarkable Rocks, Kangaroo Island. (d) Books of flakes or laminated granite in ceiling of sheet tafone on Ucontitchie Hill, northwestern Eyre Peninsula.



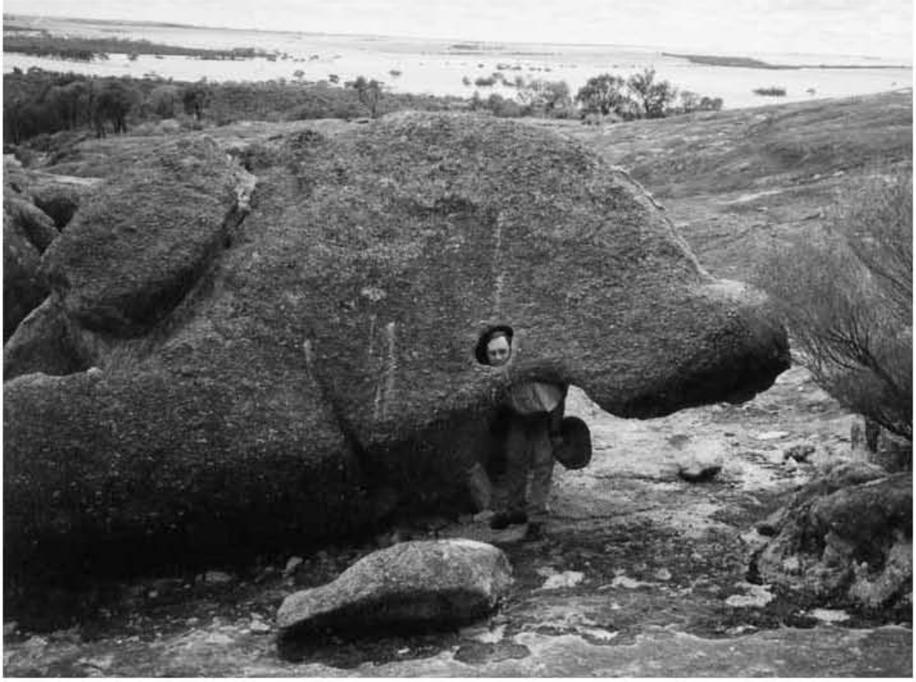


Figure 3. (e) Granite boulder with breached visor, on The Humps, near Hyden.

The hollows develop from below, typically being initiated on the underside of the boulder, block or sheeting slab or parting. Such sites are moist or moister than adjacent exposed surfaces because they are not as exposed to the sun and wind. Moreover, organic and biotic detritus that retains moisture accumulates in them. Frequently, weathering of the upper surface of the basal joint or surface is matched by weathering of the underside or surface on which rests the boulder or block (figure 3f) so that some incipient tafoni are twinned with a shallow saucer-shaped depression that will become a basin or gnamma of one type or another (TWIDALE and CORBIN, 1963). It is significant that on the platform beneath the larger tafoni shown in figure 3a is preserved a remnant of pitted granite, indicative of the former presence of soil and moisture.

Figure 3. (f) Base of boulder showing basal hollow and matching basin in platform on which the boulder stands.

The growth of tafoni has been attributed to wind erosion, frost action, microclimatic conditions, exfoliation, and haloclasty, the latter category embracing crystal growth, hydration expansion, and osmotic pressure (EVANS, 1969; WINKLER, 1975; GOUDIE and VILES, 1997). Blackwelder (1929), for instance, suggested that hydration of feldspars to clays induced 'exfoliation', that is, scaling, flaking or lamination (cf. HUTTON et al., 1977). The range of temperature and humidity is less inside tafoni than outside (DRAGOVICH, 1967). Most tafoni are so enclosed by visors that wind cannot effectively penetrate into the interior space, and so on: most suggested explanations fail to satisfy the field evidence in some degree or another.

However, there is a measure of agreement that salt weathering by crystal growth (see THOMSON, 1863) is largely responsible not only for many alveoles but also tafoni, and as with alveoles there is much supporting evidence. Both forms are commonly developed in arid and coastal environments in which salt occurs at the land surface in crystal form, suggesting that the same process may have a role in the formation of the larger as well as the smaller hollows (e.g. WINKLER, 1975; BRADLEY et al., 1978). Efflorescences of halite have been observed on the walls and ceilings of some relatively open tafoni on northwestern Eyre Peninsula. Halite is hygroscopic and water accelerates the rates of various forms of chemical weathering (e.g. McINNIS and WHITING, 1979; WINKLER, 1981). That salt crystallisation and hydration exert a force sufficient to overcome the tensile strength and rupture fresh rocks including granite has been demonstrated experimentally (WINKLER and SINGER, 1972; WINKLER, 1975; KNACKE and ERDBERG, 1975). In addition, however, the effects of hydration, and especially the production of hydrophilic clays from the reaction of feldspars and micas with water (see e.g. BLACKWELDER, 1929; LARSEN, 1946; HUTTON et al., 1977), cannot be overlooked.

Even so, haloclasty and associated processes (see GOUDIE and VILES, 1997, pp. 123 et seq.) present problems in the context of tafoni development. One is to ascertain the origin of the salt and explain how it came to be in the tafoni walls developed on outcrops distant from the sea or major salinas. Another is to explain why the visor has resisted weathering and erosion while tafoni are hollowed out in the fresh rock beneath.

As to the first problem, weathering of the minerals that form granite produces no halite or gypsum. Gneiss and schist may contain minerals with chlorite (e.g. scapolite) but there is no correlation between chlorine-bearing minerals and the distribution of tafoni.

Salts are carried on the wind and are washed from the atmosphere by rain (HUTTON, 1976). Thus, the availability of salts in coastal zones and in arid lands is not in question. The difficulty is to explain how the salts come to be at the base of rock masses, and later in walls and ceilings of tafoni. Given time, saline solutions may percolate through considerable thicknesses of rock, even rocks of low permeability such as granite, for all include small fissures. In addition, the release of lithostatic pressure consequent on the erosional unloading implied by the surface exposure of granite may have allowed separation at crystal boundaries and along cleavages (BAIN, 1931), so that in time salts deposited in rainwater or, on the coast, in spray, may have infiltrated through the rock mass to the lower surface where the salts are precipitated, and where the rock is shattered. On the other hand, weathering may be facilitated also by crystal strain consequent on stresses induced by tectonism or by gravity – by blocks of fresh rock resting on one another – which may compensate and more than compensate for any relaxation associated with erosional unloading (RUSSELL, 1935; TURNER and VERHOOGEN, 1960, p. 476; VIDAL ROMANI, 1989).

The formation of the visor has been explained in terms of a slight concentration of such minerals as iron, manganese, and silica by lichens, mosses and algae (e.g. FRY, 1926; SCOTT, 1967; though the expansion and contraction of hyphae on taking in and shedding water has been cited as a possible cause of rock disintegration: GOUDIE and VILES, 1997, p. 157). Also, exposure and comparative dryness may be a relevant factor; for water with salts in solution would tend to gravitate to the base of the rock, and any lateral seepage could result not in evaporation, but in the salts being taken up by the hyphae and roots of plants. Alternatively, the concentration of ferruginous salts at the water table appears to be responsible for some encrustations. On the bornhardt known as The Humps, near Hyden, in the southwest of Western Australia, for example, some boulders display two encrustations, one external and the second located some 20 cm deeper in the rock mass but now exposed by weathering and erosion (figure 4a).

Figure 4. (a) Weathered boulder with remnants of two case-hardened zones, The Humps, near Hyden.

Some hollows have formed but their development was either unaccompanied by visor development or the former outer crust has been wholly or largely eliminated (figure 4b). Such features are not tafoni for they lack the essential enclosure. They are flared slopes developed on boulders and are of limited extent, but they are of two-stage origin and were initiated in the shallow subsurface (TWIDALE, 1962, TWIDALE and BOURNE, 1998).

Some tafoni in the form of cliff-foot caves appear to be extensions of flared slopes and be associated with water concentrations, in this instance at the scarp foot. The waters are, however, commonly alkaline. Such a merging of concavity and cave can be seen at Kokerbin Hill, on the Yilgarn Craton of the southwest of Western Australia. Similar occurrences are seen on the southern flank of the arkosic Uluru, where, near Mutitjulu (Maggie Springs) a flare merges laterally with a cliff-foot cave. Flared slopes demonstrably are etch forms and at many sites minor flares and horizontal slots occur just above soil, slope or plain level, suggesting that they were initiated in the subsurface and have been exposed as a result of recent anthropogenically-induced erosion. Thus, on the southern flank of Uluru breaks of slope at about 35 m above present plain level coincide with deep caverns lacking a significant visor and so shaped that the tafoni warrant being described as ‘gaping-mouth’ caves. They have been interpreted as marking the position of a former fluctuating water table associated with a plain that was essentially stable and stood 35-60 m higher than the present plain (TWIDALE, 1978).

But no tafoni as such have been located in shallow exposures. Small zones of intense weathering and discrete voids have been observed (TWIDALE and BOURNE, 1975) but whether they were voids located in the subsurface or whether they were patches of intense weathering that have fallen away after exposure, is not clear. No hollows with an enclosing carapace or visor have been reported in granitic terrains. Tafoni are evidently a subaerial development.

Overall it can be argued that hydration may account for subsurface development of flared forms, but that haloclasty assumes greater significance after exposure, when the overhanging surfaces and ceilings intercept downward percolating saline solutions and where evaporation causes salt precipitation. But it is the inherent strength of crystalline granite that allows hollows developed in the rock mass to be maintained.

Figure 4. (b) Flared boulder, the concavity lacking a visor, Murphy Haystacks, west coast of Eyre Peninsula.

SUBTERRANEAN VOIDS

Granite caves appear to be of several types. Well-jointed granite with open fractures spaced up to a few metres apart can be differentiated weathered by circulating meteoric and groundwaters penetrating along partings. The rock with which it comes into contact is weathered, the corners and edges of blocks more rapidly than plane faces, so that angular blocks are converted to rounded boulders (MacCULLOCH, 1814; de la BECHE, 1898; LOGAN, 1851). The weathered granite or grus can be washed away by subsurface flushing and underground streams, thus creating connected openings or caves. The Labertouche Cave in the South Gippsland Uplands east of Melbourne, Victoria, is such a ‘fracture-controlled cavern’ some 200 m long and essentially straight, though irregular in detail (OLLIER, 1965). Caves of similar origin are reported from the Banana Range in central Queensland (SHANNON, 1975), Colorado (ARNOLD, 1980) where the caves are up to 15 m high though subject to boulder falls and prone to flooding; and from Guyana whence SHAW (1980) has described the Makatau cave system. The 'O Folon' cave near Vigo, Galicia, appears to be of similar origin (VAQUIERO RODRIGUEZ et al., 2006). FEÍNIGER (1969) reported various karstic features including caves from acid plutonic rocks (quartz diorite) in Columbia and there is anecdotal evidence of extensive linked 'between boulder' caves on the Black Mountain, a large granite nubbin near Cooktown, north Queensland.

Second, openings resulting from the preferential weathering of weaker members of a rock sequence are reported from some areas: sideritic veins in some of the High Tatra caves of southern Poland, and feldspar-rich zones in the Karkonosze Mountains (WOJCIK, 1961a, 1961b).

Third, in some areas a ferruginous crust developed on granite boulders has been breached and the underlying kaolinised rock has been preferentially weathered and fallen away (figure 5a). At the eastern end of Hyden Rock, (Western Australia) shallow voids have formed as a result of subsurface flushing (cf. RUXTON, 1958) of weathered granite to a depth of a metre or so beneath a thin but durable case-hardened skin of slightly weathered granite that is cemented by silica and colonised by algae (TWIDALE and BOURNE, 2001). Various stages of development can be observed from a clean opening to a void, to an irregular surface cut in weathered granite with a few remnants of the former crust preserved. Both the intense and widespread weathering of the granite, and the algal coating that appears to be responsible for the formation of the crust, and hence for the subterranean voids, may be associated with the proximity of the eastern sector of the inselberg to the former Camm River, one of many palaeodrainage channels preserved in the southern Yilgarn Craton and adjacent areas (VAN de GRAAFF et al., 1977). The piedmont plain adjacent to the eastern edge of Hyden Rock sounds hollow when stamped upon, suggesting that cavernous developments extend beneath the present plains surface.

Figure 5. (a) Weathered granite with remnants of cemented crust protected by algae enclosing substantial voids, eastern sector of Hyden Rock, Western Australia.

What may be an early stage in such subsurface weathering combined with the formation of a thin crust can be seen at Graham Rock, a few kilometres east of Hyden Rock and like it, immediately adjacent to the Camm drainage. Patches of the granite slopes display sinuous narrow apertures and shallow planar hollows beneath the crust (figure 5b).

Figure 5. (b) Shallow and narrow breaches and subsurface voids ('worm tubes') on Graham Rock, near Hyden.

Fourth, voids and openings of various kinds occur where blocks and slabs have been displaced either under gravity or as a result of earth tremors (figure 5c) or as a consequence result of preferential weathering, for instance along fractures though such voids are rarely covered. The formation of 'blisters' and 'A-tents', or 'pop-ups' (figure 5d), as a result of compressive stress has enclosed triangular spaces (TWIDALE and SVED, 1978; WALLACH et al., 1993). Whether they can be considered subterranean is dubious, though they are located at depths as shallow as the voids discussed above, and many are separated from space by slabs thicker than the crusts enclosing the voids featured in figures 5b and 5c. Many A-tents have formed instantaneously as a result of earthquakes (TWIDALE and BOURNE, 2000) but others evidently have formed gradually and are still in the process of conversion from blisters, continued compression producing the crestal crack that distinguishes the two forms (TWIDALE and BOURNE, 2003).

Fifth, caves have been formed as a result of weathering along sheet fractures and particularly the preferential weathering of triangular slabs like those exposed on the flanks of some inselbergs (TWIDALE and VIDAL ROMANI, 2005, p. 40) but located within the hills. The slabs are associated with sheet fractures that are planes of shear activated by lateral compression and slippage along sheet fractures of different radii (TWIDALE et al., 1996). The well-known cave within Enchanted Rock (figure 5e), in the Llano of central Texas, USA, is of this type (KASTNING, 1976).


(d)

(e)

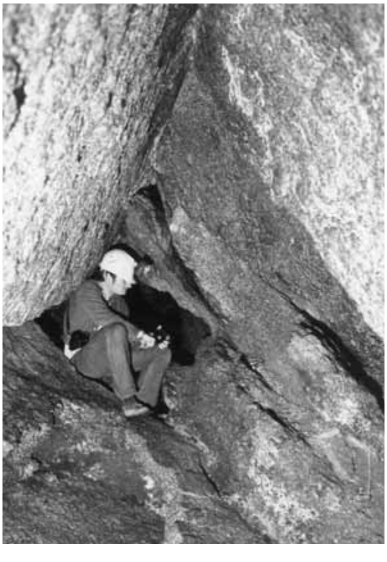


Figure 5. (c) Voids possibly caused by disturbance of blocks by earth tremor at Devils Marbles, Northern Territory, Australia. (d) A-tent, Kokerbin Hill, south-western Yilgarn Craton. (e) Part of cave within Enchanted Rock, Texas, USA (E Kastning).

DISCUSSION AND CONCLUSIONS

Caves of several shapes, sizes, and origins are found developed in granitic rocks. Most if not all have their congeners in other rock types. Though understood in general terms most still pose problems.

Tafoni are particularly well developed in granite blocks, boulders and sheet structures. This can be attributed partly to the contrasted susceptibility of granite in dry and wet microenvironments; partly to the ease with which dry granite can be further reinforced by biotic impregnation by iron oxides and silica; partly to the susceptibility of granite to hydration and haloclasty, resulting in flaking and the gradual growth of hollows, including their upward extension; and partly to the inherent strength of fresh granite which allows hollows to form without inducing the collapse of the entire rock mass.

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