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Structural or climatic control in granite landforms? The development of sheet structure, foliation, boudinage, and related features

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Abstract

Granite landforms have been interpreted in terms of climatic geomorphology, or morphogenetic regions, but the field evidence overwhelmingly points to structural control. Some features are developed after the exposure of the granitic bodies, for joggling of the brittle crust continues and external agencies also achieve change but the origin of some forms can be traced to the emplacement of the granite bodies, and to strains and stresses developed in magmatic bodies during their intrusion. Various mineral, magmatic and magnetic fabrics are produced. The consolidation of the magma begins at the contact between the emplaced body and the host rock. At this stage, the marginal zone is already crystalline and brittle. Arguably, shearing consequent on continued emplacement causes deformation and the development of planar fractures, some aligned roughly parallel with the cooling and crystallisation surface developed in the uppermost zone of the intrusive body, others imposed by lateral stresses.

Differential movements between the sheets produced by shear causes the development of stretching and/or shortening movements. Extension produces a structural fabric that is later exploited by weathering and thus may contribute to the generation of such forms as pseudobedding, foliation, polygonal cracking, boudinage, and where deformation is pronounced, the formation of spheroidal cores within cubic or quadrangular blocks. The second type of fabric, due to shortening, generates folding or buckling of the previously defined planar structures and the formation of sheet structures. Both deformational signals, though of opposite sign, are a continuum in a close spatial relationship. This indicates a simultaneous or at least sequential development of the two types of planar fabrics at the end of the emplacement stage. Once the rock is at the land surface, it is affected by external processes, and the structural fabric determines the planes of ready water access in the rocky massif thus determining the progress of weathering and significantly influencing the evolution of granitic landscapes.

Key words: climatic effects, structural control, sheet fracture, boudinage, polygonal cracking, imbrication.

BACKGROUND

Granite is a term that embraces plutonic holocrystalline rocks containing significant amounts of quartz and potash feldspar but which display variations in mineralogy and hence chemistry, texture, fabric, and fracture density and pattern. Granitic bodies vary also in size and shape and in mode of emplacement. Some authors (see WILHELMY, 1958; MIGON, 2006) consider that granite landscapes develop distinct characteristics according to climate and process, and that anomalous features reflect climatic change and landform inheritance.

Alternatively, the morphological similarity of granitic landscapes can be explained in terms of structure, with the course and rate of weathering and erosion determined by the structural characteristics of the rock developed during the emplacement of the magma (VIDAL ROMANÍ, 2008) or as a result of later and continued brittle deformation, the latter including neotectonic features (e.g. TWIDALE and BOURNE, 2000, 2003; TWIDALE and VIDAL ROMANI, 2005).

First, then, what is the status of morphogenetic theory as applied generally and outlined by such workers as PELTIER (1950), TRICART (1957), TRICART and CAILLEUX (1958), and BÜDEL (1977), and, in the context of granitic terrains, by WILHELMY (1958); and second, how do various structural factors affect granitic landform development?

CLIMATIC AND GRANITIC TERRAINS

Several morphological varieties of granitic hill have been recognised in the field and recorded in the literature. Leaving aside the unusual pillars or *pitons* like those associated with the exploitation of prominent steeply-dipping and open fractures in the Organ Mountains of New Mexico (e.g. SEAGER, 1981), the Cathedral Rocks of the Yosemite region in the Sierra Nevada of California (HUBER, 1987), The Needles of South Dakota (TWIDALE, 1971), and similar acicular forms reported from the Sierra Guadarrama of central Spain, granite hills fall into three categories (figure 1). The basic form is the domical bornhardt (BORNHARDT, 1900; WILLIS, 1934), with its geometrical variations and regional names. It has been argued (TWIDALE, 1981) that some born-

Fig. 1. Cathedral Rocks, a pair of spires, or pitons, in monzonite, Yosemite National Park, California (C. Wahrhaftig).

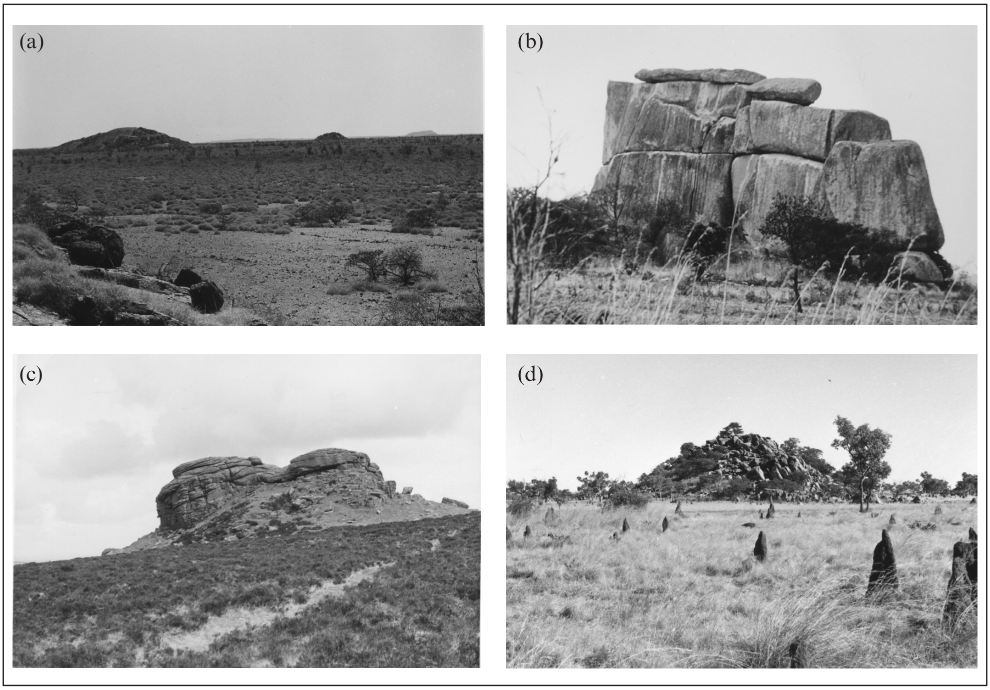

Fig. 2. (a) Bornhardt, Pilbara Craton, Western Australia. (b) Castle koppie, Zimbabwe. (c) Kestor, Dartmoor, southwestern England. (d) Nubbin, northwest Queensland.

hardts, many, perhaps most, of which are initiated by differential fracture-controlled weathering in the subsurface at the weathering front (FALCONER, 1911; MABBUTT, 1961) while still located underground, are attacked by moisture-related processes in the shallow subsurface to produce either castle koppies (the tors of Britain and parts of Europe) or nubbins (figure 2).

Bornhardts have been reported from the midlatitude deserts and the tropical rain forests, from Mediterranean lands and the cold higher latitudes. They are structural azonal forms. Their plan shape is determined by orthogonal fracture systems. They are characteristically subdivided by arcuate fractures into massive slabs known a sheet structures (DALE, 1923). Nubbins are formed as a result of the disintegration into blocks and boulders, partly in the subsurface, partly after exposure, of the outer one or two shells of these sheet structures. Evidence from quarry exposures suggests that this process is initiated in the subsurface, though it continues after exposure and most bornhardts display some surficial blocks and boulders.

Imagine a domical mass of granite the crest of which is exposed as a low large-radius dome or rock platform. It sheds water to the immediately adjacent plains underlain by regolith. The near-surface (the top 4–10 m?) regolith is rich in biota and chemicals so that the granite of the dome is altered. In cool climates the water shed from the platform is subject to freeze–thaw. Again, the weathering front migrates laterally as well as vertically,

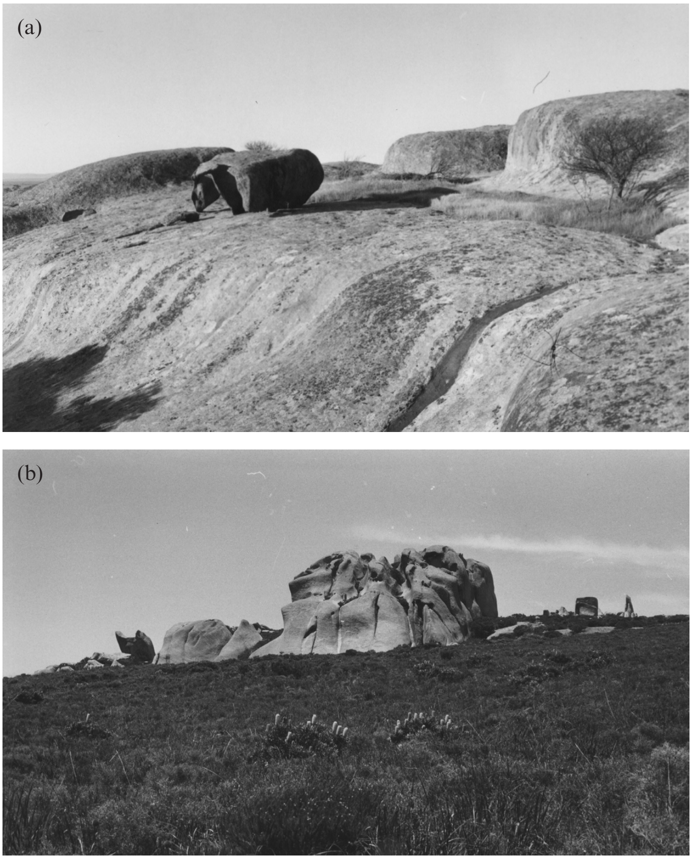

Fig. 3. (a) Stepped northwestern slope of Yarwondutta Rock, northwestern Eyre Peninsula, South Australia. (b) Multiple flared zones on the flanks of Castle Rock, a koppie located east of Albany southwestern Western Australia.

and the areal extent of the residual is reduced and koppies are markedly smaller than the bornhardts from which they are derived. For this reason the French name for such koppies is *inselberg de poche*. The erstwhile sloping flank of the dome is converted into a steep, even vertical, wall. Like several bornhardts, some are flared as a result of multiple episodes of weathering in the shallow subsurface (figure 3). With further lowering of baselevel and landscape revival, the regolith is stripped and the bedrock mass is revealed as a steep-sided castellated hill, 'about as big as a house' (LINTON, 1953, p. 354): a castle koppie in southern Africa where the regolith has been stripped by gullies and streams, or a tor in southwestern England, exposed by nival, or periglacial, processes. This is an example of convergent development with a similar form emerging as a result of the activity of different processes.

Nubbins or knolls (USA) are block- and boulder-strewn hills, but their derivation from bornhardts is suggested by the massive domes that are in some instances visible beneath the blocky veneer. Nubbins are typical of monsoon Australia (north and northwest Queensland, Darwin area, the Pilbara of

Western Australia, and of monsoon lands elsewhere e.g. southern China and India. It can be argued that in the humid tropics the regolith charged with water, chemicals and biota is capable of attacking and breaking down even massive granite (e.g. CAMPBELL and TWIDALE, 1995). Commonly, two or three shells are disintegrated, but in north Queensland, for example, some quite large nubbins such as Black Mountain, near Cooktown, appear to consist entirely of blocks and boulders.

Nubbins are found outside the humid tropics in the Sahara, the Mojave Desert of the southwestern USA, and central Australia. They are found also in semi-arid Hausaland, or northern Nigeria (FALCONER, 1911; BAIN, 1923). Some can be explained as inherited from former periods of humid climate of which there is evidence in the Sahara, and in the Mojave (e.g. OBERLANDER, 1972). But granite nubbins are found also outside the humid tropics, in local wet sites. For instance, they occur in arid central Australia just north of Alice Springs, and within the Macdonnell Ranges, and also at the Devils Marbles (figure 4), located some 50 km south of Tennant Creek, a granite exposure intrusive into a plunging anticline and flanked by the quartzite ridges of the Davenport Range (TWIDALE, 1980). The ridges are bevelled and a ferricrete crust is preserved on one granite rise. The nubbins were formed as result of differential weathering beneath a planation surface of possible Cretaceous age (TWIDALE, 2007). A humid subtropical climate prevailed during the Middle Tertiary (WOODBURNE, 1967) but in any event both the Devils Marbles and the

Fig. 4. Devils Marbles, Northern Territory, a degraded nubbin with the inner domical core exposed, but with a few remnant boulders intact.

Fig. 5. Corestones in grus, Snowy Mountains, southeastern Australia.

Macdonnell Ranges occurrences are local wet sites produced by the ridge and valley topography and the concentration of runoff and groundwaters beneath valley floors. Such sites sustain the suggestion that nubbins are developed in humid environments and are modified bornhardts. Nubbins are the only major granite form that is essentially restricted to a specific climatic zone.

Of minor forms commonly found in granitic landscapes, tafoni are found in deserts, both hot and cold, and on some coasts, that is, wherever haloclasty prevails. But most minor granite forms such as rock basins, gutters or *Rillen*, flared slopes, and pitting are found in various and contrasted climatic environments – more common and better developed in some than in others, and of course rates of development vary, but they are nevertheless widely distributed. They are also found developed in other lithologies.

On the other hand, the structural characteristics of granite find universal expression.

DEVELOPMENT OF THE STRUCTURAL FABRIC IN GRANITE BODIES

Granitic magma intrudes the crust by exploiting weaknesses in the lithosphere or by stoping into the host rock to produce stocks and batholiths, laccoliths, lapoliths and phacoliths, dikes and diapirs. Here the consequences of intrusion are considered.

The initial movement of the magma is responsible for the development of various mineral, magmatic and magnetic fabrics (TRUBACˇ et al., 2009). However, cooling and crystallisation progressively change the physical state of the magma from its initial plastic state to a more and more rigid condition (ARZI, 1978; PETFORD, 2003). The development of the structural fabric is essentially due to synintrusive deformation in the fragile field. Some authors favour the formation of the magma by fusion of the protolite in situ by shear heating without considering a later mobilization of the melting (CHEN and GRAPES, 2007). Possibly because of lithostatic loading at depth, they do not refer to any discontinuities formed at this stage, but they imply the generation of a structural fabric by shear deformation. Thus, it is likely that when crystallisation is complete, traces of this deformation episode remain and as the land surface is eroded lithostatic pressure decreases and the zones of shear become fractures.

Most authors referring to CLOOS's ideas (1923, 1931) simplify the problem and identify systems of orthogonal fractures and sets of sheet partings associated with crustal stress (TWIDALE, 1982; THOMAS, 1994; VIDAL ROMANI and TWIDALE, 1998; MIGON, 2006; TWIDALE and VIDAL ROMANI, 2005). Orthogonal systems are exploited by weathering in the shallow subsurface to produce corestone boulders (figure 5; HASSENFRATZ, 1791; MacCULLOCH, 1814; BECHE, 1839, p. 450; SCRIVENOR, 1913, 1931, pp. 364-365). In similar fashion the fractures defining very large (*ca* one km diameter) orthogonal blocks have been exploited to form bornhardts (e.g. LISTER, 1987; CAMPBELL and TWIDALE, 1991). Such forms have also emerged as a result of the differential weathering of compartments comprising numerous orthogonal blocks.

ARCUATE PARTINGS

Three types of arcuate parting, disposed parallel to fresh rock surfaces, occur in granite. Very thin scales, flakes or laminae are developed both on exposed rock surfaces and on the interior walls of tafoni. They occur seemingly wrapped around corestones (figure 6). Their formation can be attributed to preferential weathering of the corners and edges of joint blocks in the shallow subsurface (e.g. LARSEN, 1948; HUTTON et al., 1977; TWIDALE, 1986). Water infiltrating the rock reacts with mica and feldspar to produce clays, which expand on taking in water causing lamination (figure 7). The laminae break down to a granular mass of quartz feldspar and clay. Most of the feldspar is converted to clay and eventually even the quartz is dissolved so that the corestones are set in a matrix of grus (figure 5). Thus, granite is converted to a clayey regolith as a result of water attack in the shallow subsurface. Water continues to play a significant role in alteration after exposure but in addition physical processes intrude in particular circumstances – gelifraction in cold climates and including haloclasty in arid lands and on the coast, where tafoni appear (WINKLER and SINGER, 1972; BRADLEY et al., 1978). Pressure release at the granular scale also possibly contributes to disintegration (e.g. BAIN, 1931). Other, larger scale partings are referred to as pseudobedding, pseudostratification, or flaggy joints that subdivide the rock into slabs a few centimetres or a few tens of centimetres thick (figure 8). Most are discontinuous and all

Fig. 6. Lamination around weathered block in granite nubbin, Señor de la Peña, Anillaco, La Rioja, Argentina.

Fig. 7. Corestones with lamination, exposed in quarry on Karimun Island, western Indonesia.

occur within a few metres of, and parallel to, the surface. They can be attributed to the exploitation by various shallow subsurface weathering agencies, particularly the freeze–thaw action, of strain lines within the rock mass.

SHEET FRACTURES AND STRUCTURES

The third partings are the sheet fractures that define the thick slabs known as sheet structures (figure 9) that are, however, still commonly known as offloading joints. They are well and widely developed in granitic rocks, including gneiss and migmatite but also in other massive rocks such as dacite, rhyolite (cryptovolcanic facies: GONNERMANN and MANGA, 2003; BACHMANN et al., 2007), and sedimentary rocks like sandstone, conglomerate and limestone (BRADLEY, 1963; TWIDALE, 1978, 2009; BOURNE and TWIDALE, 2003). Sheeting planes cut across other bedrock structures including orthogonal systems, cleavage and foliation, crystal boundaries, rift and grain,

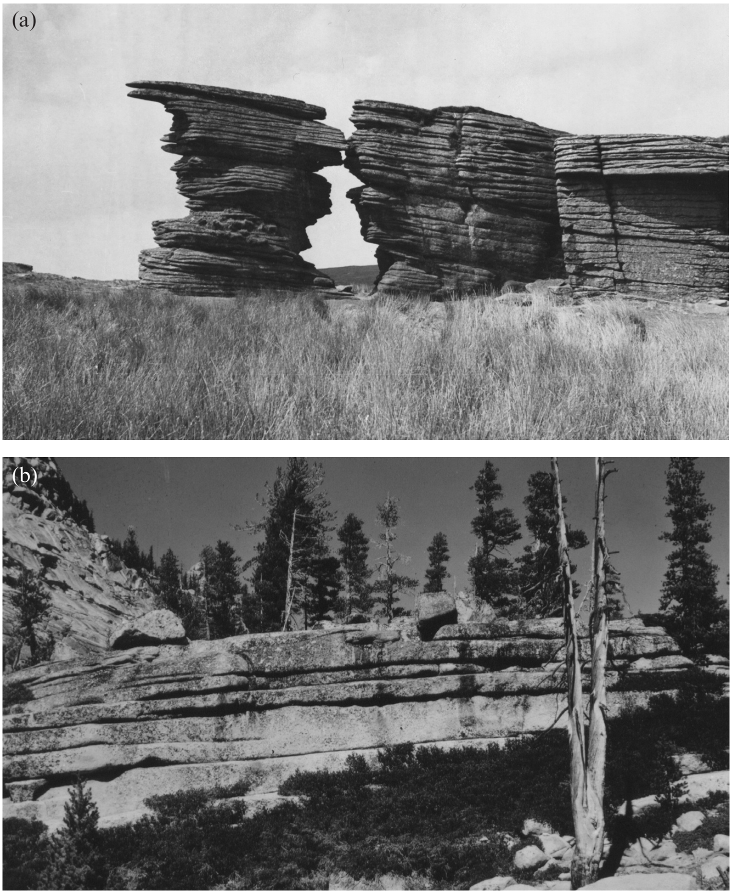

Fig. 8. Pseudobedding in granite (a) on Wattern Tor, Dartmoor, south-western England, and (b) exposed in road cutting in the Adirondack Mountains, northern New York State

flow structures and bedding. Many are intruded by pegmatite, quartz veins or by aplite sills (figure 10).

Sheet fractures are essentially continuous and of curvilinear geometry. They subdivide the rock into slabs from 50 cm to 10 m or more thickness and have been observed at depths of 100 m or more in quarries and tunnels. It is frequently claimed that the thickness of sheet structures increases systematically with depth, but there are many exceptions. Most sheet partings run roughly parallel to the land surface (or vice versa), being essentially horizontal on hill crests but dipping steeply on hillsides, and together forming basinal structures. However, at a few but significant sites the arcuate fracture sets display a synformal geometry beneath hills and domes (VIDAL ROMANI et al., 1995; TWIDALE et al, 1996).

The idea that the sheet structure is of endogenous origin dates from well before the end of the Twentieth Century. MERRILL (1897, p. 245) stated: "... with many geologists these joints, in themselves, would be accepted as due to atmospheric action. In the

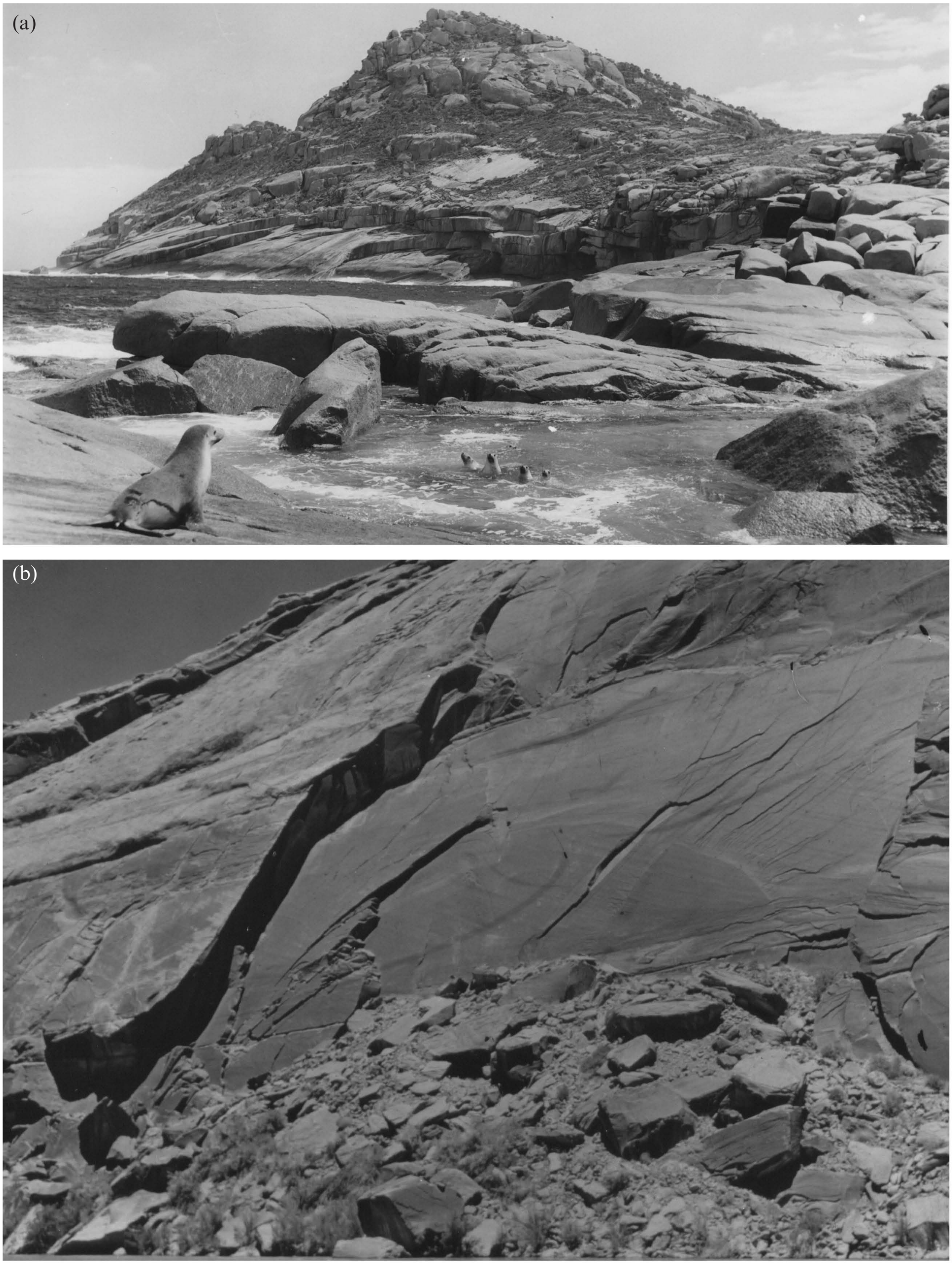

Fig. 9. Sheet structure (a) in granite, Pearson Island, Great Australian Bight, and (b) in sandstone Colorado Plateau (W.C. Bradley).

writer's opinion they are, however, the result of torsional stress and once existing are lines of weakness which become more and more pronounced as weathering progresses. Some granitic residuals as bornhardts are invariably associated with sheet structure and that give rise to the domed shape which is commonly accepted. According to MERRILL (1897, p. 245), the boss or dome-like form of the bornhardts is "incidental and consequent" on internal structure. Several writers, including some of the earliest, consider that sheet jointing and related sheet structure are due to the stresses imposed on magmas during injection or emplacement and, hence, correspond to the shape of the original pluton. As mentioned, in granite some planar fractures may be initiated during intrusion but most result from horizontal stress (e.g. DALE, 1923; VIDAL ROMANI et al., 1995; TWIDALE et al., 1996). Sheet structure is common to different types of rocks because all have suffered the same type of compressive deformation.

Thus, contrary to common belief encapsulated in the term "offloading joint" (GILBERT, 1904), sheet fractures are of endogenous origin having developed at the end of the intrusive magmatic stage when the magma has already lost mobility as its crystallisation has finished (see VIDAL ROMANI et al., 1995). Like all fractures they are an expression of diminished lithostatic pressure (CHAPMAN, 1956), but they are basically tectonic.

Other authors also have referred to the endogenous origin of the fracturing in the granite bodies but invoked and synintrusive processes (see WATERS and KRAUSKOPF, 1941). They postulated that during emplacement there are generated structural features due to brittle deformation (pro-

Fig. 10. Inverted sheeting in the aplitic sill, and both fracture and sill displaced by faulting, Joshua Tree National Monument, southern California

toclastic failure) of rock in the peripheral zones that will be affected by shear-induced fragmentation expressed as brittle fractures (ARZI, 1978; VIDAL ROMANÍ, 1990; GONNERMANN and MANGA, 2003). Obviously, however, such mechanisms cannot apply, for instance, to sheeting in sedimentary settings.

OTHER RELATED STRUCTURAL FEATURES

Planar structural fabrics developed in a magmatic body correspond to a continuum of deformation developed at the end of the emplacement stage and associated with the intrusive contact with the host rock (VIDAL ROMANÍ, 2008). In this stage sheeting is associated spatially and genetically to other types of planar structures as pseudobedding, polygonal cracking, boudinage, imbrication or overthrusting, and folding or buckling (TWIDALE, 1982; TWIDALE and VIDAL ROMANÍ, 2005; MIGON, 2006). All are related to the deformation of the pluton by planar shearing at the nearest contact with the host rock and exploitation by exogenous agencies (water–related weathering).

Though detailed analyses of the genesis of these structures in plutonic rocks is uncommon (VIDAL ROMANÍ, 1990), the deformation of jointed sedimentary rocks has been the subject of many treatises that suggest analogies with intrusive fabric in plutonic rocks (e.g. RAMSAY and HUBER, 1987). From the structural point of view the main difference between the two is that in plutonic rocks the “bedding” (sheet structure) must be developed before the other minor features noted can evolve (see e.g. VIDAL ROMANÍ, 1990), whereas bedding is usually well developed in sedimentary sequences regardless of any deformation.

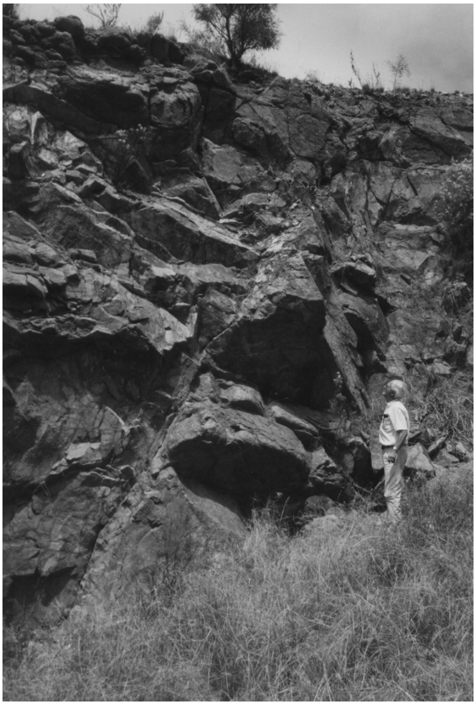

Fig. 11. Fault exposed in quarry west of Palmer, Mount Lofty Ranges, with barrel-shaped corestones and tetrahedral corners exposed in adjacent granite blocks.

The most characteristic landform of granite landscapes is the boulder or well-rounded groups of boulders (*compayrés*: TWIDALE, 1982). The morphology of such boulders can be attributed to the more rapid weathering (lamination, then granular disintegration of the corners of a joint block rather than its edges and even more than the weathering on plane faces: as MacCULLOCH (1814, p. 76) put it: *Nature mutat quadrata* – they are rendered spherical by decomposition (see also BECHE, 1839, p. 450). But some corestones are set in blocks no part of which has been weathered, for tetrahedral corners of fresh

Fig. 12.
(a) Corestones associated with mineral banding near Tooma Dam Snowy Mountains southeastern Australia, and (b) detail of Figure 12a.

rock abut the internal spherical mass (figure 11). The three-dimensional geometry of the orthogonal systems determined the size and shape of the blocks attacked by waters penetrating along the partings. This pattern suggests the shearing of preexisting orthogonal blocks (TWIDALE, 1968, pp 96-101, 1982, pp. 114-116). Elsewhere, concentric patterns of minerals suggest that weathering may have been determined by patterns of circulation developed while the magma was still fluid or plastic (figure 12).

The development of boudinage in granite as well as its relationship with the most advanced stage of deformation implies a spheroidal disjunction (VIDAL ROMANÍ, 2008). This type of structure has been interpreted as an alteration form when in fact it is a deformative structure. The three types of structures: sheet structure, boudinage, and spheroidal disjunction, are closely related forming a gradually increasing sequence of deformation developed in the fragile (or brittle) field. Boudinage in sedimentary or even metamorphic rocks, like the fabric of an augen gneiss, determines weathering patterns in detail, is explained in terms of the deformation of a layered structure formed by the alternation of materials with different competence and where the layers of less competent lithology are disrupted into elongated fragments. In some magmatic, plutonic, and cryptovolcanic rocks a striped texture is attributed to original compositional differences or to fluid structures defined in an early stage of the magmatic intrusion. It later influences the course of weathering.

In granitic rocks, boudinage follows the development of sheet structure. Thus, the differences in rheology between a relatively rigid layer and a solid but highly strained matrix are exclusively due to the different deformation grade. The rigid layer ruptures or thins ('necks') normal to the stretching direction in the rock (RAMSAY and HUBER, 1987). Because of this similarity and the apparent link to foliated rocks, this type of structure is known as "foliation boudinage" (HAMBREY and MILNES, 1975; PLATT and VISSERS, 1980).

The examples of boudinage development in granite rocks do not appear in broad zones but in very limited layers with discrete development of sheeting. Considering the intensive development of the foliation, the deformation of a massif could have been extreme giving the rock a foliated aspect. In the granite rock the boudins are individualised in layers between 40 cm and 2 m thick and some metres long. They develop by planar fracturing into parallelepipedic (rectangular in section) fragments ('torn boudins') or in the instance cited case by necking and tapering into elongate depressions and swells known as 'drawn boudins'. The boudins are separated by fracture zones known as 'boudin necks'. In all drawn boudins, the layers are deflected into the boudin neck in a characteristic geometry (GOSCOMBE et al., 2004).

In some cases, the surfaces of sheets develop stretching features (EYAL et al., 2006) that appear as sets of patterned cracks (see RAMSAY and HUBER, 1987; VIDAL ROMANÍ, 1990; PLOTNIKOV, 1994). They may be repeated in the surfaces of superposed sheets. Similar features have been described in deformed sedimentary beds and called polygonal cracking or chocolate tablet structure (RAMSAY and HUBER, 1987, using the same nomenclature for their equivalent features in plutonic rocks). Polygonal cracking consists of a pattern of cracks, some as much as 5 cm wide, developed in a superficial shell or shells of rock (figure 13): they extend to no more than a few centimetres beneath the surface of boulders, blocks or sheets. They form orthogonal, rhomboidal or polygonal patterns (though some are irregular or crazy, as in crazy-paving) defining thin plates. The polygonal plates range in diameter from 2 cm to some 24 cm, with the average and mode both near the upper end of the range. They are clearly of endogenous origin (LEONARD, 1929) because the later pegmatite or aplite dikes have frequently been intruded in them. In polygonal cracking they may separate the tiles of the mosaic (TWIDALE and VIDAL ROMANÍ, 2005; VIDAL ROMANÍ, 2008).

Such patterns have been observed on corestones recently exposed in a road-cutting in the Snowy Mountains of southeastern Australia. They are variously attributed to insolation or chemical weathering (JOHNSON, 1927), freeze–thaw action involving soil moisture (TWIDALE, 1982), cracking due to expansion of the outer layer of rock (SOSMAN, 1916; SCHUL-

Fig. 13. Polygonal cracking and tafoni in granite boulder, The Granites, near Mt Magnet, Western Australia.

KE, 1973) and weathering of exposed joint planes or desiccation and cracking of duricrusts as a result of insolation (ROBINSON and WILLIAMS, 1989).

SHORTENING STRUCTURE

Pseudoripples, described in deformed sedimentary rocks (RAMSAY and HUBER, 1987), also are found, though less frequently, in plutonic rocks (VIDAL ROMANÍ, 1990). It is a structure related to shortening planes. The imbrication and triangular and laminar wedges associated with the slippage of one sheet over another in a compressive (antiformal) structure is similar (*cf* striae developed on bedding planes as a result of slippage induced by folding).

All these effects indicate that in the final stage of magmatic emplacement the rock undergoes both stretching or shortening, associated with the generation of sheeting planes. This is comparable to the stress of opposite contrasted stresses developed during the shearing of a cubic block (e.g. WEISSENBERG, 1947).

These different types of structural fabric can be taken to suggest a deformation sequence of increasing grade and different impacts (stretching or shortening): pseudobedding, sheet fractures and structures, shearing with foliation and maximum stretching corresponding to polygonal cracking, boudinage, and spheroidal disjunctions. Buckling, sheet structure, wedges, and overthrusting are associated with compression. The formation of planar structures, caused either by stretching or shortening, leads to another set of discontinuities one disposed normal to the first, together forming radial patterns (CLOOS, 1923, 1931; BALK, 1937; MIGON, 2006). Hence, the disintegration of sheet structures into blocks is a result of weathering, either in the shallow subsurface or after exposure along fractures disposed normal to the arcuate surfaces of the slabs.

EPIGENE STAGE

The development of forms in granitic rocks has been understood as a two-stage process: first, one of etching at the weathering front and a second stage of exposure due to the stripping of the regolithic cover (TWIDALE, 2002). And this is broadly correct, but the first etching stage may have involved the exploitation of an earlier tectonic, thermal, magmatic event (GAGNY and COTTARD, 1980) which defined the structure of the rocks subjected to etching (TWIDALE and VIDAL ROMANÍ, 1994, 2005). Ancient sedimentological events also influence contemporary landform developments (TWIDALE, 2005). The exposure mechanism – by gravity, rivers, glaciers, the wind, waves – may be triggered by eustatic, isostatic-epeirogenic or tectonic processes (either altogether or in isolation). The exposure of the erstwhile weathering front as a bedrock surface reflects the structural differences imposed on the rocky massif between the final magmatic stage and the beginning of the post-magmatic stage, and hence the explanation of structures by external agencies.

CONCLUSIONS

The relief developed on granite rocks may be of exogenous or endogenous origin. Exogenous processes are directly related to the climate and contribute to the exposure of the granite rock. However, most granitic forms, major and minor, reflect the structure of the rock developed over eons of time from the stage of intrusion onwards.

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REFERENCES

ARZI, A. A. (1978). Critical phenomena in the rheology of partially melted rocks. *Tectonophysics*, **44**: 173-184.

BACHMANN, A., MILLER, C.F. and DE SILVA, S.L. (2007). The volcanic-plutonic connection as a stage for understanding crustal magmatism. *Journal of Volcanology and Geothermal Research*, **167**: 1-23.

BAIN, A. D. N. (1923). The formation of inselberge. *Geological Magazine*, **60**: 97-101.

BAIN, G. W. (1931). Spontaneous rock expansion. *The Journal of Geology*, **39**: 715-735.

BALK, R. (1937). Structural behaviour of igneous rocks. *Geological Society of America Memoir* **5**.

BECHE, H. T.de la, (1839). Report on the Geology of Cornwall, Devon and West Somerset (Geological Survey of England

and Wales). Longman, Orme, Brown, Green and Longmans, London.

BORNHARDT, W. (1900). Zur Oberflachungestaltung und Geologie Deutsch Ostafrikas. Reimer, Berlin.

BOURNE, J. A. and TWIDALE, C. R. (2003). Geomorphological development of the Baxter Hills, a conglomeratic upland near Iron Knob, South Australia. *Zeitschrift für Geomorphologie*, **47**: 351-371.

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

BRADLEY, W. C., HUTTON, J. T. and TWIDALE, C. R. (1978). Role of salts in the development of granitic tafoni, South Australia. *The Journal of Geology*, **86**: 647-654.

BÜDEL, J. (1977). *Klima-Geomorphologie*. Borntraeger, Berlin.

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

CAMPBELL, E. M. and TWIDALE, C. R. (1995). Lithologic and climatic convergence in granite morphology. *Cadernos Laboratorio Xelóxico de Laxe*, **20**: 381-403.

CHAPMAN, C. A. (1956). The control of jointing by topography. *The Journal of Geology*, **66**: 552-558.

CHEN, G. and GRAPES, R. (2007). *Granite genesis: in-situ melting and crustal evolution*. Springer-Verlag, Dordrecht.

CLOOS, H. (1923). Das Batholithenproblem. *Fortschritte der Geologie und Palaeontologie*, **1**: 1-80.

CLOOS, H. (1931). Zur Mechanik der Randzonene von Gletscher. *Schollen un Plutonen Geologische Rundschau*, **20**: 66-75.

DALE, T.N. (1923). The commercial granites of New England. *United States Geological Survey Bulletin* **738**.

EYAL, Y., OSADETZ, K. G. and FEINSTEIN, S. H. (2006). Evidence of reactivation of Eocene joints and pre-Eocene foliation planes in the Okanagan core-complex, British Columbia, Canada. *Journal of Structural Petrology*, **28**: 2109-2120.

FALCONER, J. D. (1911). *The Geology and Geography of Northern Nigeria*. Macmillan, London.

GAGNY, C. and COTTARD, F. (1980). Proposition de signes conventionnels pour la répresentation de certaines structures magmatiques acqises au cours de la mise en place et de la cristallisation. *Comptes Rendus 105ième Congrès National de la Societé de Savantes, Caen (Sciences),* **2**: 37-50.

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

GONNERMANN, H. G. and MANGA, M. (2003). Explosive volcanism may not be an inevitable consequence of magma fragmentation. *Nature*, **426**: 432-435.

GOSCOMBE, B. D., PASSCHIER, C. W. and HAND, M. (2004). Boudinage classification: end-member boudin types and modified boudin structures. *Journal of Structural Geology*, **26** (4): 739-763.

HAMBREY, M. J. and MILNES, A. G. (1975). Boudinage in glacier ice: some examples. *Journal of Glaciology*, **14**: 383-393.

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

HUBER, N. K. (1987). The geologic story of Yosemite National Park. *United States Geological Survey Bulletin* **1595**.

HUTTON, J. T., LINDSAY, D. S. and TWIDALE, C. R. (1977). The weathering of norite at Black Hill, South Australia. *Journal of the Geological Society of Australia*, **24**: 37–50.

JOHNSON, R. J. (1927). Polygonal weathering in igneous and sedimentary rocks. *American Journal of Science*, **13**: 440-444.

LARSEN, E. S. (1948). Batholith and associated rocks of Corona, Elsinore and San Luis Rey quadrangles, southern California. *Geological Society of America Memoir* **29**,

LEONARD, R. J. (1929). Polygonal cracking in granite. *American Journal of Science*, **18**: 487-492.

LINTON, D. L. (1953). The significance of tors in glaciated lands. In: *International Geographical Union Proceedings*, 17th International Congress, 8th General Assembly, Lisbon, 354-357.

LISTER, L. A. (1987). The erosion surfaces of Zimbabwe. *Zimbabwe Geological Survey Bulletin* **90**.

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

MacCULLOCH, J. (1814). On the granite tors of Cornwall. *Transactions of the Geological Society,* **2**: 66-78.

MERRILL, G. P. (1897). *Treatise on Rocks, Weathering and Soils*. Macmillan, New York.

MIGON, P. (2006). *Granite Landscapes of the World*. Oxford University Press. Oxford.

OBERLANDER, T. M. (1972). Morphogenesis of granite boulder slopes in the Mojave Desert, California. *The Journal of Geology*. **80**: 1-20.

PELTIER, L. C. (1950). The geographic cycle in periglacial regions as it is related to climatic geomorphology. *Association of American Geographers Annals*, **40**: 214-236.

PETFORD, N. (2003). Rheology of granitic magmas during ascent and emplacement *Annual Review Earth Planetary Science*, **31**: 399-427.

PLATT, J. P. and VISSERS, R. L. M. (1980). Extensional structures in anisotropic Rocks. *Journal of Structural Geology*, **2**: 397-410.

PLOTNIKOV, L. M. (1994). *Shear Structures in Layered Geological Bodies*. Russian Translation Series 104. Balkema, Brookfield, USA.

RAMSAY, J.G. and HUBER, M. (1987). *The Techniques of Modern Structural Geology. Folds and Fractures*. Volume 2, Academic Press, London.

ROBINSON, D. A. and WILLIAMS, R. B. G. (1989). Polygonal cracking of sandstone at Fontainebleu, France. *Zeitschrift für Geomorphologie*, 33: 59-72.

SCHULKE, H. (1973). 'Schildkrotenmuster' und andere Polygonalstrukturen auf Felsoberflächen**.** *Zeitschrift für Geomorphologie*, **17**: 474-488.

SCRIVENOR, J. B. (1913). Geology of Malaya. *Quarterly Journal of the Geological Society of London,* **69**: 343-369.

SCRIVENOR, J. B. (1931). *The Geology of Malaya*. Macmillan, London.

SEAGER, W. R. (1981). Geology of Organ Mountains and southern San Andres Mountains, New Mexico. *New Mexico*

Bureau of Mines and Mineral Resources Memoir **36**.

SOSMAN, R. B. (1916). Types of prismatic structure in igneous rocks. *Journal of Geology*, **24**: 215-234.

THOMAS, M. F. (1994). *Geomorphology in the Tropics. A Study of Weathering and Denudation in Low Latitudes*. John Wiley & Sons, Chichester, U.K.

TRICART, J. (1957). Application du concept de zonalité à la géomorphologie. *Koninklijk Nederlandsch Aardrijkskundig Genootschap*, **74**: 422-434.

TRICART, J. and CAILLEUX, A. (1958). *Cours de Géomorphologie. Introduction à la Géomorphologie Climatique*. Societé d'Editions d'Enseignement Superieur, Paris,

TRUBAC, J., ZAK, J., CHLUPACOVA, M. and JANOUSEK, V. (2009). Magnetic fabric of the Rícany granite, Bohemian Massif: A record of helical magma flow? *Journal of Volcanology and Geothermal Research*, **181**: 25–34.

TWIDALE, C. R. (1968). *Geomorphology. With special reference to Australia.* Nelson, Melbourne.

TWIDALE, C. R. (1971). *Structural Landforms*. Australian National University Press, Canberra.

TWIDALE, C. R. (1978). On the origin of Ayers Rock, central Australia. *Zeitschrift für Geomorphologie Supplementband*, **31**: 177-206.

TWIDALE, C. R. (1980). The Devil's Marbles, central Australia. *Transactions of the Royal Society of South Australia,* **104**: 41-49.

TWIDALE, C. R. (1981). Granitic inselbergs: domed, block-strewn and castellated. *Geographical Journal*, **147**: 54-71.

TWIDALE, C. R. (1982). *Granite Landforms*. Elsevier, Amsterdam.

TWIDALE, C. R. (1986). Granite landform evolution: factors and implications. *Geologische Rundschau,* **75**: 769-779.

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

TWIDALE, C. R. (2005). Lineage as a factor in landscape analysis. *Physical Geography*, **26**: 23-51.

TWIDALE, C. R. (2007). *Ancient Australian Landscapes*. Rosenberg, Sydney.

TWIDALE, C. R. (2009). Uluru (Ayers Rock) and Kata Tjuta (The Olgas): Inselbergs of central Australia. In: *Geomorphological Landscapes of the World.* P. Migon (Ed.). Springer, Vienna.

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

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

TWIDALE, C. R. and VIDAL ROMANÍ, J. R. (1994). On the multistage development of etch forms. *Geomorphology*, **11**: 157-186.

TWIDALE, C. R. and VIDAL ROMANÍ, J. R. (2005). *Landforms and Geology of Granite Terrains.* Balkema, Leiden.

TWIDALE, C. R., VIDAL ROMANÍ, J. R., CAMPBELL, E. M. and CENTENO, J. (1996). Sheet fractures: response to erosional offloading or to tectonic stress? *Zeitschrift für Geomorphologie Supplementband*, **106**: 1-24.

VIDAL ROMANÍ, J. R. (1990). Formas menores en rocas graníticas: un registro de su historia deformativa. *Cuadernos do Laboratorio Xeolóxico de Laxe*, **15**: 317-328.

VIDAL ROMANI, J. R. (2008). Forms and structural fabric in granite rocks. *Cadernos do Laboratorio Xeolóxico de Laxe,* **33**: 175-198.

VIDAL ROMANÍ, J. R. and TWIDALE, C. R. (1998*). Formas y Paisajes Graníticos*. Serie Monografías 55, Universidade da Coruña. Servicio de Publicacións, A Coruña.

VIDAL ROMANÍ, J. R., TWIDALE, C. R., CAMPBELL, E. M. and CENTENO, J. D. (1995). Pruebas morfológicas y estructurales sobre el origen de las fracturas de descamación. *Cadernos do Laboratorio Xeolóxico de Laxe*, **20**: 307-346.

WATERS, A. C. and KRAUSKOPF, K. (1941). Protoclastic border of the Colville Batholith. *Bulletin of the Geological Society of America*, **52**: 1355-1418.

WEISSENBERG, K. (1947). Continuum theory of rheological phenomena. *Nature*, **159**: 310-311.

WILHELMY, H. (1958). *Klimamorphologie der Massengesteine.* Westermann. Braunschweig.

WILLIS, B. (1934). Inselbergs. *Association of American Geographers Annals,* **24**: 123-129.

WINKLER, E. M. and SINGER, P. C. (1972). Crystallisation pressure of salts in stone and concrete. *Geological Society of America Bulletin,* 83: 3509-3514.

WOODBURNE, M. O. (1967). The Alcoota fauna, central Australia. *Bureau of Mineral Resources, Geology and Geophysics Bulletin* **87**.