Cuaternario y Geomorfología, 13 (1-2), pág. 33-43 ISSN: 0214-1744

ORIGIN OF MINIATURE MOGOTES IN GRANITE, KING ROCKS, SOUTHERN YILGARN BLOCK, WESTERN AUSTRALIA

C.R. TWIDALE (1), J.A. BOURNE (1) & J.R. VIDAL ROMANI (2)

(1) Department of Geology & Geophysics, University of Adelaide, South Australia 5005.
(2) Instituto Universitario de Geologia, Universidad de Coruña, Campus de Zapateira, 15071 ACoruña (España).

Abstract. Miniature mogotes occur in profusion on one sector of the western slope of King Rocks, a granitic gneiss bornhardt located in the southern Yilgarn Block of Western Australia. They are remnants of plates delineated by polygonal cracks, which developed at the weathering front. The plates were reduced in area beneath the regolith by seepage from a vegetated basin located on the slope above. The mogotes are the survivors of this process. After the stripping of the regolith and exposure of the bedrock forms, a winding stream further eroded the slope and created a channel devoid of residuals. Raised rims bordering fractures aligned downslope are due to protection afforded by good drainage, and wavy rims trending across slope to induration of biotite-rich foliation layers.

Key words: miniature mogote, linear rim, sinuous ridge, weathering front, fractures, seepage and runoff.

Resumen. Se estudia en este trabajo el origen de mesas o mogotes en miniatura muy abundantes en un sector de la vertiente occidental de King Rocks, un bornhardt en gneis granitico al sur del Yilgarn Block en Western Australia. Los microresiduales son restos de placas diferenciados desde una superficie definida por roturas poligonales puesta de manifiesto bajo el perfil de alteración. La superficie inicial de las placas se ha reducido por la meteorizacion asociada a los escurrimientos procedentes de un pilancon colonizado situado en la parte alta de la vertiente. Una vez descubierta la base del perfil de alteración la escorrentia superficial ha eliminado los mogotes de la zona de canal y ya solo se localizan en las partes mas altas, donde también se asocia al microrelieve un encostramiento por la oxidación de niveles foliados de la roca con mayor abundancia de biotita.

1. Introduction

King Rocks consists of two juxtaposed granitic domes located some 30 km northeast of Hyden, in the southern part of the Yilgarn Block in southwestern Western Australia (Figure 1). The western dome is low and stands only about 20 m above the surrounding plains. The eastern rises almost 60 m to a maximum of 408 m and is much more prominent, and for the purposes of this discussion is referred to simply as King

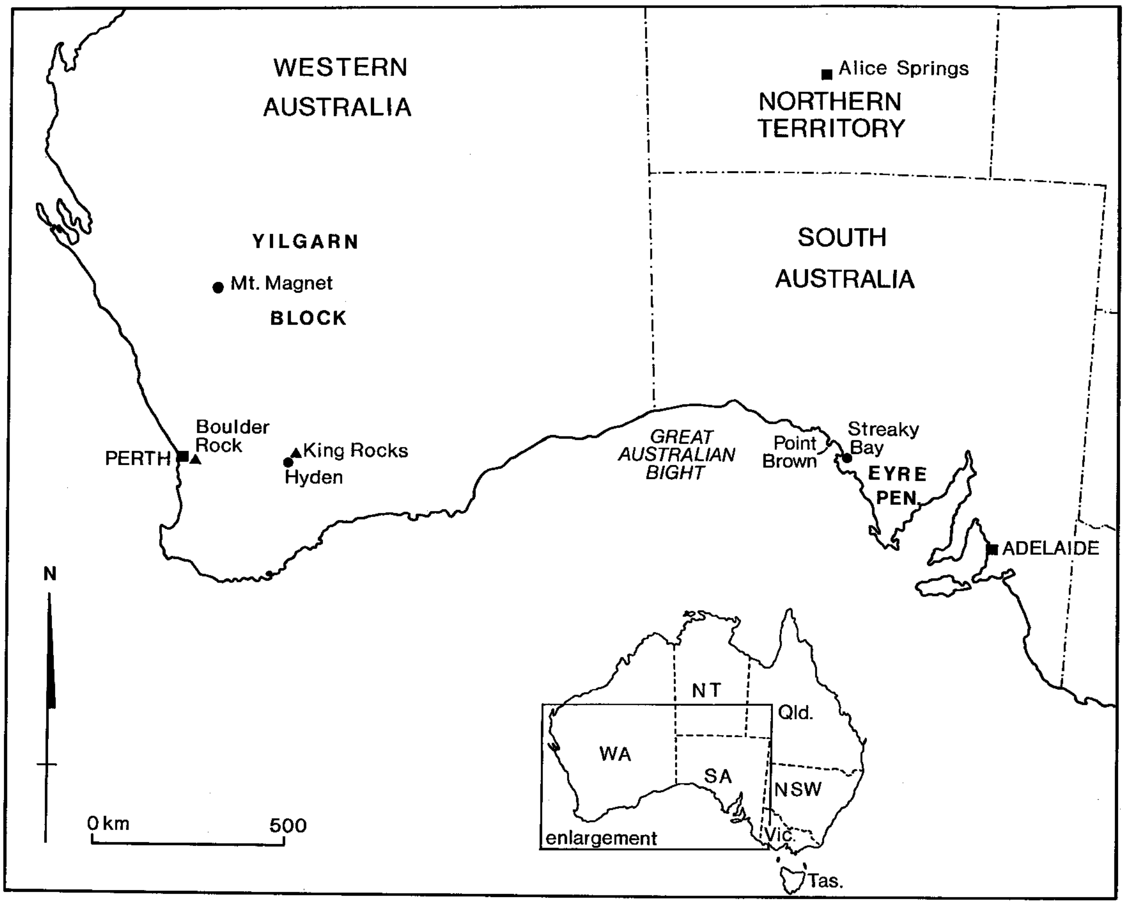


Figure 1. Location map, showing places and features referred to in the southwestern Yilgarn Block, Western Australia, and western Eyre Peninsula, South Australia.
Mapa de localización en donde se situan los lugares y formas descritas en el SW del Yilgarn Block, Western Australia y en el Oeste de la Peninsula de Eyre, South Australia.

Rocks. Numerous quite small flat-topped residuals (Fig. 2a) occur on a restricted sector of its western slope. In the same sector, fractures running downslope are bordered by low narrow rims, and in the same sector low sinuous ridges run diagonally across the slope (Figs 2b and c).

2. Terminology

The small table-like forms could be referred to as miniature mesas, but this is clumsy. The term «mogote» is commonly used as a regional (Caribbean) variant of towerkarst or *Turmkarst* (see e.g. Monroe, 1968; Sweeting, 1973; Jennings, 1985; Bates and Jackson, 1987, p. 428). In the original Spanish, however, a *mogote* is a small hill or mound in rocks of any type, and is usually applied to an isolated prominence of conical shape but with a bevelled crest. The term as applied in karst geomorphology is misleading as regards both scale and lithology. Yet «mogote» seems appropriate to the forms from King Rocks, for though its previous and established usage is a concern, the context makes clear the meaning. To obviate possible confusion with karst towers however the adjective «miniature» could be added occasionally.

The individual mogotes vary in precise size and shape but only within narrow limits: all are miniature plateaux, rounded or oval in plan form, about 30 cm diameter and 20 cm high (Fig. 2a). They are distribu-

Figure 2. Photos showing (a) miniature mogotes in broad, shallow valley on western slope of King Rocks; note residual slab-like remnants of sheet structure, (b) fracture with bordering rims and, in the middle distance, mogotes and sheet remnants, (c) group of mogotes on King Rocks showing «meander loop».

Fotografías en donde se presenta (a) Conjunto de mogotes en miniatura y el valle inicipente en la vertiente oeste de King Rocks; note - se los restos de una laja correspondientes a una estructura de descamacion, (b) fractura con reborde de endurecimiento y, a media distancia, restos de mogotes y de lajas de descamación, (c) grupo de mogotes de King Rocks dispuestos en curva meandriforme ted over the mid- and lower slopes of a particular sector of King Rocks. It is difficult to establish any plan pattern to their distribution on the slope, except for the occurrence of an arcuate area devoid of the forms (Figure 2d). The mogotes, linear rims and winding ridges are eroded in the same granitic gneiss that underlies the slope, but, though still cohesive, it is laminated with and splits away parallel with the slope surface.

3. King Rocks

3.1 *Description*

King Rocks is a large-radius domical hill eroded in a medium and coarse-grained seriate granite and adamellite of Proterozoic age (Chin *et al.*, 1984). It rises abruptly from the surrounding plain, which is lateritised, implying that the residual is at least of Late Cretaceous age (Twidale & Bourne, 1998). Most of its surface carries a patina of iron oxides. On it are developed various typical granite landforms including structural forms like sheet structures, blocks and boulders and features due to weathering such as basins (including some of unusually large diameter), *Rillen* and tafoni. The bedrock in which the mogotes are shaped is laminated parallel to the slope, but across foliation.

Sheet structures 60-200 cm thick are exposed on the slopes adjacent to the slightly lower slope sector in which the the mogotes are preserved. The thinner sheets have been broken down into blocks some of which are rounded at the edges. Polygonal weathering (or cracking) is also developed on some of the sheet structures in the sectors adjacent to that characterised by mogotes (Figure 3). Many of these forms are developed at the weathering front, beneath the regolith, on blocks, boulders and platforms, though others, usually orthogonal in pattern, result from shearing (e.g. Twidale, 1982; Vidal Romani, 1989; Vidal Romani & Twidale, 1998). The southern Yilgarn Block is known to be seismically active (e.g. Everingham, 1968; Gordon & Lewis, 1980; Chin *et al*., 1984), and at King Rocks fresh fault scarps, slipped slabs, A-tents, or pop-ups, and a collapsed tafone roof attest recent local tectonism, but the geometry of the polygonal patterns there suggests that they are due to weathering. At many sites, including those adjacent to the mogote slope at King Rocks, some of the partings have been widened so that the intervening plates are reduced in area and are separated by bedrock slopes.

Runoff from the slopes to either side washes into the broad, shallow mogote valley (Figure 2a). The depression, which is traversed by major fractures trending downslope, extends from a perched platform situated about two-thirds up the slope and within a large armchair shaped hollow, virtually to the base of the residual. The hollow is vegetated and the convergence of runoff and seepage has probably ensured that it has always been a moist site, though, given the general and regional evidence for recent climatic changes (see e.g. Kemp, 1978; Barker & Greenslade, 1982), probably with a different flora in past periods. At times, decantation flows charged with organic acids, biota and chemicals seep from the vegetated regolith and they must have been even more frequent and voluminous in past periods of humid climate. The mogotes developed in the past and are, in that sense, inherited. The entire slope may have carried a thin regolith as well as vegetation, but runoff was probably already augmented by seepage from the hollow upslope.

3.2 *Origin of miniature mogotes*

At several sites on King Rocks, and elsewhere, where polygonally cracked surfaces stand high and dry, fractures separating the polygonal plates have been widened by water weathering. Where the polygonal patterns occur at the weathering front and are covered by a regolith not only are they in virtually constant contact with moisture held in the detrital cover, but seepage and runoff along the weathering front exploits the partings. The cracks of the polygonal patterns are widened and the intervening plates are reduced in area and come to be separated by depressions several centimetres wide. On King Rocks the inclination of the slope was sufficient to maintain the flow of seepage in more-or-less definite channels though some may have become diffuse and died away because of interference by the gritty regolith. But in time the pattern of polygonal cracks was converted to a system of connected depressions. Concurrently the areal extent of

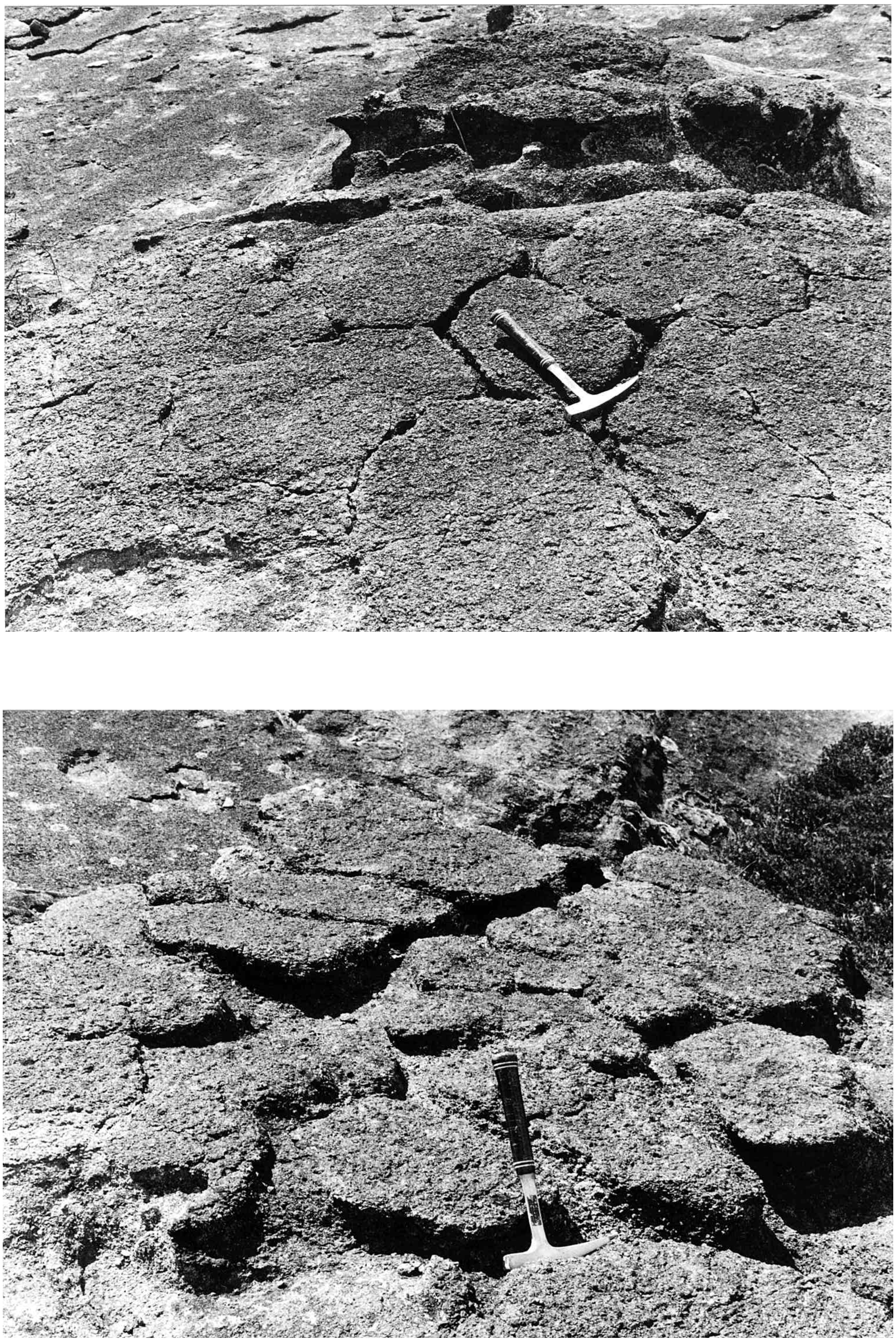


Figure 3. (a) Polygonal cracking on sheet remnants (X in Fig. 2b) on King Rocks, and in (b) the cracking has been widened by weathering and wash

(a) Roturas poligonales sobre restos de una laja (X en la figura 2b) en King Rocks, y en (b) roturas poligonales ancheadas por meteorizacion y lavado

the polygonal plates was reduced and some residuals were eliminated, so that the surviving remnants have become widely separated as mogotes.

Following the stripping of the regolith and the exposure of the weathering front, possibly during an arid climatic phase, runoff, especially that due to heavy rains, formed a winding stream which, migrating within its sinuous meander belt, eroded the mogotes in its path and created a broad curve or loop devoid of residuals (Figure 2d). Erosion after exposure seems more likely than at the weathering front where a meander would surely not have developed because of flow interference by the gritty cover.

3.3 *Origin of associated forms*

a) *Linear rims*. Either after rainstorms or when precipitation was higher, or both, seepages from the vegetation, armed with organic chemicals which possibly included polyphenols which aggressively attack iron compounds (e.g. Bloomfield, 1957; Hingston, 1962) and biota, flowed down slope, beneath and, in some measure, through the regolith and along the bedrock surface formed by the weathering front. Some of this drainage followed along major tectonic fractures aligned downslope. While adjacent areas were weathered beneath the regolith, the fractures provided narrow zones of good drainage. The regolith to either side drained into the fractures, and some of the regolithic detritus may have been washed into the fractures and evacuated. Thus narrow, dry, and hence protected, zones were formed on either side of partings. These narrow zones bordering the fractures were not weathered and eroded and became linear rims or rock levees (cf. Scott, 1967; Lister, 1973; Twidale, 1988; Figure 2b).

b) *Sinuous ridges*. The sinuous ridges preserved low on the slope are asymmetrical in cross-section, with the gentler slope dipping consistently uphill (Figure 2c). It is suggested that they are due to preferential induration of iron oxides along a zone of weakness or of, say, biotite concentration along foliation. This induration may have occurred at the weathering front (cf. Twidale, 1986), though wash has reduced the degree of discoloration due to the iron oxides on the surfaces between mogotes.

3.4 *Discussion*

Thus, as a working hypothesis, it is suggested that the three forms under review, the mogotes, linear rims and sinuous ridges, originate in different ways, though in all instances a regolithic veneer may be involved, and all explanations call for runoff and seepage from the vegetated area upslope.

Several features are consistent with these suggestions. The mogotes are found only downslope from a well vegetated topographic depression which generates considerable decantation flow; laminated bedrock is typical of the weathering front (e.g. Hutton *et al*., 1977; Twidale, 1986); the height of the mogotes is similar to the depth of rock affected by polygonal cracking at adjacent sites; sinuous zones devoid of mogotes are discernible in the plan pattern (Figure 2d); some polygonal cracking is known to be initiated at the weathering front, beneath the regolithic cover and below the land surface (Twidale, 1982, p. 316); various stages in the sequence of concurrent widening of polygonal cracks and reduction in size of polygonal plates can be observed in the field.

The explanation calls for a coincidence of polygonal cracking on a modest slope and an upslope source of seepage. This may explain the absence of mogotes elsewhere on King Rocks or, indeed, on other residuals in the district (apart, in small measure, from the east end of Hyden Rock, just to the west of Hyden township, where there are spikes capped by iron oxide possibly generated by the weathering of biotite-rich patches in the granite rock).

4. Testing the hypothesis

4.1 *The Granites, Mt Magnet, central Yilgarn Block, Western Australia*

The Granites consists of several groups of large granite boulders developed on an Archaean biotite granite exposed beneath a lateritic plateau a few kilometres north of Mt Magnet, Western Australia. The plateau is dissected and the area is drained by widely spaced streams which are fed by wash and seepage from the blocky and bouldery divides. Several of the boulders are split and displaced, tafoni are well developed, and there are also A-tents and minor fault scarps (Twidale *et al*., 1991; Twidale *et al*., 1993), but the most notable feature developed at the site is polygonal cracking. Some is due to alteration at the weathering front, some to shearing; some occurs in single, others in multiple layers. In the present context, however, the most notable feature is a pattern of shallow fractures ranging from hairline cracks bordering wide plates to wide corridors separating small, in some instances disintegrating, plates. Marginal weathering and erosion concentrated along fractures has resulted in the development of isolated residuals (miniature mogotes) comparable to mesas and buttes fringing dissected plateaux (Figure 4)**.**

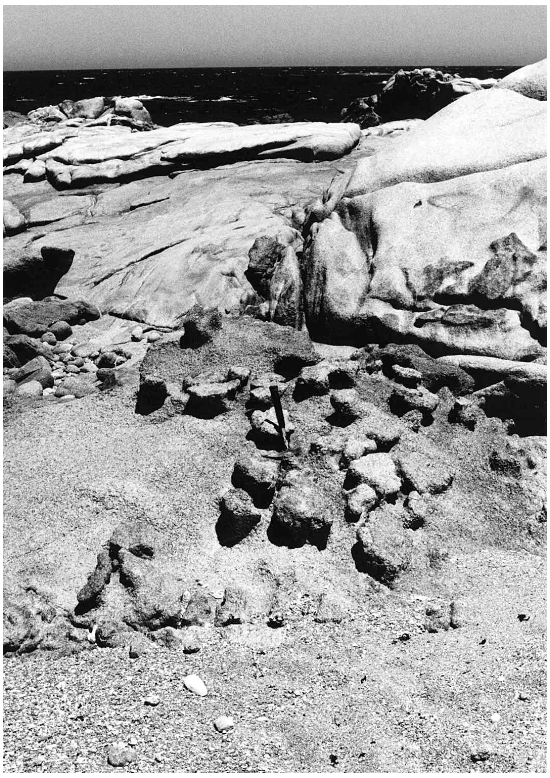
4.2 *Point Brown, northwestern Eyre Peninsula, South Australia*

Point Brown is a peninsula projecting SSW into the eastern margin of the Great Australian Bight, on the northwestern coast of Eyre Peninsula, South Australia (Figure 1). On its eastern side it is bordered by steep cliffs up to 40 m high and is underlain by a thick sequence of dune calcarenite (Bridgewater Formation) of Middle-Late Pleistocene age (Wilson, 1991) within which are several old soil horizons marked by calcrete, prominent. The calcarenite overlies foliated granite and pink granite intruded by granodioritic and basic (amphibolitic, doleritic) dykes, all belonging to the Lincoln Complex and of Palaeoproterozoic age (e.g. Rankin & Flint, 1991; Parker, 1993). The plutonic rocks are exposed only in the littoral zone at the base of the cliffs, below a major unconformity marked in many places by a ferruginous regolith of putative Pliocene age (Molina Ballesteros *et al*., 1995).

At Point Brown, well-developed miniature mogotes are preserved in one narrow sector on the eastern side of the Peninsula and on the sloping faces of granitic blocks within the tidal zone and at the base of the calcarenite cliffs (Figure 5a). The host blocks have been exposed in the last 6000-7000 years as a result of marine erosion during and since the most recent postglacial rise of sealevel, though may have been prepared by subsurface weathering during the ?Pliocene (Molina Ballesteros *et al*., 1995).

Figure 4. Mogotes about 20 cm high, from The Granites, near Mt Magnet, Western Australia
Mogotes de unos 20 cm de alto en The Granites, cerca de Mount Magnet, Western Australia

The mogotes are morphologically similar to those described from King Rocks, but they lack the obvious superficial iron oxide discoloration, possibly due to constant wash by breaking waves. They occur on granite outcrops below the point of debouchment of a gully and wash draining the calcarenite cliff (Figure 5b). Nearby are several gently inclined surfaces in which are developed polygonal cracks. Some are quite wide and have miniature flared sidewalls, suggesting development at the base of the ferricreted ?Pliocene rego-



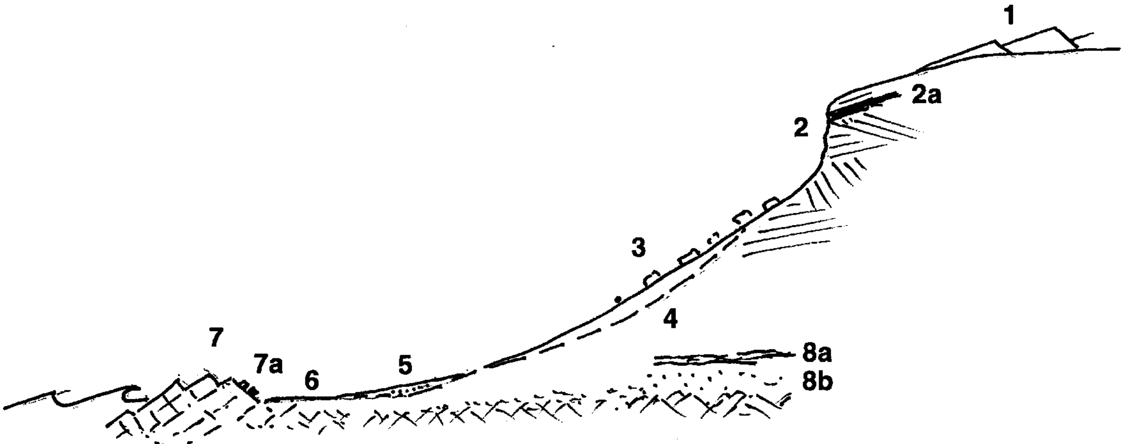


Figure 5. (a) Mogotes at Point Brown, western Eyre Peninsula, and (b) sketch of setting of the Point Brown mogotes.
1 - dunes on cliff-top; 2 - calcarenite cliff-face; 2a - calcrete horizon; 3 - debris slope; 4 - stream profile; 5 - depositional; 6 - beach; 7 - bedrock; 7a - miniature mogotes; 8a - ferruginous zone; 8b - weathered bedrock

(a) Mogotes en Point Brown, al oeste de la Peninsula de Eyre, y (b) esquema de localización de mogotes en Point Brown.
1 - Dunas en la parte alta del acantilado; 2 - acantilado tallado en calcarenita; 2a - horizonte en calcreta; 3 - talud de derrubios; 4 - Perfil del canal; 5 - zona de sedimentacion; 6 - playa; 7 - basamento rocoso; 7a - mogotes en miniatura; 8a - zona de ferruginosizacion; 8b - substrato rocoso alterado

lith. During later Pleistocene times, however, groundwaters seeping through the dune calcarenite would have ensured an alkaline weathering environment, and the widening of the partings. Later, after exposure, spray and wash from the oceans would have further widened the partings —minerals such as feldspars are readily weathered in seawater (Joly, 1901)— and thus enhanced the separation of the residual mogotes.

Along the rocky coast of Point Brown, and also at other sites such as Point Drummond, some 225 km to the southeast, systems of orthogonal fractures are commonly exposed, and many have been exploited by weathering and erosion in varying degrees to produce minor landform patterns similar to those of mogotes. Not all are polygonal: many are basically orthogonal, suggesting that in this narrow sense mogotes may be convergent forms. In addition, small rounded protuberances due to differential weathering along fractures have also been noted (core-cobbles rather than core-boulders) and irregular projections capped by concentrations of iron oxides have been formed by the differential erosion of the ?Pliocene regolith.

Thus though coastal as opposed to terrestrial, the setting of the Point Brown mogotes is similar to that at King Rocks, and the minor granite forms at the former can be regarded as congeners of those developed at the latter. The waters draining the adjacent cliff are alkaline and aggressively attack the granitic rocks (cf. Twidale (1979) and Bourne and Twidale (1998) for examples of the aggressive action of alkaline waters on siliceous rocks). Acting either on exposed bedrock, or at the base of an earlier (?Pliocene) regolithic cover, such runoff and seepage may have exploited polygonal cracking and caused the reduction and isolation of mogotes.

4.3 *Boulder Rock, Darling Range, Western Australia*

The above examples show that polygonal cracking can evolve into mogote-type minor topography. At some sites, however, polygonal cracks form foci of induration rather than weakness. Boulder Rock is a large radius dome of Archaean granodiorite located some 30 km southeast of Perth (Figure 1). On the crest is a tesselated pavement consisting of interlocking polygonal plates, the edge of each of which is a rim indurated by iron oxides (haematite?). The reason for the fractures being indurated rather than widened may be that Boulder Rock stands below the level of the lateritised land surface of the Darling Ranges (e.g. Mulcahy, 1973), so that groundwaters would have been rich in iron oxides. King Rocks on the other hand stands above the equivalent surface around Hyden (Twidale & Bourne, 1998) and though some iron oxides would have been available from earlier phases of weathering and landscape development, it would not have been as readily available as at Boulder Rock.

5. Conclusion

Miniature mogotes are described from two contrasted sites. Nevertheless they evolve in similar environments and by comparable mechanisms. In both instances small scale fracture patterns developed in granitic rocks have been exploited and developed by waters rendered especially aggressive by the characteristics of their catchments. In this way the plates delimited by polygonal cracking are either eliminated, or they are reduced in area and become separated and isolated as mogotes. The fractures exploited to produce mogotes may be polygonal or orthogonal, and as these are quite widely developed, so are mogotes. The mogotes at King Rocks catch the eye because they are prolific and are concentrated in a specific slope sector. This is due to the development of small scale (polygonal) cracking and its exploitation by seepage and runoff from a basin floored by a vegetated regolith which not only retains moisture, so that seepage is prolonged, but also probably renders that water aggressive by the addition of chemicals and biota.

References

Barker, W.R. & Greenslade, P.J.M. (Eds.) (1982): *Evolution of the Flora and Fauna of Arid Australia.* Peacock/Australian Systematic Botany Association/ANZAAS, SA Division, Frewville, South Australia, 392 p.

Bates, R.L. & Jackson, J.A. (1987): *Glossary of Geology.* American Geological Institute, Alexandria, Virgina, 788 p.

Bloomfield, C. (1957): The possible significance of polyphenols in soil formation. *Journal of the Science of Food and Agriculture,* 8, 389-392.

Bourne, J.A. & Twidale, C.R. (1998): Pediments and alluvial fans: genesis and relationships in the western piedmont of the Flinders Ranges, South Australia. *Australian Journal of Earth Sciences,* 45, 123-135.

Chin, R.J., Hickman, A.H. & Thom, R. (1984): *Hyden, Western Australia,* map sheet SI/50-4 International Index. Geological Survey of Western Australia, 1:250,000 Geological Series - Explanatory Notes.

Everingham, I.B. (1968): Seismicity of Western Australia. *Commonwealth of Australia Bureau of Mineral Resources Report*, 132.

Gordon, F.R. & Lewis, J.D. (1980): The Meckering and Calingiri earthquakes October 1968 and March 1970. *Geological Survey of Western Australia Bulletin,* 126.

Hingston, F.J. (1962): Activity of polphenolic constituents of leaves of *Eucalyptus* and other species in complexing and dissolving iron oxide. *Australian Journal of Soil Research,* 1, 63-73.

Hutton, J.T., Lindsay, D.S. & Twidale, C.R. (1977): The weathering of norite at Black Hill, South Australia. *Journal of the Geological Society of Australia,* 24, 37-50.

Jennings, J.N. (1985): *Karst Geomorphology.* Blackwell, Oxford, 293 p.

Joly, J. (1901): Expériences sur la dénudation par dissolution dans l'eau douce et l'eau de mer. *Proceedings of the 8th International Geological Congress, Paris,* 774-784.

Kemp, E.M. (1978): Tertiary climatic evolution and vegetation history in the southeast Indian Ocean region. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 24, 169-208.

Lister, L.A. (1973): The microgeomorphology of granite hills in north-eastern Rhodesia. *Geological Society of South Africa Special Publication,* 3, 157-161.

Molina Ballesteros, E., Campbell, E.M., Bourne, J.A. & Twidale, C.R. (1995): Character and interpretation of the regolith exposed at Point Drummond, west coast of Eyre Peninsula, South Australia. *Transactions of the Royal Society of South Australia*, 119, 83-88.

Monroe, W.H. (1968): The karst features of northern Puerto Rico. *National Speleological Society Bulletin*, 30, 75-86.

Mulcahy, M.J. (1973): Landforms and soils of southwestern Australia. *Journal of the Royal Society of Western Australia*, 56(1&2), 16-22.

Parker, A.J. (1993): Kimban Orogeny. In: Drexel, J.F., Preiss, W.V. & Parker, A.J. (Eds.): The Geology of South Australia. 1. The Precambrian. South Australia. *Geological Survey of South Australia Bulletin*, 54, 71-82.

Rankin, L.R. & Flint, R.B. (1991): *Streaky Bay, South Australia.* 1:250,000 Geological Atlas Series, map sheet SI 53-2.

Scott, G.D. (1967): Studies of lichen symbiosis 3. The water relations of lichens on granite kopjes in central Africa. *Lichenologist*, 3, 368-385.

Sweeting, M.M. (1973): *Karst Landforms.* Columbia University Press, New York, 362 p.

Twidale, C.R. (1979): The character and interpretation of some pediment mantles. *Sedimentary Geology*, 22, 1-20.

Twidale, C.R. (1982): *Granite Landforms.* Elsevier, Amsterdam, 372 p.

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

Twidale, C.R. (1988): Granite landscapes. In: Moon, B.P. & Dardis, G.F. (Eds.): *The Geomorphology of Southern Africa.* Southern Book Publishers, Johannesburg, (320 p.), 198-230.

Twidale, C.R. & Bourne, J.A. (1998): Origin and age of bornhardts, southwest Western Australia. *Australian Journal of Earth Sciences,* 45, 903-914.

Twidale, C.R., Schubert, C. & Campbell, E.M. (1991): Dislodged blocks. *Revue Géomorphologie Dynamique*, 40, 119-129.

Twidale, C.R., Campbell, E.M. & Vidal Romani, J.R. (1993): A-tents from The Granites, Mt Magnet, Western Australia. *Revue Géomorphologie Dynamique*, 42, 97-103.

Vidal Romani, J.R. (1989): Geomorfología granítica en Galicia (NW España). *Cuadernos do Laboratorio Xeoloxico de Laxe*, 13, 89-163.

Vidal Romani, J.R. & Twidale, C.R. (1998): *Formas y Paisajes Graníticos.* A Coruña, Servicio de Publicacións da Universidade da Coruña, Serie Monografías 55, 411 p.

Wilson, C.C. (1991): *Geology of the Quaternary Bridgewater Formation of southwest and central South Australia.* Unpubl. Ph.D. thesis, Flinders University of South Australia, Adelaide, 341 p.

Recibido el 1 de Diciembre de 1998
Aceptado el 20 de Febrero de 1999