Journal of Iberian Geology 41 (3) 2015: 365-383
http://dx.doi.org/10.5209/rev_JIGE.2015.v41.n3.48860

www.ucm.es/info/estratig/journal.htm
ISSN (print): 1698-6180. ISSN (online): 1886-7995

Journal of Iberian Geology
AN INTERNATIONAL PUBLICATION OF EARTH SCIENCES

Polygonal cracking associated to vertical and subvertical fracture surfaces in granite (La Pedriza del Manzanares, Spain): considerations for a morphological classification

M. García-Rodríguez[1], M. Gomez-Heras[2,3], M. Alvarez de Buergo[3], R. Fort[2,3]*, J. Aroztegui[4]

[1]*Grupo de Geología Facultad de Ciencias, Universidad Nacional de Educación a Distancia (UNED). c/ Paseo Senda del Rey, 9. 28040, Madrid, Spain.*
[2]*CEI Campus Moncloa, UCM-UPM. c/ José Antonio Nováis 12, 28040, Madrid, Spain*
[3]*Grupo de Petrología aplicada a la Conservación del Patrimonio. Instituto de Geociencias (CSIC, UCM). Madrid, Spain*
[4]*Facultad de Psicología. Universidad Complutense de Madrid (UCM). Campus de Somosaguas, 28223,Madrid, Spain*

*e-mail addresses: manu.garo@ccia.uned.es (M.G-R); miguel.gomez.heras@gmail.com (M.G-H); alvarezm@geo.ucm.es (M.AB); rafael.fort@csic.es (R.F, *Corresponding author); jarozteg@ucm.es (J.A)*

Received: 20 April 2015 / Accepted: 30 November 2015 / Available online: 20 December 2015

Abstract

The area known as Pedriza de Manzanares forms part of the Upper Manzanares River Basin and of the recently (June 2013) listed Sierra de Guardarrama National Park, located in the Spanish province of Madrid. The region is home to Late Palaeozoic granites characteristic of the Spanish Central Systam, which were intruded during the Variscan Orogeny and uplifted to their present position during the Alpine Orogeny.

Previous studies of polygonal cracking in granite suggest several possible control mechanisms. Some authors contend that weathering patterns are governed by internal geodynamic factors, such as the final stages of magmatic consolidation or differential movements in fault planes as a result of their structural position. Others claim that climate-related external factors, specifically insolation rates and thermal differences, can explain the predominance of a given orientation in such patterns.

The present paper is a study of the effect of case hardening on polygonal cracking, and the role of variables such as temperature and rock surface hardness in granite weathering. It also aims to establish a general systematic classification for polygonal cracking, focusing particularly on the cracking associated with the sub-vertical planes of fracture at Pedriza de Manzanares. The morphometric parameters associated with cracks and fractures, including strike and dip, are analysed, along with the height of occurrence and shape of polygonal cracks.

Keywords: Polygonal cracking, case hardening, granite weathering, Sierra de Guardarrama National Park

La Pedriza de Manzanares forma parte de la cuenca alta del río Manzanares en la provincia de Madrid, y desde junio de 2013 forma parte del Parque Nacional de la Sierra de Guadarrama. La zona está formada por granitos característicos del Sistema Central Español que intruyeron a finales del Paleozoico durante la orogenia Varisca y sufrieron un levantamiento hasta su posición actual durante la orogenia Alpina.

Trabajos previos sobre agrietamientos poligonales en granitos sugieren diversos posibles mecanismos de control. Algunos autores mantienen que los patrones de meteorización están controlados por factores geodinámicos internos relacionados con estados tardíos de consolidación magmática, o por movimientos diferenciales de planos de fractura, como consecuencia de su posición estructural. Otros autores apuntan que los factores externos tales como el clima, específicamente por diferencias térmicas debido a la insolación, pueden explicar la abunadancia de estas formas de acuerdo con un patrón de la orientación del afloramiento.

En este trabajo se estudia la influencia de los endurecimientos superficiales en la evolución de los agrietamientos poligonales, y se analizan variables como la temperatura y la dureza de la superficie rocosa en el proceso de meteorización del granito. Además, el trabajo trata de presentar una clasificación general de los agietamientos poligonales, incidiendo en los agrietamientos asociados a planos de fractura subverticales identificados en La Pedriza de Manzanares. Los parámetros morfométricos estudiados de los agrietamientos poligonales, incluyen la dirección e inclinación de la pared rocosa, la altura de aparición y su forma.

Palabras clave: Agrietamiento poligonal, meteorización de granito, Parque Nacional de la Sierra de Guadarrama

1. Introduction

1.1. Polygonal cracking: origin and description

Some rocks, most notably sandstones and granites but other types of rock as well, may develop cracks that form striking polygonal patterns. Polygonal cracking results in a mosaic in which the plate elements are separated by cracks or grooves that tend to form rhomboidal patterns (Twidale, 1982). These surface shells usually measure around 5 cm thick and vary in diameter from 2 to 24 cm (Vidal Romaní and Twidale, 2010).

Certain features of polygonal cracking can be attributed to the characteristics and fabric of the granite in the final stage of magmatic consolidation (Leonard, 1929). Intrinsic factors include the existence of fracturing and prior planes of weakness, rock composition and texture, or proximity to the land surface. Shearing-induced differential movement between planes may prompt rock stretching or shortening/compression (Twidale and Vidal Romaní, 2005; Martel 2011; Riley *et al* 2012), creating a surface fabric over these planes that may favour the advent of polygonal cracking (Bruner, 1984).

A number of exogen factors are known to be involved in polygonal cracking, the most prominent of which are climate-related (Johnson, 1927; Campbell, 1995), such as the weathering induced by insolation and chemical agents, rupture due to expansion of the shell or outer-most surface of the rock (Sosman, 1916; Schulke, 1973; Bradley *et al*. 1978), freeze-thaw processes that affect rock moisture (Twidale, 1982).

Polygonal cracks may form as a result of compression or decompression affecting the rock surface, but more likely the former (Robinson and Williams, 1987; Riley *et al*. 2012). Twidale (1982) describes polygonal cracking on convex surfaces of boulders in some parts of Australia, which denote compressive stress. Vidal Romaní (1990) associates the inception of polygonal cracks with a rigid-ductile process that would take place when the magma is practically consolidated, in the absence of fluid flow. In the presence of intense strain (Ramsay and Huber, 1987), spheroidal corestones are formed in the cubic or quadrangular blocks on which cracks also form (Twidale, 1982; Thomas, 1994; Twidale and Vidal Romani, 2005; Migon, 2006). When these fractures are weathered due to the presence of groundwater, corestone boulders are formed. Such forms normally occur parallel to the granite alteration front immediately above the unaltered rock. Their formation is attributed to preferential weathering of boulder corners and edges across the subsoil fracture network (Twidale, 1982). Groundwater circulating through the cracks reacts with micas and feldspars to form clay, which may take up water and expand, contributing to boulder scaling (Vidal and Twidale, 2010). Flaking is also often the result of spheroidal disjunction, a common structure in plutonic rock at the magma – host rock interface (Vidal Romani, 2008). When the sandy and clayey fraction is eroded out from the areas between the corestones, the concomitant decay entails loss of the structural layers. The result is the formation of landscapes dotted with granite boulders.

A general consensus appears to be in the making to the effect that the primary cause of curved fracture planes in granite is related more to compressive stress than to the decompression resulting from the relief of the surface load (Twidale and Burne, 2009). This would explain the prolific cracking on the radial surfaces in the area studied here. The surface area of spherical bodies raises the expansive power of rocks by 2/3, which would favour the development of polygonal cracking (Robinson and Williams, 1987).

Martel (2011) explained that in a curved surface under compressive stress, the stress state at any given point is defined by horizontal (or tangential) compression and vertical (or radial) tension may be exerted simultaneously, and three-dimensional stresses may vary with position

Further to Martel's model (2011) for the formation of parallel fracturing on curved surfaces, Riley *et al*. (2011, 2012) studied the formation of polygonal cracks on curved planes of fracture at Yosemite National Park.

In most cases the geometry of these polygons is impacted by the slope of the rock surface. In vertical walls, polygons are observed to elongate in the direction of the strike. Moreover, in vertical walls fractures often intersect at right angles, favouring the formation of square or rectangular polygons (Robinson and Williams and, 1987). With one-way stresses, the earliest cracks tend to form at right angles, giving rise to "orthogonal polygons" (Lachenbruch 1962, 1966). "Non-orthogonal" polygons forming five- or six-sided plates tend to be associated with very homogeneous materials exposed to abruptly applied stress (Lachenbruch 1962, 1966).

Vidal Romani (1991) related the formation of polygonal cracks on flat surfaces to the concentrations of forces parallel to the plane of fracture. Polygonal cracking associated with this process is common on dikes or sills whose composition differs from the composition of the host rock. When the rock mass moves along the fault plane, deformation may cause changes in the form and position of its constituent particles. Recent stress modelling studies (Lan *et al*., 2010) on granite indicate that the uneven geometry of mineral grains is the most significant factor in micro-scale cracking. Incipient cracks of tectonic origin continue to develop when exposed to the air (Twidale, 2002).

Insolation is a potential weathering agent due to the stress generated as a result of temperature differences (Rice 1976; Smith, 1977, Hall and André, 2003; Gomez-Heras *et al*., 2006, 2008; Riley *et al.,* 2012). In heterogeneous rock such as granite, the quartz and feldspar crystals have different thermal expansion coefficients and consequently react differently to weathering.

Moores *et al*. (2008) proposed a model in which hydration- and thermal weathering-mediated crack growth depends on the local water content around the rims of the cracks. Cracks exposed to less solar radiation retain more moisture than those receiving more radiation and are altered more quickly.

Although a number of authors have noted that the term polygonal cracking covers a variety of related forms that may have different origins, no attempt has ever been made to date to systematise these forms. Rather, the studies conducted have grouped them all under the same heading in pursuit of a single, all-encompassing cause. Geomorphological morphometric studies may give rise to misleading arguments if similar forms generated by different processes are bundled into the same terminological package, however. Polygonal cracking is a case in point, in which forms ranging from surface roughness to clearly developed polygons have been stamped with the same label.

1.2. Polygonal cracking and case hardening

Polygonal cracking in granite is often related to the presence of case hardening on the rock. The origin of such hardening is much debated and still open to question. The literature contains reports of case hardening on rocks of variable lithology in likewise variable climates. Papers have been published, for instance, on granite in France and Morocco (Wilhelmy, 1964; Robinson and Williams, 1987; Robinson ad Williams, 1992), Australia (Branagan, 1983) and many other areas of the world. In granite, case hardening is often associated with planes of fracture and corestone scaling. Depending on the characteristics of the hardened surface, the origin may be related to processes taking place under or on the surface.

Twidale (1982) and Campbell and Twidale (1995) found that sub-surface case hardening may be attributed to the concentration of iron, manganese and silica oxides (Twidale and Bourne, 1975), in turn the outcome of subedaphic alteration in areas where the rock was exposed to shear stress (Vidal and Twidale, 1998). It may also be a vestige of the iron concentration at the alteration front, which is often two- to threefold greater than in the fresh rock. Twidale nonetheless acknowledged that these oxides are not present in all polygonal cracks.

The origin of surface case hardening in granite is believed to lie in the evaporation-induced mobilisation of solutions containing weathered material on the rock surface and inner to outer capillarity. Precipitation of these materials would form a surface crust, creating a hardened surface (Garner, 1974; Twidale, 1982; Watson and Pye, 1985). Under these circumstances, the water in the rock may carry salts toward the surface where they precipitate and weakening the core (Hobbs, 1919).

As granite boulders often have concentric layers, cracks may be found cutting through several of these layers. This cracking pattern has been observed on corestones (e.g. in the Snowy Mountains, New South Wales) as well as on recently exposed bornhardts (Campbell and Twidale, 1995).

Fig. 1.- Location of the study sites (La Pedriza, Cenicientos, Zarzalejo and Valdemanco) in the Central System (Madrid Province, Spain).

Hardened surfaces help protect granite against erosion. When this hard shell cracks, weathering advances rapidly inward across weak areas such as small cavities or fractures, favouring differential surface weathering and forming micro-reliefs.Many factors contribute simultaneously to these weathering processes.

Ishimaru and Yoshikawa (2000) defined thermal gradients as one of the main factors contributing to micro-scaling. Van Autenboer (1964) contended that periodic humidity changes and salt crystallisation (Bradley *et al.,* 1978) are the mechanisms primarily responsible for the first phase of alteration in exposed granite surfaces. The present study explored the effect of solar radiation-induced temperature change (Gomez-Heras *et al*.; 2006; Riley *et al*., 2012; Vidal Romaní and Twidale, 2010) as one of the main agents of the surface alteration involved in polygonal cracking.

1.3. Aims

This paper contains an analysis of areas exhibiting polygonal cracking in the Spanish Central Range in the region of Madrid (Fig. 1). The general characteristics of the cracking identified at Cenicientos, Zarzalejo and Valdemanco are described, and the polygonal cracking at La Pedriza de Manzanares is studied in depth.

As part of the general aim, polygonal cracking in the region of Madrid was classified on the grounds of location, either on fracture planes or corestone scaling. More specifically, polygonal cracking was studied on vertical to sub-vertical planes of fracture on flat surfaces at La Pedriza de Manzanares and relationships were established among variables such as the height of cracking occurrence on the walls studied, orientation and dip of the planes where cracking appears, the dimensions, morphometry and geometry of the polygons formed, and crack depth. Granitoid surface temperature and hardness were studied as factors with an impact on polygonal cracking formation.

The polygonal cracking identified at La Pedriza, always associated with planes of fracture, was found in two environments: 1) on dikes intruding into the granite and exposed after one of the blocks covering it detached; and 2) on the surface itself of vertical and subvertical planes of the granite, which was often observed to exhibit case hardening. The present study explored the origin of the cracks on the latter type of surfaces in detail.

La Pedriza constitutes an essential part of the Sierra de Guadarrama National Park (Official State Journal-A-2013-6900), the acknowledgement of whose scientific and cultural significance dates back to the mid-nineteenth century, when the earliest descriptions of forms of granite alteration such as tafoni appeared (de Prado, 1864, ref. 1975). The geomorphological value of La Pedriza contrasts with the relative paucity of papers, particularly in international journals, on the forms and processes of granite alteration in the area. The present article aims to contribute to a scientific understanding of this emblematic region.

2. State of the art in the Sierra de Guadarrama

Polygonal cracks are often present in the granitoids that comprise the Sierra de Guadarrama, a sub-range of the Spanish Central Range (Fig. 1).

The petrological properties of the granitoids comprising the various plutons in the Sierra de Guadarrama favour the forms of decay observed (Centeno, 1988; Villaseca, 1985). The granite outcrops with the largest grain size (medium-coarse grain monzogranite), such as in the Cenicientos and Zarzalejo areas (Fort *et al.*, 2013), exhibited greater disaggregation than the rock with smaller grain sizes. Earlier studies on the Central Range (De Pedraza, *et al.,* 1989; García-Rodríguez *et al.*, 2014 a, b; Martínez, 2011) identified polygonal cracking on: planes of fracture; intrusive dikes with lithology that differed from the host rock; and convex surfaces on granite boulders.

By way of introduction to polygonal cracking on granite boulders in the Spanish Central Range, outcrops at or around Cenicientos and Zarzalejo in the province of Madrid are described here as examples of a characteristic boulder-strewn

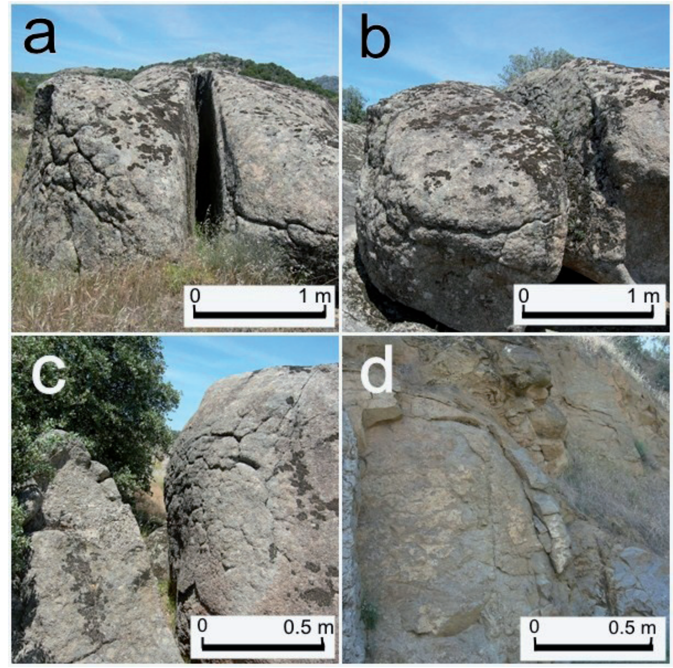


Fig. 2.- (a) Boulder split by a fault in the SSW-NNE direction, with polygonal cracking on the S, SW and W faces, in which the central fracture, protected from solar radiation, has no cracks; (b) boulder split by a fracture in the SSW-NNE direction, with displacement of both parts and polygonal cracking on the S, SW and W faces, including the top of the central fault exposed to solar radiation; (c) cracks on the convex surfaces of granite boulders facing SW; (d) weathering-induced subsoil boulder formation along concentric planes of fracture or corestone.

landscape with substantial polygonal cracking. A petrographic study conducted at Cenicientos (Martínez, 2011) identified the primary constituents of the granite to include quartz, alkaline feldspar, plagioclase and biotite. Zircon and apatite were found to be the most abundant accessory phases, and sericite aggregates the predominant secondary minerals. According to García-Rodríguez *et al.* (2014 a), polygonal cracking is present on both vertical planes of fracture and convex surfaces on boulders in the area around Cenicientos. In both cases, the cracks were located facing E, S and W only, suggesting a relationship between crack origin and solar radiation (Martínez, 2011). Support for such a relationship is found in the presence of cracks at the top of fractures, part of which would be exposed to greater radiation after displacement, favouring crack development (García-Rodríguez *et al.,* 2014 a) (Figs. 2a and 2b). García-Rodríguez *et al.* (2014 a) related the origin of the cracking in the boulders at Cenicientos to the main directions of regional fracturing and to corestone scaling in such boulders prior to granite exhumation (Fig. 2c and 2d).

On granite boulders at Cenicientos and Zarzalejo, polygonal cracking was found to be related to case hardening, which generates an outer surface more resistant to erosion than the inner stone. In crystalline rocks such as granite, this process entails a loss of inner cohesion (Conca, 1985). When cracks develop on granite boulders, the hardened plate often detaches altogether, giving rise to tafoni near the bottom (de

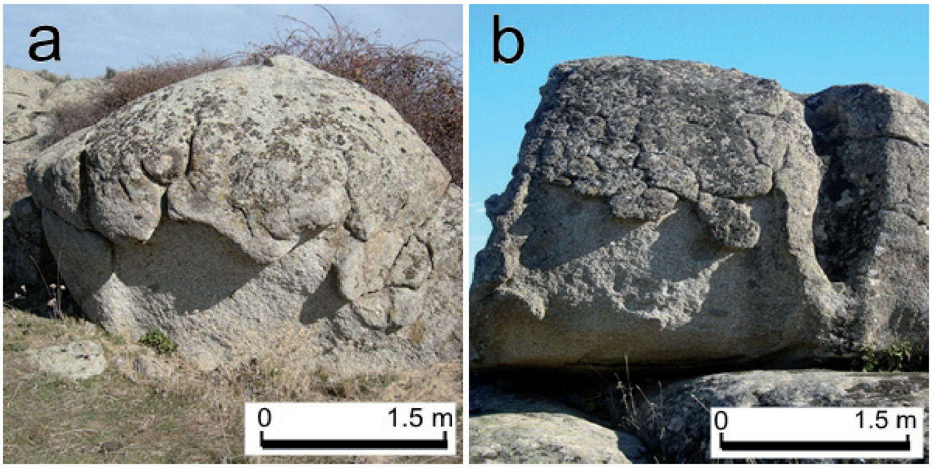


Fig. 3.- (a and b) Incipient tafonisation in granite altered due to the detachment of the hardened plates of polygonal cracks at Zarzalejo, Madrid, Spain.

Prado, 1864, ref. 1975) on an area where the material is less hard (Vidal Romani, 2008) (Fig. 3). While a general review of the polygonal cracking identified at different places in the Spanish Central Range (Madrid area) was conducted to study the characteristics of the cracking associated with vertical and sub-vertical planes of fracture, the present study focused on La Pedriza de Manzanares. This location is distinctive in that not a single case of polygonal cracking was observed on boulders such as discussed above.

3. La Pedriza de Manzanares

La Pedriza de Manzanares stretches across 4,958 Ha (Comunidad de Madrid, 2007) on the southern side of the Sierra de Guadarrama, where it forms a complex slope between the Cuerda Larga Range (elevation > 2 000 m) and pediment near Manzanares el Real, a village located at an elevation of 900 m.

La Pedriza de Manzanares can be divided into two well-defined areas with somewhat different mineralogical and geomorphological properties, known as *La Pedriza posterior* (rear La Pedriza) and *La Pedriza anterior* (front La Pedriza). La Pedriza posterior is located north of La Pedriza anterior and includes the highest lying areas, such as Torres de la Pedriza (2 029 m). La Pedriza anterior, where the area studied here lies, stretches from Manzanares el Real to the Dehesilla Pass - Cabrón Pass fault, covering a total land area of 1 580 Ha. The elevation fluctuates from around 900 m in the village to 1 719 m at Yelmo summit.

The region has Mediterranean climate, temperate to cold and relativelely humid (due to the orographic effect on rains). In the lower parts of Pedrida (altitude between 800 and 1200 m) rainfall annual average is 800-900 mm, and annual average temperature is 11-12°C. In the upper parts (altitude 1200-1600 m) rainfall is 1000-1500 mm, and temperature is 9-10°C.

The Central Range, once a part of the Variscan ranges in western Europe although most of the relief had been eroded away by the late Cenozoic, has been studied since the mid-twentieth century (Peinado *et al.*, 1981; Díaz *et al.,* 2007). The present Central Range arose when the Alpine Orogeny reactivated Variscan fractures and created a series of uplifted and down-thrown blocks. The three major phases of that orogeny extended across the Oligocene and the Quaternary (Capote *et al*., 1990), initiating an erosive process that gave rise to correlative sediments in the Madrid basin (Mejías *et al.*, 1883).

The predominant fracture system stretches in the E-W, ENE-WSW direction. At least two types of fractures can be distinguished. The first ones consist of, approximately plane, orthogonal cracking network characterised by a lattice of parallel fractures that may be vertical, horizontal or slanted. Such a large-scale fracture system and intense weathering initiated in the rock massif under subaerial conditions have made balanced rocks or tors very common formations at La Pedriza. In the second, curvilinear fractures follow along planes of fracture more or less parallel to the convex surface of the outcrops, forming concentric layers, known as onion-skin weathering or spalling. The resulting reliefs contain domal formations and give rise to large walls of varying dip (Centeno and García-Rodríguez, 2005). These curved planes run predominantly E-W and face south. As a rule, they are more “sub-vertical” (as studied surfaces dip between 70 and 90 degrees), at the base and have a shallower strike at the top. In La Pedriza specifically, the Alpine uplift generated a staircase morphology, while weathering along the fractures favoured the formation of regoliths and, as they eroded, the present etched landforms (De Pedraza, 1978; Centeno, 1988; De Pedraza *et al.,* 1989; García-Rodríguez *et al.,* 2008).

The La Pedriza pluton, and in particular the La Pedriza anterior pluton, is a coarse to medium-grained leucogranite. While this leucogranite has a very homogeneous texture, the grain size may decreases towards the contact surface.

The most prominent petrographic and mineral features of the La Pedriza leucogranites can be summarised as follows: crystallised microperthitic K-feldspar prevails, followed by quartz and plagioclase, and usually some biotite. Zircon, apatite, xenotime and monazite are the most common minority minerals. Plagioclase occurs as poorly-zoned, subhedral to anhedral crystals. An intergranular albite-rich (in some cases, myrmekitic) plagioclase film commonly develops between the plagioclase and K-feldspar crystals. Biotite, the main mafic mineral in the La Pedriza leucogranites, occurs as subhedral to euhedral flakes (Pérez-Soba and Villaseca, 2010). Further information on regional leucogranite mineralogy, petrography and chemical composition can be found in Villaseca *et al.* (1998), Bea *et al.* (1999) and González del Tánago *et al*. (2004). At La Pedriza, hypabyssal rocks, most prominently microdiorite/aplites and granitic porphyry constitute dikes running inside the granitic rock matrix in an E-W direction.

4. Methodology

4.1. Identification of polygonal cracking typologies

An exhaustive field study was conducted to locate polygonal cracking at La Pedriza de Manzanares.

The cracks identified were initially classified by the type of surface on which they were found: (1) the upper slopes of curvilinear fractures surfaces (2) the underslope of curvilinear fractures surfaces (3) the lower part of vertical walls, and (4) on vertical or subvertical planes of fracture, including balanced rocks, and always along the planes of fracture. No cracks were detected on the convex surfaces of granite boulders.

Convex planes of fracture, which are common at La Pedriza, range from just a few to around one hundred metres in size (García-Rodríguez *et al*., 2014c). Their origin is associated with compressive stress, as attested to by certain a-tent structures and decompression-induced scaling (Pedraza *et al.,* 1989). Cracking is more highly developed on convex planes fracture (Riley *et al.* 2011; 2012) and features characteristics that differ from the properties found in vertical plane cracking and, therefore, this paper does not deal with them. Nonetheless, as the information gathered about those sites during the field work conducted proved to be of interest, it is mentioned in the results.

This review of the types of cracking present in the area studied was followed by an inventory of the sites exhibiting cracking on vertical planes only, to confine the research to a single pattern. The following information was entered in the inventory (Table 1): cracking order number, name of the wall where cracking was identified, geographic coordinates and elevation, location on the wall and orientation, wall strike and dip, height of occurrence measured from the ground, and shape of the polygons.

Since the study aimed to explore crack morphometry and establish relationships among the variables analysed (size, shape, height relative to the ground, plane orientation and dip, depth of the crack and frequency of occurrence in the cracking sites), the focus was placed on a series of walls with the same genetic pattern located within the confines of La Pedriza anterior.

4.2. Selection of sites with polygonal cracking on vertical planes

The area chosen met the characteristics defined: rocks with a homogeneous mineralogy, presence of vertical fracture planes with flat surfaces and the same morphoclimatic environment. The area studied stretched across 1 400 hectares, with elevations ranging from 1 000 to 1 500 m.

Six representative sites (known locally by climbers as Murito, Muro de Snoopy, Risco del Martes, Pared Naranja, Camino del Tranco and Bloque de los Brezos) were chosen from among the ones inventoried (Fig. 4). All of them exhibited well-developed polygonal cracking and sufficient accessibility (by mountaineering as required) to take the measurements (Table 2).

The parameters chosen to characterise the occurrence, orientation and morphometry of polygonal cracking were as follows.

Nº	Name	X	Y	Z (m)	Location and orientation	Strike	Dip	Height off ground (m)	Shape PC*
1	Murito(E)	40º44'59,34"N	3º53'17,20"W	1180	Frac. plane, wall (S)	N82ºE	50ºS- 90ºS	2-6.5	Qua.
2	Murito(W)	40º44'59,34"N	3º53'17,20"W	1180	Frac. plane, wall (S)	N80ºE	70ºS- 87ºS	4–6	Rho.
3	Pared Naranja	40º45'08,50"N	3º53'10,66"W	1204	Frac. plane, block (S)	N60ºE	85ºNW	0.5-4.9	Rec.,Irr.
4	Bloque los Brezos	40º45'03,12"N	3º53'12,32"W	1162	Frac. plane, balanced rock (E)	N5ºE	85ºE	3–4.25	Irr.
5	La Nuez	40º45'06,54"N	3º53'10,31"W	1186	Frac. plane, balanced rock (W)	N2ºE	70ºE	15-20	Irr.
6	Tres Puntas	40º44'53,09"N	3º53'09,63"W	1232	Frac. plane, wall (N)	N74ºE	88ºN	2–10	Rec.
7	Reloj(S)	40º44'48,47"N	3º52'54,53"W	1192	Frac. plane, wall (S)	N80ºE	78ºS	2–5.5	Irr.
8	Reloj(W)	40º44'48,47"N	3º52'54,53"W	1192	Frac. plane, wall (W)	N0º	90ºW	20-25	Irr.
9	Muro de Snoopy	40º44'52,25"N	3º52'33,44"W	1253	Frac. plane, wall (SE)	N48ºE	71ºSE	15-20	Qua.
10	Caracol	40º44'48,96"N	3º51'55,63"W	1234	Frac. plane, wall (S)	N85ºE	68ºS	12-15	Irr.,Qua.
11	Camino delTranco	40º44'41,98"N	3º52'52,09"W	1068	Frac. plane, wall (W)	N170ºS	89ºW	4.5-5	Rec.
12	Risco del Martes	40º45'03,50"N	3º51'49,41"W	1322	Frac. plane, wall (E)	N172ºE	74ºW	3-4.5	Rec.
13	Peñas Cagás (S)	40º45'11,90"N	3º51'30,17"W	1383	Frac. plane, wall (SE)	N64ºE	71ºSE	20-50	Irr.
14	Peñas Cagás (W)	40º45'11,90"N	3º51'30,17"W	1383	Frac. plane, wall (W)	N178ºE	90º	30-40	Irr.
15	Cinco Cestos (E)	40º45'06,02"N	3º52'29,60"W	1405	Frac. plane, balanced rock (E)	N0º	88ºE	8-12	Irr.

*** Polygonal crack shape:** Qua:quadrangular; Rho: rhomboidal; Rec: rectangular; Irr: Irregular

Table 1. Inventory of areas identified in La Pedriza where polygonal cracking on vertical and subvertical planes was detected.

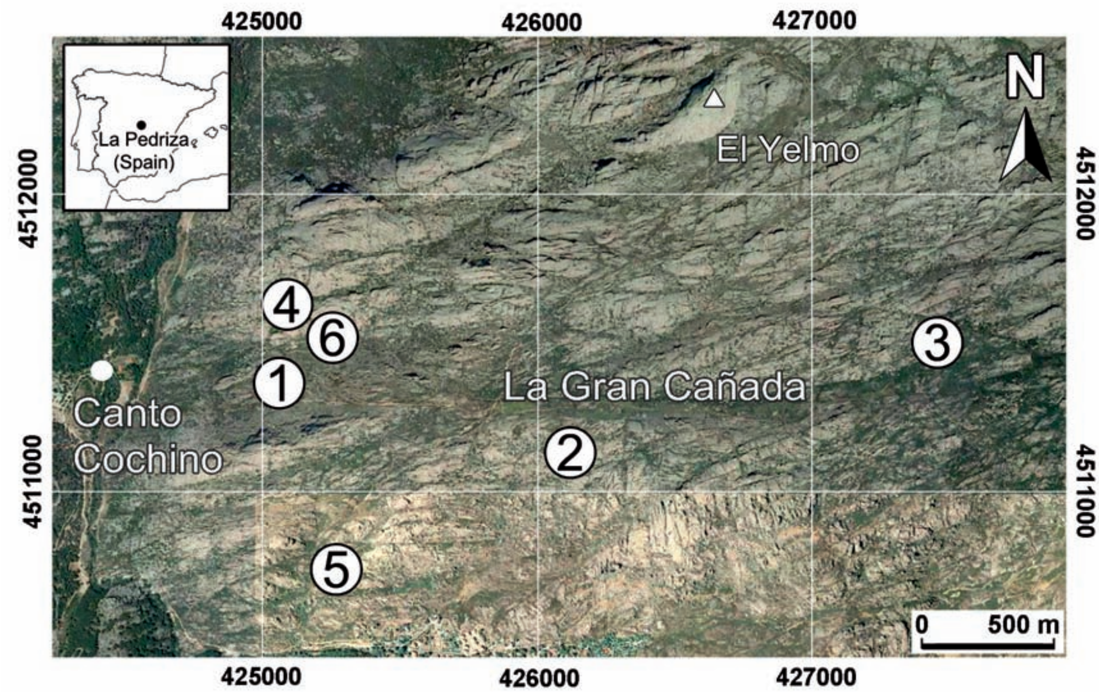


Fig. 4.- Orthophoto of Pedriza anterior (source: Comunidad de Madrid), showing the location of the polygonal cracking sites selected for this study. 1- Murito, 2- Muro de Snoopy, 3-Risco del Martes, 4-Pared Naranja, 5- Camino del Tranco, 6- Bloque de los Brezos.

The height of cracking occurrence with respect to the base of the wall studied was measured to identify relationships between the polygon size and groove depth on the one hand and height and distance from the ground on the other.

The mean inclination for the section describes the angle and direction in each section of wall where polygonal cracking was detected. The aim of these measurements was to select walls with a homogeneous inclination to be able to establish morphometric relationships between cracks located on similarly vertical walls. In addition to the wall dip angle, the direction of the dip was recorded with respect to the cracking orientation. This measurement identified the walls that were slightly cantilevered, to determine the possible effect of that configuration on morphometric relationships.

The lengths of the longer (M) and shorter (m) polygon axes were measured at right angles to one another. This paper reports the mean values for five to nine measurements of the long and short axes at each height interval selected for each wall. The number of readings depended on the proliferation of shapes in each section and wall. The total (N) per axis in each interval, along with the mean and standard deviation, are given in Table 2. The measurement intervals ranged in size from 0.5 to 1 m, depending on the height of the wall and total area of cracking occurrence.

A size factor relating the long and short axes of the polygons measured at right angles, defined as (M+m)/2, was used to facilitate data analysis so that just one value per section would reflect the variation in polygon size with height. This factor was not intended to define the geometric shape of the cracking, but rather to simply express the relationship between variations in size and height. The geometric shape of the polygons in each section was described. Polygons may be quadrangular, rhomboidal, rectangular or irregular. The shape was described to establish the relationship between the orientation of the sides of the polygons and the fracture system affecting the wall. More specifically, the geometric description of the polygons was used to identify the relationship between the fracture network and rectangular, quadrangular and rhomboid cracks. Determining the angular relationships that define the polygon vertices was not one of the aims pursued.

A gauge was used to measure groove depth in each section. This measurement furnished information on the variation in crack depth with height over the ground.

The angle formed between the pre-existing fracture lines on the wall affected by polygonal cracking and the sides on the polygons (grooves) was determined to study the angular deviation between them.

The angles between the fracture lines and the sides of the polygons were measured to verify whether polygon morphology varies depending on the pre-existing fracture system. Orthogonal photographs of the wall were used for these measurements. A 0º angle means that the fracture line concurs with the grooves, while a 90º angle is the maximum angular difference between fractures and polygons. These measurements were taken on five of the six sites selected, but had to be ruled out in “Bloque de los Brezos” due to the irregularity of its polygons and severe weathering of its sides.

The mean size factor values for each interval and wall were plotted on the same graph to determine the existence or otherwise of a relationship between the height of occurrence measured from the ground and the size of the polygons expressed as their size factor. The statistical techniques used should be

Name (height) sample	Height off ground (m)	Dip	M (mm)	m (mm)	(M+m)/2	PC shape*	Depth range (mm)
Murito W (9 m high) N=28	6.5-5.5	70ºS	M=374.25 SD=147.97	M=224.25 SD=85.53	M=299.25 SD=112.13	Qua. Rho.	10–50
	5.5–5	85ºS	M=287.87 SD=72.29	M=212.37 SD=53.17	M=250.12 SD=59.44	Qua. Rho.	4–20
	5-4.5	87ºS	M=200.67 SD=34.19	M=146.11 SD=43.17	M=173.39 SD=35.29	Qua. Rho.	4–20
	4.5–4	87ºS	M=213.57 SD=89.38	M=152.86 SD=49.55	M=183.21 SD=65.07	Qua. Rho.	Negligible
	4–0	87ºS	No cracking observed				
Muro de Snoopy (33 m high) N=64	20-19	70ºSE	M=240.37 SD=58.87	M=168.41 SD=58.95	M=204.37 SD=58.87	Qua. Rho.	40–50
	19-18	71ºSE	M=242.75 SD=58.72	M=174.67 SD=54.00	M=208.71 SD=53.04	Qua. Rho.	10–20
	18-17	70ºSE	M=220.41 SD=46.47	M=147.92 SD=37.55	M=184.17 SD=36.80	Qua. Rho.	10–20
	17–16	72ºSE	M=254.77 SD=40.40	M=183.62 SD=72.41	M=184.81 SD=73.29	Qua. Rho.	10–20
	16–15	71ºSE	M=214.53 SD=32.99	M=141.67 SD=29.16	M=141.67 SD=29.16	Qua. Rho.	5–10
	15–0	72ºSE	Rhomboidal fractures but no cracking				
Risco del Martes (5.5 m high) N=21	4.5–4	74ºW	M=210.14 SD=92.19	M=145.14 SD=19.72	M=177.64 SD=52.79	Obl. Rec.	10–25
	4–3.5	74ºW	M=157.86 SD=55.16	M=90.29 SD=26.44	M=124.07 SD=36.93	Obl. Rec.	5–20
	3.5–3	74ºW	M=123.57 SD=53.53	M=85.57 SD=27.60	M=104.57 SD=37.87	Irr.	4–10
	3–0	74ºW	No cracking observed				
Pared Naranja (5 m high) N=34	5–4	85ºNW	M=284.00 SD=51.47	M=140.00 SD=43.20	M=212.00 SD=40.22	Ver. Rec.	10–20
	4–3	85ºNW	M=320.00 SD=102.54	M=155.00 SD=94.26	M=237.50 SD=68.82	Ver. Rec.	10–20
	3–2	85ºNW	M=395.56 SD=76.01	M=177.78 SD=49.44	M=286.67 SD=58.31	Irr.	10–20
	2–1	85ºNW	M=594.29 SD=137.46	M=262.86 SD=85.97	M=428.57 SD=80.71	S-ho. Rec.	5-5
	1-0	85ºNW	No cracking observed				
Camino del Tranco (9.5 m high) N=8	5–4.50	89º W	M=653.00	M=27.00	M=340.00	Rec.	20–70
	0–4.50	89º W	Shapes poorly defined				
Bloque los Brezos (5 m high) N=13	4.25–3.25	85º E	M=319.62 SD=76.68	M=257.75 SD=67.97	M=288.69 SD=71.71	Irr.	20–50
	3.25- 3	85º E	M=142.75 SD=116.37	M=108.50 SD=71.08	M=125.62 SD=93.72	Irr.	5– 30
	0–3.25	85º E	No cracking observed				

Table 2. Summary of measurements taken in the six sites selected.

considered, in this context, as an exploration analysis. New studies should follow the current one using wider samples and more rigorous statistical techniques such as weighted least-squares fitting or the like.

Pearson's correlation coefficient was used to determine the strength of the relationship between size factor and height. This coefficient may adopt values of -1 to 1, in which "0" denotes no relationship between the variables studied. A value of 1 means that the two characteristics are perfectly and directly related (rise or decline in parallel), while a value of -1 indicates a perfect but indirect relationship, whereby one of the variables rises when the other declines. In other words, if more than one variable proves to impact polygon size, Pearson's coefficient identifies the relative importance of each.

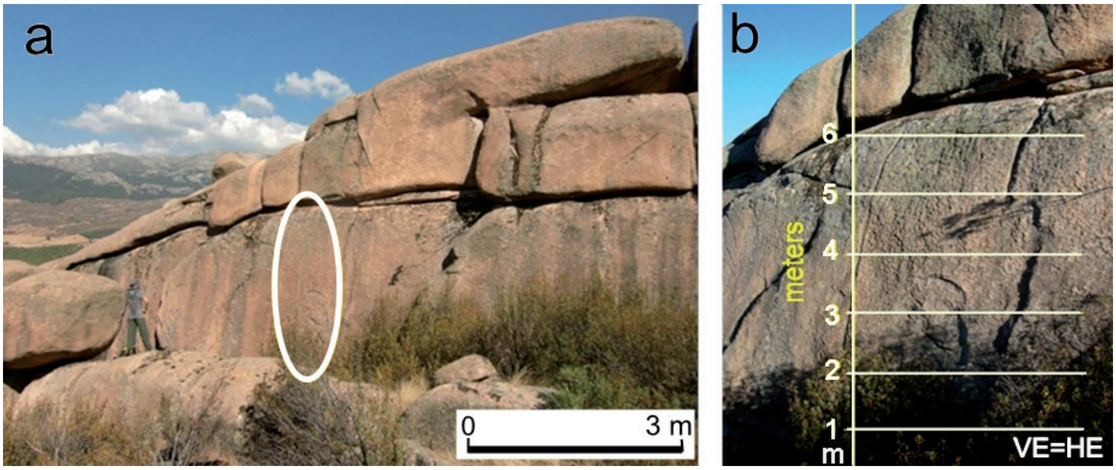


Fig. 5.- (a) Overview of the rock wall studied showing the specific area examined; (b) detail of sections into which the strip was divided. VE= vertical scale VH= horizontal scale.

Finally, the coefficient of determination was calculated to establish the weight of the relationship between height and size factor, or more technically, the percentage of the variation in the response variable (plate or polygon size) explained by the explanatory variable (height). A determination coefficient with a value $r^2 = 0$ is an indication that the variability of the response variable (size factor) is unrelated to the variation in cracking height. By way of (a fictitious) example, an r^2 value of 0.80 would mean that for the wall in question, approximately 80 % of the variability in the size factor would be associated with variations in height.

4.3. On site characterisation

A fuller understanding of grooving in polygonal cracking on vertical walls was sought by determining its relationship with variables such as solar radiation, the presence of case hardening and hardness. The east wall of Murito was monitored for that purpose. The polygonal cracking at the top of Murito (E) was studied, together with wall micro-roughness, as precursor of polygonal cracking, along a strip 1.5 m wide running from the ground to a height of 6.5 m (Fig. 5).

Murito (E) slants at angles ranging from 50º S at the top (from 6 to 6.5 m) to nearly 90º S at ground level. The wall surface exhibits a series of parallel pre-existing fractures spaced at 5 to 50 cm. The surface strip studied ran uninterruptedly from the ground to the top along a single plane of fracture. Fracture surfaces or spalls on the sides of the strip selected were disregarded, for they may have left the rock surface exposed for a longer or shorter time, with concomitant differences in the degree of weathering. The surface studied corresponded to a single pre-existing fracture plane.

In addition to the parameters studied for the cracking at La Pedriza in general, the following were measured at Murito (E).

Micro-roughness size and shape were measured with a measuring tape along the entire height of the wall at 0.5-m intervals to ensure systematic measurement. At least five readings of rock irregularities were taken at each 0.5-m interval on the strip selected. The long and short lengths and depth of each protrusion were measured, along with its height off the ground and the wall slant. The axis measurements were applied to find the (M+m)/2 factor explained in Phase I.

The wall surface temperature was logged with i-button type sensors positioned at several heights. The aim was to relate the temperature variations recorded along the height of Murito to the degree of roughness and the presence of case hardening. Readings were logged continuously for a year, between 15 September 2012 and 15 September 2013. Four sensors (B1, B2, B3 and B4) were placed on the south side of Murito and a fifth one (B5), placed on the north side of a block in front of Murito for comparison. Sensors B1 and B2 were placed on the upper part of Murito: B1 at a height of 6.2 m on the polygonal crack plate and B2 at a height of 6.1 m in the groove between polygons. Sensors B3 and B4 were positioned at heights of 4.2 and 2.3 m, respectively in the area where polygonal cracking has not developed yet.

Granite hardness measurements were taken with a Proceq N34 Schmidt hammer across the entire studied strip. Five measurements were taken in each 0.5-m interval on the peaks of the protrusions and a further five in the valleys. As a rule, the measurements were taken on polygons or the remains of case hardenings and in the grooves or areas where the hardening had detached.

A one way ANOVA was run on the relationship between the rock hardness measurements on the external and internal areas of the polygons.

4.4. Petrography and mineralogy

Representative samples of case hardening and substrate were taken. These samples were analysed with X-ray diffraction (XRD). A thin section mineralogical study was also conducted on the La Pedriza granitoids, both with case hardening and in the more weathered areas where it had detached.

5. Results and discussion

5.1. Polygonal cracking, general classification

As mentioned elsewhere, geomorphological studies may give rise to misleading arguments if similar forms generated by different processes are bundled into the same terminological package. The authors of this paper propose the following classification of polygonal cracking (Fig. 6). Although this classification is based primarily on the observations in the various areas of the Central Range studied, it is general enough to describe polygonal cracking in granites anywhere. D and E polygonal cracking on boulders was not found in La Pedriza.

5.2. Polygonal cracking in La Pedriza

The polygonal cracking observed at La Pedriza de Manzanares can be divided into three basic types.

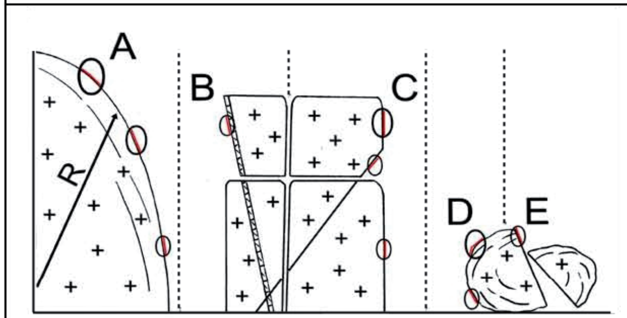
a) Cracking on large radial surfaces (Type A, Fig. 6). As a general rule, the cracking observed on these large radial surfaces has much more highly developed and more intensely weathered grooves (Riley *et al*., 2012) than the cracking on subvertical planes. Moreover, while the subject was not specifically addressed in this study, very highly developed cracks were also identified in connection with the fractures on the curved upper slopes of very high walls. The polygons on these outcrops were observed to be larger at the upper slope and decline in size at the underslope, where their position is vertical-subvertical. In these areas the gap between the cracking plates and the wall measures up to 5 cm, and the two are attached at the bottom only, forming what are known locally as "mushrooms". The intense development of these polygons and the depth of the groove along their edges may be explained by the fact that rainwater and runoff are retained longer in areas with a shallower slope, further to the model proposed by Moores *et al*. (2008), in which hydration- and thermal weathering-mediated crack growth depends on the local water content around the rims of the cracks.

b) Cracking on intrusive dikes that fill fractures in the granite (Type B, Fig. 6), identified in the area but not studied here.

c) Cracking identified on vertical-subvertical planes (90º-70º) affecting the granite itself, often related to 1-2-mm case hardening (Type C, Fig. 6). Such cracking forms an orthogonal or semi-orthogonal fracture network running W-E or WSW-ENE and N-S. The heights of the walls comprising these planes range from only a few to over one hundred metres.

This study is focussed on the establishment of relationships between polygon shape, fracture network and size distribution and height in Type C polygonal cracking (including some balanced rocks). This type was selected because cracks positioned on curved planes were not measurable due to the extreme weathering prevailing in the grooves. The cracks on intrusive dikes could not be analysed for similar reasons. No cracking was observed along the lowest portion of the outcrop in any of these cases (Types A and C). That may be due to the fact that the time of exposure to the agents of decay (insolation-moisture) is necessarily longer at the upper slope, favouring greater weathering, action which interred lower areas would be spared. This lowest portion was considered therefore precursor of Polygonal cracking.

Classification of polygonal cracking (PC)



Type	Description	Appearance General trend	Examples
A	PC associated with large radial planes of fracture Normally over 30 m high	Irregular shapes with deeply grooved cracks denoting severe erosion Plate size and groove depth tend to decline with height	Pedriza
B	PC associated with intrusive dikes of different lithology than the host granite	Highly variable shape, dependent upon dike lithology Neither size nor shape exhibits a recognisable pattern	Pedriza Valdemanco
C	PC associated with straight, vertical or slanted planes of fracture Includes tor planes	PC shape conditioned by the direction of the network of secondary fractures Plate size and crack depth tend to decline with height	Pedriza Valdemanco Cenicientos Zarzalejo
D	PC on granite boulders and corestone	PC with irregular shapes Plate size and crack depth tend to decline with height	Cenicientos Zarzalejo
E	PC in fractured boulders	PC with irregular shapes Common on the outer areas exposed to solar radiation	Cenicientos Zarzalejo

Fig. 6.- Proposed classification of polygonal cracking (PC) with examples in the Spanish Central Range around Madrid.

5.3. Type C polygonal cracking in La Pedriza

Due to the staircaise structure of La Pedriza, the tallest walls usually face south and have a likewise south-oriented dip. The proliferation of W-E faults is responsible for the step-like relief on the slope of La Pedriza anterior seen from Manzanares el Real, a nearby village. Muro de Snoopy would be an example of the walls in the area studied with heights of 80 to 150 m, whereas vertical walls measuring 3-4 to 40 m high are frequently observed. Examples of the latter discussed in this paper include Murito, Pared Naranja, Los Brezos and Camino del Tranco.

A review of Table 1 reveals that the most prolific and highly developed polygons face south-southeast (46.6 % of the cases), west (26.6 %) or east (20 %). At 6.6 %, north-oriented cracking was found to be the least frequent. The inference is that solar radiation appears to play a significant role in cracking formation, which is more frequent in the orientations where it is most intense.

The distribution of the cracking plates by shape was recorded as follows: irregular, 60 %; rectangular, 23%; quadrangular, 10 %; rhomboidal, 7 %. Where the slope is shallower near the top of the walls, the depth of the inter-plate fissures is greater in those areas. This may be the result of runoff moisture. Crack depth was also found to be determined by the secondary fracture system orthogonal to the wall and the maximum depth of the cracks is impacted by the grooves formed by pre-existing fracture systems. Figures 7a and 7b show the directions of the fracture system in La Pedriza anterior. In Figure 7a, the regional scale fractures were graphed on the grounds of a random sample of 148 measurements. The characteristics of the strikes for the walls selected (see inventory in Table 1), shown in Figure 7b, were subsequently used to study of the shapes of the polygons developing on their surface.

The occurrence of polygonal cracks on certain balanced rocks (Los Brezos, La Nuez and Cinco Cestos), where the original planes of fracture are perfectly visible, revealed the existence of a direct relationship between the planes of fracture and polygonal cracking. The spherical balanced rocks resulting from subsoil weathering observed at La Pedriza show no sign of cracking, despite having been exposed for the same amount of time as other rocks with obvious planes of fracture. This may be explained by the paucity of granite boulders with concentric fractures, in whose absence the development of cracking along such pre-existing planes of fracture is not favoured. At Cenicientos and Zarzalejo, where more corestone-like structures were observed, the situation was very different (García-Rodríguez *et al*., 2014a).

The measurements taken at the six sites listed in Table 1 (Murito (W), Muro de Snoopy, Risco del Martes, Pared Naranja, Camino del Tranco and Bloque de Los Brezos) are given Table 2. Details of the polygonal cracking in each are illustrated in the photographs in Figures 8, 9 and 10.

Wall	Angle between fracture lines and sides of polygons (grooves)
Murito (W)	3.90
Muro de Snoopy	7.80
Risco del Martes	5.63
Pared Naranja	5.63
Camino del Tranco	4.88
Mean	4.47

Table 3. Smallest angle between fracture lines and sides of polygons (n = 44).

The measurements taken at the six sites selected and listed in Table 2 were used to establish morphometric relationships. The findings are discussed below.

For nearly all the sites studied, a direct relationship was found between fracture system orientation (fracture lines) and spacing on the one hand and cracking geometry on the other. In one case, cracking polygons with curved sides were identified, following the pattern of curved secondary cracks that lie perpendicular to the vertical and planar wall (Risco del Martes). The angle formed between the fracture lines and sides of polygons (grooves) for each individual wall and the mean angle for all the walls are listed in Table 3. A very small angle indicates that the cracking is closely aligned with the fracture system. Due to the irregularity of the sides of the polygons on the Bloque de Los Brezos wall, which are deeply weathered, the angles formed with the fracture lines could not be measured. As a result, no data are given for this site in Table 3.

Angles measure groove rotation relative to walls' fracture networks. A large angle means that cracking geometry deviates from, i.e., is scantly aligned with, the fracture system. The values obtained, from 3.90º to 7.80º with a mean of 4.47º, denote close alignment between cracking and the fracture system. In a similar vein, Figure 11 shows the size of the angles formed between the cracking polygons and the fracture system, based on measurements taken at each interval on each wall. The number of measurements with angles between cracking and fractures of under 5º was very high for all the studied outcrops, supporting the hypothesis that cracking is aligned with the fracture systems.

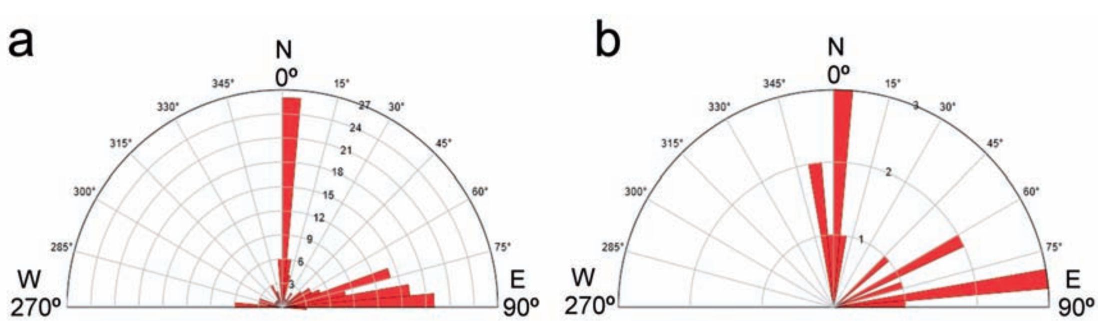


Fig. 7.- Strikes: (a) main planes of fracture in Pedriza anterior based on a random sample of 148 measurements (b) walls with cracks inventoried in Table 1.

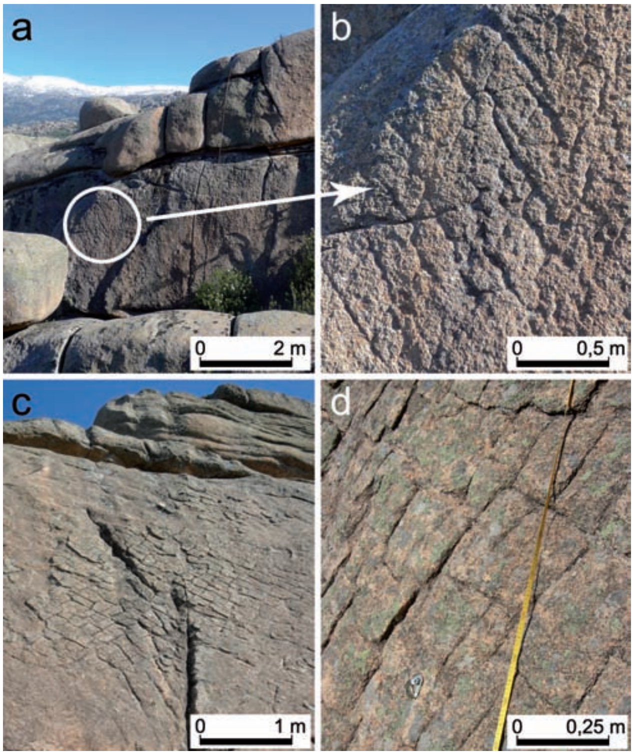


Fig. 8.- (a) Murito, overview; (b) detail of cracking on Murito (W), where the measurements were taken; (c) polygonal cracking on Muro de Snoopy, system of quadrangular or rhomboidal cracks running along a secondary fracture system perpendicular to the main wall; (d) detail of cracks.

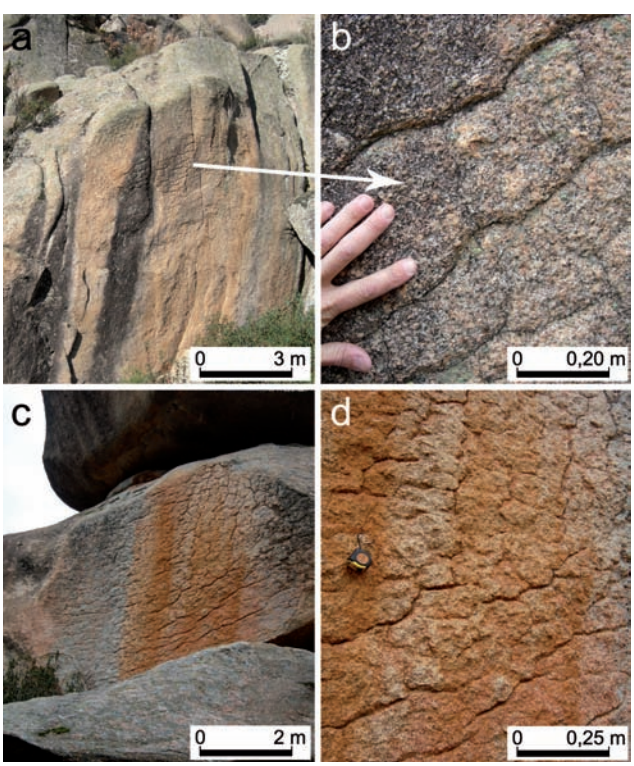


Fig. 9.- (a) Overview of Risco del Martes wall and fracture system; (b) cracking detail (east orientation) and detail of fracture lines associated with polygon shape; (c) overview of polygonal cracking on Pared Naranja, showing the plane of fracture on which it is located; (d) detail of cracks at the base of Pared Naranja with a predominance of elongated structures.

A review of the graph in Figure 12 that plots size factor as defined above against height of occurrence affords some initial insight into that relationship. The positive slope on the curves for Murito, Muro de Snoopy, Risco del Martes and Camino del Tranco means that the size factor rises with height. An indirect relationship was found for Pared Naranja, while no relationship could be drawn for Bloque de Los Brezos, as data at that site were available for a single interval only.

The Pearson correlation coefficients given in Table 4 show the relationship between polygon size and height of occurrence, supplementing the graph in Figure 12. Positive values, ranging from 0.40 to 0.76, were found for Muro de Snoopy, Risco del Martes and Camino del Tranco. The coefficient for Pared Naranja proved to be high and negative: -0.75. In other words, at this site, the plate size rises with declining height. As in Figure 12, Camino del Tranco is absent from Table 4 because data were available for only one interval at that site.

Based on the field observations and the other findings reported here, the explanation for the anomalous arrangement of the polygonal cracking observed on Pared Naranja might lie in the slightly cantilevered configuration of the wall, with an inverted, northwestwardly slant. Moreover, it may have been differently affected by insolation and runoff flow than the other blocks studied due to the presence of a boulder in front of the block, which shades it partially, and of oxides, which modify the original surface.

The three groups that can be distinguished on the grounds of their coefficients of determination (Table 4), in turn, supplement the information on the Pearson correlation coefficient values. The first group has only one member, Muro de Snoopy, in which the variation in height explains only 16 % of size factor variability. This means that the remaining 84 % is due to other factors. In the second group, comprising Murito and Risco del Martes, 31 and 32 %, respectively, of the variation in the size factor could be correctly predicted from variations in height. The higher values for these sites than for Muro de Snoopy are an indication that height of occurrence plays a more significant role in the former two walls. In the third group, whose members are Pared Naranja and Camino del Tranco, 56 and 58 %, respectively, of the variation in cracking polygon size factor are explained by the variation in height. These findings support the notion that in these two walls height of occurrence is an essential factor in the size of the polygons. Future studies should enlarge the sample size and use other statistical techniques (such as weighted least-square fitting) to confirm or contest the tendencies shown here.

An analysis of the coefficients of determination for all the walls together infers that the huge gap between the first and second group values may be explained by the difference in the height of occurrence of the cracking plates. The Muro de Snoopy polygons are located 10 to 15 m higher than the plates in the group two walls, and have therefore been exposed to the elements much longer. Further support for this idea is provided by the greater percentage of the variation

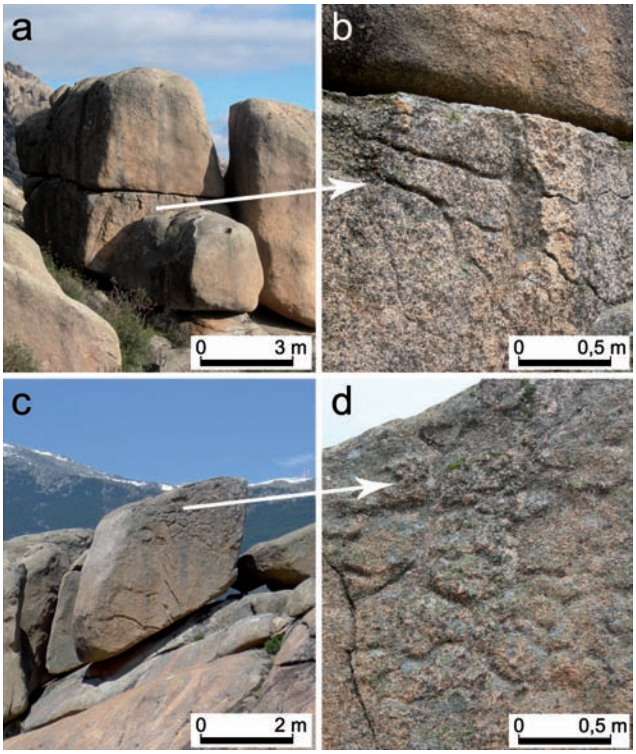


Fig. 10.- (a) Overview of blocks in Camino del Tranco; (b) cracking detail on the fracture plane with a strike of 170ºE; plane exhibiting cracking and uncracked portion of the same plane, where shaded by another boulder; (c) overview of Bloque de los Brezos, balanced rock resulting from the intersection of fractures running N-S and E-W and south-oriented curved planes at the base and on the surface (strike=N5ºE); (b) detail of irregular cracking on a vertical plane facing east, where case-hardening disappeared almost completely.

explained by height in Pared Naranja and Cancho de los Brezos, where cracking is positioned at a lower height relative to the ground. The form factor is an indication of the size of the polygons along a vertical line, always relative to the same plane of fracture. An analysis of this parameter consequently reflects a trend when viewed in each wall separately. Moreover, each wall may be affected by fractures that vary in density and orientation.

The mean coefficient for all the walls is $r^2 = 0.39$. In other words, approximately 40 % of the variability in the size factor for these walls is associated with the variation in cracking height. That finding is indicative of the significance of height in gaining an understanding of the geomorphological characteristics considered, for the higher the cracking elevation, the smaller is the coefficient of determination. It also reveals a need to explore polygonal cracking in greater depth in future studies with a view to reaching predictability values as close to 100 % as possible for the response variable, based on a series of pertinent explanatory variables.

5.4. Factors affecting surface weathering

The study of the strip established on (east) Murito revealed three distinct areas: an upper area with polygonal cracking, a transition area where polygonal cracking was found to be

Wall	Pearson corr. coefficient	Coeff. of determination
Murito (E)	0.55	0.31
Muro de Snoopy	0.40	0.16
Risco del Martes	0.57	0.32
Pared Naranja	-0.75	0.56
Bloque los Brezos	0.76	0.58

Table 4. Pearson correlation coefficients and coefficients of determination for the size factor-wall height relationship.

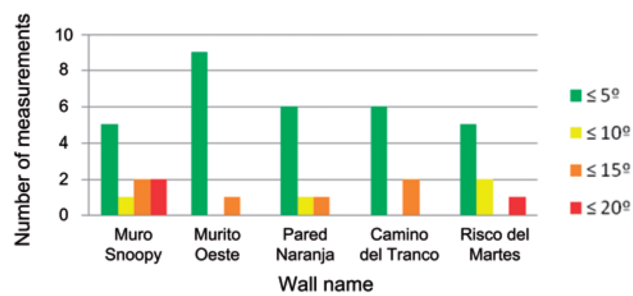


Fig. 11.- Distribution of measurements taken at each site by the angle in degrees formed by the fracture strike and groove direction.

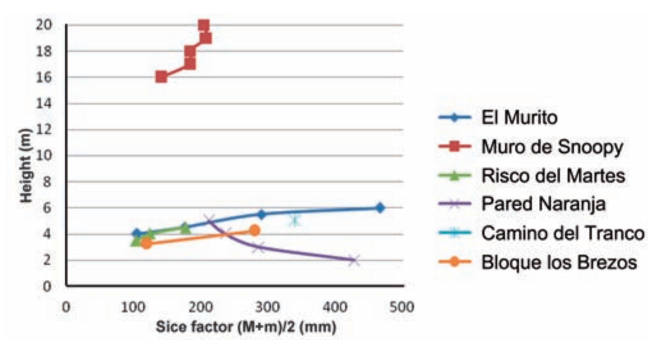


Fig. 12.- Polygon size (measured as size factor) versus wall height.

more diffuse, and a micro-relief area with well-defined protrusions (Table 5). The surface on the lower 2.5 m was observed to be flat with no polygonal cracking and barely any significant protrusions.

The highest area, located 6 to 6.5 m off the ground, was observed to have well-defined quadrangular polygonal cracks (PC) (Fig. 13). The orientations of the cracks forming the polygons were related to the orientations of the fractures in the area (García-Rodríguez *et al.,* 2013), i.e., the sides were oriented north-south like the vertical fractures, and the top and bottom were associated with horizontal fractures. Of all the areas studied, this was the one with the smallest slant, with a section mean of 52º. The case hardenings on the crack plates were very well preserved. The mean Schmidt hammer hardness was 40, the highest observed on the wall. This, then, was the area in which case hardening was most fully developed and least weathered. Groove depth ranged from 1 to 2.5 cm.

The section of wall between 5 and 6 m was observed to be a transition area between the polygonal cracking at the top and the micro-relief at the bottom. The mean slant in this section was measured to be 73º. The hardness of the protrusions between 5.5 and 6 m was 27 and 25 in the outer and inner ar-

Section height (m) and No. measurements (N)	Slant	Long axis (mm)	Short axis (mm)	Section form factor (M+m/2)	Shape Depth range (mm)
6 -6.5 m N = 9	52ºS	443	217	330	Polygonal cracking (PC) 10-25 in crack
5.5-6 m N = 11	71ºS	103	71	87	Transition PC/roughness 2 - 10
5 – 5.5 m N = 7	75ºS	94	50	72	Very diffuse 2 - 4
4.5 – 5 m N = 9	77ºS	94	42	68	Well defined 4 - 6
4 – 4.5 m N = 9	82ºS	121	78	99	Very well defined 4 - 6
3.5 – 4 m N = 10	84ºS	62	39	51	Very well defined 4 - 6
3 -3.5 m N = 10	84ºS	62	37	49	Poorly defined 2 - 5
2.5 -3 m N = 10	84ºS	47	29	38	Very poorly defined 2 - 3
2 – 2.5 m N = 8	86ºS	64	41	52	Very poorly defined 2 -3
0 – 2.5 m	88ºS	-	-	-	Unrecognisable 2 - 3

Table 5. Size of protrusions on the rock-wall.

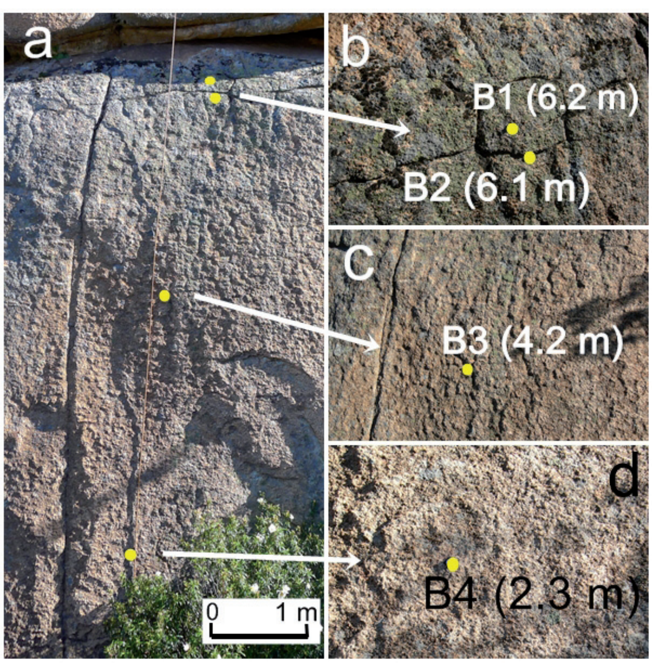


Fig. 13.- (a) i-button distribution on Murito; (b) detail of polygonal cracking; (c) micro-relief in the 3.5-4.5-m section; (d) detail of the 2-2.5-m section.

eas, respectively, denoting the near disappearance of the case hardening in this section: in other words, this was the most weathered area in the wall. The loss of case hardening in this section would appear to be attributable primarily to the effect of the surface runoff channelled along the sides of the polygons near the top, leaving elongated shapes in the direction of the slope. Immediately below, at 5 to 5.5 m, the irregularities were found to form harder, isolated protrusions, denoting that the case hardening was more intact.

The area with the most prominent protrusions was at 3.5 to 5 m, where the protrusions measured 4 to 6 mm (Fig. 12c). The slant on the section in question ranged from 77º at the top to 84º at the bottom. It was characterised by shapes with outer case hardening and mean hardness values of 31 to 44 (Table 6). The hardness values at the inner areas, where the hardening had disappeared, ranged from 23 to 29. The grooves forming the irregularities were essentially vertical lines generated by surface water runoff. This directionality, with very large maximum axes, was confirmed by the form factor calculated, 99 (section between 4 and 4.5 m).

Section height (m) / No. measurements	Wall slant (facing south)	Mean case-hardened area	Mean Grooves
6 – 6.5 m / 5	52º	40	30.8
5.5 - 6 m / 5	71º	27.4	25.2
5 – 5.5 m / 5	75º	36.6	29
4.5 – 5 m/ 5	77º	38.2	23.6
4 – 4.5 m/ 5	82º	39	29.2
3.5 – 4 m/ 5	84º	44	25.6
3 – 3.5 m/ 5	84º	31.2	25.4
2.5 - 3 m/ 5	84º	38.4	25.8
2 – 2.5 m/ 5	88º	30.5	26
1.5 - 2 m/ 5	88º	36.4	26.2
0 -1.5 m/ 4	88º	28.2	23.8
Mean	**79.4**	**35.4**	**26.4**

Table 6. Schmidt hammer data for the rock wall.

At heights of 0 to 3.5 m, the case hardening on the granite exhibited 2- to 3-mm grooves, shallower than in the higher sections where protrusions scarcely existed (Fig. 12d). In this section the case hardening was more continuous and the weathering- induced protrusions were less abundant.

A one way ANOVA was run to compare rock hardness measures on the inner and outer areas of the protrusions. The sample size was n=54 measurements in each group. The differences proved to be statistically significant ($F(1,106) = 42.64$, $p < 0.01$). These findings showed that the rock is harder on

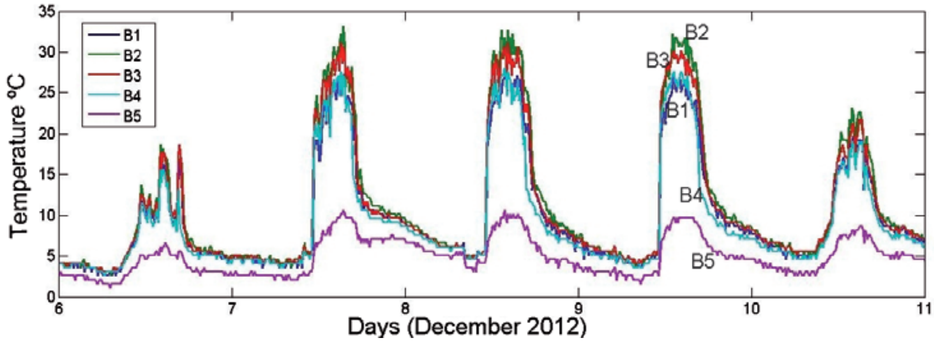


Fig. 14.- Temperature readings from five sensors in the rock-wall between 6 and 11 December 2012, with clear skies on days 7, 8 and 9.

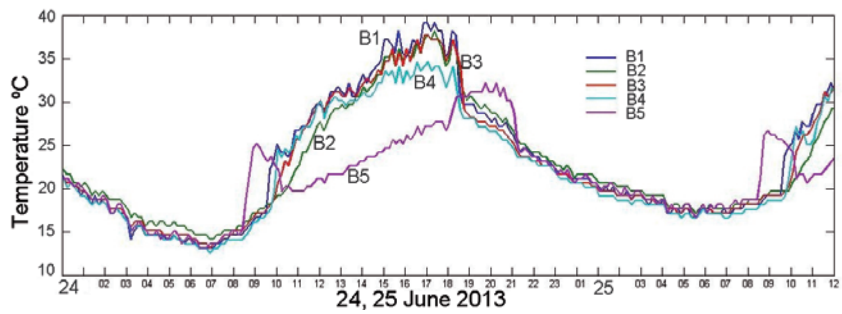


Fig. 15.- Temperature fluctuations logged by five sensors in the rock wall, 24 and 25 June, 2013.

the polygons delimited by the cracks and outer micro-relief protrusions than in the cracks and on inner micro-reliefs.

The wall temperature readings for a full year showed daily temperature fluctuations on clear days of 20 to 35 °C, with temperatures on the strip studied ranging from 0 to 52 °C, depending on the season of the year. A study of temperature variations with height in the months of January and June, for instance, showed that the top of the wall was 5 °C warmer than the bottom in both periods. These findings exclude the data for B5, located on a different, north-facing wall. Table 7 summarises the temperatures recorded from 22 November to 21 December 2012 and 30 May to 28 June 2013.

These periods were selected because they include the year's shortest and longest days. Moreover, consecutive days with no rainfall were chosen to ensure greater reliability of the effect of solar radiation on temperature. Figures 14 and 15 show the temperature for short representative periods during the months studied.

In December, a daily temperature difference of up to 6 °C was recorded between the plate surface (B1) and the groove (B2), with the greatest values in B2, where the wall is most vertical.

In June (Fig. 15), when the sun's rays are most vertical and hence the angle of incidence on the surface is smallest, the difference in the plate (B1) and groove (B2) temperatures tended to decline, although the highest readings were recorded for the plate (B1).

A joint analysis of the temperature variations on the Murito wall as a whole, excluding the data for B1 which was positioned on a less slanted surface, showed that in January the temperature rose with wall height. In June the temperatures tended to be more uniform, although the maxima were logged in the highest areas and the minima in the lowest. Polygonal cracking was most highly developed in the upper areas of all the rock walls studied, including on the Cenicientos and Zarzalejo boulders.

The temperatures recorded on the granite surface of Murito, with the exception of the polygonal cracking at the uppermost part, showed that the greater the temperature fluctuations (upper areas), the greater was the roughness and loss of case hardening.

The case hardening in Murito was observed to have partially fallen away, although alteration progressed in a more or less homogenously. Along the bottom, the crust was found to be well conserved, fairly continuous and scantly cracked. At the top it exhibited typical polygonal cracking, an indication of solute migration and a somewhat advanced phase of alteration. In the medium-high section, just under the polygonal cracking, the crust was missing entirely. Lastly, in the medium-low section, alteration was found to have destroyed the case hardening nearly completely, leaving traces on the "peaks" of tiny protrusions.

Hardness was clearly related to the integrity of the case hardening, with a mean value of 35 on the hardening and 26 on the altered areas. The form factor in Murito furnished some information on the size of the micro-relief protrusions. Especially in the medium-low area, the protrusions with case hardening exhibited an elongated geometry with an axis parallel to the slope.

The XRD patterns revealed compositional differences between the case hardened area and the substrate. The more in-

22 November – 21 December 2012					
	B1	B2	B3	B4	B5
Minimum	0.6	0.6	1.1	0.6	-0.4
Maximum	30.7	35.7	34.2	30.6	21.6
Mean	8.7	9.4	7.6	8.4	5.5
Range	30.1	35.1	33.1	30	22
30 May – 28 June 2013					
	B1	B2	B3	B4	B5
Minimum	5.1	5.6	5.1	5.1	4.6
Maximum	53.6	51.6	53	51	51.6
Mean	21	20.8	20.6	20	18.7
Range	48.5	46	47.9	45.9	47

Table 7. Rock wall temperatures.

tense diffraction lines in the former denoted a higher quartz content.

This was confirmed by the petrographic analysis of samples from the outer case-hardened and substrate areas. The rock in this area (Fig. 17) is a heterogranular, hypidiomorphic, medium-to-coarse grain leucogranite (with a silica content normally over 75 %) in which its primary mineral constituents are quartz, feldspar, plagioclase and biotite. The potassium feldspar, which consists of orthose and microcline, is intensely weathered and has an allotriomorphic texture and albitised pertites. The plagioclase has oligoclase nuclei and albitic rims. Myrmequite was found at the interface between these minerals. Biotite is subidiomorphic and alotriomorphic, reaching up to 5% of the mineral volume and, like the potassium feldspar, is intensely weathered which is responsible for the iron oxide cementing fissures. The accessory minerals included zircon, apatite, ilmenite, sillimanite and monazite, while muscovite, chlorite, anatase, sericite and pinite were identified as the secondary minerals.

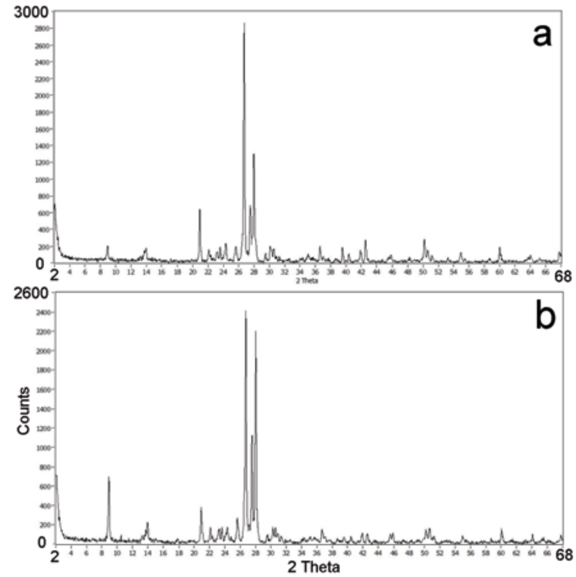


Fig. 16.- XRD patterns for (a) the hardened surface and (b) the substrate.

Mainly inter- and intracrystalline fissures several mm long with widths ranging from 40 to 100 µm were observed near the granite surface in areas bearing white crust. Silica (probably quartz crystals) was found filling these fissures in a "palisade" arrangement (Figs. 17c and d). The presence of such high-silica cement is consistent with the XRD findings, according to which the outer granite had a higher quartz content than the inner part of the rock. That cement, moreover, may be the outcome of feldspar alteration (Oustrière and Sureau, 1985).

Deeper into the granite, fewer fissures were detected, and they were smaller and narrower than on the surface. Some were cemented with iron oxide generated during Fe mineral alteration.

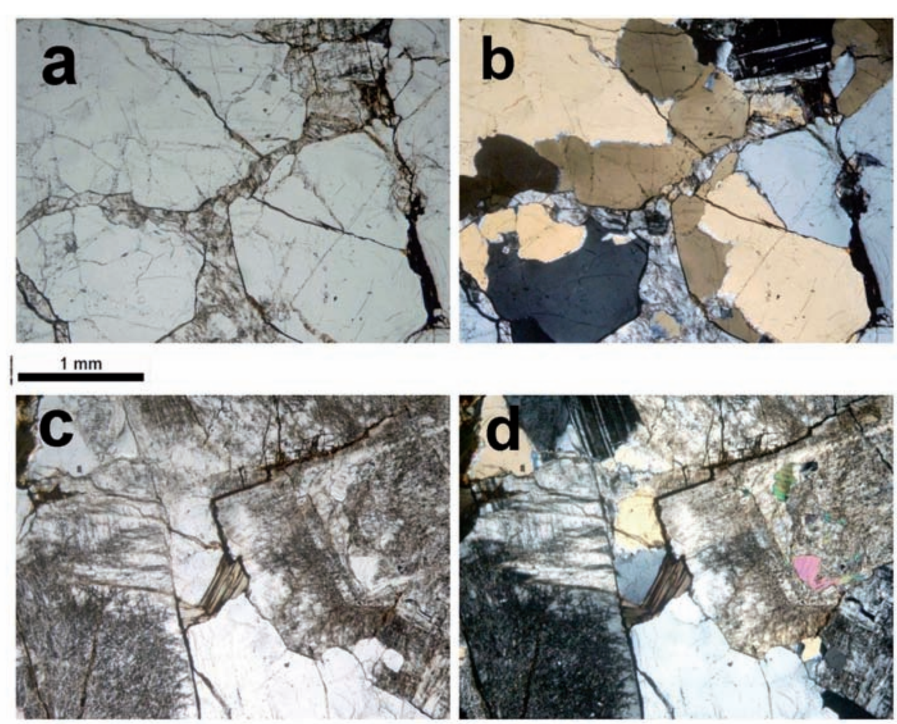


Fig. 17.- Petrographic images of granite thin sections: a) and b) overview showing quartz, potassium feldspar, plagioclase and biotite crystals in granite showing the high silica cement inside the fissures; c) and d) granite surface showing the fissure network; (a and c): plane polarized light; (b and d): crossed polarized light.

6. Conclusions

This paper proposes a classification for polygonal cracking based on the variability in the location and geomorphology of the granitic rocks where it occurs (Fig. 6). The five types of PC defined partially address the complexity underlying the polygonal crack formation, which to date has often been assumed to be the result of a single weathering process.

An example of the variable occurrence and development of polygonal cracking can be found at Sierra de Guadarrama, an area of particular significance in the history of the description of granite weathering. The present study focused on La Pedriza de Manzanares, an area characterised by the proliferation of vertical and horizontal fracturing and variably dipped surfaces, as well as curved planes of fracture with a declining dip at the upper slope. Two types of polygonal cracking were identified: 1) associated with vertical planes at different heights; and 2) associated with large radial planes. No cracking was observed on granite boulders at La Pedriza de Manzanares. Morphometric relationships were determined on the cracking on vertical fault planes. The cracking associated with radial fracture planes, while not measured, is described in this paper. Despite the fact that the study was confined to only one of the types of polygonal cracking defined in the proposed classification, different sizes and morphologies were observed, even within the same outcrop.

This runs counter to previous models, in which the origin of polygonal cracks was analysed in terms only of the material, stress fields or even merely macroscale weather conditions. From the lithological standpoint, the shapes formed by polygonal cracking in vertical planes appear to be loosely determined by alignments and pre-existing cracks. Moreover, although polygonal cracking is markedly directional (with cracks appearing primarily on the south and west faces). They also showed that the resulting polygonal shapes vary across the surface of vertical granite walls: cracking plates on vertical walls are generally larger and the grooves deeper at higher locations. This was observed in association with graduated surface hardness, the conservation of quartz encrustations and surface temperature change throughout the year.

This variation ranges from well-developed polygons at the highest locations to the complete absence of polygonal cracking at the lowest portion of the outcrops. Between these situations, the medium portion of vertical to sub-vertical planes do not show polygonal cracking but a micro-roughness, which is the result of alternating areas with and without case hardening. The morphology of this alternation resembles the distribution of polygonal cracking and can be considered its precursor.

The foregoing suggests that polygonal cracking at these specific locations is determined by weathering differences induced by wall-scale temperature and humidity fluctuations and the retention from surface runoff. The weathering has a dual effect. Firstly, it conditions the formation of quartz encrustations (as petrographic and mineralogical observations show), which in turn condition the formation of polygonal cracking. Secondly, it impacts polygon conservation.

This suggests the existence of a feedback mechanism in which cracks in surface encrustations lead to backweathering around the cracked area, with the concomitant appearance of surface polygons. In the model proposed further to the present findings, wider surface temperature variations are found on the upper areas of walls facing southwest, where weathering is consequently more intense. Weathering initially leads to quartz encrustation due to its re-precipitation from feldspar. As encrustation is greater on the upper wall, surface cracking is deeper there. Backweathering induces groove formation more effectively in this section of the wall. The outcome is the present situation in which polygonal cracking is more fully developed in the upper than in the lower areas of vertical walls.

Acknowledgements

This study was funded by the project GEOMATERIALES 2 (S2013/MIT-2914). The support of the (Complutense University of Madrid) Research Group “Alteración y conservación de los materiales pétreos del patrimonio” / Alteration and conservation of heritage stone materials (ref. 921349) is gratefully acknowledged. MG’s participation was partially funded by the Moncloa Campus of International Excellence (UCM-UPM, CSIC) under an International Talent Acquisition Programme (PICATA) postdoctoral fellowship. Authors would like to thank Dr. Patricia Vázquez and another anonymous reviewer for their comments and suggestions, which helped greatly to improve this manuscript.

References

Bea, F., Montero, P., Molina, J.F. (1999): Mafic precursors, peraluminous granitoids, and late lamprophyres in the Ávila batholith, A model for the generation of Variscan batholiths in Iberia. *Journal of Geology* 107, 399-419. doi: 0022-1376/1999/10704-000201.00

Branagan, D.F. (1983): Tesselated pavements. In: *Aspects of Australian sandstone landscapes.* R.W. Young; G.C. Nanson (eds.). Australiana and New Zealand Geomorphology Group Special Publication nº 1, Wollongong, pp. 11-20.

Bradley, W.C., Hutton, J.T., Twidale, C.R. (1978): Role of salts in the development of granitic tafoni, South Australia. *The Journal of Geology* 86, 647-654. doi: 0022-1376/78/8605-001000.81.

Bruner, W.M. (1984): Crack growth during unroofing of crustal rocks, Effects on thermoelastic behavior and near-surface stresses. *Journal of Geophysical Research* 89, 4167-4184. doi: 10.1029/JB089iB06p04167.

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

Capote, R., de Vicente, G., González Casado, J.M. (1990): Evolución de las deformaciones alpinas en el Sistema Central Español. *Geogaceta* 7, 20-22.

Centeno, J.D. (1988): *Morfología granítica de un sector del Guadarrama Occidental. Editorial Complutense*. Colección Tesis Doctorales nº262/88. Madrid.

Centeno, J.D., García-Rodríguez, M. (2005): El papel de los procesos gravitacionales en los relieves graníticos, el derrumbe de Peña Sirio (Pedriza de Manzanares, Madrid). *Tecnologí@ y Desarrollo* 3, 1-18.

Comunidad de Madrid (2007): Atlas. El medio ambiente en la Comunidad de Madrid. Dirección General de Promoción y Disciplina Ambiental. Consejería de Medio Ambiente y Ordenación del Territorio. Madrid.

Conca, J.L. (1985): Differential weathering effects and mechanisms. Dissertation Thesis, California Institute of Technology, Pasadena, 251 pp.

De Pedraza, J. (1978): *Estudio geomorfológico de la Zona de Enlace entre las Sierras de Gredos y Guadarra (Sistema Central Español)*. Tesis Doctoral. Universidad Complutense de Madrid. 432 pp.

De Pedraza, J., Sanz, M.A., Martín, A. (1989): Formas graníticas de la Pedriza. Agencia de Medio Ambiente. Comunidad de Madrid. 205 pp.

De Prado, C. (1864) 1975, Descripción física y geológica de la provincia de Madrid. Publicaciones especiales Colegio de Ingenieros de Caminos, Canales y Puertos, Madrid, 325 p.

Díaz de Neira, A., López-Olmedo, F., Solé, Hernáiz, Calvo Sorando, J.P. (2007): *Mapa geológico de España 1:50000, Hoja número 580 (Villa del Prado)*. IGME, Madrid, España

Fort, R., Álvarez de Buergo, M., Pérez-Monserrat, E., Gómez-Heras, M., Varas, M.J., Freire, D.M., Evolution in the use of natural building stone in Madrid, Spain. *Quarterly Journal of Engineering Geology and Hydrogeology* (in press, doi: 10.1144/qjegh2012-041).

García-Rodríguez, M., Centeno Carrillo, J.D., de Pablo, M.A. (2008): Relieve y agua en regiones graníticas, un modelo cuantitativo con aplicaciones en la gestión del agua y la geodiversidad. *M+A Revista Electrónic@ de Medioambiente UCM* 5, 41-57.

García-Rodríguez, M., Centeno, J.D., Alvarez de Buergo, M. (2012): *Weathering landforms exposure and erosion phases in Pedriza de Manzanares (Spanish Central Range)*. Geophysical Research Abstracts. Vol. 14, EGU2012-6279-1, 2012. EGU General Assembly 2012.

García-Rodríguez, M., Centeno, J.D., Gomez-Heras, M., Fort González, R., Alvarez de Buergo, M. (2013): *Thermal and structural controls on polygonal cracking in granite of La Pedriza de Manzanares (Spain)*. Abstracts Volume 8th International Conference (AIG) on Geomorphology "Geomorphology and Sustainability". Paris, 27-31 August 2013, p. 303.

García-Rodríguez, M., Gómez-Heras, M., Fort, R., Álvarez de Buergo, M., Centeno, J.D. (2014a): Caracterización de agrietamientos poligonales sobre granito en la Pedriza de Manzanares y en Cenicientos, Madrid (Sistema Central). *M+A Revista Electrónic@ de Medioambiente UCM* 15 (1): 22-36. doi: 10.5209/rev_MARE.2014.v15.n1.45567.

García-Rodríguez, M., Gómez-Heras, M., Fort, R., Álvarez de Buergo, M., Centeno J.D. (2014b): Influencia de los endurecimientos superficiales en el micro-relieve de las superficies graníticas de la Pedriza de Manzanares. Parque Nacional de Guadarrama (España). *Tecnologí@ y Desarrollo UAX* 12, 1-23.

García-Rodríguez, M., García Rodríguez, M., Salcedo Miranda, J.L. (2014c): El Hueso de la Pedriza, origen, estructura y rasgos geomorfológicos. *Tecnologí@ y Desarrollo, UAX* 12, 1-20.

Garner, H.F. (1974): *The origin of landscapes, a synthesis of geomorphology*. Oxford University Press, New York, 734 pp.

Gomez-Heras, M., Smith, B.J., Fort, R. (2006): Surface temperature differences between minerals in crystalline rocks, Implications for granular disaggregation of granites through thermal fatigue. *Geomorphology* 78 (3-4): 236-249. doi:10.1016/j.geomorph.2005.12.013

Gomez-Heras, M., Smith, B.J., Fort, R. (2008): Influence of surface heterogeneities of building granite on its thermal response and its potential for the generation of thermoclasty. *Environmental Geology* 56 (3-4): 547-560. doi: 10.1007/s00254-008-1356-3

González del Tánago, J., Pérez-Soba, C., Villaseca, C. (2004): Minerales accesorios de Nb-Ta-Ti e Y-Re-Th-U en el Plutón granítico de La Pedriza, Sistema Central Español. *Geotemas* 6, 57-60.

Hall, K., André, M.F. (2003): Rock thermal data at the grain scale, applicability to granular disintegration in cold environments. Earth Surf Process Landf 28, 823-836. doi:10.1002/esp.494

Hobbs, W.H. (1919): Earth features and their meaning. An introduction to geology for the students and the general reader. McMillan, New York.

Instituto Tecnológico y Geominero de España, ITGE (1990): Hoja geológica nº 508 (Cercedilla). *Mapa Geológico de España. Escala 1:50.000.* 2ª Serie, 1ª edición. ITGE. Madrid.

Ishimaru, S., Yoshikawa, K. (2000): *The weathering of granodiorite porphyry in the Thiel Mountains, inland Antartica*. Geografiska Annaler, 82A, 45-57.

Jonhson, R.J. (1927): Polygonal weathering in igneous and sedimentary rocks. *American Journal of Science* 13, 440-444. doi: 10.2475/ajs.s5-13.77

Lachenbrunch, A.H. (1962): Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. *Geological Society of America, Special Paper*, 70. 69 p. doi: 10.1130/SPE70-p1

Lachenbrunch, A.H. (1966): Contraction theory of ice wedge polygons, a qualitative discussion. Proceedings of the Permafrost International Conference 63-71. Natl. Acad. Sci. Natl. Research Council Pub. 1287.

Lan, H., Martin, C.D., Hu, B. (2010): Effect of heterogeneity of brittle rock on micromechanical extensile behavior during compression loading. *Journal of Geophysical Research* 115, 14 pp. doi: 10.1029/2009JB006496.

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

Martel, J.S. (2011): Mechanics of curved surfaces, with application to surface-parallel cracks. *Geophysical Research Letters*, Vol. 38, L20303. doi: 10.1029/2011GL049354.

Martínez Pérez, L. (2011): *Condicionantes petrológicos y geomorfológicos de las grietas poligonales en granitos, influencia en el deterioro del patrimonio arqueológico in situ. Trabajo Máster*. Universidad Complutense de Madrid Facultad de Ciencias Geológicas. 48 pp.

Mustoe, G.E. (1982): The origin of honeycomb weathering. *Geological Society of America Bulletin* 93(2): 108-115. doi: 10.1130/0016-7606.

Megías A.G., Ordóñez Delgado, S., Calvo Sorando, J.P. (1983): Nuevas aportaciones al conocimiento geológico de la Cuenca de Madrid. *Revista de Materiales y Procesos Geológicos* 1, 163-191.

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

Moores, J.E., Pelletier, J.D., Smith, P.H. (2008): Crack propagation by differential insolation on desert surface clasts. *Geomorphology* 102, 472-481. doi: 10.1016/j.geomorph.2008.05.012.

A.C.M., Oustrière, P., Sureau, J.F. (1985): Experimental Investigation of Clogging of Fissures and Pores in Granite. Mineralogical Magazine 49/351, 223-231. doi: 10.1180/minmag.

Peinado, M., Fúster, J.M., Bellido, F., Capote, C., Casquet, C., Navidad, M., Villaseca, C. (1981): *Caracteres generales del Cinturón Hercínico en el Sector Oriental del Sistema Central Español.* Editor, Universidad Complutense. Departamento de Estratigrafía; Instituto de Geología Económica (CSIC).

Pérez-Soba, C., Villaseca, C. (2010): Petrogenesis of highly fractionated I-type peraluminous granites, La Pedriza pluton (Spanish Central System). *Geologica Acta* 8, 131-149.

Ramsay, J.G., Huber, M. (1987): The Techniques of Modern Structural Geology. Folds and Fractures. Volume 2, Academic Press, London.

Rice, A. (1976): Insolation warmed over. *Geology* 4, 61-62. doi: 10.1130/0091-7613

Riley, P., Tikoff, B., Murray, A.B. (2011): Quantification of fracture networks in non-layered, massive rock using synthetic and natural data sets. *Tectonophysics* 505(1-4), 44-56. doi:10.1016/j.tecto.2011.04.002.

Riley, P., Murray, A.B., Tikoff, B. (2012): Geometric scale invariance, genesis, and self-organization of polygonal fracture networks in granitic rocks. *Journal of Structural Geology* 42, 34-48. doi: 10.1016/j.bbr.2011.03.031.

Robinson, D.A., Williams, R.B.G. (1987): Surface crusting of sandstones in southern England and northern France. In: V. Gardiner (ed.), *International Geomorphology 1986 Part II*. Wiley & Sons, London, pp. 623-635.

Robinson, D.A., Williams, R.B.G. (1992): Sandstone weathering in the High Atlas, Marocco. Zeitschrift fur Geomorphologie, 36, 413-429.

Smith, B.J. (1977): Rock temperature measurements from the northwest Sahara and their implications for rock weathering. Catena 4 (1-2),41-63.

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

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

Twidale, C.R. (1982): Granite Landforms. Elsevier, Amsterdam. 312 pp.

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. doi: 10.1016/S0012-8252(01)00059-9

Twidale, C.R., Bourne, J.A. (2009): On de origin of A-tents (pop-ups), sheet structures, and associated forms. *Progress in Physical Geography* 33(2): 147-162.

Twidale, C.R., Vidal Romaní, J.R. (2005): Landforms and Geology of Granite Terrains. Balkema, Leiden.

Van Autenboer, T. (1964): The geomorphology and glaciar geology of Sor Rondane, dronning maud land. In: Adie, R. (ed.), *Antartic geology*. Amsterdam, North Holland, 81-103.

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 Romaní, J.R. (1991): Tipos de fábrica plana y su relación con la generación de formas graníticas.*Cuadernos do Laboratorio Xeolóxico de Laxe* 16, 301-312.

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., Twidale, C.R. (2010): Structural or climatic control in granite landforms? The development of sheet structure, foliation, boudinage, and related features. *Cadernos do Laboratorio Xeolóxico de Laxe* 35,189-208.

Villaseca, C. (1985): Los granitos de la Sierra de Guadarrama. *Revista Real Academia de Ciencias Exactas, Físicas y Naturales* 79, 573-587.

Villaseca, C., Barbero, L., Rogers, G. (1998): Crustal origin of Hercynian peraluminous granitic batholiths of central Spain, petrological, geochemical and isotopic (Sr, Nd) constraints. *Lithos* 43, 55-79. doi: 10.1016/S0024-4937(98)00002-4

Watson, A., Pye, K. (1985): Pseudokarstic micro-relief and other weathering features on the Mswati Granite (Swaziland). Zeitschrift fur Geomorphologie, 29, 285-300.

Wilhelmy, H. (1964): Cavernous rock surfaces in semi-arid and arid climates. *Pakistan Geographical Review* 19(2):8-13.