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REVIEW ARTICLE

Geo-Climbing and Environmental Education: the Value of La Pedriza Granite Massif in the Sierra de Guadarrama National Park, Spain

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Abstract Since the late nineteenth century, the Guadarrama mountain range (listed as a National Park in 2013) has attracted the attention of intellectuals, naturalists and mountaineers, for whom it has served as a scientific laboratory and area for mountaineering and climbing. La Pedriza or La Pedriza del Manzanares in the Spanish province of Madrid, with a granite landscape characterised by a craggy geomorphology consisting of high walls alternating with loose boulders, is perhaps the most emblematic part of this park. The many smooth walls towering over a hundred metres from the ground have made the area Spain's and arguably Europe's most prominent friction climbing training ground. With a view to supplementing writings on the area's value for science, education and sports initiated over 150 years ago, this article contains a detailed explanation of the geological and geomorphological processes involved in the formation of rock surfaces and their relationship to mountaineering. The findings described are applicable to similar geomorphologies where this sport is practised.

Keywords La Pedriza del Manzanares · Case hardening · Polygonal cracking · Geomorphology and climbing

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Introduction

Beginning in the last third of the nineteenth century, the Guadarrama Mountains became a meeting place for scientists, naturalists and intellectuals who introduced a practical and multi-disciplinary approach to education, in keeping with international trends. In particular, due to the appealing morphology of La Pedriza de Manzanares (the background for Velázquez's seventeenth century equestrian portrait of King Philip IV), as early as 1864, it became an object of study for geologists and naturalists. Casiano de Prado published the first physical description of the area in that year (de Prado 1864, ref. 1975). In the early twentieth century, Bernaldo de Quirós (1923) and Hernández Pacheco (1931) authored reputed studies of geological interest on the area, which among others favoured La Pedriza's 1930 listing as a Natural Site of National Interest, one of the country's first locations to be awarded this distinction. During and after the 1936–1939 Civil War, scientific and intellectual activity in the Guadarrama Mountains came to a standstill that lasted through the 1970s. Later, in 1978, La Pedriza was integrated into the Upper Manzanares Basin Natural Park, reclassified as a regional park in 1985. In the 1990s, it was listed as a UNESCO Biosphere Reserve, and in 2013, it was finally included in the recently created Guadarrama Mountains National Park (Salazar Rincón et al. 2015).

La Pedriza's tradition for hosting mountain sports dates back as far as the early naturalist explorations, when Casiano de Prado culminated the first ascent to Yelmo Peak in 1860. It was not until 1900, however, when mountaineering took off in Guadarrama, particularly with the creation of the Sociedad de Alpinismo de Peñalara (Vías 2011). Ever since, La Pedriza's many 100-plus-metre granite walls have made the area a splendid training ground for mountaineers and climbers. At the same time, its 40 km^2 of 'geological nudity' constitute a school of indisputable value for geologists, with virtually inexhaustible resources in every corner of its granite labyrinth.

Climbing has traditionally been a crucial tourist attraction at La Pedriza, where visitors find a natural resource for practising a sport that has indirectly led to the study of the local geology (Carcavilla 2012, 2014). From the scientific and educational standpoints, the climbing routes that have been opened both at La Pedriza and other areas of the world have proven to be ideal scenarios for studying geomorphologies that would be difficult to research without such routes and sporting activity (Pozza et al. 2009; Bollati et al. 2014). Some examples of other countries with granite massifs and domal morphologies similar to La Pedriza's and where mountaineering is practised include Yosemite National Park (USA), Spitzkoppe National Park (Namibia), Val di Mello Natural Reserve (Italy), Freycinet National Park (Tasmania, Australia) and Gorkhi-Terelj National Park (Mongolia).

La Pedriza del Manzanares is presently the primary climbing school in the region of Madrid, with over 2000 routes open and grades of difficulty that range (on the French scale) from IV to 8c. The technical difficulty of routes is defined on an open scale on which the mountaineering community has reached a consensus. Up to grade V, the scale is expressed in Roman and from 6 onward in Arabic numerals, followed by the letters a, b or c, which denote rising difficulty. Because of the domal morphology of the generally smooth La Pedriza walls, 'friction' climbing is the technique most commonly used, although itineraries may be found in which cracks in the rock due to fracture, gullies or vales are used in ascents. Friction climbing consists in making one's way along nearly smooth surfaces with slopes of 50–90°, capitalising on the friction between the ('sticky rubber') sole of the climber's shoes and the rock and resting with hands and feet on ledges consisting of phenocrysts, nodules or flakes due to erosion-induced surface scaling that protrude only a few millimetres off the wall.

This article aims to spotlight the role of 'geo-climbing' (Valeria Panizza and Mennella 2007; Bollati et al. 2014) as an activity that adds value to this natural area's scientific, tourist and sporting heritage. Protected under a national park listing (Carcavilla 2012), the resource has contributed largely to development in the area and serves as the grounds for an environmental education system applicable to similar areas anywhere in the world. Given its descriptive and interpretational focus on the processes involved in modelling the rock surface, the article is a field guide for visitors interested in obtaining a fuller understanding of the landscape and the geodynamic processes that formed it. The paper explains the geological and geomorphological properties that generated the irregularities in these granite domes and determine the technical difficulty of the existing routes. It also addresses the surface characteristics of walls where friction climbing is practised, such as case hardening (CH), microrelief (MR), micro-flaking (MF) and polygonal cracking (PC) (García-Rodríguez et al. 2012, 2014b). With the aim of establishing possible relationships between climbing, geology and geomorphology, it is neccesary to identify and define some structural characteristics, such as the main fracture directions, the orientation of the outcrop surfaces that shape the walls for the practice of climbing and also the slope of these surfaces.

Geological Setting

La Pedriza de Manzanares is located in the Spanish Central System, in the 'foothills' on the south side of the Guadarrama Mountains. Its elevations range from around 900 m near the town of Manzanares el Real to slightly over 2000 m at the Cuerda Larga summits. The region has a damp, temperate-to-cold Mediterranean climate with mean yearly rainfall and temperature of 800-900 mm and 11-12 °C, respectively, at elevations of 800-1200 m, and around 1000-1500 mm and 9-10 °C at elevations of 1200-1600 m (IGME 1988).

The Spanish Central System (SCS), backbone of the Iberian Belt formed during the Variscan Orogeny, has been studied since the mid-twentieth century (Peinado et al. 1981; Díaz de Neira et al. 2007). Several stages of plutonic body intrusions took place toward the end of that orogeny. La Pedriza was formed by a late intrusion of type I highly fractionated granites (Pérez-Soba 1992; Pérez-Soba and Villaseca 2010). That intrusion was followed by a long period of denudation in the Iberian Belt (De Pedraza 1978, 1989). The Alpine Orogeny uplifted the present Central System, reactivating Variscan fault planes and creating a relief characterised by alternating horsts and grabens, bounded by thrust faults (Capote et al. 1990; De Vicente et al. 2007).

The area's structural separation into boulders and domes and the formation of walls with heights ranging from only a few to over a hundred metres are attributable to the complex fault system (Fig. 1) inherited from the Variscan and Alpine orogenies (De Vicente et al. 2007). The predominant fractures system has the E-W and ENE-WSW direction. At least two types of faults can be distinguished: (a) rectilinear fractures forming an orthogonal lattice of parallel fractures that may be vertical, horizontal or slanted; and (b) curvilinear fractures that follow along planes of fracture more or less parallel to the convex surface of the outcrops, resulting in reliefs containing domal forms. These curved planes run predominantly E-W and outcoping surfaces face south. The sliding of large boulders over the domal walls, often forming overhangs, is favoured by the intersection of the various families of fractures. In La Pedriza, specifically, the alpine uplift both induced the step-like formation (De Pedraza 1989) whose reliefs are the result of the penetration of the fractures by weathering agents (Fig. 2), and favoured the evacuation of regoliths into the Tagus River basin (De Pedraza et al. 1989). 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

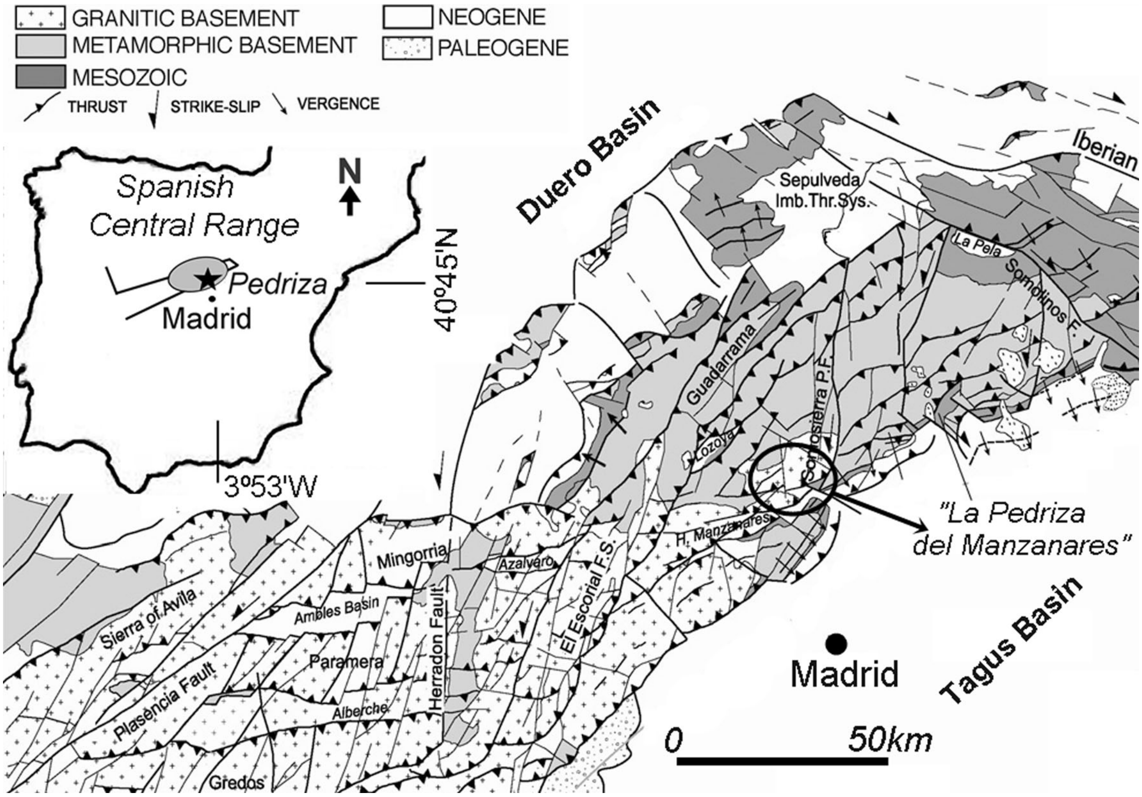

Fig. 1 Geological and tectonic map of Spanish Central Range (modified from De Vicente et al. 2007)

formations at La Pedriza (De Pedraza 1978; Centeno 1988; De Pedraza et al. 1989).

The Pedriza pluton, and in particular the lower Pedriza pluton, is a coarse to medium-grained leucogranite. In this very homogeneously textured leucogranite, the grain size may decline around the contact surface (Pérez-Soba 1992).

The most prominent petrographic and mineral features of La Pedriza leucogranites include the following: crystallised microperthitic K-feldspar, quartz, plagioclase and usually some biotite. 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 (Pérez-Soba and Villaseca 2010). These dikes are normally no more than a few centimetres thick, although locally they may extend to over a metre. As they are more erosion-resistant than the leucogranite in the host rock, the differential weathering of the stone massif creates protrusions, floors and similar.

Surface Forms

Overall, the huge walls in this national park are associated with sub-vertical and domal surface with greater verticality toward the base (De Pedraza et al. 1989). The surfaces of these walls have been modelled over thousands of years by weathering, resulting in forms such as case hardening or surface crusts, microreliefs, micro-flaking and polygonal cracking (Fig. 3). On occasion, some of these forms, such as PC, CH or MF are related to endogenous processes occurring prior to granite exhumation, as explained in the following sections.

Hydrolysis and hydration are the external processes that contribute most to granitoid alteration and disintegration (Twidale 1982; Matsukura and Tanaka 2000). Freeze-thaw events, temperature fluctuations and desiccation of the outermost surface of the rock (Schulke 1973; Twidale 1982), along with the activity of microorganisms, also induce surface cracking and disintegration (Viles and Gouide 2004). In heterogeneous rock such as granitoids where the constituent crystals have different heat expansion coefficients, thermal fluctuation is one of the primary causes of surface microscaling (Ishimaru and Yoshikawa 2000; Hall and André 2003; Gómez-Heras et al. 2006). As a rule, the relief on crags and cliffs is more abrupt at the higher (Upper Pedriza) than at the lower (Lower and Mid-Pedriza) elevations, which are more rounded.

Earlier studies of La Pedriza revealed substantial daily variations in temperature all year round. On the south-facing walls, for instance, variations of 20 to 35 °C are recorded, with extremes ranging from 0 to 52 °C depending on the season of the year (García-Rodríguez et al. 2015a).

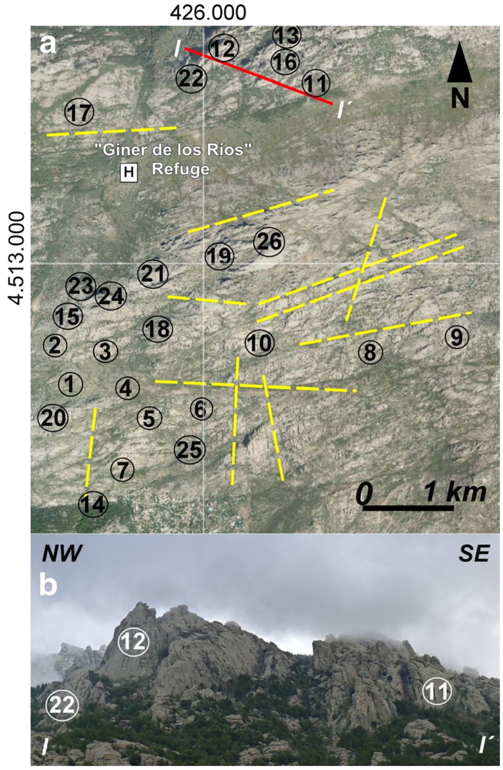

Fig. 2 Guadarrama National Park and La Pedriza locations within Spain. **a** National Geographic Institute's Ortophoto with the location of all the climbing walls mentioned in the article. 1. El Murito, 2. Pared Naranja, 3. Bloque Brezos, 4. Tres Puntas, 5. El Reloj, 6. Muro Snoopy, 7. CaminoTranco, 8. Zona del Martes, 9. Peñas Cagás, 10. Zona Cinco Cestos, 11. El Hueso, 12. El Pájaro, 13. Pared de Santillana, 14. Cancho Redondo, 15. Peña Sirio, 16. Risco Gargajo, 17. Placa Ninja, 18. Risco de los Principiantes, 19. Pan de Kilo, 20. Cancho Butrón, 21. Cueva de la Mora, 22. Platillo Volante, 23. El Euro, 24. Risco de la Peseta, 25. Placa del Nueve, 26. El Yelmo. The figure includes some examples of the main fault directions in the area. **b** Location of some of the Pedriza's most remarkable ridges such as El Pájaro, Platillo Volante and el Hueso (*red colour profile*)

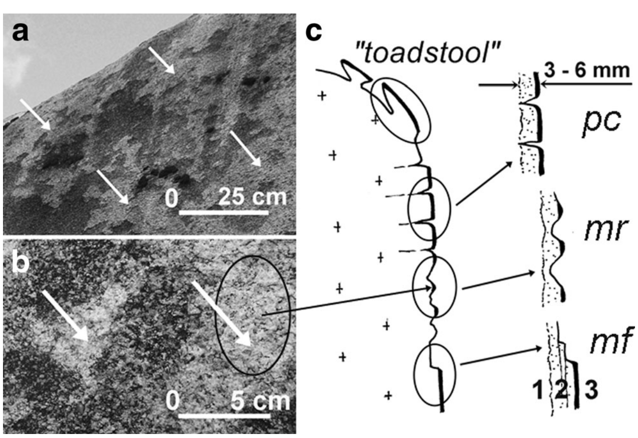

Fig. 3 **a**, **b** Microreliefs formed by alternating light-hued crusted areas (*arrows*) and darker-toned areas with no such hardening. **c** Idealised cross-section of a rock wall labelling the features studied: polygonal cracking (*pc*), microreliefs (*mr*), micro-flaking (*mf*), fresh rock (*1*), altered rock (2) and case hardening (3)

Case Hardening, Microrelief, Micro-Flaking

Case hardening is a common process that creates an outer surface that is harder and more erosion-resistant than the rock below (Dorn 1998). In granite, case hardening forms a surface crust generally attributed to iron and silica oxide solutions. The process is initiated in burial conditions; this dissolved weathered material is mobilised by evaporation and capillarity from inside the rock and precipitates on the surface (Twidale 1982). During this process, as the outer part hardens, the rock immediately underneath the crust tends to weaken (Conca 1985). Granite outcrops with this type of crusts have a more stable, erosion- and weather-resistant surface than surfaces without them. When these crusts break, weathering progresses swiftly for a few millimetres inward, as the weakened inner zones undergo granular disintegration (Fig. 3). Crustless areas usually have a reddish hue due to the oxidation of the iron in biotites and are often colonised by lichens, moss or both. Detachment of the hardened surfaces generates a micro-relief over the rock surface, a development described by García-Rodríguez et al. (2014a).

Surface scaling and the formation of micro-flakes (Fig. 4) entail two mechanisms that sometimes occur in parallel, namely granular disintegration and the disintegration and detachment of tiny plates parallel to the wall surface or alteration front (De Pedraza et al. 1989). These mechanisms are induced by mechanical, chemical or biological weathering. Surface scaling is particularly intense in areas with extensive pre-existing microcracks parallel to the surface, constituting planes of weakness where the aforementioned processes take place. The presence of previous fractures can be caused either by compressive stresses related to regional tectonics or by decompression processes during the exhumation of the granite massif.

Polygonal Cracking

The term polygonal cracking is used to designate a mosaic of polygonal (rhomboid, quadrangular) or irregularly shaped plates separated by cracks or grooves. While such cracks affect different types of rock, they are found very frequently on La Pedriza granitoids (De Pedraza et al. 1989; García-Rodríguez et al. 2012).

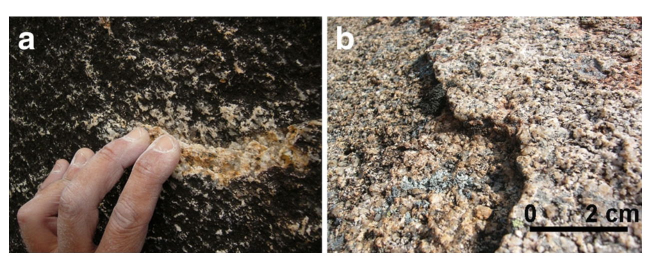

Fig. 4 **a**, **b** Examples of micro-flaking

Certain features of polygonal cracking (Leonard 1929) can be attributed to the characteristics of the granite in the final stage of magmatic consolidation. Shearing-induced differential movement between planes of weakness may prompt rock stretching or shortening/compression (Vidal Romaní 1990), creating a surface fabric over these planes that would favour the advent of PC. Twidale (1982) related PC on curved surfaces to compressive stress and called the development the 'self-weight series'; Riley et al. (2012) studied this same type of cracking at Yosemite National Park, one of the world's major granite-climbing sites.

The most prominent external factors inducing crack development include chemical weathering, rupture due to expansion in the outermost rock surface (Schulke 1973), freeze-thaw (Twidale 1982) and solar radiation-induced desiccation and rupture of rock surfaces (Robinson and Williams 1989). These weathering processes are more effective and form deeper cracks in the presence of a network of pre-existing cracks that form planes of weakness (García-Rodríguez et al. 2014a).

When cracks forming polygonal shapes are exposed to the atmosphere for very long periods of time, they may deepen several centimetres and form plates that separate from the wall. At La Pedriza such formations are known locally as 'toadstools' (De Pedraza et al. 1989), whose outer surface often comprises a hardened crust that makes them more weathering- and erosion-resistant.

The degree of development of PC and 'toadstools' normally differs depending on their upper or lower location on the wall and the vertical or curved shape of the outcrop plane. García-Rodríguez et al. (2013) classified PC on the grounds of crack location relative to planes of weakness (Fig. 5). This classification is relevant when characterising mountaineers' routes, for the degree of PC development is essential to climbing. Figure 6 depicts some examples of PC identified on routes at La Pedriza.

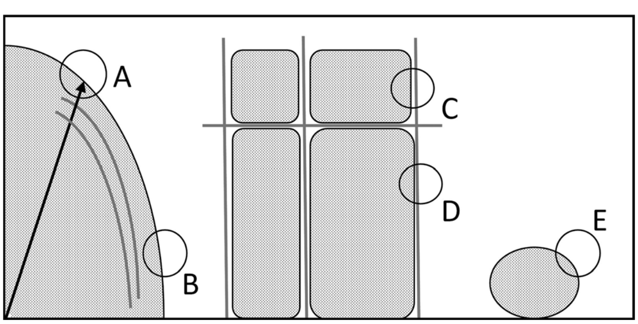

Fig. 5 Positions where polygonal cracking was found (García-Rodríguez, et al. 2013). **a** On the upper slope of large radial fault planes, characterised by irregular shapes, with deep grooves denoting erosion. **b** On the underslopes of large radial fault planes and on vertical walls, where they are less intense than on the upper slope and the cracks are less altered and shallower. **c**, **d** On vertical or sub-vertical fault planes (90–70°), with cracking more highly developed as a rule on the upper than on the lower wall, while position C cracking is often visible along fault planes on balanced rocks. **e** On the convex swells of granite boulders

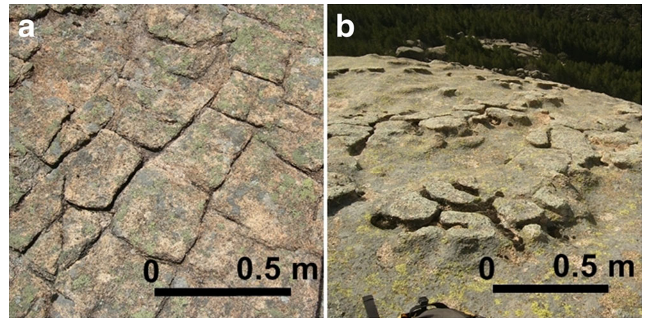

Fig. 6 Examples of polygonal cracking. **a** Type D PC in the 'Mano Lolo' route (6c+) on Muro de Snoopy. **b** Type A PC in the Tito L5 route (IV) on El Hueso

Geomorphological elements are, moreover, closely correlated to climbing route safety systems, with a prevalence of permanent anchors (parabolts) drilled into the rock in plates, pendulums and low friction passages, as well as pins, pitons, plugs, holds… in areas with grooves and cracks where climbing entails using very small to small-scale structural discontinuities in the rock massif.

Methodology

The first stage of the study consisted in a visual inspection in the field to identify all the rock walls and surfaces in the surrounds exhibiting one or several of the geomorphological features analysed, including case hardening, microreliefs, surface scaling, polygonal cracking and 'toadstools'. Since prior studies (García-Rodríguez et al. 2014b) found case hardening to rupture more frequently on the south walls, all the observations discussed here were conducted on the walls facing that direction.

Surfaces with silica-high case hardening are readily detected thanks to their whitish hues. Crust thickness and hardness were measured with a Schmidt hammer (SH) further to the methodology described in earlier geomorphological studies (Gouide 2006; Valeria Panizza and Mennella 2007). The dimensionless SH value provides an indication of rock hardness and consistency. See García-Rodríguez et al. (2015b) for additional information and illustrative figures on how to perform these mesurements and the instrumentation used. This paper shows measurements carried out in eight different walls distributed randomly throughout the study area, in which the presence of contiguous areas with CH and altered zone was evident. One hundred twelve measurements were taken on each, 56 on crusted areas and 56 on the altered perimeter. The location of the areas where measurements have been performed and the values obtained are shown in Table 1.

As microreliefs (MR) form undulations on the rock surface as a result of differential weathering of case-hardened surfaces, they were initially identified visually. Schmidt hammer

Table 1 Schmidt hammer values for eight walls with different crust thicknesses

	1C	1 W	2C	2 W	3C	3 W	4C	4 W	5C	5 W	6C	6 W	7C	7 W	8C	8 W
Mean	65	46	67	41	56	41	63	42	51	38	56	44	51	41	35	26
Std dev.	7.8	8.1	4.9	5.3	7.6	6.8	5.1	7.0	7.0	4.6	9.4	5.8	6.2	7.1	8.4	6

Location (zone): 1 Martes, 2 Brezos, 3 Euro, 4 Butrón, 5 Principiantes, 6 Hueso, 7 Peña Sirio, 8 Murito

C crust, *W* weathered area

Crust thickness: 1C (10–20 mm); 2C (10 mm); 3C (5–10 mm); 4C (7 mm); 5C (3 mm); 6C (3 mm); 7C (1–3 mm); 8C (1–2 mm). $N = 56$. Fresh granite (reference value): mean = 62, Std. dev. = 6.6

readings were taken when doubts arose about whether crust fragments remained on the outer- or inner-most parts or whether the crust had fallen away completely.

Surface scaling is readily identified, for the micro-flakes (MF) formed can often be removed from the wall by hand. These areas are more intensely altered than the zones with CH or MR and more actively weathered after CH surfaces become fully detached. The Schmidt hammer was unusable in these areas, for the micro-flakes, which are no more than 1-cm thick, would have broken under the impact.

Polygonal cracking and 'toadstools' often constitute the remains of more erosion-resistant case hardening. This geomorphological feature, characteristic of La Pedriza, has long made it possible to open climbing routes, capitalising on the good grips and anchors it affords. This study includes a fairly comprehensive inventory of PC on walls that are climbed and others that are not. The inventory has a dual purpose: to identify and classify the various types of PC defined in earlier classifications (García-Rodríguez et al. 2013), and to establish the role of such cracking in granite wall climbing and relate its practice to the classification, signalling the value of the area's scientific and sporting potential.

The second stage entailed selecting a group of climbing routes with the geomorphological features described. The inventory focused on friction climbing, the type most commonly practised at La Pedriza. The geomorphological features described generate protrusions, small steps or millimetric ledges that facilitate climbing. For this purpose only south-facing walls and climbing routes were chosen to be able to relate the associated geomorphology to the Schmidt hammer measurements taken on the walls with that orientation.

The methodology for identifying and inventorying surface forms and climbing routes was facilitated by the authors' own 30-plus-year mountaineering experience in the area, with the concomitant compilation of climbing and geomorphological data, along with rock sampling, photographs and measurements. The aim is to enhance the value of this contemplative sport, 'rope-teaming' here in writing.

As noted in the introduction, the technical difficulty of the routes was graded on the French scale. American scale equivalents are given where appropriate.

Results and Discussion

Case Hardening and Microreliefs

The SH values revealed a direct relationship between crust thickness and hardness, which can be explained by the high silica content in the crusts. Table 1 lists the readings for the eight granite walls tested. The values in each two consecutive columns give the measurements for unaltered crust and the adjacent weathered area. Crusted areas have very different thicknesses, varying from only 1–2 mm up to 10–20 mm. This variability is common throughout Pedriza and can be explained by two main reasons: (a) by migration of different amounts of silica to the front of the alteration zone that took place when the rock was still buried and (b) by a reduction in the crust thickness due to increased weathering-erosion produced in aerial conditions.

The lowest numbers (35C/26 W) denote the thickest crusts and the highest (65C/46 W) the thinnest. These results are coherent because the Schmidt hammer readings furnished information on two properties of these rocks: (a) hardness or compactness, which depends on mineralogy and degree of alteration; and (b) roughness, which depends on the greater or lesser differential weathering of the constituent minerals. As noted, the highest hardness values were found for the thickest crusts, which in addition to being silica-high, had a smoother surface. At the opposite end of the scale, the lowest Schmidt hammer values were observed in the silica-low altered areas immediately underneath case hardened surfaces (Table 1), to which the silica had migrated (García-Rodríguez et al. 2015a). This was the most intensely weathered area due to the differential alteration of biotites and potassium feldspar and also the area where micro-roughness was observed. Measuring points 1C, 3C and 6C exhibited case hardening that concurred with polygonal cracking plates.

The Schmidt hammer proved to be a useful tool for identifying degrees of alteration in the outer millimetres of the granite surface, for it furnished quantitative data that supported visual observations. The findings were consistent with the geomorphological interpretation of the origin of silica crusts given in prior studies (Twidale 1982; Conca 1985). That silica-high hardened areas that have the smoothest surfaces where friction is lowest has obvious implications for climbing. In the areas where the crust has weathered away, biotite oxidation creates a somewhat more porous and rougher surface where friction is greater and the ascent easier. Furthermore, the differential alteration of the crust and the appearance of microreliefs favour the formation of millimetric ledges or pits where the toes of sticky rubber shoes can be inserted to continue the climb.

Micro-Flaking

When case hardening vanishes, the rock may become more vulnerable to physical and chemical weathering, favouring spalling or MF (García-Rodríguez et al. 2014a). The result is the formation of small ledges scantly 2–3-mm wide, which are often the only support for climbers in their ascent along nearly vertical, completely smooth walls. In contrast, where weathering is more severe, these scales or micro-flakes become readily detached from the wall, hampering the ascent.

Polygonal Cracking

The identification of PC on the main walls at La Pedriza (Table 2) led to its classification by categories or types, further to a definition proposed by García-Rodríguez et al. (2013), and to the establishment of correlations between its origin and degree of development and its role in climbing. For more about the origin of PC from La Pedriza see García-Rodríguez et al. (2015b). The data in Table 2 serve a dual purpose. The first is geomorphological, typing the PC further to the classification in Fig. 5. The parameters analysed include location on the wall, type of surface (vertical or curved), orientation, slope, height and shape. The second is to provide a qualitative assessment of cracking development on each wall to establish the relationship between it and the ease or difficulty of ascent. Three levels of PC development were defined on the grounds of the incision depth of the perimetric cracks: shallow (0–20 mm), medium (20–50 mm) or deep (over 50 mm). Shallow cracks barely suffice to get a finger grip, while the medium cracks can be used to climb and the deep cracks constitute PC that has developed into 'toadstools' affording ample support.

The findings in Table 2 that relate the geomorphological features studied to climbing include the following.

1. The PC incision is deeper in the upper areas than in the areas closer to the ground, denoting longer exposure to solar radiation and moisture in the former.
2. The development of 'toadstools' is normally associated with type A PC in the upper parts of large radial erosional surfaces where the wall is less vertical and moisture

Table 2 Polygonal cracking (PC) inventory

Wall name	Orientation	Dip	PC shape, height from the ground (m), crack depth (mm)	PC type	PC development
El Murito	S	70° S	Rectangular; 6–6.5; 25	A	Medium
Pared Naranja	S	85° NW	Rectangular; 1–5; 4	D	Shallow
Bloque Brezos	E	85° E	Irregular; 3–4; 3	C	Shallow
Tres Puntas[a]	N	88° N	Rectangular; 3–10; 5	D	Shallow
Reloj[a]	S	78° S	Irregular (toadstool); 20–25; 25	A	Deep
Muro Snoopy[a]	SE	71° SE	Quadrangular; 5–15; 5	D	Shallow
			Irregular (toadstool); 15–20; 30	A	Medium
Camino Tranco	W	89° W	Rectangular; 4,5-5; 25	D	Medium
Zona del Martes[a]	E	74° W	Rectangular; 3–4,5; 5	D	Shallow
Peñas Cagás[a]	S	71° SE	Irregular (toadstool); 30–50; 60	A	Deep
			Irregular (toadstool); 20–30; 30	B	Deep
Zona Cinco Cestos	E	88° E	Irregular (toadstool); 8–12; 5	C	Deep
El Hueso[a]	S	60° S	Irregular (toadstool); 100–120;70	A	Deep
El Pájaro[a]	S	60° S	Irregular (toadstool); 150–190;90	A	Deep
Pared de Santillana[a]	S	70° S	Irregular (toadstool); 40–120; 80	A	Deep
			Irregular (toadstool); 10–40; 50	B	Deep
Cancho Redondo[a]	S	50° S	Irregular (toadstool); 20–45; 90	A	Deep
Peña Sirio[a]	S	60° S	Irregular (toadstool); 15–60; 80	A	Deep
			Irregular (toadstool); 15–60; 70	B	Deep

Note: A: large radial surface plane on the upper part of the wall; B: large verticalised radial plane on the lower side of the wall; C: vertical plane on balanced rock; D: vertical plane

[a] Walls where climbing is practised

remains in the rock longer. These are the areas that have been exposed to the elements for the longest. Examples of highly developed toadstools can be found on *El Hueso, El Pájaro, Pared de Santillana* and *Cancho Redondo*.

3. Further to the PC inventory, in the routes with polygonal cracking, the areas closest to the ground are harder to climb than the higher areas where PC has developed into toadstools.
4. The case hardening is very well preserved on areas with PC. The Schmidt hammer values for the PC plates are the same as the readings in the crusted areas (1C, 3C and 6C in Table 1).

Examples of How Geomorphology Conditions Climbing

Friction climbing is practised at La Pedriza on walls with 50–90° slopes, whose technical difficulty varies depending on the slope and the presence or, otherwise, of the geomorphological features studied. The combination of wall verticality and the presence or absence of certain geomorphological features results in routes with widely ranging grades. For instance, some routes with 90° slopes have such well-developed polygonal cracking that they are graded IV, while others on gentler (60–70°) but case-hardened slopes may be graded 6c.

Table 3 gives a few specific examples of the effect of geomorphology on climbing route difficulty, including the name of the wall, name and length of the route, grade, geomorphological feature that characterises the route and slope.

The qualitative information in Table 3 attests to the wide spectrum of technical difficulty that may be encountered. The presence of PC, for instance, is no guarantee of climbing ease, which depends on the depth of the perimetric cracks and wall slope. The ‘Sur clásica’ route on *Pared de Santillana*, for example, is very vertical but graded low because dike alteration has led to highly developed PC and mosaics. The ‘Gargajo amarillo’ route on *Risco del Gargajo* lies on the opposite end of the scale, whose extreme difficulty is due to the minimal depth of its PC along the route.

On case-hardened surfaces, the prevalent variable in determining difficulty is wall verticality. As friction is very precarious on such surfaces, walls with 60° slopes graded at over 6b are not uncommon. To climb walls with these characteristics and verticality of near 90°, the case hardening must have become at least partially detached, forming microreliefs that enhance rock friction or scaling that forms millimetric ledges. In general, though with some exceptions, pathways that allow for greater vertical elevation for the same level of difficulty are, in this order, those with PC, MF, MR and CH.

Three sample routes with varying degrees of difficulty, characterised by some of the geomorphological features studied are depicted in Fig. 7. In 6a, the route changes from a weathered area (w) to a surface with highly developed case hardening (ch) on a wall with a constant slope. This entails a

Table 3 Selected climbing routes at La Pedriza and geomorphological features determining their technical difficulty

Wall name	Route	French grade	American grade	Geomorphological feature	Slope
Cancho Redondo	Jungla de Otoño	6b	5.10c	Polygonal cracking	70°
Peñas Cagas	Tentaciones L3	V	5.8	Polygonal cracking	80°
El Pájaro	Sur Clásica L5	III	5.4	Polygonal cracking	60°
Risco del Gargajo	Gargajo amarillo	7c	5.12d	Polygonal cracking	90°
Pared de Santillana	Sur Clásica L2	IV+	5.7	Polygonal cracking	85°
Cinco Cestos	La envidia es “mu” mala	6c	5.11a	Case hardening	70°
Placa Ninja	Kisangani	7c+	5.13a	Case hardening	75°
El Yelmo	Eclipse de Vela	6b+	5.10d	Case hardening	65°
Risco de los Martes	Kuka	V	5.8	Case hardening	60°
Risco de los Principiantes	Puta hernia de los cojones	6c	5.11a	Case hardening	70°
Pan de Kilo	Tronchamoñigos L2	7b+	5.12c	Microrelief	75°
Cancho de los Brezos	Tu coge los trozos	7b	5.12b	Microrelief	75°
Cancho Butrón	Hijo del Vudú L1	6a	5.10a	Microrelief	70°
Cueva de la Mora	Paciencia infinita L3	7a+	5.12a	Microrelief	75°
Platillo Volante	23-F	6b+	5.10d	Microrelief	70°
El Euro	Cornucopión	6c	5.11a	Micro-flaking	80°
Risco de la Peseta	Odisea 2001 L1	7b+	5.12c	Micro-flaking	85°
Cancho de los Brezos	El arquero y el pez	6c+	5.11b	Micro-flaking	80°
Placa Nueve	Farfolla	6b+	5.10d	Micro-flaking	75°
Cancho de los Brezos	Aintza	6c+	5.11b	Micro-flaking	75°

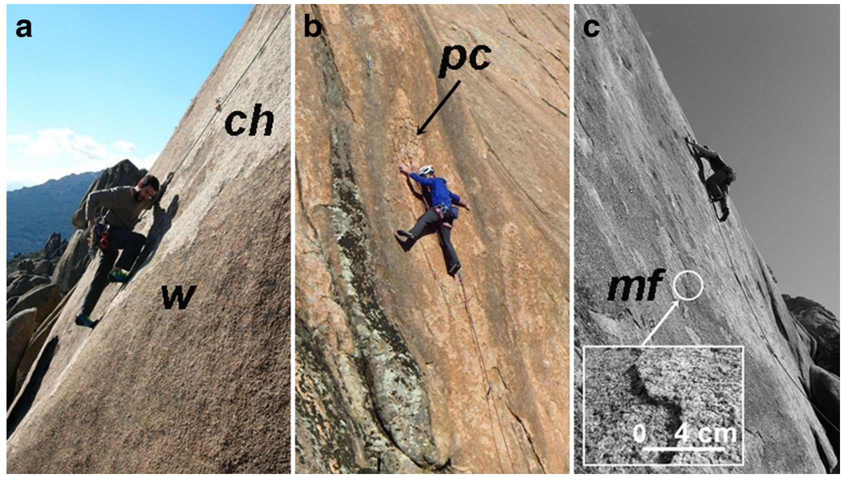

Fig. 7 **a** ‘La envidia es mu mala’ route on Cinco Cestos (6c). **b** ‘Free variation’ route on Tres Coronas (6c+). **c** ‘El arquero y el pez’ route on Cancho de los Brezos (6c+). *ch* case hardening, *w* weathered area, *pc* polygonal cracking, *mf* micro-flaking)

change from grade 6b/b+ to 6c (Lujan and Zapata 2005; Samtamaría 2008). All the geomorphological features studied are present in the ‘Free variation’ route on *Tres Coronas* shown in Fig. 7b. The area below the climber is characterised by microreliefs generated by differential alteration of case hardening. Immediately above him is the area of greatest difficulty and verticality, where the presence of (type D) PC favours the ascent, despite the minimal depth of the perimetric cracks. Case hardening still exists on the plates in this PC. Figure 7c is an example of how walls with slopes of greater than 70° can be climbed thanks to millimetric ledges formed by micro-flaking on which to rest toe- and fingertips.

The relationship between geomorphology and climbing on a given wall is clearly illustrated by *El Hueso*, as well as the routes listed in Table 3. *El Hueso*, [the bone] also called *Peñalarco*, is a huge, 170-m-high wall facing SE (Fig. 8). It derives its name from a column- or bone-shaped arched structure on its west end (García-Rodríguez et al. 2014c). The middle of this 90-m-tall column is separated from the main wall, which exhibits all the surface geomorphological elements studied here.

The climbing routes on *El Hueso* and their geomorphological features are shown in Fig. 8. Case hardening (1) prevails on the lower wall, micro-flaking (2) and microreliefs (3) in the intermediate area and very highly developed (type A) PC (4) near the top. Artificial aids are normally required for the ascent over the roofs. More specifically, the ‘Clavel rojo’ route cuts across the arch in *El Hueso*, the longest open arch in Pedriza.

Table 4 lists the names of the routes in Fig. 8, along with their degree of difficulty and the geomorphological features present. The references to the lengths of the climb across each area are based on the Lujan and Zapata (2005) climbing guide.

In addition to the educational benefits of geo-climbing, other factors such as the Tourist-Sport Potentiality Index (TSPI) (Bollati et al. 2014), the climbing ‘aesthetic’, the chain of precise movements demanded of climbers, and the density or concentration of elements of value in the area involved, in this case climbing routes, should be taken regarded as key classification criteria.

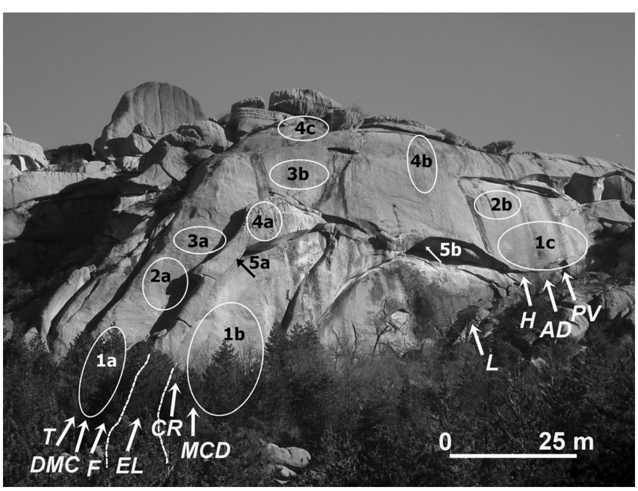

Fig. 8 El Hueso wall showing instances of case hardening (*1*), micro-flaking (*2*), micro-relief (*3*), polygonal cracking (*4*), and roofs (*5*) [*arrows* = starting points for the climbing routes listed in Table 4 and abbreviated here]

Conclusions

La Pedriza del Manzanares, a geosite of considerable geological, educational and scientific interest, has been the subject of very few publications that relate climbing to earth science and environmental education.

Geo-climbing is another form of geo-tourism with a high educational component associated with contemplative sport, which affords the activity growing value in terms of accessibility and general connectivity. The educational tools afforded are highly promising given the variety of climber profiles. The more diverse the group (age, skill, experience…), the broader is the range of observer identification with its members. Here, the old Spanish saying whereby ‘he who sees most knows most’ obviously holds.

Table 4 Examples of *El Hueso* climbing routes and geomorphological features

Area (Fig. 7)	Route name	French grade	American grade	Geomorphological feature
1a	Tito L2	V+	5.9	Case hardening
1b	MCD L1	7b	5.12b	Case hardening
1c	Heliotrópica L1	7b+	5.12c	Case hardening
	Pabellón de verdetroncha L1	7a+	5.12ª	Case hardening
	Complejo de lagartija L1	7a	5.11c	Case hardening
2a	Tito			Micro-flaking
	De Madrid al cielo L2	6b+	5.10d	Micro-flaking
2b	Heliotrópica L1	6c+	5.11b	Micro-flaking
	Alicantropía del desparramo L1	6c+	5.11b	Micro-flaking
3a	Tito L4	V	5.8	Microrelief
3b	Fulgencio L4	V	5.8	Microrelief
4a	Fulgencio L3 Espolón lunático L3	V V	5.8 5.8	(Type A) polygonal cracking with 'toadstools'
4b	Lucas L4	IV+	5.7	Polygonal cracking
4c	Tito L5	III+	5.5	Polygonal cracking
5a	Clavel rojo L1	Ae	Ae	Roof
5b	Lucas L2	A2	A2	Roof

Climbing routes combine points of geological and geohistorical interest with sporting and cultural elements, in which climbers are inspired or even seduced by the beauty of earth science and geo-diversity.

La Pedriza is a very dynamic geosite, both as regards the action of external geodynamic agents (resulting in widely diverse geological and geomorphological resources) and its anthropic components, with a climbing culture that has witnessed the advent of certain historic landmarks, such as free climbing or soloing.

This work explains the origin of some external features (PC, CH, MF, MR) present on the surfaces of granite walls, linking them to the endogenous, subsurface and air processes involved in their origin. The study of morphological, some textural and compositional characteristics of rocks have revealed relationships, that are partially quantified, that influence the difficulty of climbing routes. The information provided in this document can be used in the preparation of future guides which place value on geological heritage as an added element for sport and tourism. This document is a useful study with international scope as adherence climbing is practised on a large number of granite walls around the world.

Associating climbing route difficulty with geomorphological and environmental elements such as verticality or orientation are resources that must be borne in mind when cataloguing wealth La Pedriza has to offer for environmental education. This would also pave the way for establishing new routes of geo-touristic interest with a higher geo-climbing content and vested with new environmental values and effective educational tools. Such resources would include guided day tours as well as specific geo-climbing educational activities for professional mountaineering and climbing guides.

Climbing and landscape interpretation guides should include elements relating to the environmental and educational value of the area at issue, associated both with geo-climbing and its history, culture, rites and myths, the value of which is largely contingent upon the age and culture of the target population.

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