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Exfoliation microcracks in building granite. Implications for anisotropy

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ABSTRACT

Granite is found in many world heritage monuments and cities. It continues to be one of the most widely used stones in today's construction, given its abundance, uniformity and durability. Quarrymen traditionally cut this rock along its orthogonal slip planes, where splitting is easier. Ranked by ease of splitting, these planes are rift, grain and hardway. Granite is traditionally quarried along the rift plane where coplanar exfoliation microcracks coalesce developing a flat surface. This splitting surface minimizes the cost and effort of subsequent hewing. Rift plane was predominantly used on the fair face of ashlars in heritage buildings worldwide. Determining the petrographic and petrophysical behaviour of these three orthogonal splitting planes in granite is instrumental to understanding decay in ashlars and sculptures. The decay of building granite is different in each splitting plane.

Alpedrete granite was the stone selected for this study based on the orientation and distribution of exfoliation microcracks and the characterisation of their implications for the anisotropy of petrophysical properties such as ultrasonic wave propagation, capillarity, air permeability, micro-roughness and surface hardness. Inter- and intracrystalline microcrack length and spacing were also measured and quantified.

The findings show that the splitting planes in Alpedrete granite are determined by the orientation of exfoliation microcracks, which as a rule are generally straight and intracrystalline and determine the anisotropy of the petrophysical properties analysed.

Splitting planes are the orientation that should be applied when performing laboratory tests for the petrographic and petrophysical properties of building granite.

1. Introduction

Granite has been one of the most widely used construction stones throughout history due to its abundance, petrophysical characteristics, durability, compositional and textural uniformity. It is found on building façades, walls and sockets, on plinths for sculptures and as a base for large-scale structures. Microcracks play an essential role in building granite decay, they are due to genesis, tectonic history and denudation of the rocky massif where quarries are sited (Catlos et al., 2011).

The present study addresses exfoliation microcracks, i.e., microscopic fissures located between what in the literature are termed Bankung, Lägerklufte, exfoliation, sheet, sheeting, pressure-release, stress-release, unloading, offloading and post-uplift joints (Ziegler et al., 2014); generated due to decompression on and near the surface of the granite massif (Gorbatsevich, 2003). Referred to hereunder as exfoliation joints, they are found in all climates and in many types of rock, with specific characteristics that are common the world over. Flat and open, they are the youngest natural cracks in outcrops. The width of their openings narrows and their spacing grows (from millimetres to several metres) with depth. They are normally confined to a few decametres, i.e., to the quarry depth, although they may extend up to 100 m below the surface (Goodman, 1993). Their displacement is insignificant and their orientation sub-parallel to the actual surface of the relief or palaeo-relief. They may coalesce, producing macroscopic structures. Such exfoliation joints, which may spread laterally across distances of over 100 m, are used in quarries to define the 'floor' or springline in levels or banks. They accelerate alteration (Sajid et al., 2016) and may induce mass movements in granite slopes (Chigira, 2001).

Lateral expansion due to vertical or sub-vertical fractures favours the sub-vertical cracking and microcracking that originate granite tors or boulders, i.e., the remains of solid rock present in layers of mantle rock. Such regoliths, which may range in depth from a few to 25 m or even 30 m, exhibit a higher degree of alteration than the underlying granite (García-Rodríguez, 2015). The exfoliation microcracks found in tors are normally pseudo-concentric, giving rise to what is known as spheroid exfoliation. Traditionally, tors were used to hew ashlars for use in monument construction (Fort et al., 2010).

In traditional quarrying the slip planes formed by mineral orientations or the presence of oriented cracks (Chen et al., 1999) were used to extract and dimension granite blocks. The three orthogonal splitting

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planes are known as rift (R), grain (G) and hardway (HW) (Fig. 1). Rift is the plane in which the stone is most readily split, followed by grain and lastly by hardway (Vasconcelos et al., 2009). Table 1 lists the names of these three planes in several languages.

The traditional quarrymen needed the existence of exfoliation microcracks to make the artisanal splitting of granite blocks easier. In historic granite quarries the presence of well-defined R was essential to operation, to ensure that blocks could be cut with less effort by hammering wedges into the granite in direction R. Quarrymen traditionally identified the rift plane touching the granite planes on the grounds of surface roughness, for plane R is smoother than planes G and HW. A granite quarry with no or a weak R is usually not productive.

Today ground penetrating radar (GPR) is used to locate blocks and exfoliation joints and to identify fresh rock in ornamental granite quarries (Porsani et al., 2006). As the granite is normally cut with diamond-blade tools or jet flames (Baltuille et al., 2004), R no longer conditions the quarry, although joints and microcracks continue to be help define the banks and extract large blocks (Sousa, 2007, 2010; Yarahmadi et al., 2015; Sousa et al., 2016).

Stone anisotropy can be defined as the difference of measure when a property is measured along different axes. Due to the anisotropy, the granite position on buildings define its hydraulic and mechanical behaviour (Fort et al., 2011) as well as its resistance to decay, particularly when it, and hence the microcracks it bears, are subject to temperature change (Gómez-Heras et al., 2009; Freire-Lista et al., 2015a).

The exfoliation microcracks had never been studied from the point of view of the anisotropy applied to building ashlars. This paper aims to instrumentally determine the role of exfoliation microcracks in the anisotropy in granite used in construction and characterise the anisotropy of petrophysical properties when measured along the three splitting planes (rift, grain and hardway) in Alpedrete granite. It has been observed that these microcracks have great importance in the building granite decay processes. With the findings in hand, this orientation can be reproduced in new constructions, restorations and petrophysical tests, particularly in accelerated ageing tests conducted to study granite specimen durability.

2. Material and methods

2.1. Granite samples

The stone quarried in the Guadarrama Mountains (Spanish Central System) is generically known as Piedra Berroqueña (Freire-Lista and Fort, 2016a). One of the varieties is Alpedrete, a medium-to-fine grained, sub-automorphic, equigranular monzogranite (Fort et al., 2011). It has been widely used as a building material in Madrid and surrounding areas, as well as in France. It has been nominated as a Global Heritage Stone Resource (Freire-Lista et al., 2015b) given its traditional use in emblematic monuments and its export potential. The literature contains many references to its origin tectonic deformation (Villaseca et al., 2009), historic quarries, petrological characteristics, durability and use in buildings (Fort et al., 2010, 2013; Pérez-Monserrat et al., 2013).

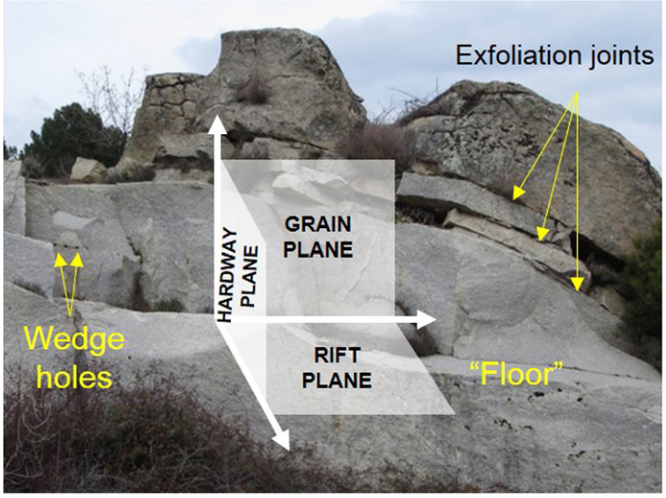

Fig. 1. Quarry front from which the samples were extracted, showing rift, grain and hardway.

Table 1
Names of splitting planes in several languages.

English	Rift/run	Grain	Hardway/headgrain
Spanish	Ley/andar	Mano buena	Mano mala
Japanese	Ichino-me	Ninome-me	Sanno-me
Swedish	Svall		Borst
Austria	Heber	Gang	Schechle Seite
Norwegian	Kløv		Bust
Brazilian	Corrida	Segundo	Trincante

The samples were taken from a historic granite quarry at Alpedrete (40°39″45.7″N 4°00″47.7″W), approximately 40 km northwest of Madrid. A quarryman cut a single block in the traditional manner, along the orthogonal rift, grain and hardway planes (Fig. 2). Three chips (<1 cm^2) were also taken from each splitting plane for electron microscope observation. Surface micro-roughness was measured on each splitting plane (rift, grain, hardway) of the traditionally quarried block. Ten 7 × 7 × 7 cm specimens were cut from the block by disk saw at low speed (120 rpm) and low voltage. A thin section was taken on each splitting plane from one of the specimens for observation under an optical microscope. The following parameters were measured in the remaining nine specimens: surface hardness, P- and S-wave velocity (V_p and V_s), capillary absorption and air permeability. The tests were conducted on the three splitting planes on all nine specimens, after they had been dried at 70 °C to a constant weight (<1‰ variation in two consecutive weighings over 24 h) and cooled to ambient temperature in a desiccator with silica gel.

2.2. Analytical techniques

2.2.1. Optical surface micro-roughness (OSR)

Optical surface micro-roughness was measured non-destructively along the three splitting planes (R, G and HW) on the unsawn, unpolished sample. The TRACEiT handheld roughness metre used delivered high precision 3D topography with a resolution of 1 μm on the Z axis and 2.5 μm on the X and Y axes. Measuring field dimensions were 5 × 5 mm. A total of 2000 data points on the X/Y axes were recorded for each measurement. Roughness parameters were computer calculated as laid down in European and international standard DIN EN ISO., 4287., 1984. These Roughness parameters are R_a, it is the arithmetic mean of the absolute values of the deviations from the mean; R_q, it is the square root of the deviation and R_z, it is the sum of the vertical distances between the five highest and five lowest values found for the sample.

Fifteen micro-roughness readings were taken on the freshly cut, unsawn, unpolished surface along planes R, G and HW and the mean was calculated for each plane.

2.2.2. Scanning electron microscope (SEM)

The morphological study of the surfaces on small Alpedrete granite chips (planes R, G and HW) that were unexposed prior to detachment (hereafter 'unexposed surfaces') was conducted with a JEOL JSM 6400 scanning electron microscope. The operating conditions were: voltage acceleration, 0.2^{-40} kV; current, 6×10^{10} A; vacuum, 10^{-5} Torr; resolution, 35 Å at a distance of 8 mm; and voltage acceleration for imaging, 35 kV and 20 kV. The microscope was used in conjunction with an Oxford Inca energy dispersive spectrometer (EDS) with a resolution of