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RESEARCH ARTICLE

Preliminary Ornamental Classification of Biotitic Granites from Cubal (SW of Angola)

Clasificación ornamental preliminar de los granitos biotíticos de Cubal

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ABSTRACT

Key points:

- Ornamental characterization of granites in Cubal, SW Angola based on textural, compositional, technological, and geographic characteristics.
- Study of fracturing in granite masses and definition of dominant zones of fracturing orientation.
- Preliminary classification of granite masses and outcrops in four levels of increasing potential.

In the Cubal region between Benguela and Huambo (SW of Angola), grey biotite granites of middle Paleoproterozoic age occur on a planation surface as residual reliefs, either of inselberg or inselgbirge type. The objective of this work is to carry out the preliminary classification of the grey granites of the Cubal region (SW of Angola), ranking the areas in relation to their potential in granites as ornamental rocks. Six granite lithotypes were identified, which can be grouped into 3 sets according to their textural characteristics. The petrographic analysis reveals that from a mineralogical point of view, granitic lithotypes are very similar with a significant content of plagioclase. The samples chemical analysis shows a homogeneous acidic composition in the granite composition range. Tests were carried out to determine real and apparent density, total and open porosity, water absorption at atmospheric pressure, compressive strength, and bending strength. The results show that the Cubal granites have the characteristics of quality ornamental stones, which in general can be used in all types of applications, in interior and exterior environments. Based on a set of variables, an empirical classification of the ornamental potential of the granites was made, where 4 levels of increasing potential in the study area are established.

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RESUMEN

Puntos clave:

- Caracterización ornamental de granitos en Cubal, SO Angola, basada en características texturales, compositivas, tecnológicas y geográficas
- Estudio de fracturación en masas graníticas y definición de zonas dominantes de orientación de fractura
- Clasificación preliminar de masas y afloramientos graníticos en cuatro niveles de potencial creciente

En la región de Cubal entre Benguela y Huambo (SO de Angola), granitos biotíticos grises de edad Paleoproterozoica media se encuentran sobre una superficie de planación como relieves residuales del tipo *inselberg* o *inselgbirge*. El objetivo del trabajo fue realizar la clasificación ornamental preliminar de los granitos grises presentes en la región de Cubal (SO de Angola), jerarquizando las áreas en relación con su potencial en granitos como rocas ornamentales. Se identificaron seis litotipos de granito, los cuales se pueden agrupar en 3 conjuntos según sus características texturales. El análisis petrográfico revela que desde el punto de vista mineralógico los litotipos graníticos son muy similares. El análisis químico de las muestras muestra una composición ácida homogénea en el rango de composición del granito e indica un contenido significativo de plagioclasas. Los resultados de los ensayos realizados para determinar la densidad real y aparente, la porosidad total y abierta, la absorción de agua a presión atmosférica, la resistencia a la compresión y la resistencia a la flexión, en su conjunto, muestran que los granitos de la zona de Cubal tienen características de piedras ornamentales de calidad, que en general se pueden utilizar en todo tipo de aplicaciones, ya sea en ambientes interiores o exteriores. Con base en un conjunto de variables se realizó una clasificación empírica del potencial ornamental de los granitos, donde se establecen 4 niveles de potencial creciente en el área de estudio.

Palabras clave: Granito; Piedra ornamental; Cubal; Potencial; Clasificación

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1. Introduction

The identification of rocks with ornamental potential has a great importance both from an economic and mining industry point of view, as it is a valued commodity, and from the land use and environmental planning perspective, as this identification promotes safeguarding the mineral resource and an efficient exploitation, avoiding the proliferation of unsuccessful attempts, which are subsequently abandoned, with the consequent visual impact. The present work aimed to carry out a preliminary ornamental classification of the grey granites occurring in the Cubal region (SW of Angola), ranking the areas with ornamental potential. The studied area is in the southwest of Angola (approximately 100 km to the ESE of Benguela and 180 km to the WSW of the city of Huambo) being well served in terms of the road network between two of the largest cities in Angola, both provincial capitals, which allows an effortless flow of raw materials.

This study is part of the mapping and characterization work on rocks with ornamental potential carried out for IGEO, within the scope of the Chart of Rocks and Industrial Minerals of Angola (CARMINA) subproject, of the PLANAGEO project, completed in 2022. The target area of the study corresponds to CARMINA sheet 277-A, Cubal.

2. Geological and geomorphological setting

The study area belongs to the cratonic interior of the Angola Shield, specifically the Central-West Domain, definitively stabilized at the end of the Eburnean episode (2.1 - 1.92 Ga) (Pereira *et al*., 2011, 2013; McCourt *et al*., 2013; Rodrigues *et al*., 2021). The geology of the Cubal region is dominated by vast outcrops of late to post-tectonic Eburnean biotitic-amphibolic granitoids (Silva & Caessa, 2021). The almost exclusively granite and granodiorite lithologies that occur in the area (Fig. 1) fall within the so-called "Eburnean Acid Plutonic Suite" (Silva & Caessa, 2021). It is, in general, a suite of granitoids with a metaluminous character, biotitic to biotitic-amphibolic, with a granodioritic to monzogranitic composition, generally free from ductile deformation and exhibiting an isotropic fabric, although it may include slightly foliated facies. They reveal petrographic and geochemical characteristics that link them to calc-alkaline magmatism (Barbarin, 1999, 2011).

These granitoids can be classified as I-type granites, generated by the fusion of infracrustal rocks of an igneous nature (e.g., Chappell & White, 1974, 2001), with an intermediate to basic composition. They have isotopic ages (U-Pb/SHRIMP II) close to 2.0 Ga (Silva & Caessa, 2021), which confine them to the Orosirian period.

From a geomorphological point of view, the preponderant forms are the residual reliefs resulting from granitic and granodioritic domes exposed by coupled action between heterogeneous chemical alteration and physical removal of the weathered materials during pediplanation periods. These residual reliefs can occur singly (inselberg) or in groups of them (inselgebirge), rising in the landscape from an extensive planation surface. Geologically, they correspond to granitoid lithologies that, due to differential erosion and/or slight mineralogical changes in relation to the surrounding rock, were more resistant to erosive dismantling. Most of these relief figures have domed profiles with rounded or tapered tops. From the partial weathering of the reliefs, thin layers of coarse-grained detrital material occur locally in the pediplain surface, which comprises part of the basin of the Cubal and Halo (Caimbambo) rivers, with altitudes ranging from 800m to 950m.

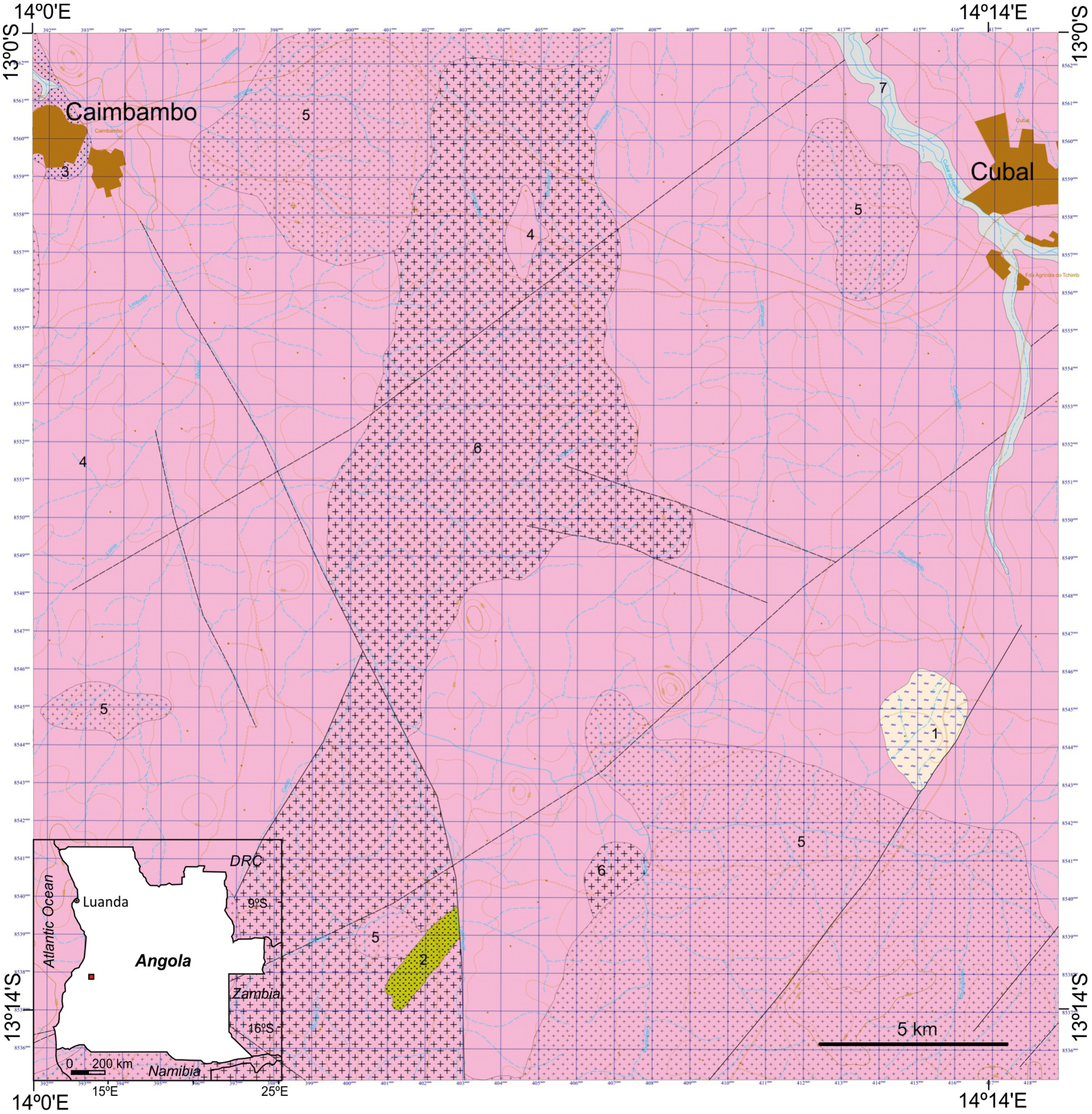

Figure 1. Study area corresponding to the sheet 277-A (CARMINA) geological map, according to the mapping of sheet D-33/I Cubal, scale 1:250,000. Cubal – Caluquembe Gneiss-Migmatite Complex: 1- Diatexites. Vila Branca Group: 2-Quartzites. Eburnean Acid Plutonic Suite: 3-Biotite ± amphibolic, equigranular, fine- to medium-grained granites and granodiorites; 4-Biotitic ± amphibolic granites and granodiorites, equigranular, medium to coarse grained; 5-Biotitic ± amphibolic porphyroid granites, medium to coarse-grained (1987 ± 7 Ma); 6-Biotitic ± amphibolic porphyroid granites, with pegmatitic grain (1978 ± 6 Ma). Surface Deposits: 7-River and surface runoff deposits.

Figura 1. Área de estudio correspondiente al mapa geológico de la hoja 277-A (CARMINA), según el mapeo de la hoja D-33/I Cubal, escala 1:250.000. Complejo Gneisso-Migmatitico de Cubal – Caluquembe: 1- Diatexitas. Grupo Vila Branca: 2-Cuarcitas. Suíte plutónica ácida eburneana: 3- granitos y granodioritas biotíticos ± anfibólicos, equigranulares, de grano fino a medio; 4-Granitos y granodioritas biotíticos ± anfibólicos, equigranulares, de grano medio a grueso; 5-Granitos porfiroideos biotíticos ± anfibólicos, de grano medio a grueso (1987 ± 7 Ma); 6-Granitos porfiroideos biotíticos ± anfibólicos, de grano pegmatítico (1978 ± 6 Ma). Depósitos Superficiales: 7-Depósitos fluviales y de escorrentía superficial.

3. Methodology

Fieldwork constituted the fundamental basis of the survey with systematic outcrops assessment, identification of different granite lithotypes present and detailed characterization of those that show potential for exploitation. Data and sample collection, whenever justified, was carried out at previously selected recording stations in accordance with the defined CARMINA methodology (Suaréz *et al*., 2018, PLANAGEO 2020), although some had to be replaced due to lack of access to the location.

The fracturing in a massif determines its suitability for exploitation as ornamental stone. Preceding the fieldwork, photointerpretation of regional fracturing was carried out, which was then studied in the field. To characterize the fracturing at the outcrop level, the scanline method was used in each of the recording stations in which one or two scanlines were carried out perpendicular to each other. The strike and frequency of the fractures, and average spacing between fractures of the same joint set were registered.

Analyses and tests were carried out in the laboratory, on selected samples, collected in massifs with higher potential for possible exploitation and use. This study comprised petrographic analysis of polished thin sections of the samples and chemical analysis of each of the defined lithotypes. These analyses were carried out in the laboratory of the Laboratório Nacional de Energia e Geologia (LNEG), in Portugal and in the laboratories of the Instituto Geológico y Minero de España (IGME), in Spain. The study of physical-mechanical properties was carried out in Angola, at the IGEO Geoscientific Laboratory, in Congenge (Lubango). The tests considered most relevant in the characterization of ornamental rock were carried out in selected granite samples from each of the lithotypes and included the determination of the following physical properties: 1) real density and apparent density using the wire basket method, open and total porosity (6 cube-specimens of side 50 mm), all in accordance with NP EN 1936:2006; 2) water absorption at atmospheric pressure (6 cube-specimens of side 50 mm) in accordance with NP EN 13755:2008; 3) uniaxial compressive strength using a Proeti HO245/EX equipment (10 cube-specimens of side 50 mm) in accordance with NP EN 1926:2008; and 4) flexural strength under concentrated load using a Proeti SO358 apparatus (10 test-specimens 50×50×300 mm) in accordance with NP EN 12372:2008. The standards used (NP EN) are the Portuguese translated versions of the corresponding European standards (EN).

4. Results and discussion

4.1. Identification of granite lithotypes

The granites have good exposure, are generally isotropic or have minor deformation, and considering the fracturing they are slightly fractured to moderately fractured.

Six granite lithotypes were identified (Fig. 2):

- Equigranular fine-grained leucogranite; (FEq)
- Equigranular, fine to medium grained granite (FMEq);
- Equigranular, medium to coarse grained granite (MCEq);
- Fine to medium grained granite with a porphyroid tendency (FMPhd);
- Medium to coarse grain porphyroid granite (MCPhd);
- Coarse to very coarse-grained porphyritic granites (VCPhd)

Six All granites, with exception of leucogranites, are biotitic, grey in colour, representing a common granite typology.

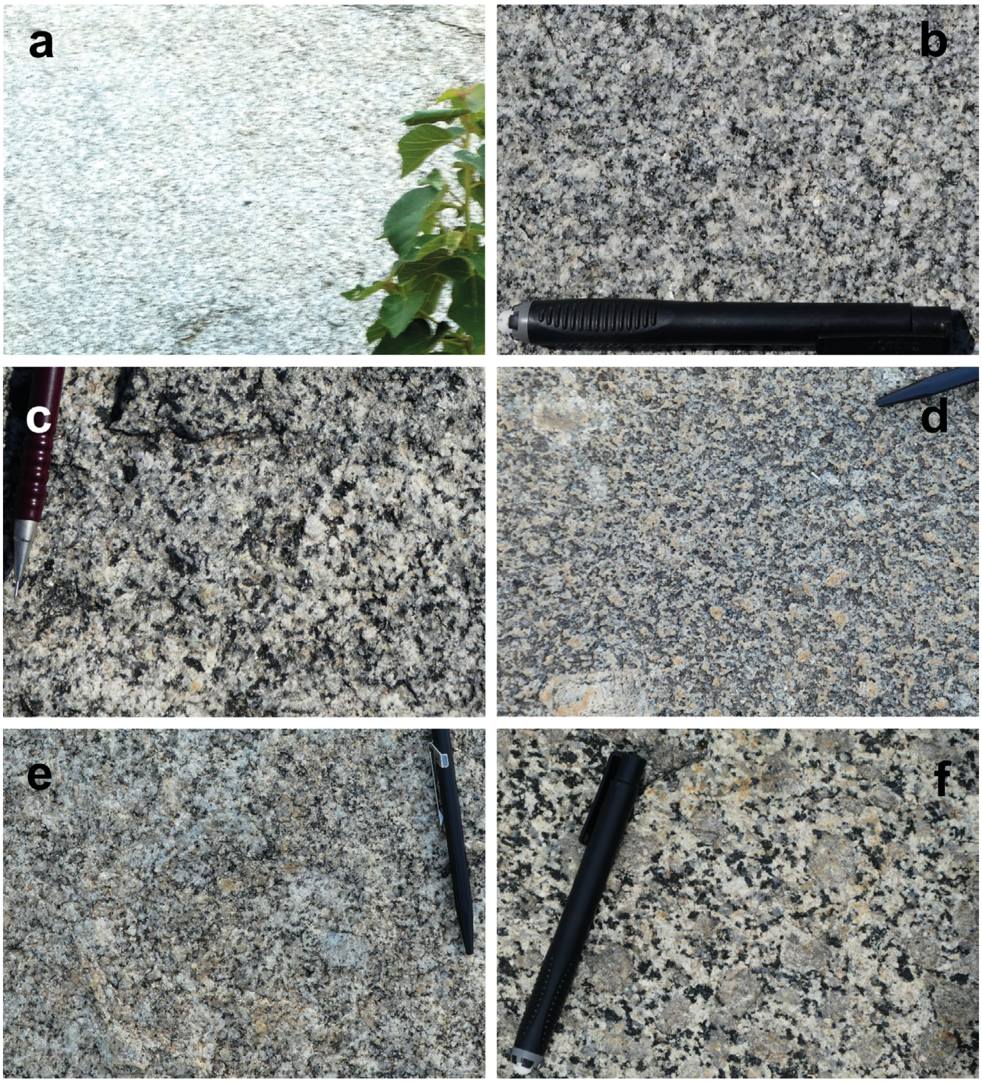

Figure 2. Main granitic lithotypes identified in the Cubal area. (a) Equigranular fine-grained leucogranite (FEq); (b) Equigranular, fine to medium grained granite (FMEq); (c) Equigranular, medium to coarse grained granite (MCEq); (d) Fine to medium grained granite with a porphyroid tendency (FMPhd); (e) Medium to coarse grain porphyroid granite (MCPhd); (f) Coarse to very coarse-grained porphyritic granites (VCPhd).

Figura 2. Principales litotipos graníticos identificados en la zona de Cubal. (a) Leucogranito equigranular de grano fino (FEq); (b) Granito equigranular de grano fino a medio (FMEq); (c) Granito equigranular de grano medio a grueso (MCEq); (d) Granito de grano fino a medio con tendencia porfiroidea (FMPhd); (e) Granito porfiroideo de grano medio a grueso (MCPhd); (f) Granitos porfídicos de grano grueso a muy grueso (VCPhd).

According to textural characteristics, especially in terms of grain size and homogeneity, and mineralogy (colour), which make it possible to make a first distinction from an ornamental point of view, granite lithotypes can be grouped into 3 sets (Fig. 3):

1. Equigranular fine-grained leucogranite. This granite represents light-coloured granites, essentially quartz-feldspathic, with a low concentration of mafic mineralogy (Bt ≈ 5%), little fractured, and with a rare presence of schlierens, enclaves, and veins/dykes. They are, however, the least frequent lithotypes and generally occur in small occurrences;
2. Coarse to very coarse-grained porphyritic granite. Late-stage granite intrusion, little fractured, with rare schlierens, enclaves, and veins/dykes, but which tend to be localized and abundant, when they occur. This granite lithotype outcrop on a large extent, essentially along a N-S corridor in the central part of the sheet, however, it has a high concentration of enclaves (sometimes representing 30% to 50% of the total rock volume);

3. All the remaining lithotypes. They have similar characteristics/appearance, observing only textural changes (grain size and presence/absence of phenocrysts) between the different characterized lithotypes. The presence of enclaves, schlieren-type structures and leucogranitic and aplite-pegmatite veins and dykes is common. Sometimes they present slight foliation.

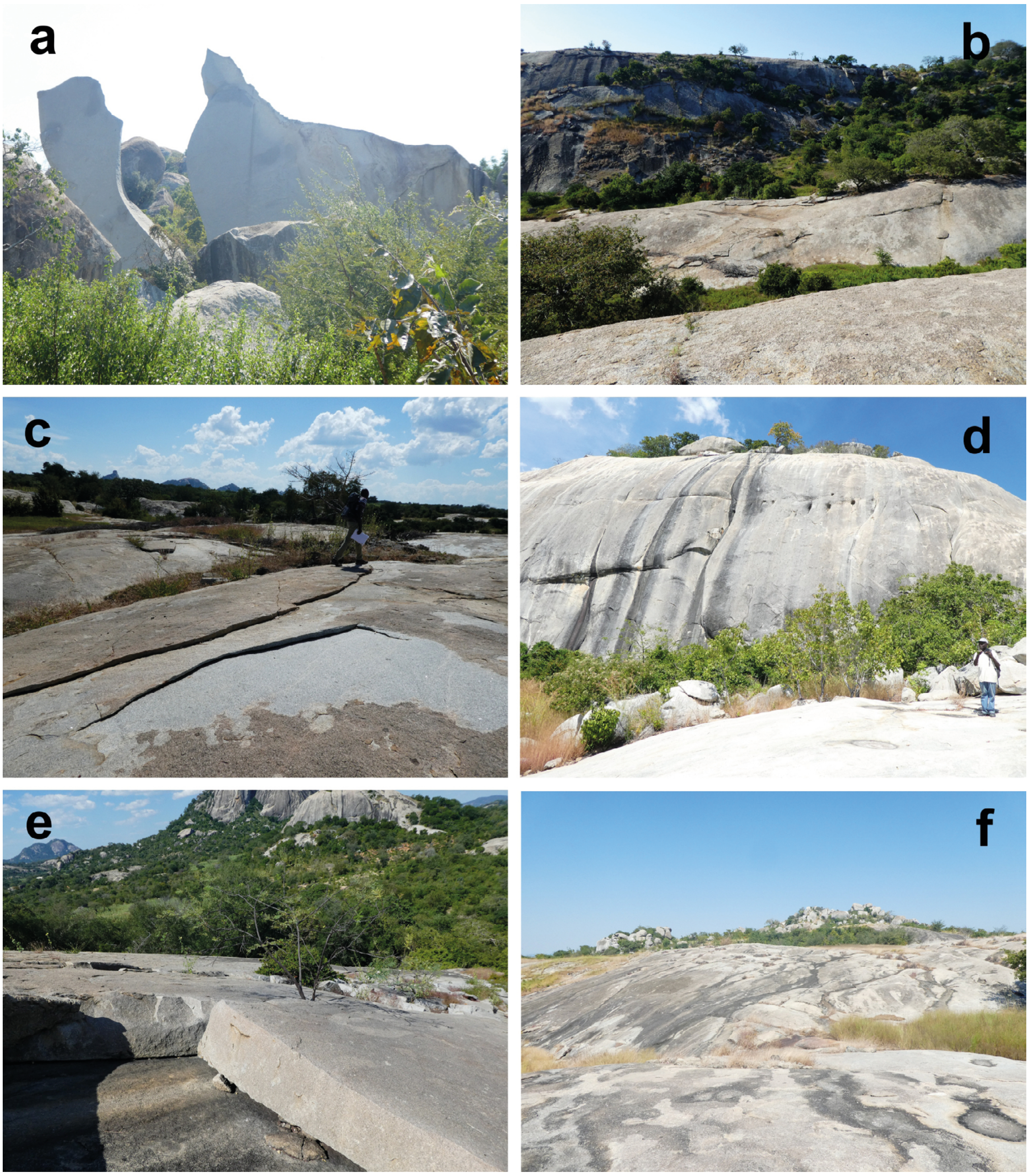

Figure 3. Examples of outcrops of the main granite lithotypes identified in the Cubal area. (a) Equigranular fine-grained leucogranite (FEq) in Calunga, municipality of Caimbambo; (b) Coarse to very coarse-grained porphyritic granites (VCPhd) in Caluma, municipality of Caimbambo; (c) Equigranular, fine to medium grained granite (FMEq) in Calongamba, municipality of Caimbambo; (d) Equigranular, medium to coarse grained granite (MCEq) in Caibango, municipality of Caimbambo; (e) Fine to medium grained granite with a porphyroid tendency (FMPhd); (f) Medium to coarse grain porphyroid granite (MCPhd) in the area west of Cubal, municipality of Caimbambo.

Figura 3. Afloramientos ilustrativos de los principales litotipos graníticos identificados en el área de estudio. (a) Leucogranito equigranular de grano fino (FEq) en Calunga, municipio de Caimbambo; (b) Granitos porfídicos de grano grueso a muy grueso (VCPhd) en Caluma, municipio de Caimbambo; (c) Granito equigranular de grano fino a medio (FMEq) en Calongamba, municipio de Caimbambo; (d) Granito equigranular de grano medio a grueso (MCEq) en Caibango, municipio de Caimbambo; (e) Granito de grano fino a medio con tendencia porfiroide (FMPhd); (f) Granito porfiroideo de grano medio a grueso (MCPhd) en la zona al oeste de Cubal, municipio de Caimbambo.

4.2. Fracturing

Considering the importance of fracturing in defining the ornamental potential of a rock massif, that factor significantly contributes to the preliminary classification of granites.

In Figure 4, the joint sets found in each group of outcrops or zone are represented in rose diagrams, superimposed with the photo-interpreted regional fracturing pattern. The total number of joints (827) measured in the study area are mostly sub-vertical and show a clearly predominant trend in the NE-SW direction (N45°-60°) (Fig. 5). A secondary fracture trend can be considered with sets N60-80°W. There is some dispersion in other directions, which is residual in regional terms. The relationships between the regionally observed fracture directions and the six distinct granite typologies identified are not evident.

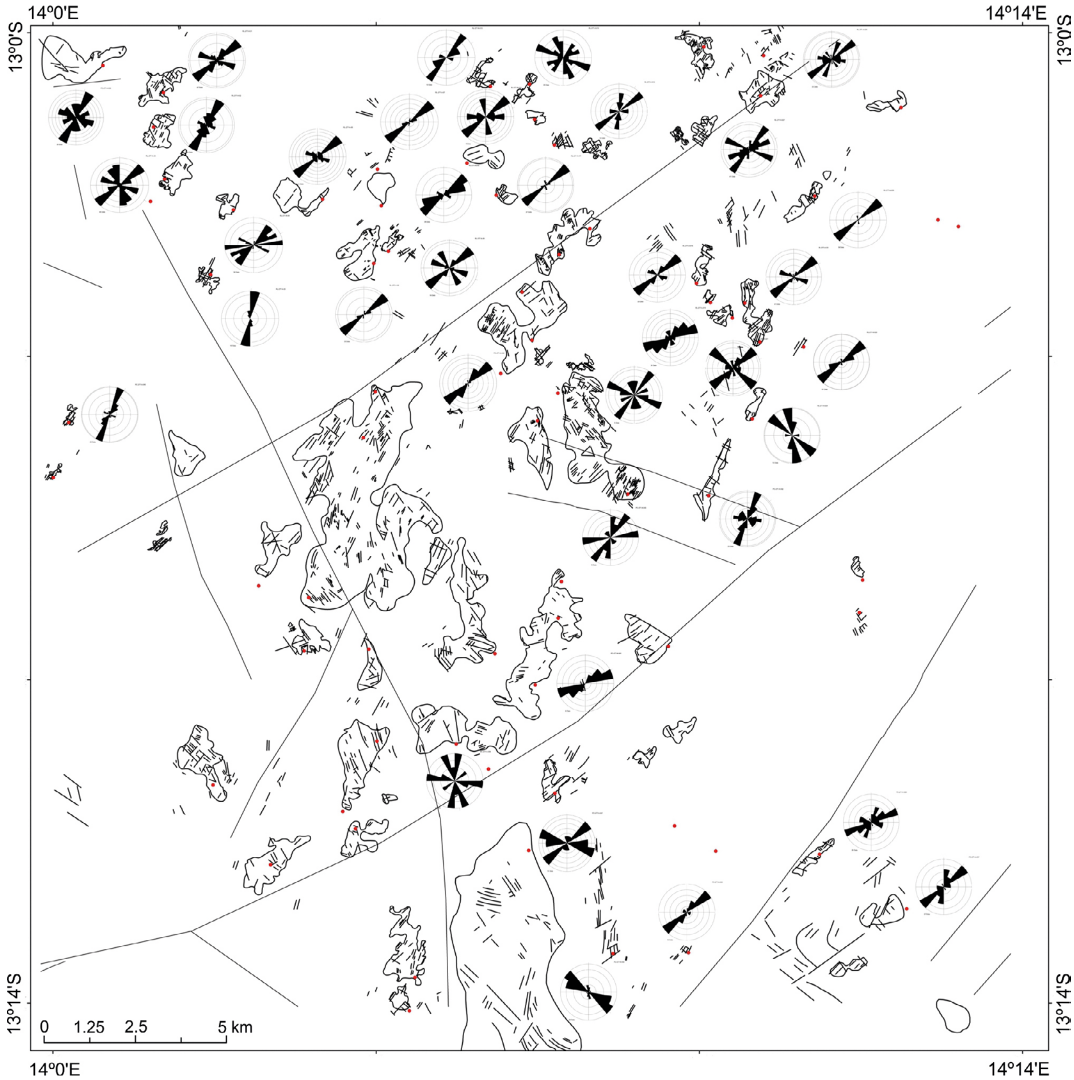

Figure 4. Map of granite outcrops with rose diagrams referring to fracturing measured in scanlines, superimposed on photo-interpreted fracturing.

Figura 4. Mapa de afloramientos graníticos con diagramas de rosas que hacen referencia a la fracturación medida en *scanlines*, superpuestas a la fracturación fotointerpretada.

The main fracture direction corresponds, in principle, to the most favourable partition plane of the rock and, therefore, to the orientation that the massif dismantling should follow and hence its importance for exploitation. At a global level, the fracturing is favourable for granite exploration, as the spacing of the main joint sets observed in the observation points (according classification in García 1995) are mostly wide (2.5-6.25m) and often very wide (6.25m -15.62m), rarely extremely wide (>15.62m);

reduced spacing (<1m) were registered in few observation points. Also, a single main joint set is found in many outcrops.

The relative orientation between the joint sets is an equally important factor in the extraction of blocks, with the most favourable situation occurring when there are two main sub-vertical orthogonal sets and a horizontal one. Regarding the orientation of the main sets, this situation was not observed in any of the outcrops. However, mostly there is only one main set (except for the central domain where two sets with similar frequencies occur), but the spacing found are favourable, generally with little fracturing.

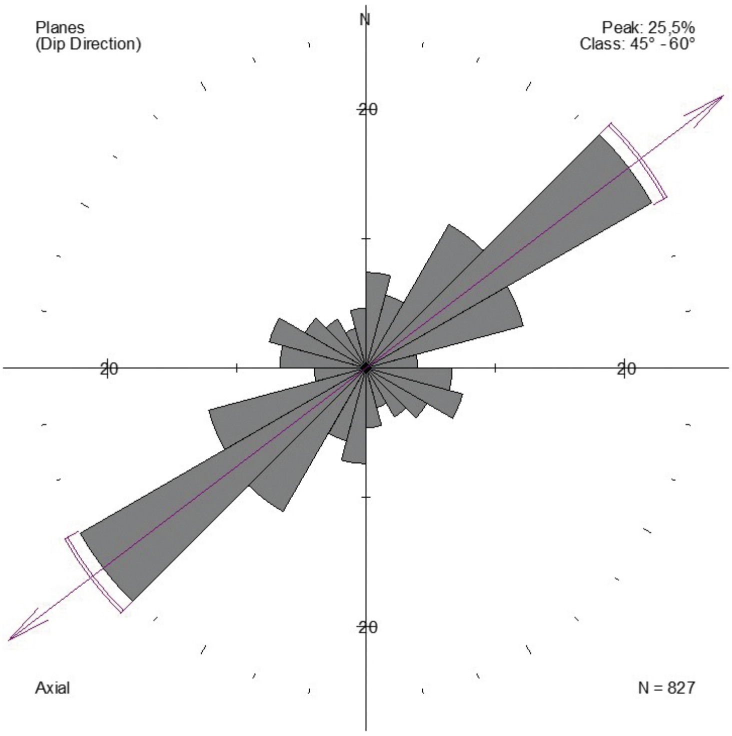

Figure 5. Rose diagram with the total joints measured in outcrops (scanlines)

Figura 5. Diagrama de rosas con el total de juntas medidas en afloramientos (scanlines)

The fracture frequencies (number of fractures per meter) in the outcrops measured in the scanlines, also show in general, a relatively low fracturing density, with an average of 0.3 fractures per meter. The VCPhd lithotype is the one with the lowest average fracture frequency (0.11), followed by FEq (0.21), FMPhd (0.22), MCPhd (0.34), MCEq (0.35), and FMEq (0.50), the latter usually suggesting a more fractured stone.

4.3. Petrographic analysis

All samples of the lithotypes, observed on thin section under a petrographic microscope (Fig. 6), are holocrystalline and phaneritic. The separation of the facies in the geological map was based essentially on textural criteria, as from a mineralogical point of view they are very similar. Following are their textural and mineralogical description.

The fine-grained to medium-equigranular facies (FMEq, samples 018 and 024) corresponds to granitic rock with a granular, isotropic, fine-grained hypautomorphic texture. It is essentially made up of plagioclase, microcline, quartz, biotite, and hornblende. The accessory minerals consist of titanite, epidote, apatite, zircon, and opaque minerals (magnetite?). Secondary minerals include the presence of chlorite, rutile, sericite, epidote, and clay minerals. The feldspathic component is dominated by the occurrence of elongated subhedral plagioclase crystals, generally zoned and with strongly sericitized and epidotized nuclei (saussuritization). Plagioclase (oligoclase to oligoclase-andesine) occurs in much higher proportions than potassium feldspar. Potassium feldspar is made up of anhedral and interstitial microcline crystals, generally with a well-defined checkerboard twinning pattern. More rarely, microcline perthite occurs, with exsolutions of sodium plagioclase in venules. Quartz is relatively common, occurring in anhedral grains, with regular to slightly indented contours, and showing undulating extinction. The paragenesis of mafic minerals, with a percentage of around 25% to 30%, is composed of biotite, green hornblende, titanite, epidote and opaque minerals. Titanite (sphene) is the most abundant accessory mineral in the rock.

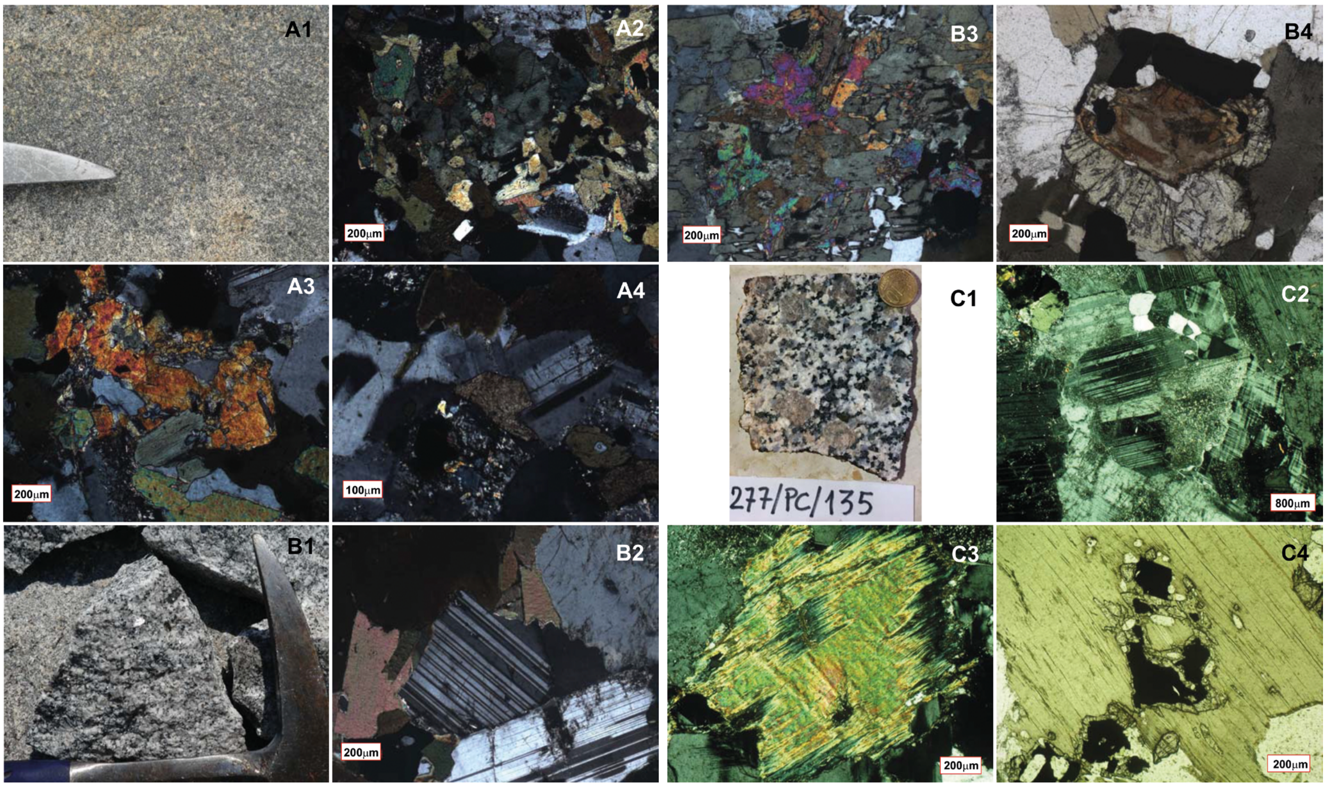

Figure 6. Microphotographs in parallel and crossed nicols under the petrographic microscope of thin sections of granite samples. A. Fine to medium equigranular grained granite. A1) Hand sample; A2) microscopic texture, illustrating an aggregate of mafic minerals consisting of green hornblende, biotite, opaque minerals, and epidote, surrounded by quartz and plagioclase, NX, 50x; A3) subhedral crystals of epidote, in association with amphibole (green hornblende), opaque minerals, and biotite. NX, 50x; A4) subidiomorphic titanite, in the centre, contacting with sericitized plagioclase crystals. NX, 100x.; B. Medium to coarse-grained porphyroid granite. B1) Hand sample; B2) subidiomorphic plagioclase crystals, moderately sericitized, associated with tabular biotite and quartz. NX, 50x; B3) green hornblende crystal showing strong epidotization, with chloritized biotite and quartz. NX, 50x; C. Coarse to very coarse-grained porphyritic granite. C1) Hand sample (coin diameter = 19.75 mm); C2) microscopic texture, showing subhedral plagioclase crystals, with locally intense sericitization, associated with interstitial microcline and quartz. NX, 25x; C3) biotite crystal in an advanced chloritization process. NX, 100x; C4) biotite crystal with opaque mineral inclusions (titanomagnetite/magnetite?), apatite, zircon, and titanite, the latter being found in coronitic textures, around opaque minerals. NX, 100x.

Figura 6. Microfotografías en nicoles paralelos y cruzados bajo el microscopio petrográfico de secciones delgadas de muestras de granito. A. Granito de grano equigranular fino a medio. A1) aspecto macroscópico de la muestra; A2) apariencia textural microscópica, que ilustra un agregado de minerales máficos compuesto por hornblenda verde, biotita, minerales opacos y epidota, rodeados de cuarzo y plagioclasa, NX, 50x; A3) cristales subédricos de epidota, en asociación con anfíbola (hornblenda verde), opacos y biotita. NX, 50x; A4) titanita subidiomorfa, en el centro, en contacto con cristales de plagioclasa sericitizados. NX, 100x.; B. Granito porfido de grano medio a grueso. B1) aspecto macroscópico de la muestra; B2) cristales subidiomorfos de plagioclasa, moderadamente sericitizados, asociados a biotita tabular y cuarzo. NX, 50x; B3) cristal de hornblenda verde que muestra una fuerte epidotización, invadido por biotita cloritizada y cuarzo. NX, 50x; C. Granito porfídico de grano grueso a muy grueso. C1) aspecto macroscópico de la muestra (diámetro de la moneda = 19,75 mm); C2) aspecto textural microscópico, mostrando cristales subédricos de plagioclasa, con sericitización localmente intensa, asociados a microclina intersticial y cuarzo. NX, 25x; C3) cristal de biotita en un proceso avanzado de cloritización. NX, 100x; C4) cristal de biotita con inclusiones opacas (¿titanomagnetita/magnetita?), apatita, circón y titanita, esta última encontrada en texturas coroníticas, alrededor de minerales opacos. NX, 100x.

The medium to coarse-grained porphyroid facies (MCPhd, samples 001 and 039) corresponds to granitic rock with a xeno-hipidiomorphic, inequigranular texture, in which the modal distribution of granularity is characterized by a seriate fabric, tending to be porphyroid. The paragenesis of felsic minerals is dominated by plagioclase, to which quartz and potassium feldspar are associated. Plagioclase crystals reveal subhedral morphologies and multiple, oscillatory optical zoning, with idiomorphic edges of crystalline growth. The feldspars are clear to moderately sericitized and saussuritized, with wide-ranging dimensions (seriate, inequigranular texture). The determined composition of plagioclase varies from An24 (oligoclase) to An37 (andesine). Potassium feldspar is interstitial, anhedral, and exhibits fusiform twinning according to the albite law, sometimes associated with the pericline twinning, forming the checkerboard pattern typical of the microcline. The percentage of microcline is clearly lower than that of plagioclase. The content of mafic minerals is around 25% to 30%, consisting predominantly of biotite, to which green hornblende, epidote, titanite and relatively abundant opaque minerals are associated. Biotite is pleochroic, and has inclusions of zircon, apatite, and acicular rutile. It is partially chloritized, a process that is accompanied by the exudation of granular rutile. Hornblende crystals tend to have subhedral morphologies and are invariably epidotized, with inclusions of quartz, biotite, and opaque minerals. Accessory minerals include green hornblende, titanite, epidote (pistachite and allanite), titanite, apatite, zircon, and opaque minerals (magnetite?). Being the metamict variety of epidote, allanite exhibits its internal structure strongly destroyed by the radioactive disintegration of some of the chemical elements that constitute it, producing radial fracturing in the surrounding minerals. Allanite crystals have inclusions of zircon, apatite, and opaque minerals. Secondary minerals include sericite/muscovite, chlorite, saussurite, rutile, and clay minerals.

The coarse to very coarse-grained porphyritic facies (VCPhd, samples 044 and 049) corresponds to granitic rock with a very coarse-grained, porphyroid, hypidiomorphic texture, with a megacrystalline phase represented by the perthite microcline. The essential minerals consist of oligoclase-andesine, quartz, microcline perthite, biotite and hornblende. Subordinately, titanite, apatite, zircon, epidote, and opaque minerals are observed. Secondary minerals include the presence of chlorite, rutile, sericite, epidote, clay minerals and iron hydroxides. The average composition of plagioclase, estimated by optical methods, is variable from An35 to An28 (andesine; oligoclase-andesine), although it can also reveal slightly lower anorthitic molecule contents (An16), and thin edges of more sodic composition. In the matrix, plagioclase crystals are dominant over interstitial microcline crystals. The sericitic and saussuritic alteration of feldspars is relatively intense and pervasive. Quartz is a common mineral, forming anhedral crystals with regular to slightly lobed contacts, undulating extinction and some intracrystalline plastic deformation. Mafic minerals often form aggregates, which include biotite, hornblende, titanite, epidote (pistachite) and opaque minerals (magnetite?, titanomagnetite?). Biotite is pleochroic and has inclusions of apatite, zircon, titanite and opaque minerals. It is often deferrified and chloritized, changing, in this case, to the pennine variety of chlorite, with typical interference colours (Berlin blue). Green hornblende is a quite common mineral, found in percentages equal to, or slightly lower than biotite. Titanite (sphene) is a relatively common primary accessory mineral, associated with aggregates of mafic minerals. Sometimes, there is the occurrence of coronitic textures, in which the formation of titanite rims around opaque minerals is observed. The rock denotes some supergenic alteration, which manifests itself in the deferrification of biotites and impregnation of iron oxides/hydroxides resulting in microcracks that affect, above all, the potassium feldspar crystals.

4.4. Chemical analysis

Regarding the chemical composition of the selected granite samples, only one sample was subject to conventional chemical analysis. Therefore, the results of the analysis of samples carried out by X-ray fluorescence, with a portable equipment from the X-MET8000 series from Hitachi High-Tech Analytical Science, are also shown; this equipment can analyse all elements between Mg and U (Table 1).

Sample	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	P.R. (%)
030-FEq	71.05	12.90	2.26	0.06	2.99	0.97	–	3.68	0.19	0.20	–
030-FEq*	70.22	15.04	2.51	0.05	2.45	0.92	3.57	3.74	0.34	0.12	0.90
044-PPhd	70.90	13.52	1.42	0.03	1.31	0.84	–	5.81	0.60	0.15	–
049-PPhd	65.96	16.95	1.39	0.03	2.09	0.84	–	6.60	0.19	0.14	–
001-MCPhd	70.76	13.08	2.78	0.05	2.41	1.92	–	2.86	0.34	0.22	–
040-MCPhd	74.48	12.33	1.08	0.03	1.92	0.91	–	3.24	0.15	0.09	–
039-FMCPhd	71.45	12.41	2.50	0.04	3.33	0.93	–	3.19	0.22	0.22	–

*analysis carried out by dosage of major elements (XRF)

Table 1. Results of chemical analyses carried out on granite samples (per sample, average value of 8 measurements).

Tabla 1. Resultados de los análisis químicos realizados a muestras de granito (por muestra, valor medio de 8 mediciones).

The ensemble of the analysed rock samples presents a very homogeneous acidic composition in the granite composition range, with the content of Ca (and Na in sample FEq), frequently denoting the substantial occurrence of plagioclase. The higher K content in the samples of the pegmatitic grained porphyroid lithotype, may be related to the megacrystalline microcline phase identified in the petrographic analysis.

4.5. Physical-mechanical properties

The tests carried out to determine apparent density, open porosity, water absorption at atmospheric pressure, compressive strength, and bending strength, focused on 9 representative samples of 5 of the 6 defined granite lithotypes (Table 2); The medium to coarse equigranular grained granite (MCEq) lithotype was not analysed due to lack of an adequate sample.

The apparent density of a rock depends on the density of rock-forming minerals and their porosity, making it possible to deduce the hydrothermal and acoustic insulation properties of natural stone, and at the same time determine the self-weight of the constructive element, transmitted to the building structure. The granites tested present average density values, in accordance with those common in this lithology. All samples revealed a density greater than the minimum value required for quality products of granite, greater than 2560 kg/m^3, in accordance with the specifications in the ASTM and CEN / TR 17024 standards for apparent density (Molina, 2017). The values proved to be considerably homogeneous across the set of samples studied (Table 2).

Sample	Apparent density (kg/m^3)	Open porosity (%)	Water absorption (%)	Compressive strenght (MPa)	Flexural strenght (MPa)
030-FEq	2600	0.9	0.4	191	n.a.
044-PPhd	2620	0.8	0.4	164	13.6
049-PPhd	2730	0.1	0.1	154	11.5
001-MCPhd	2630	0.7	0.4	221	12.3
026-MCPhd	2590	1	0.4	171	17.8
040-MCPhd	2630	1	0.4	161	18.4
018-FMEq	2670	1	0.4	537	18.9
024-FMEq	2630	1.7	0.6	141	16.3
039-FMPhd	2630	0.8	0.4	186	n.a.
Average *Std.-deviation*	*2637* *41*	*0.9* *0.4*	*0.4* *0.1*	*214* *123*	*15.5* *3.1*

n.a. – not available

Table 2. Results of technological tests carried out on granite samples.

Tabla 2. Resultados de las pruebas tecnológicas realizadas a muestras de granito.

The water absorption value is expressed as the percentage by weight of water that the rock is capable of absorbing. Therefore, it is equivalent to the increase in weight of the rock when it is completely saturated, which can be useful for calculating the weight of an exterior coating or paving unit on site. In interior coverings or floors, the water absorption value makes it possible to evaluate their behaviour against the infiltration of liquids, and consequently their susceptibility to stains, alteration by chemical agents and proliferation of microorganisms. Coverings or floors in interior areas frequently exposed to humidity, spills, or splashes of liquids and in general those that require a special degree of hygiene (hospitals, daycare centres, etc.) must have the lowest possible absorption value.

Open porosity is expressed as the percentage by volume of connected or open pores contained in the rock. In certain cases, open porosity can be a useful value for choosing the type of resin or mortar to be placed. In commercial natural stones, porosity values between <1 and 4% can often be found (Molina, 2017).

Regarding open porosity and water absorption, the studied rocks generally show good quality (average open porosity of 0.9% and average water absorption of 0.4%), corresponding to medium to low values (Moura, 2006; Molina, 2017) and falling within common values for granitoids between 0.4 and 1.5% for open porosity and 0.2 and 0.5% for water absorption (Moura *et al.*, 2000). Furthermore, the values verified for both properties (Table 2) mostly fit the values according to the specifications (ASTM, AFNOR, etc.) for the best quality granites.

Compressive strength makes it possible to evaluate a rock's ability to withstand significant loads and fulfil the structural functions that its end use requires. It is, therefore, a test for classifying rock according to its resistance and determining its deformability. The values obtained in the compressive strength test (average 214 MPa) showed some heterogeneity, but always higher than those commonly required for quality granites (>100 MPa), given that the values of this property in granites usually range between 80 and 300 MPa (Moura *et al.*, 2000).

Considering the possible uses, bending strength is the parameter of greatest interest. Its relevance in natural stone is due to the flat shape of the tiles and slabs, which implies, from a mechanical point of view, stress in bending, fundamentally, and is also due to the heterogeneous internal structure of the stone, characterized by the existence of internal planes of weakness on one or more scales (contacts between grains, laminations, foliation, etc.) which ultimately determine its resistance.

Bending strength is a characteristic of the material that fundamentally depends on the bonding forces between the particles and, theoretically, independent of the product's dimensions (length, width and thickness). However, in rocks with strong discontinuities or very coarse grains, when the thickness is smaller than the size of the discontinuities, much lower resistances are obtained.

Based on specifications (ASTM, AFNOR, etc.), which establish recommended values for bending strength depending on the type of stone, all results obtained (Table 2) exhibit values higher than the minimum required, set at 8.3 MPa (Molina, 2017) or 10.3 MPa for better quality products (Moura, 2006); the values obtained for this parameter also fall within the range of values for ornamental granites, between 8 and 36 MPa (Moura *et al.*, 2000).

4.6. Classification of granite massifs and outcrops

When characterizing the granite masses, aspects related to accessibility (very important for commodity streaming and, therefore, indirect valorisation of the stone), volume of the massifs and their fracturing pattern, presence of flaws (grain heterogeneities, schlieren, enclaves, veins and dykes, etc.), all were considered. Based on these variables, an attempt was made to create an empirical classification of the ornamental potential of the granites (which will necessarily have to be confirmed by subsequent detailed work) defining areas of ornamental potential, where 4 levels of increasing potential are established (Fig. 7): No Potential, Low Potential, Medium Potential and High Potential. Zones without potential refer to areas where the presence of flaws is high, making exploitation for ornamental purposes unfeasible or where knowledge of the area is low, due to lack of access. On the contrary, in a high potential zone conditions for exploitation are suitable, due to the absence of flaws, little fracturing, large granite masses, and accessibility to the massif.

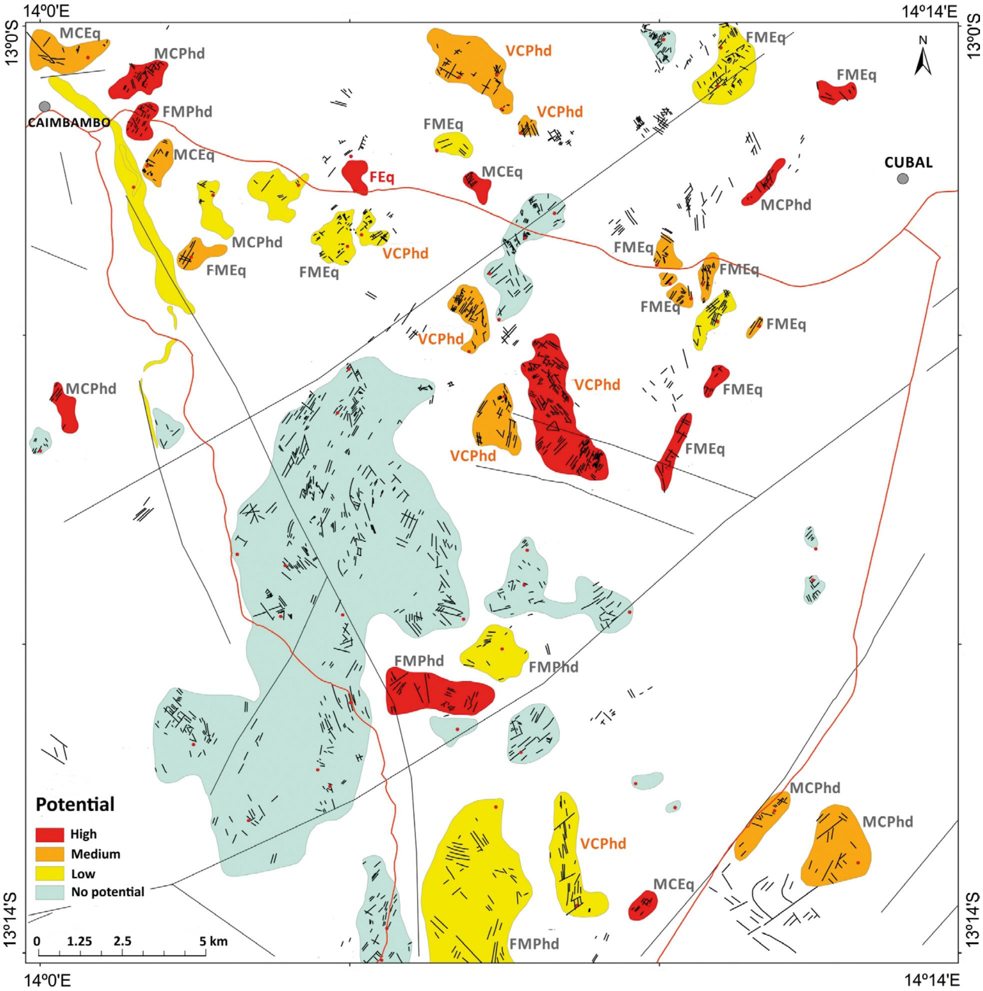

Figure 7. Empirical classification of areas of ornamental potential, based on observed characteristics, defining 4 classes of increasing potential.

Figura 7. Clasificación empírica de áreas de potencial ornamental, basada en características observadas, definiendo 4 clases de potencial creciente.

These zones represent the set of outcrops (Fig. 7), located close to the study sites (observation and sampling points), assuming that the characteristics observed at the specific recording stations are representative of the defined evolving zones.

According to this interpretation, the "equigranular fine-grained leucogranites" have the highest potential, despite relatively limited resources compared to other lithotypes, always with estimates of high to very high resources. "Coarse to very coarse-grained porphyritic granites" have variable potential, ranging from low to high, mainly due to the occurrence of swarms of mafic enclaves in several areas; this lithotype tends to be the one with the lowest fracture density. "Medium to coarse equigranular grain granite" has medium to high potential, conditioned in some areas by the occurrence of clusters of enclaves or veins/dykes.

The remaining lithotypes have variable potential from low to high, conditioned mainly by the occurrence of enclaves and/or veins/dykes, chromatic and granularity heterogeneities, and more rarely more intense fracturing or unfavourable strike relationship between the main joint sets (forming acute and obtuse angles).

5. Conclusions

Concluding, the results of analyses and tests carried out show that as a whole, the granites from the Cubal area correspond to quality ornamental stones, which in general can be used in all types of applications, whether indoors or outdoors. The petrographic analysis revealed some mineralogical alteration of the granites, globally more pronounced in the porphyroid pegmatite grain lithotype. The possibility of excessive textural heterogeneity, and particularly in certain areas, the characteristics of fracturing, must be considered as constraints to the ornamental potential of these rocks.

Authorship contribution statement

José Vítor Lisboa: Writing - Original Draft, Investigation, Conceptualization, Methodology, Visualization, Supervision, Project administration, Formal analysis.
Paulo Nuno Caessa: Resources, Data Curation, Investigation, Writing - Review & Editing.
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Álvaro Oliveira: Data Curation, Formal analysis, Writing - Review & Editing.
Paulo Bravo Silva: Data Curation, Formal analysis, Writing - Review & Editing.
Jorge Fernández: Methodology, Writing - Review & Editing.
José Feliciano Rodrigues: Methodology, Writing - Review & Editing.
José Manuel: Writing - Review & Editing.

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