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Enclaves in Graciosa Island (Açores, Portugal): preliminary data

Enclaves en la Isla de Graciosa (Azores, Portugal): datos preliminares

Patricia Larrea [(1)], Marceliano Lago [(1)], Zilda França [(2)], Elisabeth Widom [(3)], Carlos Galé [(1)], Teresa Ubide [(1)] and Enrique Arranz [(1)]

[(1)] Departamento de Ciencias de la Tierra. Universidad de Zaragoza. C/ Pedro Cerbuna 12, 50009, Zaragoza (España). plarreamarquez@gmail.com; mlago@unizar.es; teresaubide@gmail.com; earranz@unizar.es; carlos.gale@gmail.com
[(2)] Departamento de Geociências, Universidade dos Açores. Ap. 1422, 9501-801, Ponta Delgada (Portugal). zfrança@notes.uac.pt
[(3)] Department of Geology, Miami University. 207 Shideler Hall, Oxford, 45056, Ohio (USA). widome@muohio.edu

RESUMEN

En este trabajo se ha realizado el estudio petrológico de los enclaves asociados a la Unidad del Vulcão Central de la isla de Graciosa (Azores). Estos enclaves comprenden tanto xenolitos como xenocristales que aparecen englobados en una colada basáltica, siendo escasas las relaciones de reacción entre ambos. Se reconocen xenocristales de olivino, plagioclasa, piroxeno y anfíbol, cuya composición química indica su posible relación con los xenolitos, disgregados de los mismos. En cuanto a los xenolitos, se distinguen gabros alcalinos y gabros transicionales a subalcalinos. Los primeros se subdividen en tres tipos en función del grado de fraccionación, que se interpretan como diferentes niveles de acumulados de una misma cámara magmática, en tanto que los segundos tienen características químicas diferentes, por lo que su fuente es claramente distinta.

Key words: *Xenolito, xenocristal, alcalino, Graciosa, Azores*

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Introduction

The Graciosa Island belongs to the Central Group of the Azores archipelago, between 39º and 39º06' N latitudes and 27º56' and 28º05'2 W longitudes. It is located close to the Azores Triple Junction, where the Eurasian, African and American plates meet (Fig. 1A). As the other islands, Graciosa emerges from the Azores Platform, a topographic high near the Mid Atlantic Ridge (MAR). Its WNW-ESE elongated shape, around 13 km long and 7 km wide (with a total surface of 62 km^2), is a consequence of the main regional structures. In this work we present the first compositional data on minerals from Graciosa island basic xenoliths (Fig. 1B).

Geology of Graciosa Island

Previous authors (Zbyszewski *et al.*, 1972; Maund, 1985; Forjaz & Pereira, 1976; Gaspar, 1996, Almeida, 2001, Hipólito, 2009) studied the geology, geochemistry and volcanostratigraphy of the island. Gaspar (1996) recognized three main complexes (Fig. 1B):

1. The Serra das Fontes Volcanic Complex is the oldest subaerial part of the island (620 ± 120 ky, Féraud *et al.*, 1980). It is mainly composed of basaltic effusive products.
2. The Serra Branca Volcanic Complex (350 ± 40 ky, Féraud *et al.*, 1980) presents trachytic products.
3. The Vitória-Vulcão Central Volcanic Complex is the most recent one and comprises two contemporaneous units: the Vitória basaltic Unit and the Vulcão Central Unit, which comprises basaltic to trachytic terms.

Materials and methods

The studied enclaves were sampled from a basaltic lava flow within the Vulcão Central Unit (Fig. 1B).

Nine representative xenoliths and several xenocrysts were selected for electron microprobe analyses. The analyses were carried out with a JEOL JXA-8900M electron microprobe in the Complutense University of Madrid. Mineral formulae were calculated according to the IMA recommendations. Fe^{+3} contents in anhydrous minerals were estimated applying the Droop (1987) algorithm.

Xenoliths

The xenoliths outcrop aligned and present dark gabbroic compositions. They are 5 to 30 cm long and show subrounded shapes and sharp contacts. A discontinuous reaction rim between the xenoliths and the host basalt has been recognized. Where the plagioclase or pyroxene are in contact with the basalt a clear contact appears; in contrast, a large rim is observed between amphibole phases and the basalt. This rim is 200 to 400 µm in size and is composed of allotriomorphic olivine, pyroxene, plagioclase, ilmenite and Ti-magnetite.

Most enclaves are alkaline gabbros; however, one transitional to sub-alkaline micro-enclave has been also recognized. According to their mineralogical and petrological composition, four groups have been defined: (1) plagioclase rich gabbros, (2) amphibole rich gabbros, (3) pyroxene bearing gabbro, (4) transitional to subalkaline gabbro.

1. Plagioclase-rich gabbros. This is the principal group with five samples. Their mineral assemblage is plagioclase (67-88%), kaersutite (5-12%), clinopyroxene (8%), Fe-Ti oxides (6%), olivine (1-5%) and apatite (<2%).

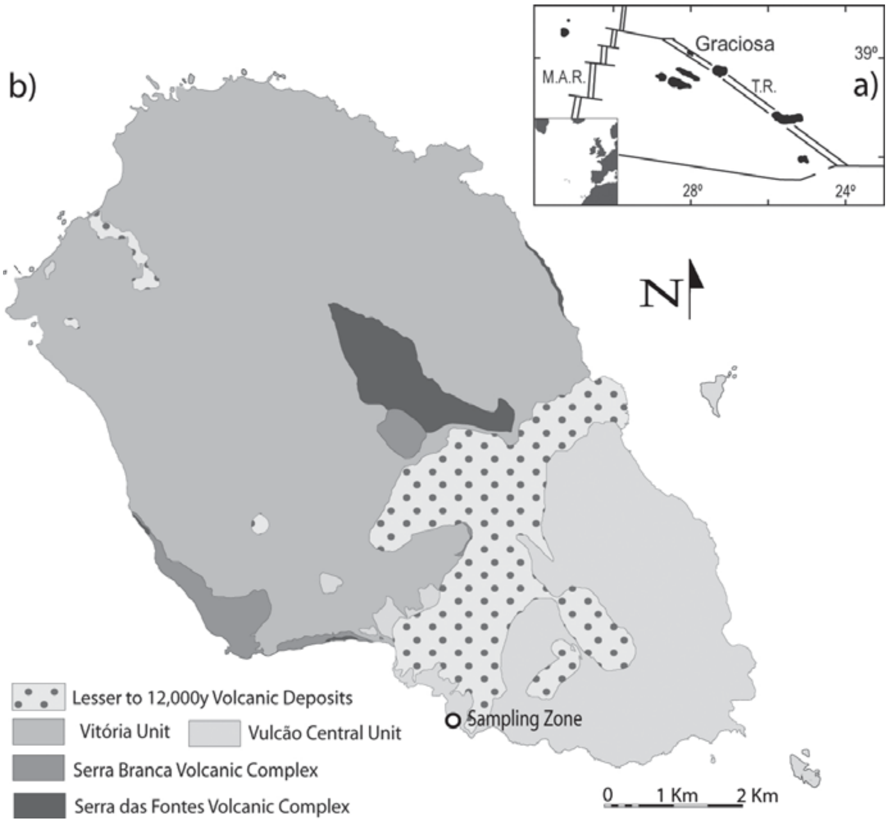

Fig. 1.- a) Location of Graciosa Island within the Azores Archipelago (M.A.R.: Middle Atlantic Ridge; T.R.: Terceira Rift); b) Volcanological map of Graciosa (modified from Gaspar, 1996).

Fig. 1.- a) Localización de la isla Graciosa en el Archipiélago de Azores (M.A.R.: Dorsal Medio Atlántica; T.R.: Rift de Terceira); b) Mapa vulcanológico de Graciosa (Figura modificada de Gaspar, 1996).

Plagioclase is the first mineral to crystallise. Interstitial olivine and clinopyroxene are surrounded by amphibole, which is the last crystallising phase. Plagioclase ranges from An_{77}-An_{34} (Fig. 2A). The low K_2O (< 1%) contents, which increase for the most evolved terms (Or reaches 5%; Fig. 2A) indicate an alkaline affinity. Olivine displays a wide fractionation range (Fo_{76}-Fo_{53}) and low MnO (0.1-1%) and CaO (0.1-0.4%) contents. Pyroxenes are augite-diopsides (Fig. 2B) and range from Fs_9 to Fs_{15}. Their TiO_2 contents reach 2.7%. Ti *vs.* Ca + Na (per formula unit - p.f.u.) plot (Fig. 2C) indicates a typical alkaline trend. Amphibole is kaersutite in composition, with high TiO_2 contents (4.79-6%) and 0.7-0.63 mg# values. This fractionation is consistent with a 1059-1025ºC crystallization temperature (Otten, 1984). Opaque minerals are ilmenites. F-rich apatite occurs as accessory mineral in some cases.

2. Amphibole-rich gabbros. There are two samples from this group, with amphibole (37-70%), plagioclase (28-57%) and opaque minerals (2-3%); apatite is present in one of the samples. Interstitial matrix is recognized too, disaggregating the crystals. Plagioclase ranges from An_{62} to An_{40} (Fig. 2A), with low K_2O (< 1%) contents which increase for the most evolved terms (Or up to 4%; Fig. 2A). Amphibole, which grows surrounding smaller plagioclase, is kaersutite with high TiO_2 contents (4.77-6.25%) and a narrow fractionation range (mg#: 0.7-0.64). This fractionation is consistent with a 1064-1026ºC crystallization temperature (Otten, 1984). Accessory minerals are Ti-Fe rich oxides and F-rich apatite.

3. Pyroxene-bearing gabbro (1 sample). Its mineral assemblage is composed of clinopyroxene (35%), plagioclase (35%), kaersutite (20%), olivine (4%) and Fe-Ti oxides (6%). Olivine displays a wide fractionation range (Fo_{73}-Fo_{71}) and low MnO (0.1-0.4%) and CaO (0.1-0.2%) contents. Pyroxenes are augite-diopsides (Fig. 2B) and range from Fs_{10} to Fs_{13}. Their TiO_2 contents reach 2.1%. Ti *vs.* Ca + Na (per formula unit - p.f.u.) plot (Fig. 2C) indicates a typical alkaline trend. Amphibole is kaersutite in composition, with high TiO_2 contents (5-6%) and 0.7-0.67 mg# values. This fractionation is consistent with a 1059-1031ºC crystallization temperature (Otten, 1984). Plagioclase is less abundant than in the other groups and appears as smaller subhedral crystals. Its composition varies from An_{68} to An_{65} (Fig. 2A), having the lowest K_2O contents (< 0.2%). Or proportion increases with fractionation (up to 1%; Fig. 2A), indicating an alkaline affinity. Opaque minerals are Fe-Ti oxides.

4. Transitional to subalkaline gabbro. There is an only micro-enclave included in this type. It contains isolated pyroxene crystals (10%) in its central part, surrounded by a majority of plagioclase crystals (85%); opaque minerals (5%) and apatite (<1%) are also present. Pyroxenes are augite-diopsides (Fig. 2B), more fractionated than the ones from the other groups, with Fs_{19}-Fs_{27} values. Their low TiO_2 content (0.14-0.33%), makes them plot close to or in the subalkaline area (Fig. 2C), unlike those from the other groups. The plagioclase from this sample is the most fractionated (An_{59}-An_{15}; Fig. 2A), with ~1% K_2O contents and maximum Or values (6%) for the most evolved crystals (Fig. 2A). Accessory minerals are Ti-Fe oxides and F-rich apatites.

Xenocrysts

The most frequent are amphibole and plagioclase crystals, followed by clinopyroxenes; one olivine crystal has also been recognized.

Most amphiboles are 800 μm wide and 1000 μm long, but bigger crystals (2x3 cm) have also been recognized. All of them show a reaction rim, similar to the one described above for the contact between xenoliths and their host basalts. They are kaersutites with high TiO_2 contents (4.99-6.09%) and 0.69-0.64 mg# values. This fractionation yields a 1061-1059ºC crystallization temperature (Otten, 1984).

Plagioclase crystals are 600x1200 μm in size. They are euhedral without reaction rims. Their composition ranges between An_{51} and An_{47}, with K_2O values < 0.3%, which increase for the most evolved terms (Or reaches 2%; Fig. 2A), indicating an alkaline affinity.

Pyroxenes are 800x2000 μm euhedral crystals; no reaction rims have been recognized. They are augite-diopsides (Fig. 2B) and range from Fs_{12} to Fs_{13}. Their TiO_2 contents reach 2.2% and, according to the Ti *vs.* Ca + Na (per formula unit - p.f.u.) plot (Fig. 2C), their affinity is alkaline.

Finally, one olivine xenocryst has been also found. It is 400x500 µm in size, euhedral and without reaction rim. Its composition is slightly fractionated from the centre (Fo_{79}) to the rim (Fo_{70}). MnO and CaO concentrations are 0.1-0.4% and 0.22-0.25% respectively.

Considerations

Both xenoliths and xenocrysts have been identified in the Vulcão Central Unit of Graciosa island. The xenoliths are gabbros that can be arranged in three alkaline groups and one transitional to subalkaline type. Single amphiboles, plagioclases, clinopyroxenes and one olivine appear as xenocrystic phases.

Mineral chemistry reveals the similarity between the xenocrysts and the corresponding phases within the alkaline xenoliths. Therefore, it is likely that the origin of the xenocrysts is related to the disaggregation of the alkaline xenoliths.

The big size of the xenoliths and the absence of reaction between them and the host lava indicate the magma rose quickly.

The alkaline gabbros are compositionally similar, indicating they may be cogenetic. However, some differences have been identified. All the *An* in plagioclase, the *Fs* in pyroxene, the *mg#* in amphibole and the *Fo* in olivine indicate that plagioclase-rich gabbros (group 1) are the least differentiated. According to the same values, amphibole-rich gabbros (group 2, without olivine and pyroxene) are the most differentiated, while the pyroxene-bearing gabbro (group 3) occupies an intermediate position. Therefore, these three groups may correspond to different cumulate levels from the same magma chamber.

On the other hand, the transitional to subalkaline gabbro (group 4) shows clearly distinctive chemical characteristics. Firstly, it is more differentiated than the alkaline gabbros, as it has no olivine and presents the lowest *An* and the highest *Fs* values. Secondly (and mainly), its pyroxenes have the lowest TiO_2 proportions, which make them plot in the subalkaline area (Fig. 2C). These criteria indicate that this xenolith must come from a transitional to subalkaline source, clearly different from the one mentioned for the alkaline gabbros.

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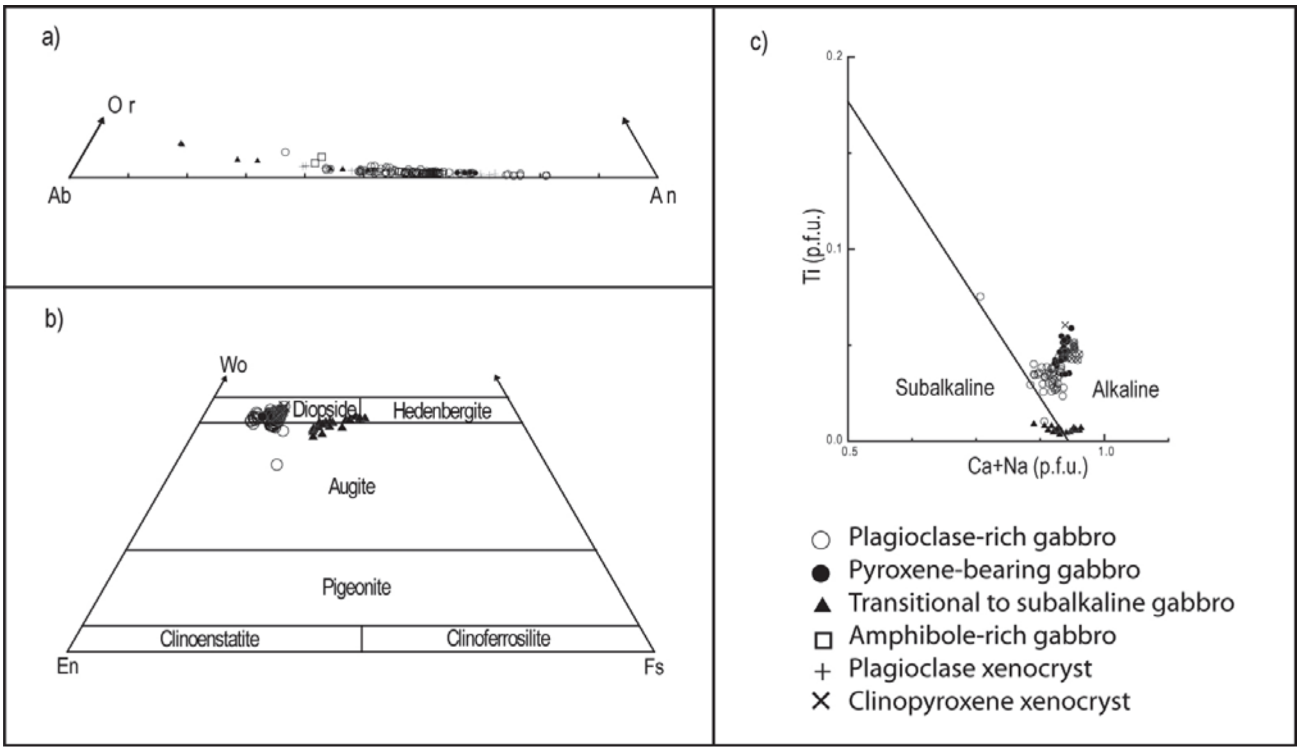

Fig. 2.- a) Ab-An-Or classification diagram for plagioclases; b) En-Wo-Fs classification diagram for pyroxenes; c) Ti vs. Ca+Na (p.f.u.) diagram of clinopyroxenes from xenoliths and xenocrysts (Leterrier *et al.*, 1982).

Fig. 2.- a) Diagrama de clasificación de plagioclasas Ab-An-Or; b) Diagrama de clasificación de piroxenos En-Wo-Fs; c) Diagrama de Ti vs. Ca+Na (p.f.u.) en clinopiroxenos de los xenolitos y de los xenocristales (Leterrier **et al.*****, 1982).***

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