The Holocene volcanism at El Hierro: insights from petrology and geochemistry

El volcanismo holoceno en El Hierro: petrología y geoquímica

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ABSTRACT

The Holocene volcanism at El Hierro consists of basaltic monogenetic volcanic fields associated with o the three rift systems present in this island. In this work we report preliminary petrological and geochemical data of Holocene lava flows belonging to the WNW-striking rift. Sampling was focused in three zones: Orchilla, Verodal-Sabinosa, and Tanganasoga. Petrography of the studied lavas shows that they are homogeneous. All samples are porphyritic with macrocrysts of clinopyroxene and olivine immersed in a groundmass formed by microcrysts of plagioclase, Fe-Ti oxides and clinopyroxene. Clinopyroxenes are diopsides, olivines have forsterite contents ranging from 74 to 84 % and anorthite in plagioclase varies from 66 to 76% (labradorite). Whole-rock geochemical results evidence that all magmas are basic in composition, ranging from picrobasalts to phonotephrites. Major, trace elements and isotope support fractional crystallization as the main process of magma evolution. However, petrography and chemistry of clinopyroxene cores agree with a xenocrystic nature of some of them. We suggest that these clinopyroxene cores crystallized from a genetically related magma and subsequently were entrapped or cannibalized by the basic rising magmas.

Key-words: *El Hierro, Holocene, volcanism, petrology, geochemistry.*

RESUMEN

El volcanismo holoceno en El Hierro está formado por campos volcánicos monogenéticos asociados a las tres estructuras de tipo rift que modelan la isla. En ese trabajo se presentan los resultados petrológicos y geoquímicos preliminares de las lavas holocenas del rift de dirección ONO. El muestreo se concentró en tres zonas: Orchilla, Verodal-Sabinosa y Tanganasoga. La petrografía de las lavas estudiadas muestra que son bastante homogéneas. Todas las lavas son porfídicas con macrocristales de clinopiroxeno y olivino inmersos en una matriz formada por microcristales de plagioclasa, óxidos de Fe-Ti y clinopiroxeno. Los clinopiroxenos son diópsidos, los olivinos presentan contenidos en forsterita que varían entre 74 y 84% y el contenido en anortita en las plagioclasas varía entre 66 y 76% (labradorita). Los resultados geoquímicos de roca total evidencian que todos los magmas son básicos, con composiciones que varían entre picrobasaltos y fonotefritas. Los elementos mayoritarios, trazas e isótopos sugieren que la cristalización fraccionada es el principal proceso de evolución magmática. Aun así, la petrografía y química de los núcleos de los clinopiroxenos sugieren que algunos de ellos son xenocristales. Se sugiere que estos núcleos cristalizaron a partir de un magma genéticamente relacionado y que posteriormente fueron atrapados o canibalizados por el magma básico en ascenso.

Palabras clave: *El Hierro, Holoceno, volcanismo, petrología, geoquímica.*

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Introduction

El Hierro (1.12 Ma) is, together with La Palma, the youngest island of the Canarian Archipelago. Both islands are in the shield stage of their volcanic growth, which implies a high volcanic activity during the Holocene period. The submarine eruption of October 2011 at El Hierro awakened the interest of the scientific community for the understanding of El Hierro volcanism. Consequently, numerous scientific works related to this eruption were published in a short period of time (*e.g.,* geophysics: Gonzales *et al.,* 2013; Roberts *et al.*, 2016; petrology and geochemistry: Troll *et al.*, 2012, Martí *et al.*, 2013; geomorphology and bathymetry: Rivera *et al.*, 2013; monitoring and crisis management: Carracedo *et al.*, 2015; Sobradelo *et al.*, 2015). By contrast, recent onshore studies are restricted to the works of Longpré *et al.* (2011), Pedrazzi *et al.* (2014) and Becerril *et al.* (2015, 2016a, b). Nowadays, there is no full understanding of the magma system below the island (detailed petrological and geochemical studies are lacking), how and when Holocene eruptions have taken place (radiocarbon ages are scarce), and how future eruption will (for hazard assessment). In this work we report preliminary petrological and geochemical data of Holocene lavas erupted in the WNW rift necessary for a detailed volcanic hazard evaluation.

Geological setting

El Hierro is the smallest and westernmost island in the Canarian Archipelago. It has a surface of *circa* 280 km^2 and a maximum elevation of 1501 m above sea level (Pico Malpaso). This island represents the emerged part of a volcanic edifice that rests on an ocean floor located at 3500-4000 m depth. The morphology and structure of the island is determined by the presence of a regular three rift system and several giant landslides that give the island its present geometry, like a "Mercedes star" (*e.g.*, Carracedo *et al.*, 2001). The subaerial development of El Hierro includes three volcanic cycles: (1) Tiñor edifice (1.12-0.88 Ma), (2) El Golfo-Las Playas edifice (545-176 ka), and (3) Rift volcanism (158 ka-present) (Fig. 1). The Tiñor edifice represents the first stage of subaerial growth of El Hierro. Its volcanic products, which crop out in the NE sector of the island, consist of picritic to tephritic lavas (Guillou *et al.*, 1996). El Golfo volcanic edifice is mainly located in the NW sector and shows a variable chemical composition ranging from nephelintes to trachytes. Magmas belonging to the rift stage are picrites, basanites and tephrites. The three volcanic cycles are separated by giant gravitational collapses being the youngest ones (1) Las Playas I and II (*ca.* 545-176 ka and 176-145 ka, respectively), (2) El Julan (>158 ka) and El Golfo (*ca.* 130 ka- 39 ka, 13 ka?) (*e.g.*, Guillou *et al.*, 1996, Longpré *et al.*, 2011). It seems there is a clear connection between these catastrophic events and the rift structures. Moreover, the giant landslides have also been related to changes in the magmatic system of El Hierro. Manconi *et al*. (2009) evidenced that the El Golfo gravitational collapse affected the magmatic plumbing system at that time, resulting in the eruption of less evolved magmas than previously.

The petrological and geochemical knowledge about the magmatic feeding system beneath the island suggests the presence of small reservoirs located at 14-30 km depth (Stroncik *et al.*, 2009). These depths are consistent with those determined for the submarine eruption of October 2011 (10-25 km, Gonzales *et al.*, 2013).

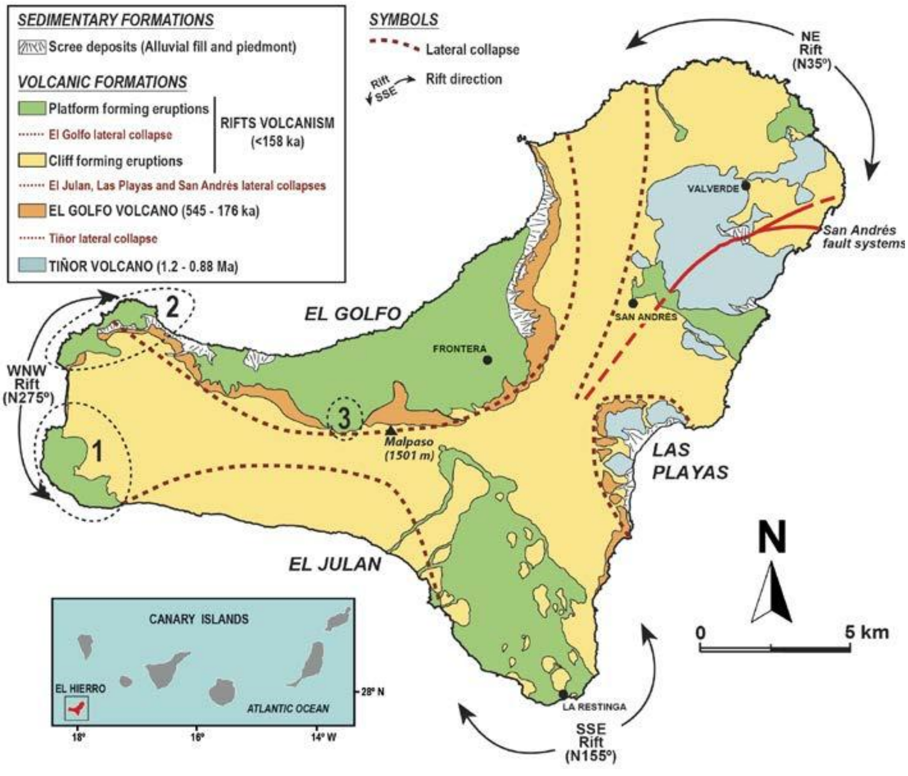

Fig. 1.- Simplified geological map of El Hierro. The studied areas are indicated (1 Orchilla, 2 Verodal-Sabinosa and 3 Tanganasoga). See color figure in the web.

Fig.1.- Mapa geológico simplificado de El Hierro. Se señalan las áreas estudiadas (1 Orchilla, 2 Verodal-Sabinosa y 3 Tanganasoga). Ver figura en color en la web.

The subaerial Holocene volcanism

The Holocene volcanism in El Hierro consists of basaltic monogenetic volcanic fields related to the three rift systems present in this island. The eruptive mechanisms are typically strombolian with minor phreatomagmatic pulsations. The most recent eruptions, which form coastal platforms, are younger than the Last Glacial Maximum (*ca.* 18 ka, Carracedo *et al.*, 2001). The Tanganasoga volcano (6.74 ka, Pellicer, 1977) is the most voluminous and representative Holocene volcano. The available radiocarbon ages indicate that Montaña Chamuscada is the youngest subaerial eruption in El Hierro (2.5 ka, Carracedo *et al.*, 2001).

Sample location and methodology

The analyzed samples correspond to lavas from the WNW rift structure. Lavas were collected in three distinguished zones where Holocene volcanic products are exposed (Fig. 1): (1) Orchilla, (2) Verodal-Sabinosa and (3) Tanganasoga.

The geochemical study includes whole-rock major and trace element analyses and Sr and Nd isotope ratios of selected element composition of the main mineral samples, and major element composition the main mineral phases. Whole-rock major elements were measured by XRF at the Centres Científics i Tecnològics de la Universitat de Barcelona (CCiTUB) whereas trace elements were determined by HR-ICP-MS at the LabGEOTOP from the Institute of Earth Sciences Jaume Almera (ICTJA-CSIC). Sr and Nd isotope ratios of representative samples were analysed at the Osservatorio Vesuviano (OV-INGV). Mineral chemistry was done by EMPA at the CCiTUB.

Petrography and mineral chemistry

All the studied lavas are porphyritic with macrocrysts of olivine and clinopyroxene (and minor plagioclase in some samples) immersed in an microlitic groundmass. The presence of vesicles is also observed in all samples. Locally, macrocrysts show glomeroporphyric textures. Groundmass is characterized by the presence of plagioclase microlites as well as clinopyroxene microcrysts. Fe-Ti oxides are accessory minerals mainly occurring as microcrysts in the groundmass.

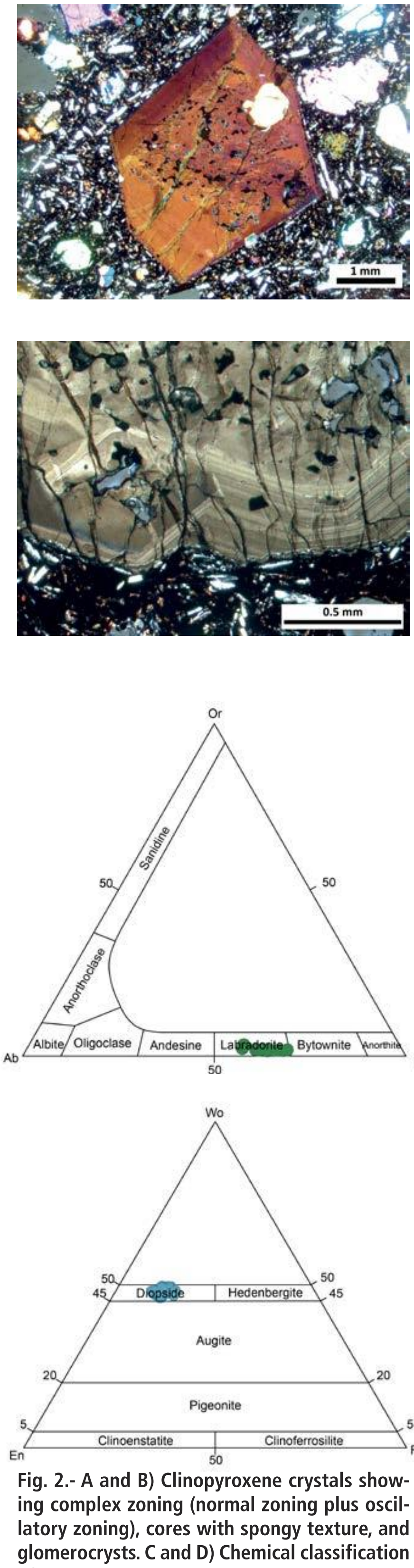

Fig. 2.- A and B) Clinopyroxene crystals showing complex zoning (normal zoning plus oscillatory zoning), cores with spongy texture, and glomerocrysts. C and D) Chemical classification of clinpyroxenes and plagioclases. See color figure in the web.

Fig. 2.- A y B) Cristales de clinopiroxenos mostrando una zonación compleja (zonación normal y oscilatoria), núcleos con textura en colador, y glomerocristales. C y D) Clasificación química de los clinopiroxenos y plagioclasas. Ver figura en color en la web.

Most of the clinopyroxene macrocrysts show a complex growth history. They often display normal and oscillatory zoning. It is also frequent the presence of cores with disequilibrium textures such as spongy cellular/sieve texture (Fig. 2A). In addition, several clinopyroxenes present glomerocrysts (Fig. 2B).

The chemical analyses of clinopyroxenes indicate that they are all diopsides with $Wo_{46.7-49.3}$, $En_{37.5-42.4}$, $Fs_{9.5-15.8}$ (Fig. 2C). Normal zoning is reflected by cores with higher contents of MgO and CaO and lower contents of FeO_T and TiO_2 compared to rims. Forsterite (Fo) in olivine ranges from 74 to 84% and NiO abundance from 0.07 to 0.31%. Plagioclase composition is labradorite with anorthite (An) contents varying from 56 to 66% (Fig. 2D). Finally, opaque minerals are classified as ilmenites.

Whole-rock geochemistry

Holocene lava flows in El Hierro range in composition from picrobasalts to phonotephrites and follow an alkaline trend in the Total Alkali Silica diagram of Le Bas *et al.* (1986) (Fig. 3A). They belong to the alkaline sodic series and are silica-undersaturated rocks (nepheline normative).

Overall, covariation diagrams (not represented) show a negative correlation of SiO_2, Al_2O_3, K_2O, Na_2O and positive correlation of FeO_T and CaO with MgO, TiO_2 versus MgO show a segmented trend, with a positive correlation between 4 and 7 wt% MgO, followed by a negative correlation. Most trace elements show negative correlation except for Ni, Cr and Sc. REE contents depict a typical OIB pattern with enrichment in LREE and depletion in HREE and without significant Eu anomalies. In addition, the bell-shaped trend in the multi-element diagram, together with a positive Nb anomaly is typical of OIB type (Fig. 3B).

Sample	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
HIR-25	0.702993	0.512939
HIR-38	0.702998	0.512936
HIR-39	0.703005	0.512941
HIR-40	0.703006	0.512940

Table I.- Sr and Nd isotope ratios of the analyzed lavas.

Tabla I.- Isótopos de Sr and Nd de las lavas analizadas.

The Sr isotope ratios measured on selected Holocene lavas range from 0.702993 to 0.703006, and $^{143}Nd/^{144}Nd$ varies from 0.512936 to 0.512941 (Table I). These results are in accordance with those reported by Day *et al.* (2010) for subaerial lavas of El Hierro. Nd isotope signatures are also very similar to those reported for the submarine eruption of 2011-2012 in la Restinga area (*e.g.,* Sigmarsson *et al.*, 2013).

Discussion and conclusions

The studied lava flows are basic in composition, with SiO_2 ranging from 40 to 50 wt%. They belong to the sodic alkaline series and are silica undersaturated. Major and trace elements and Sr and Nd isotopes of the studied samples are consistent with an OIB origin. Moreover, all these results are in accordance with those reported in previous works (*e.g.,* Stroncik *et al.*, 2009; Day *et al.*, 2010).

Several geochemical trends such as positive correlation of FeO_T, CaO, Ni or Cr, and negative correlation of Al_2O_3, K_2O or most

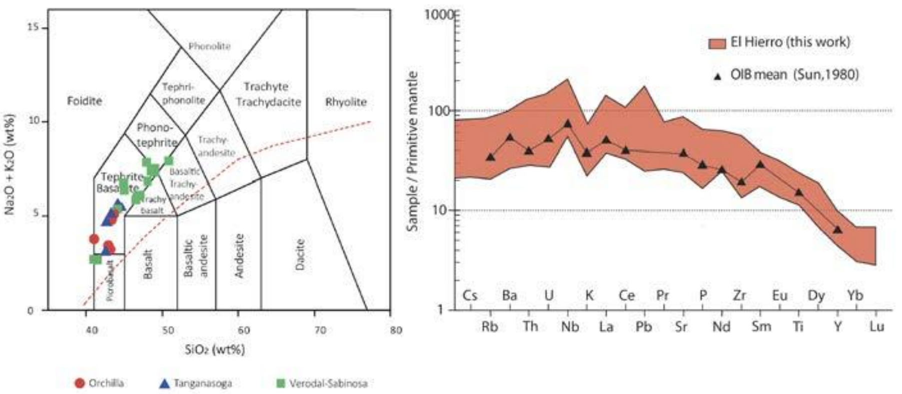

Fig. 3.- Whole-rock composition of analyzed samples are represented in the TAS diagram. Multielement diagram normalized to Primitive Mantle (Sun, 1980). See color figure in the web.

Fig.3.- La composición de las muestras analizadas se representan en el diagrama TAS. Diagrama multielemenal normalizado al Manto Primitivo (Sun, 1980). Ver figura en color en la web.

of trace elements with MgO, show good geochemical coherence. All these tendencies are compatible with a chemical evolution of magmas by fractional crystallization of the observed mineral phases. Normal zoning in some clinopyroxene crystals, with cores enriched in MgO and depleted in FeO_T, also supports this hypothesis.

However, clinopyroxene cores with spongy cellular/sieve textures due to resorption also indicate the involvement of other magmatic processes, such as magma mixing/mingling or assimilation. Resorption in clinopyroxene cores is an indication of open magmatic plumbing system. Thus, these cores could represent antecrysts that did not crystallize directly from the host magma in which are contained, but from a previous event genetically related to the magmatic system (Jerram and Martin, 2008). They may correspond to recycled crystals through different magma replenishment events or to stored crystals in crystal accumulations from the magma.

These antecrysts are wrapped by fine growth bands showing an oscillatory zoning that can be combined with sector zoning. These kinds of zoning are usually related to kinetic effects. Crystal growth rates depend on melt supersaturation and undercooling at the crystal melt interface but also on the crystal orientation (sector zoning). It occurs because the growth rate is too fast relative to the rate of diffusion of chemical components in the melt.

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