Volcano-structure of El Hierro (Canary Islands)

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ABSTRACT

The first complete volcano-structural map of El Hierro (Canary Islands, Spain) has been developed in order to provide a tool for volcano-tectonic analysis and volcanic hazard evaluation on the island. This map is a synthesis of collated and interpreted field data and bathymetric maps. We have integrated information obtained from: (1) high-resolution digital elevation models, (2) bathymetric information, (3) topographic, geologic and geomorphological maps, (4) aerial photographs and orthoimages, (5) previous reports and scientific publications, and (6) new detailed field surveys. The 1:100,000-scale map includes the main volcano-structural elements such as vents, eruptive fissures, dykes, faults, and landslides scars. This information has been used for analysing the volcano-tectonic evolution of El Hierro and for estimating the probability of new vent opening on the island (i.e. volcanic susceptibility). We expect that this map will underpin future geological studies and future volcanic risk assessment.

1. Introduction

Volcano-structural studies provide important information on the structural patterns within volcanic systems and on their former and current stress and strain fields. In turn, these studies constitute the basis for reliable volcanic hazard and risk assessments. The first step in carrying out volcano-structural studies involves construction of a map showing the main volcano-structural elements of the study area, such as vents, eruptive fissures, dykes, faults, fumaroles or springs, landslides scars, etc.

Such maps have already been produced for volcanic areas such as Etna volcano (Sicily, Italy) (Azzarro, Branca, Gwinner, & Coltellli, 2012), Taupo Volcanic Zone (New Zealand) (Cole & Spinks, 2009), Teide-Cañadas (Tenerife, Canary Islands, Spain) (Galindo, 2005), or La Garrotxa Volcanic Field (Catalonia, Spain) (Bolós et al., 2015). Under the same theme, the study presented here aims at identifying, mapping, and interpreting the main volcano-structural elements of El Hierro (Canary Islands, Spain; Figure 1), in both submarine and subaerial parts of the volcanic edifice. These elements include dykes, vents, eruptive fissures, faults (exposed and inferred), and landslide scars and their deposits.

El Hierro is an active volcano and the last eruption took place on its southern submarine flank in 2011–2012 (red triangle on the Main Map). The subaerial part of the volcanic edifice forms the smallest (~269 km²) and youngest island of the Canary archipelago (1.12 Ma; Guillou, Carracedo, Torrado, & Badiola, 1996). In its current form the volcanic edifice, including the submarine part, has an estimated total volume of 5500 km³. It rises about 5500 m above the surrounding seafloor (Schmincke & Sumita, 2010). Most of the landforms of El Hierro volcano have been generated by a combination of constructive and destructive volcanic processes. The subaerial part of the volcano is constructed by three consecutive volcanic edifices: the Tíñor Edifice (1.12–0.88 Ma), the El Golfo-Las Playas Edifice (545–176 ka), and the Rift Volcanism (158 ka–present) (Carracedo, Badiola, Guillou, De La Nuez, & Pérez Torrado, 2001; Guillou et al., 1996; IGME, 2010a, 2010b, 2010c, 2010d). Submarine features are in the distal south, with the Southern Ridge interpreted as an old edifice (van den Bogaard, 2013; Gee, Masson, Watts, & Mitchell, 2001a).

The El Hierro volcano geological history has been modified by at least six large destructive flank collapses or giant landslides (Carracedo, Day, & Guillou, 1999; Carracedo et al., 2001; Longpré, Chadwick, Wijbrans, & Iping, 2011; Masson, 1996; Masson et al., 2002; Urgeles, Canals, Baraza, & Alonso, 1996, 1997), which have notably changed its overall form (or shape) (Main Map). These structures are described in more detail in Section 3.

Existing maps of the subaerial part of the volcano are the geological (IGME, 2008, 2010a, 2010b, 2010c, 2010d) and geomorphological map-sheets (Llorente-Isidro, 2014) produced by the Spanish Geological Survey, along with the geological map of Carracedo et al. (2001). The first volcano-tectonic studies on El Hierro...
were mainly concerned with depicting the general tectonic elements and fractures on the island (Hausen, 1964; Coello, 1971). In 1977, Pellicer developed the first volcano-structural map, which included schematic outlines of eruptive vents and lineaments. This map was further refined by Navarro and Soler (1995), who analysed the island’s main volcano-structural elements, paying special attention to the distribution of dykes, particularly inside water galleries. Day, Carracedo, and Guillou (1997) focused their research on the ‘San Andrés’ fault system, the main brittle structure exposed in the island, which was mapped by IGME (2010a) and Klimeš et al. (2016). Other work have been mainly focused on exploring the geological and tectonic evolution of the island (Carracedo, 1996; Carracedo et al., 2001; IGME, 2010a, 2010b, 2010c, 2010d). The only study that highlights some of the structural features on the submarine sector of the edifice is Acosta et al. (2003b). Other studies have focused on documenting the extent and characteristics of the giant landslides on El Hierro and their offshore deposits (Gee et al., 2001a, 2001b; Masson, 1996; Masson et al., 2002; Mitchell, Masson, Watts, Gee, & Urgeles, 2002).

Here, we present the first complete volcano-structural map of El Hierro volcano including both submarine and subaerial elements. This map has been constructed mainly from a high-resolution digital elevation model (DEM) and constrained by geological data and new field surveys and thus is an integrated approach underpinned by volcano-tectonic analysis. On the basis of this map, exhaustive comprehensive volcano-structural analysis for El Hierro has been carried out and provides a coherent model for the magma ascent paths and showing the main stress fields (Becerril, Galindo, Martí, & Gudmundsson, 2015). Furthermore, part of this data set has been used for a volcanic susceptibility study of the Island (Becerril, Cappello, Galindo, Neri, & Del Negro, 2013a).

2. Materials and methods

A thorough analysis of previous studies and a revision and interpretation of available maps of El Hierro has been undertaken. Thereafter, we carried out an extensive field campaign focused on the collection of information on the volcano-structural elements, including their exact geographical position as obtained by a handheld global positioning system (GPS) receiver.

Once we obtained the field data, construction of a structural map was performed using ESRI© ArcGIS 9.2, 9.3 and 10 at a scale of 1:5000 mainly using orthoimages (1:5000) and high-resolution coloured aerial photographs (1:18,000) from GRAFCAN (2009) (www.grafcan.com). We also used the digital geological map from the Spanish Geological Survey (IGME, 2008) (1:25,000) (available at: http://cuarzo.igme.es/sigeco/), the LIDAR DEM (5 m resolution) from the National Geographic Institute (IGN) (available at: http://centrodescargas.cnig.es/CentroDescargas/index.jsp), and bathymetric data from the Spanish Navy Hydrographical Institute (IHM), the Spanish Institute of Oceanography (IEO), and relevant information from Somoza et al. (2012). The bathymetry for the submarine sectors used for the volcano-structural map was obtained from the data of the EEZ Program in the

Figure 1. Location map of the El Hierro volcano. The topography and bathymetry data were derived from the ‘GEBCO_2014’ bathymetric model (Weatherall, 2015). The main features related to the geodynamic setting of El Hierro such as sedimentary basins, mountain ranges, seamounts and its volcanic province are indicated. The area covered by the main map is defined using a red square.
Canary Islands area (Cliff & Acosta, 2005): the hillshade of the seafloor is available at http://www.ideo-
elhierro.ieo.es (IEO, 2013) and the data can be acquired through the EMODnet project (http://www.emodnet-
bathymetry.eu).

A spatial database was designed and implemented with different data sets containing all of the volcano-
structural information obtained for this study (Bartolini, Becerril, & Martí, 2014; Becerril, 2009, 2014;
Becerril & Galindo, 2010). These data sets comprise: dykes, faults, vents, eruptive fissures, and those elements related to avalanche scars and their deposits, including elements located in the off and onshore part of the volcano. Dykes were mapped in the field and their traces checked and completed using geological maps and aerial photographs. Feeder dykes were also identified based on the criteria of Galindo and Gudmundsson (2012). All of these features were mapped using the WGS84 UTM 28N coordinate system and were represented in the map at 1:100,000 scale.

The volcano-structural map was complemented by additional information that includes some cross sections (A–A’; B–B’ and C–C’) reflecting the general morphology of the El Hierro volcanic edifice, and a simplified block diagram that shows its magmatic sys-
tem. The two 3D views and the three topographic profiles were produced using the ArcScene module of ArcGIS and the Easy Profile tool for ArcGIS 9.3 (available at: http://arcscripts.esri.com/details.asp?dbid=16031), respectively. These graphics help with a complete visualisation of El Hierro as a volcano that rises 5500 m from the ocean floor. It also shows clearly how the shape of the island has been modified by volcanic processes and giant landslides. An outline of the volcanic system of El Hierro is also included on the map. This simple graphic, in the bottom left side of the map, shows the location of the island’s magma plumbing system. It was compiled using mathematical (Becerril, Galindo, Gudmundsson, & Morales, 2013b), petrological (Martí et al., 2013a, 2013b; Meletlidis et al., 2012), and geophysical information (Domínguez Car-
dena, del Fresno, & Gomis Moreno, 2014; Gorbatikov et al., 2013; González et al., 2013; López et al., 2012).

3. Volcano-structural elements description

A brief description of relevant volcano-structural elements is provided in this section. Thorough vol-
cano-structural analyses using this data can be consulted in the work of Becerril et al. (2015).

3.1. Vents

El Hierro Island has the highest density of monogenetic volcanoes per square kilometre of the Canary Islands (~ 0.82 volcanoes per km²). This corresponds to more than 220 cones belonging to the most recent volcanic cycle of the island. Most subaerial vents are distributed along the rift zones that are defined by dilata-
tional ground cracks through which magma rises (Walker, 1999). Submarine vents are common on the submerged flanks of the island. The areas with the lowest density of vents are the sectors of the volcano modi-
fied by giant landslides.

Subaerial vents were mapped according to the criteria of Becerril et al. (2013a): (1) as individual points placed at the centre of craters of isolated cinder cones (Figure 2(a)), (2) as craters of coalescent cinder cones (Figure 2(a)), (3) as craters without an associated cinder cone, related to lava extrusion where vent activity did not produce any rampart around or, eroded craters in which we only recognise the residual spatter (Figure 2(b)) and also (4) as vents that belong to hornitos (Figure 2(c)) and spatter ramparts (Figure 2(d)). We differentiate on the map between magmatic (Figure 3(a) and 3(b)) and hydromagmatic vents (Figure 3(c)); the latter normally being mapped inside phreatomag-
matic craters.

Regarding submarine eruptive vents, only those that are morphologically recognisable as volcanic cinder cones were considered, and were mapped as individual points corresponding to their summits.

3.2. Eruptive fissures

Eruptive fissures were identified via alignment of two or more vents that form part of coalescent craters-
cones (Figure 2(a), 3(a) and 3(b)). Elliptical craters were also defined as eruptive fissures when cones are located in flat areas with less than 4° of slope (Figure 3(c)) (Tibaldi, 1995). In those cases where cin-
der cone rims were incomplete, we constructed the best-fit ellipses and calculated the axial ratios for each vent (Paulsen & Wilson, 2010).

Each eruptive fissure was reported as a lineament linking the volcanic vents opened during the same eruption, with a linear pattern that can be continuous or discontinuous. Most of the onshore fissures are related to the last cycle of activity of El Hierro (the past 158 ka) and are often partially buried by lava flows, thus representing segments of originally more extended lineaments.

3.3. Dykes

Dykes are the most numerous volcano-structural elements on El Hierro. They are part of a complex dyke swarm that is exposed predominantly on the main landslide headwalls and on the oldest ravines (Figure 4(a)). The scale of the map (1:100,000) prevents the clear observation of the dyke traces but is enough for identifying the sectors of the island with the highest density of dykes.
Most of dykes are subvertical (Figure 4(a)), trending parallel to axis of the rift where they are located and range from 0.1 up to 12.5 m thick (Figure 4(a)). Dykes of El Hierro are predominantly mafic in composition.

Dyke-rocks usually contain round or elongate millimetre to centimetre vesicles (Figure 4(b)). Commonly, it is observed an increase in vesicularity towards the centre of the dyke, although sometimes they are irregularly distributed within the dyke rock. The host rock

Figure 2. Types of subaerial vents distinguished in the text: (a) craters of isolated cinder cones (red dots), and craters belonging to the same eruptive fissure (dashed yellow line) building coalescent pyroclastic cones; (b) vents without an associated cinder cone, characterised by lava flows erupted from a single well-defined point; (c) vent related to a hornito; (d) vents defining a spatter rampart of Mt. Escobar (dashed black line); main vents are marked as red dots.

Figure 3. Types of eruptive fissures defined in the text: (a) and (b) Tanganasoga Volcano. Picture (a) shows an aerial view of the main vents that form a N–S fissure (Image (a) from GoogleEarth, GRAFCAN 2014); (b) Tanganasoga Volcano from a NW view in which a long N–S cone is observed; (c) Hoya de Fileba hydromagmatic crater. Inset figure shows the eruptive NE–SW fissure defined through one vent with an elliptical crater.
Figure 4. Some of El Hierro dyke's characteristics: (a) dyke swarm in the Sabinosa wall; (b) millimetric to centimetric elongate and round vesicles in a dyke; (c) glassy chilled margin; (d) one of the ten feeder dykes identified on the island; (e) detailed picture of magma drops or ‘stalactite’-like fingers on a feeder dyke cavity wall.
consists primarily of alternating lava flows and pyroclastic layers (Figure 4(a)). Many dykes have chilled margins with a glassy selvage at the contact with the host rock (Figure 4(c)).

Ten dykes were identified as feeder dykes, that is, dykes directly connected to their eruptive fissures (Becerril et al., 2013b, 2015) (Figure 4(d)). They contain vesicles which increase in size and number towards the surface, and even contain cavities (less than 1 m size) at their very top. Occasionally the cavity walls feature magma drops or ‘stalactite’-like fingers on the cavity walls (Figure 4(e)). The characteristics of these feeder dykes (mainly strike, thickness and length) enabled assessment of the depth of their source (i.e. magma reservoir) (Becerril et al., 2013b).

3.4. Faults

Orthophoto examination and interpretation was carried out in order to check previously mapped faults (Carracedo et al., 2001; Coello, 1971; Day et al., 1997; Navarro & Soler, 1995; Pellicer, 1977; IGME, 2010a, 2010b, 2010c, 2010d) and to identify new ones. Exposed faults on the island exhibit normal to oblique components and dipping fault planes. Their lengths range from about 100 m to several kilometres. They crop out and have the highest number density along the Tiñor Edifice. However, only a few faults dissect the Rift Volcanism deposits.

Faults are most easily recognisable on the island’s NE sector, where a graben system, nearly 6 km long and 1.5 km wide (Becerril et al., 2015; IGME, 2010a), has been identified and associated to the San Andrés Deep-seated Gravitational Slope Deformation (DSGSD) (Klimeš et al., 2015) (Figure 5(a) and 5(b)). These are well exposed with steeply dipping planes striking ENE–WSW (Day et al., 1997). The southeastern boundary fault is visible in discontinuous exposures over a distance of 5 km and represents the antithetic fault to the north-western boundary fault (Figure 5(c)). Inside the graben, up to three smaller antithetic faults are identifiable through indistinct surficial expression (Figure 5(c)). The north-western boundary fault dips at an average of 65° to SE and the height of its escarpments, and thus the minimum throw, is about 30 m (Figure 5(d)). The cross-section C–C’ of the Main Map is devoted to the San Andrés DSGSD where a possible failure plane was hypothesised taking into account the geometry of Las Playas II avalanche.

Southern and western rifts show few outcropping faults with N–S and E–W strikes, respectively. The exposure of these faults is limited because they are partially obscured by the deposits of the latest eruptions.

We also mapped landslide faults running parallel to the scarp of El Golfo, and dipping towards the embayment (Figure 5(e) and 5(f)). Impressive cliffs up to 1000 m high delineate these faults that favour the development of lateral spreading and sliding phenomena. Large blocks of volcanic rock are detached from the edges of the El Golfo landslide scarp producing staircase normal fault geometry. Some of these faults show open tension cracks suggesting that these gravitational structures are currently active (Figure 5(e)).

3.5. Inferred faults

Volcanic landscapes change with each eruption. The deposits from these events can obscure or hide active faults. However, sometimes the fault scarp is high enough such that a rectilinear slope change is recognised coinciding with the fault trace. Such morphologies have been mapped as inferred faults on El Hierro. We do not have complete certainty that these lineaments corresponds to buried faults; only specific geophysical surveys may prove their existence. Most of the inferred faults included on the volcano-structural map were already identified by Pellicer (1977), Navarro and Soler (1995) and are also represented on the Geological Map of IGME (2008).

3.6. Avalanche scars and deposits

Avalanche scars and deposits include volcanic landforms resulting from large scale flank collapses. These processes of gigantic landslide generate scars with morphologies such as wide horseshoe-shaped depressions and high steep-sided break-away scarp creating an amphitheatre shape typical of volcano sector collapses (Figure 6). On El Hierro, up to six giant landslides have been identified so far: Tiñor (<880 ka), El Julan (>158 ka), Las Playas I (545–176 ka) and II (176–145 ka), El Golfo (87–39 ka), and Punta del Norte (unknown) debris avalanches (Carracedo et al., 1999, 2001; Longpré et al., 2011; Masson, 1996; Masson et al., 2002; Urgeles et al., 1996, 1997). Their headwalls show different erosional degrees (El Golfo, Las Playas and Punta del Norte) or have been totally buried by younger lava flows (Tiñor and El Julan) (Main Map).

We have delineated both onshore and offshore, the landslide scars and the limits of their debris avalanche deposits according to the maps published previously (Acosta et al. 2003a, 2003b; Carracedo et al., 1999, 2001; Gee, Watts, Masson, & Mitchell, 2001b; Holcomb & Searle, 1991; Longpré et al., 2011; Masson, 1996; Masson et al., 2002; Urgeles et al., 1996, 1997). In the cases of El Julan, Las Playas and El Golfo landslides, we have outlined the escarpments bounding the landslide scars, the latter also referred to as landslide valleys (Gee et al., 2001b) (Main Map). The upper limit of the Tiñor avalanche was inferred by Carracedo et al. (2001) and IGME (2010a) using stratigraphic and relative geochronological criteria. The empty space left by
the landslide was filled by subsequent discordant volcanic materials. On the volcano-structural map, the edge of the Tiñor landslide is indicated by a dashed line since its exact location and trace is not known with the required accuracy (Main Map).

In addition, the onshore scar of a smaller landslide has been delineated in this work. This landslide was called ‘Punta del Norte avalanche’ by Acosta et al. (2003a). These authors mapped the offshore part of this landslide (See Figure 11 in Acosta et al. (2003a)) and they describe it as a minor avalanche, though they do not establish its connection with its onshore scarp in the Tamaduste area.

4. Conclusions

The first complete volcano-structural map of El Hierro is presented here and integrates all the volcano-
structural elements previously described: vents, eruptive fissures, dykes, faults, and landslide scars, both onshore and offshore. The map is produced in DIN A1 format at 1:100,000 scale and it is accompanied by two 3D views of the volcanic edifice, three topographic profiles and one simplified scheme of the volcano's plumbing system.

This map represents the state-of-the-art on the knowledge of the structural setting of the El Hierro volcano, providing an upgraded cartographic document in which all mapped elements are consistent with each other and are constrained by different methodological approaches.

Software
Georeferencing and digitisation of the volcano-structural elements was performed using ESRI® ArcGIS 9.2, 9.3 and 10. 3D images on the map were produced using ArcScene module. Topographic profiles were produced using the Easy Profile tool for ArcGIS 9.3., and Microsoft Excel® 2007. All the information (vector and raster) were stored in a georeferenced database called VERDI (Bartolini et al., 2014; Becerril, 2009, 2014; Becerril & Galindo, 2010). The final design was carried out using Adobe® Illustrator® CS2.

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