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Deep intrusions, lateral magma transport and related uplift at ocean island volcanoes

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ABSTRACT

Oceanic intraplate volcanoes grow by accumulation of erupted material as well as by coeval or discrete magmatic intrusions. Dykes and other intrusive bodies within volcanic edifices are comparatively well studied, but intrusive processes deep beneath the volcanoes remain elusive. Although there is geological evidence for deep magmatic intrusions contributing to volcano growth through uplift, this has rarely been demonstrated by real-time monitoring. Here we use geophysical and petrological data from El Hierro, Canary Islands, to show that intrusions from the mantle and subhorizontal transport of magma within the oceanic crust result in rapid endogenous island growth. Seismicity and ground deformation associated with a submarine eruption in 2011–2012 reveal deep subhorizontal intrusive sheets (sills), which have caused island-scale uplift of tens of centimetres. The pre-eruptive intrusions migrated 15–20 km laterally within the lower oceanic crust, opening pathways that were subsequently used by the erupted magmas to ascend from the mantle to the surface. During six post-eruptive episodes between 2012 and 2014, further sill intrusions into the lower crust and upper mantle have caused magma to migrate up to 20 km laterally, resulting in magma accumulation exceeding that of the pre-eruptive phase. A comparison of geobarometric data for the 2011–2012 El Hierro eruption with data for other Atlantic intraplate volcanoes shows similar bimodal pressure distributions, suggesting that eruptive phases are commonly accompanied by deep intrusions of sills and lateral magma transport. These processes add significant material to the oceanic crust, cause uplift, and are thus fundamentally important for the growth and evolution of volcanic islands. We suggest that the development of such a magma accumulation zone in the lower oceanic crust begins early during volcano evolution, and is a consequence of increasing size and complexity of the mantle reservoir system, and potentially the lithospheric stresses imposed by increasing edifice load.

1. Introduction

Volcanic ocean islands and seamounts form the largest volcanoes on Earth. They are partly formed of, and are underlain by, magmatic intrusions that can be of significantly larger volume than volcanic outputs (Contreras-Reyes et al., 2010; Crisp, 1984; ten Brink and Brocher, 1987). Field studies at deeply incised volcanoes show that many, perhaps most, shallow basaltic intrusions are steeply dipping sheets (dykes) that have either fed eruptions or became stalled in the shallow crust. Beneath volcanic rift zones, dykes occur as swarms that can reach tens of kilometres in length; in some rifts shallow dykes can propagate laterally for considerable distances (Rubin, 1995; Walker, 1999). Shallow sills are also common, for example at the Seamount Complex of La Palma (Canary Islands) that consists largely of sills with subordinate dykes and some small plutons (Staudigel and Schmincke, 1984). Inclined sheets are common at many large composite volcanoes and are typically associated with a shallow magma chamber, as exemplified by central volcanoes of Iceland (Gudmundsson, 2006) or Gran Canaria (Schirnick et al., 1999). For many oceanic intraplate volcanoes, however, there is no evidence for a long-lived shallow magma chamber (e.g., Hildner et al., 2012; Klügel et al., 2000), probably because magma fluxes are too small for persistent shallow magma chambers to develop (Clague and Dixon, 2000; Gudmundsson, 2012).

The geometry and extent of intrusions deeper beneath volcanic edifices are comparatively poorly resolved because outcrops for

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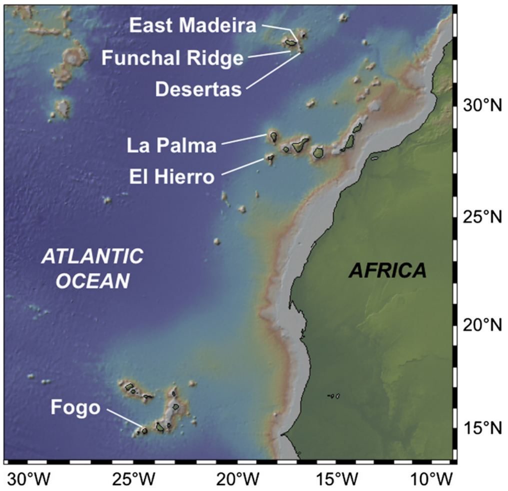

Fig. 1. Map showing intraplate volcanoes in the eastern Atlantic Ocean. All investigated volcanoes sit on Jurassic to Cretaceous oceanic crust far from plate boundaries. Map produced using GeoMapApp, http://www.geomapapp.org.

field studies are very rare. Our understanding of such deep intrusions is largely based on seismic and geodetic data obtained at a few active volcanoes. At Kilauea, Hawaii, a magma chamber at ca. 2–4 km depth and two shallow rift zones emanating from it are thought to be underlain by a dense dyke complex and a vertical magma body (molten core), which extend to a decollement at ∼10 km depth that exerts strong control on magma injections and flank slip (Delaney et al., 1990). Around the central feeder conduit the deep intrusive core is thought to consist of a complex of sill-like ultramafic cumulates within the lower oceanic crust and some local tabular bodies (Hill and Zucca, 1987). Deep magma transport at Kilauea is probably vertical from the mantle source to 35–30 km depth, then subhorizontal over a distance of ca. 20 km, and then near-vertical again from ca. 30 km depth to the shallow magma chamber (Wright and Klein, 2006). Large volcanoes such as those in Iceland may be fed by a double magma chamber, e.g., a deep-seated reservoir near the Moho connected to a shallow crustal chamber (Gudmundsson, 2006), or by complex magma chamber systems where mixing of distinct melts at different levels occurs (Neave et al., 2013).

Less is known about magma storage and transport at volcanoes that erupt only rarely and are not continuously monitored. A case in point are the Canary Islands (Fig. 1) where models for magma plumbing systems are based largely on petrological and geochemical investigations of volcanic rocks (e.g., Hansteen et al., 1998; Klügel et al., 2000; Stroncik et al., 2009). Testing of such models by geophysical data was not possible until 2011 when a submarine eruption occurred south of the island of El Hierro, the youngest Canary Island. It was the first Canarian eruption to be fully monitored with modern instrumentation. The combination of detailed petrological–geochemical investigations with seismic and ground deformation data yield an unusually clear picture of intrusion propagation and magma plumbing associated with this eruption (González et al., 2013; Longpré et al., 2014; Martí et al., 2013a). Excellent agreement between geobarometric and seismic data was observed (Longpré et al., 2014), which demonstrated that these geobarometric methods are a reliable tool to reconstruct magma pathways of past eruptions.

In this study we use public seismic and GPS data to show that widespread magmatic intrusions and concomitant rapid uplift occurred over a period of two years following the El Hierro eruption. We also compile and examine published geobarometric data from Atlantic intraplate volcanoes to demonstrate striking similarities with those from El Hierro. Our results suggest that lateral magma movement and accumulation within the lower crust beneath oceanic intraplate volcanoes is a common process, which has important implications for volcano evolution.

2. Methods and data sources

2.1. Seismicity

Open access data from the Spanish Instituto Geográfico Nacional (IGN; www.ign.es) catalogue were filtered to include only seismic events with a magnitude greater than or equal to 2 and with maximum horizontal and vertical location errors smaller than 10 and 8 km, respectively. The filtered dataset has mean maximum and minimum horizontal errors of 5.7 ± 1.9 km and 3.4 ± 1.2 km, respectively, and a mean vertical error of 3.9 ± 1.1 km. Domínguez Cerdeña et al. (2014) applied an improved algorithm to perform a relocation of the pre-eruptive earthquakes listed in the IGN catalogue. These authors' results suggest an earthquake distribution slightly shallower and more compact than shown in Fig. 2.

2.2. Ground deformation

GRAFCAN (www.grafcan.es) operates a permanent global navigation satellite system (GNSS) network in the Canary Islands and raw data are publicly available. We processed GPS data from the FRON station on El Hierro (30-second sampling) using Bernese software version 5.0 (Dach et al., 2007) in a regional network mode together with other GPS sites, both on El Hierro and surrounding areas. Five of these stations were used to determine the ITRF2008 reference frame (Altamimi et al., 2011). We used double-differenced phase data to form baselines and the QIF strategy (Dach et al., 2007) to resolve ambiguities. Our calculations used ocean-loading model FES2004 (Lyard et al., 2006), and both absolute antenna phase centre models and precise satellite orbits from the International GNSS Service (IGS). The daily northing, easting, and vertical components of our position time series were calculated from the precise coordinates obtained by this process.

2.3. Compilation of geobarometric data

For our study we have compiled published geobarometric data from several localities (Fig. 1, Table 1). The compilation includes only localities where both clinopyroxene–melt and fluid inclusion geobarometers were applied, which differ in terms of their response rate. Clinopyroxene compositions preserve conditions of their crystallisation over months (Klügel et al., 2005), whereas fluid inclusions in crystals can re-equilibrate to new ambient pressures within hours to days and record even brief stalling periods of ascending host magma (Hansteen and Klügel, 2008; Wanamaker and Evans, 1989). The suitability and comparison of both methods have been discussed in detail (Hildner et al., 2011; Klügel et al., 2005). In order to obtain a consistent data set, we recalculated some of the published original data so that the same calibrations and equations were used for all localities (see below). The complete dataset is presented in Supplementary Table S1.

2.3.1. Clinopyroxene–melt barometry

The published data for clinopyroxene–melt barometry used in our compilation involve euhedral clinopyroxene phenocrysts in textural equilibrium with ultrabasic to basic host melt (matrix). Melt compositions were derived from analyses of matrix glass or from fused groundmass separates as described in the respective publications. Clinopyroxene rim compositions were obtained by averaging a number of point analyses at 5–10 μm distance from the rims by electron microprobe. For each crystal–melt pair we applied the calibration of Putirka et al. (2003) to obtain a single