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Volcanic tremors: Good indicators of change in plumbing systems during volcanic eruptions

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ABSTRACT

Geophysical and geochemical signals recorded during episodes of unrest preceding volcanic eruptions provide information on movements of magma inside the lithosphere and on how magma prepares to reach the surface. When the eruption ensues continuous volcanic monitoring can reveal the nature of changes occurring in the volcano's plumbing system, which may be correlated with changes in both eruption behaviour and products. During the 2011–2012 submarine eruption of El Hierro (Canary Islands), the seismic signal, surface deformation, a broad stain on the sea surface of the eruption site, and the occasional appearance of floating lava balloons and pyroclastic fragments were the main observable signs. A strong continuous tremor in the vent accompanied the eruption and varied significantly in amplitude, frequency and dynamical parameters. We analysed these variations and correlated them with changes in the distribution of earthquakes and in the petrology of the erupting magma. This enabled us to relate variations in tremors to changes in the (i) stress conditions of the plumbing system, (ii) dimensions of the conduit and vent, (iii) intensity of the explosive episodes, and (iv) rheological changes in the erupting magma. The results obtained show how the tremor signal was strongly influenced by stress changes in the host rock and in the rheological variations in the erupting magma. We conclude that the tracking of real-time syn-eruptive tremor signals via the observation of variations in plumbing systems and magma physics is a potentially effective tool for interpreting eruption dynamics, and suggest that similar variations observed in pre-eruptive tremors will have a similar origin.

1. Introduction

Volcanic tremors consist of long-lasting seismic signals that are often associated with the movement of fluids through a volcanic conduit in an active volcano (Schick and Riuscetti, 1973; Chouet, 1996; McNutt, 2005; Jellinek and Bercovici, 2011). The characteristics of these tremors vary considerably between volcanoes and eruptive phases (McNutt, 1994; Jellinek and Bercovici, 2011) and depend on source effects, conduit and vent geometries, the rheological behaviour of the magma, and pressure variations in the plumbing system caused by external (tectonic and gravitational readjustments) or internal (magma degassing and crystallisation) (McNutt, 2005; Jellinek and Bercovici, 2011) changes. Tremor amplitude and frequency depend on the geometry and size of the volcanic conduit, as well as the intensity (degree of explosivity) of the eruption (McNutt, 1994; Chouet, 1996; McNutt and Nishimura, 2008). The existence of further changes can be revealed by the study of other parameters based, for example, on dynamical systems theory, as in the case of volcanoes such as Stromboli (Carniel and Di Cecca, 1999), Ambrym (Carniel et al., 2003), Villarrica (Tárraga et al., 2008) and Popocatepetl (Tárraga et al., 2012). Therefore, tremors can provide information on source variations, erupting magma and/or the conduit and vent before and during the eruption (Chouet, 1996; Denlinger and Hoblitt, 1999; Goto, 1999; McNutt, 2005; McNutt and Nishimura, 2008), all of which are crucial for understanding unrest and how changes in plumbing systems affect eruption dynamics.

The 2011–2012 El Hierro submarine eruption lasted for nearly five months, from 10 October 2011 to the end of February 2012, and was accompanied by a continuous tremor signal located at the vent (Abella et al., 2012). The eruption was characterised by significant changes in the stress conditions of the plumbing system and in the rheology of the erupting magma (Martí et al., 2013a,b), which in turn were reflected in changes in the location and intensity of the seismicity and the degree of crystallinity of the magma. Martí et al. (2013a) suggest that some of these changes might also have influenced some of the alterations noted in the tremor signal, although no clear cause/effect relationship has yet been established. Here we analyse the amplitude, and spectral and dynamical parameters of the whole tremor signal recorded during the eruption. Our aim was to interpret tremor variations in terms of changes in the (i) stress conditions of the plumbing system, (ii) dimensions of the conduit and vent, (iii) intensity of the explosive episodes, and (iv) rheological changes in the erupting magma at a point in time

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with a clear correspondence between tremor changes and variations in seismicity and/or the petrology of the erupted products. We thus identified the main tremor changes using the same type of tremor signal analysis as applied to volcanoes such as Stromboli (Carniel and Di Cecca, 1999), Ambrym (Carniel et al., 2003), Villarrica (Tárraga et al., 2008) and Popocatépetl (Tárraga et al., 2012), and compare these changes with the variations in earthquake distribution and erupting magma petrology identified by Martí et al. (2013a,b). Subsequently, we establish a cause/effect relationship between tremor changes and changes in the stability of the plumbing system and/or the rheological behaviour of the magma during the El Hierro eruption. In addition, we discuss the applicability of this type of analysis to the characterisation of eruption dynamics and its potential in the interpretation of unrest episodes when applied to pre-eruptive signals.

2. El Hierro eruption

El Hierro is the youngest of the Canary Islands and its oldest subaerial rocks are dated at 1.12 Ma (Guillou et al., 1996). The island consists of a shield structure formed by different volcanic edifices and includes three rift zones along which recent volcanism is concentrated (Fig. 1). The formation of El Hierro has been affected by large sector collapses that have left scars at El Golfo, Las Playas and El Julan (Fig. 1). Stroncik et al. (2009) suggest that this island's plumbing system is characterised by a multi-stage ascent of magmas with major fractionation in the uppermost mantle, where incoming magma batches mingle or mix thoroughly with other ascending batches.

An unrest episode characterised by heightened seismic activity, surface deformation and gas emissions started on 17 July 2011 (López et al., 2012). Before the start of the eruption on 10 October 2011, nearly 11,000 seismic events were recorded, with local magnitudes of up to 4.3. Most hypocentres were located around 10–15 km (Fig. 1) below El Hierro's volcanic edifice (http://www.ign.es/ign/layoutIn/sismoFormularioCatalogo.do). The total seismic energy released before the eruption was 8.1×10^{11} J and the accumulated surface horizontal deformation reached 40 mm. High rates of CO_2 flux were measured in the area on land in which the epicentres were concentrated (López et al., 2012).

The eruption of basanitic magma began on 10 October 2011 at 4:35 a.m. with the opening of a N 20°-oriented fissure on the southern flank of the island at a depth of 900 m b.s.l. Over the next three days the focus of the eruption migrated northwards to a depth of 300 m, where it established a permanent central conduit and a main vent encircled by a volcanic edifice built from the accumulation of pyroclastic material. By the end of the eruption, the edifice had reached a height of 220 m with a basal diameter of over 1 km (Martí et al., 2013a). The total amount of erupted material was of the order of 0.33 km^3 (Rivera et al., 2013), with an average eruption rate of 15–20 m^3/s; part of the eruption corresponds to a lava flow that was emplaced in a south-westerly direction from the base of the cone. The eruption continued in a similar fashion until late February 2012, when all evidence of magma output ceased. Although the magma composition did not vary significantly, its crystal content varied from 3% during the first episodes to 44% in later ones (Martí et al., 2013b).

By comparing petrological and geophysical data Martí et al. (2013b) were able to distinguish two main eruptive episodes – each with different phases – and to identify two interconnected magma reservoirs at a depth of 20–25 and 10–15 km. The establishment of the central conduit a few days after the onset of the eruption coincided with the appearance on the sea surface of the first low-density pyroclasts and lava fragments (15 October 2011). These had a pumice-like white core of silicic composition surrounded by a black scoriaceous basanite carapace. Sigmarsson

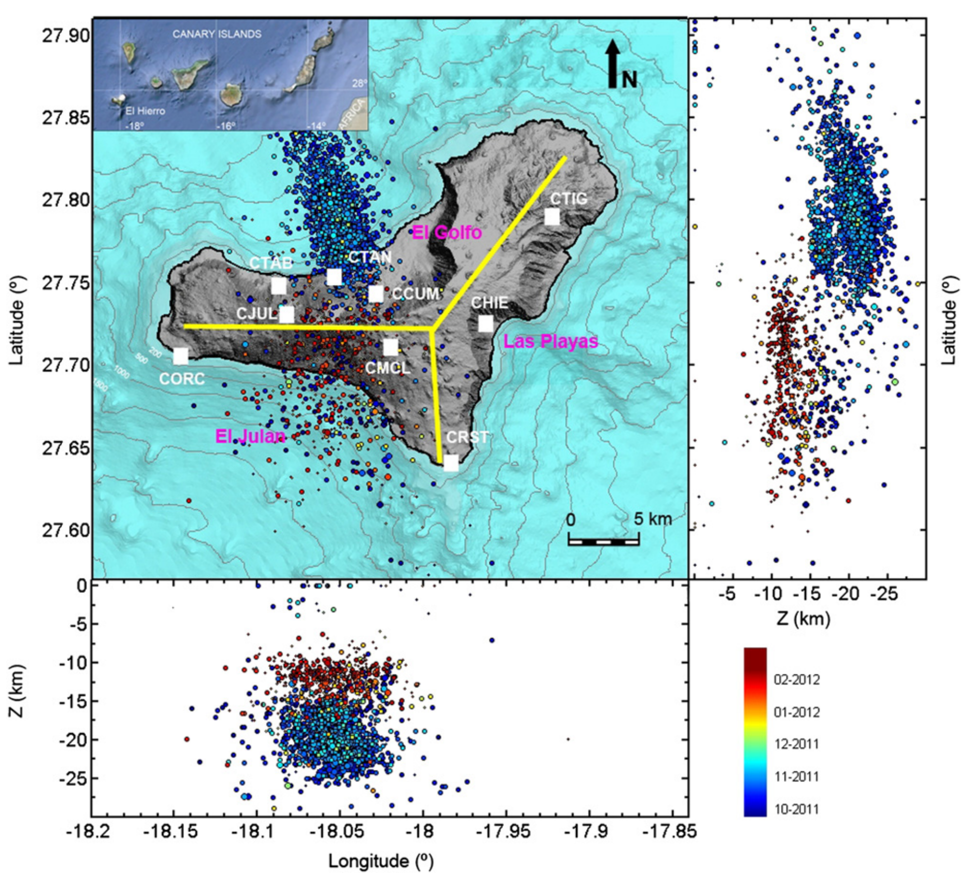

Fig. 1. DEM of El Hierro showing the main structural and morphological features, the IGN seismic network and the distribution of seismic events recorded from 10 October 2011 to the end of February 2012 (around 3500 events).