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Magma emission rates from shallow submarine eruptions using airborne thermal imaging

Pedro A. Hernández [a,b,*], Sonia Calvari [c], Antonio Ramos [b,d], Nemesio M. Pérez [a,b], Antonio Márquez [e], Roberto Quevedo [b,f], José Barrancos [a,b], Eleazar Padrón [a,b], Germán D. Padilla [a,b], Dina López [b,g], Ángel Rodríguez Santana [b,h], Gladys V. Melián [a,b], Samara Dionis [b], Fátima Rodríguez [b], David Calvo [b], Letizia Spampinato [c]

[a] División de Medio Ambiente, ITER, Granadilla de Abona, Tenerife, Canary Islands, Spain
[b] Instituto Volcanológico de Canarias, INVOLCAN, Puerto de la Cruz, Tenerife, Canary Islands, Spain
[c] Istituto Nazionale di Geofisica e Vulcanologia, Obsservatorio Etneo, Sezione di Catania, Catania, Italy
[d] Division of Robotic and Computational Oceanography (SIANI), Facultad de Ciencias del Mar, Universidad de Las Palmas de Gran Canaria, Canary Islands, Spain
[e] Unidad de Helicópteros UTF, Guardia Civil, Zona de Canarias, Tenerife, Canary Islands, Spain
[f] Bionerics Research, Teror-Arucas, Gran Canaria, Canary Islands, Spain
[g] Department of Geological Sciences, OH University, Athens, USA
[h] Departamento de Física, Facultad de Ciencias del Mar, Universidad de Las Palmas de Gran Canaria, Canary Islands, Spain

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ABSTRACT

The effusion rate is the most important parameter to gather when a volcanic eruption occurs, because it controls the way in which a lava body grows, extends and expands, influencing its dimensional properties. Calculation of lava flow volume from thermal images collected by helicopter surveys has been largely used during the last decade for monitoring subaerial effusive eruptions. However, due to the depths where volcanic activity occurs, monitoring submarine volcanic eruptions is a very difficult task. The 2011–2012 submarine volcanic eruption at El Hierro, Canary Islands, has provided a unique and excellent opportunity to monitor eruptive processes occurring on the seabed. The use of a hand-held thermal camera during daily helicopter flights allowed us to estimate for the first time the daily and total erupted magma volumes from a submarine eruption. The volume of magma emitted during this eruption has been estimated at 300 Mm^3, giving an average effusion rate of ~25 $m^3 s^{-1}$. Thermal imagery by helicopter proved to be a fast, inexpensive, safe and reliable technique of monitoring volcanic eruptions when they occur on the shallow seabed.

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1 . Introduction

Volcanoes are widely spread out over the seabed of our planet, being concentrated mainly along mid-ocean ridges. Due to the depths where this volcanic activity occurs, monitoring submarine volcanic eruptions is a very difficult task. There have been only two occasions where a deep (>500 m) submarine eruption has been directly observed, on the West Mata submarine volcano in the northeast Lau Basin, southwest Pacific Ocean (Resing et al., 2011) and at the Monowai submarine volcano, Kermadec arc (Chadwick et al., 2008). Observations of shallow submarine activity have been done at Kilauea and Mauna Loa by scuba divers and remotely operating vehicles, revealing channelized flows and submarine lava tubes (Tribble, 1991), pillows and a large amount of fragmental debris formed by lava quenching when entering the sea (Garcia & Davies, 2001; Moore & Chadwick, 1995; Moore, Phillips, Grigg, Peterson, & Swanson, 1973). However, performing long-term monitoring in such an environment is challenging and expensive, and is normally done for short periods of time and through the use of autonomous ocean bottom systems (Deardorff, Cashman, & Chadwick, 2011). Thus, when a submarine eruption occurs at shallow depths, there is an excellent opportunity to monitor and study the eruptive activity and test new techniques. Typical phenomena associated with shallow submarine eruptions are floating lava fragments, rising water columns, explosions and discoloration of sea water (Deardorff et al., 2011; Nogami, Yoshida, & Osaka, 1993). Therefore, it is possible to guess the eruption point and intensity of volcanic activity from the color tone, shade and dimensions of the discoloration area (Nogami et al., 1993).

When dealing with a volcanic eruption, the effusion rate and Time Averaged Discharge Rate (TADR) are the most important parameters to measure, because they control the way in which a lava body grows, extends and expands, influencing its dimensional properties, such as length, width, thickness, volume and/or area (Harris, Dehn, & Calvari,

* Corresponding author at: Instituto Volcanológico de Canarias, INVOLCAN, Puerto de la Cruz, Tenerife, Canary Islands, Spain.
E-mail address: phdez@iter.es (P.A. Hernández).

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2007). Calculation of lava flow volume and TADR from thermal images collected by helicopter surveys has been widely used during the last decade for monitoring subaerial effusive eruptions at Etna and Stromboli (Italy), Kilauea (Hawaii, USA), and other volcanoes (Spampinato, Calvari, Oppenheimer, & Boschi, 2011). Other authors (Harris et al., 2005) developed a useful routine to calculate TADR from thermal helicopter surveys during the 2002–03 eruption of Stromboli. However, when lava flows spread under the sea, calculations are more complex.

The recent submarine eruption at El Hierro Island in the Canaries started on October 12, 2011, and has offered an excellent opportunity to monitor the volcanic activity and apply novel methodologies for the detection and understanding of the eruptive process. Thermal surveys of the sea surface heated by the emission of lava, fragmented ejecta, and hydrothermal fluids, have been performed on a regular basis to estimate the erupted volume and to correlate the temporal variation of the surface measured temperatures with the level of activity, mainly based on the seismicity. This study presents the first estimates of emitted magma volume from a submarine volcano during a long period of observation by means of thermal surveys from a helicopter.

The Canary Islands consist of an east–west trending volcanic chain of seven islands, with El Hierro being located at the south westernmost end of the archipelago (Fig. 1). With an area of 268 km^2 and a maximum altitude of 1501 m above sea level, El Hierro has a characteristic trilobed shape. It is the youngest of the Canary Islands, with the oldest subaerial rocks dated at 1.12 Ma, and is believed to be near the present hotspot location (Guillou, Carracedo, Pérez Torrado, & Badiola, 1996; Hoernle, Tilton, & Schmincke, 1991). The island is truncated to the north by a large escarpment (Fig. 1), as the result of a gravitational collapse of El Golfo volcano about 130,000 years ago; other smaller collapse features are present on the island (Masson et al., 2002). The subaerial portion of the volcano, which consists of Quaternary lava flows and tuffs capped by numerous cinder cones, contains the greatest concentration of young vents in the Canary Islands (Becerra, Guillén, & Dóniz, 2007). Recent volcanic activity occurred along radial directions, focusing mainly along the three volcanic ridges bearing NE, S and SW with respect to the El Golfo depression (Fig. 1). Morphometric analyses of the volcanic cones that form these ridges (Gee, Watts, Masson, & Mitchell, 2001) reveal several monogenetic structures, indicative of the occurrence of low-volume eruptions with predominantly effusive character. The submarine extension of the S-Ridge, in contrast, is defined by a 38 km long, narrow ridge curving gently to the southwest and extending to a depth of 3700 m (Gee et al., 2001). El Hierro had no confirmed eruptions during the last 500 years; some uncertainty exists about a possible event in 1793 (Hernández Pacheco, 1982). Based on a thermobarometric and petrologic study (Stroncik, Klügel, & Hansteen, 2009) of basanites that erupted from young volcanic cones along the submarine portions of the three El Hierro rift zones (NE-Ridge, NW-Ridge and S-Ridge) to reconstruct magma plumbing and storage beneath the island, the authors concluded that the plumbing system beneath El Hierro rather resembles the magma storage systems beneath Madeira and La Palma islands, indicating that small, intermittent magma chambers might be a common feature of oceanic islands fed by plumes with relatively low fluxes, which results in only limited and periodic magma supply.

On July 19, 2011, the two seismic stations of the National Geographical Institute (IGN) deployed at El Hierro recorded the start of some unusual low magnitude seismic activity ($M < 2.5$) at depths between 8 and 15 km, indicating the start of volcanic unrest. During the first two months, seismic activity was concentrated mainly to the north of El Hierro. From mid-September, seismicity began to migrate southwards (Ibáñez et al., 2012). After almost three months of intense seismic activity, on October 10, 2011, at 05:15 (UTC), seismicity changed from discrete earthquakes to continuous tremor (Ibáñez et al., 2012). An underwater eruption was confirmed on October 12, 2011 by visual observations off the coast of El Hierro, about 2 km south of the small village of La Restinga, when a brown patch of warm water appeared on the sea surface.

Since the start of the submarine eruption, a large water discoloration area was observed on the sea surface most of the time (Fig. 2a), from light-green to dark-brown in color, due to the intense discharge of high temperature hydrothermal fluids, magmatic gases, and volcanic ash (Nogami, 2004). More than 12,000 seismic events occurred during the whole eruption, with the largest of magnitude 4.6 recorded on

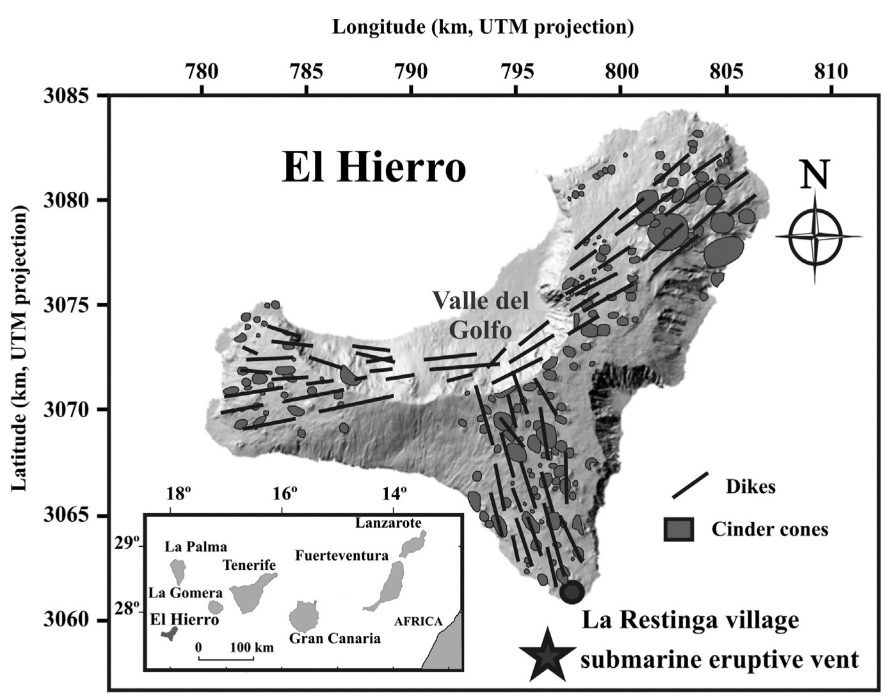

Fig. 1. Location of El Hierro Island and simplified volcano-structural map of the island (modified from Navarro & Soler, 1994). Star indicates the location of the submarine eruption. For bathymetry see Rivera et al. (2013).

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