We present here a bathymetric map of a new underwater volcano which began its growth on 10 October 2011 to the south of El Hierro Island (Canary Is., Spain). The map scale is 1:25,000 and the map covers 210.9 sq. km. In July 2011, the seismic monitoring network of Spanish National Geographic Institute (IGN), began to detect an increase in low-intensity earthquakes around El Hierro Island along with ground deformation. This seismic crisis culminated on 10th October with a submarine eruption 2 km south of the small port of La Restinga, and lasted until March 2012 when IGN determined the end of the eruption process. After eight surveys monitoring the morphological and bathymetric evolution during the eruptive phase that ended in March 2012, Spanish Oceanographic Institute and the Hydrographic Institute of the Navy, carried out a survey from the 6th to the 8th of December 2012 to map the bathymetric and morphologic situation after the 2011–2012 eruptive period. The map presented here is based on full seafloor coverage by multibeam swath data echosounder carried out when the submarine volcano was in a quiet phase, using a grid mesh size of 12 × 12 meters.

Keywords: submarine volcano; multibeam bathymetry; Canary Islands; oceanography; volcanic hazards; acoustic techniques; seabed mapping; civil defense

1. Introduction

El Hierro is the youngest and smallest island of the Canary archipelago (Guillou, Carracedo, Torrado, & Badiola, 1996; Van den Bogaard, 2013). It has a surface area of 273 km², lies up to 1500 m above sea level and is located at the westernmost point of the Canary archipelago (Figure 1). Geologically, it is still in a ‘juvenile stage’ of shield growth, and is probably located over the present position of the Canary Hotspot that generated the islands (Holik, Rabinowiz, & Austin, 1991).

In plan view the island has three lobes whose intersections form a central tableland on which are superimposed numerous extinct cinder cones. The submarine geomorphology presents a three submarine rifts: Northeast, Northwest and South. The ridge-like submarine South Rift, also known as the Southern Ridge, curves southwestward from its mid-section outwards and is...
asymmetrical in cross-section, with its steeper side facing southeast. The width of the rift ranges from 3 km on its proximal end to 18 km at its distal end (Acosta et al., 2005).

In the middle of July 2011, the Spanish National Geographic Institute (IGN) seismic network detected an increase in seismicity with hypocenters migrating from the North of the Island to the South. On 10th October, after the occurrence of more than 10,000 seismic events (López et al., 2012) IGN recorded a volcanic tremor (indicative of the onset of a submarine eruption), off the coast of the village of La Restinga and approximately 1.8 km southwestwards. In the following days dead fish appeared in the vicinity of the eruption area as well as a huge stain in the sea water caused by the presence of pyroclasts, gases and other products of the submarine eruption. This stain varied in shape and size due to interaction with the ocean currents throughout the eruptive process and was visible from NASA’s satellites (Figure 2a), (Allen & Simmon, 2012).

The Civil Defense and Emergency Attendance for Volcanic Risk Special Plan in The Canary Islands PEVOLCA (for its acronym in Spanish), asked for the advice and scientific collaboration of the Spanish Oceanographic Institute (IEO), because of the potential eruption hazard may evolve into a Surtseyan eruption (Vaughan & Webley, 2010).

The IEO commissioned their brand-new ship Research Vessel (R/V) Ramón Margalef, which at the time was conducting sea trials in Vigo (NW Spain). The vessel navigated to the eruption area and provided real-time information needed by PEVOLCA scientific committee to advise and manage the possible risks arising from the submarine eruption. The R/V Ramón Margalef

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Figure 1. Location of Canary Archipelago (Globe). (a) Shaded bathymetry from IEO-IHM, EEZ program. (b) Age of Canary Islands according to Van der Bogaard, 2013.
arrived at El Hierro on 23rd October, 13 days after the eruption began on 24th October, the multi-beam record located the new volcanic edifice on the southwest flank of the South Rift in a submarine canyon at a depth of about 300 m.

The research vessel then started a series of oceanographic cruises alternating between geophysical and physicochemical surveys. The first cruise focused on mapping and geology, and the second on the study of water column conditions in the eruption area. A total of 12 legs were conducted, six of them focused on geophysical tasks and six on physicochemical (Table 1). The IEO team completed its scientific advisory mission in the eruption area in March 2012, when IGN officially declared the eruptive process over.

Because of the unusual physicochemical conditions of the water column (Fraile-Nuez et al., 2012), as well as the high content of suspended material during Bimbache cruises (Figure 3), acquisition and processing of bathymetric data was slow and laborious. After the return to a period of calm in the eruptive process, and in order to establish the exact bathymetry and morphology of the new volcano, a new geological/hydrographic cruise was carried out in December.
2012 aboard R/V Angeles Alvariño, sister ship of R/V Ramón Margalef, incorporating in the scientific staff a team of hydrographers from IHM.

2. Methods

Various ships and different methods have been used to collect data bathymetric data depending on the stage of research in which the studies were conducted. Research vessels used were; R/V

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Table 1. The table summarizes the different campaigns and datasets used in this work. Area and km refer to the surface prospected and the km traveled in each project or leg.

| DATE       | VESSEL            | PROJECT/LEG    | AREA (Ha) | Km    | DEM  |
|------------|-------------------|----------------|-----------|-------|------|
| 1998–2000  | BIO Hesperides    | ZEE            | ————     | ———— | IHM98|
| 23, 24, 25/10/2011 | RH Malaespina    | N.Charts       | ————     | ———— | IHM98|
| 25, 26, 27/10/2011 | R/V R. Margalef  | BM-Leg01       | 12816     | 352.10| S1025|
| 27, 28/10/2011  | R/V R. Margalef  | BM-Leg02       | 4262      | 41.22 | E1028|
| 28, 29/10/2011  | R/V R. Margalef  | BM-Leg02       | 2838      | 50.14 | S1029|
| 30, 31/10/2011  | R/V R. Margalef  | BM-Leg02       | 982       | 18.89 | S1031|
| 12/11/2011    | R/V R. Margalef  | BM-Leg04       | 10465     | 127.97| N1112|
| 12, 13/11/2011 | R/V R. Margalef  | BM-Leg04       | 16547     | 270.44| S1113|
| 1, 2/12/2011   | R/V R. Margalef  | BM-Leg06       | 23169     | 320.64| S1202|
| 6–8/12/2011   | R/V A. Alvariño  | HIERRO12       | 20398     | 991.15| S1212H|

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Figure 3. Water column from multibeam echo sounder record. Color scale means signal amplitude in dB from blue (less reflective) to red (more reflective). On top, figure A, shows a profile along track. The arrow indicates vessel direction (Heading SSW) and scale. The white dotted line marks a ‘cross_track slice’ showed in the bottom; figure B, these fans represent all the beams pinged in this particular swath. In both sections there are vertical trails, probably due to degassing pyroclasts ascending to surface. Depth scales in meters is shown at the right side of the figures.

2012 aboard R/V Angeles Alvariño, sister ship of R/V Ramón Margalef, incorporating in the scientific staff a team of hydrographers from IHM.
Hespérides and Malaspina (pre-eruptive), R/V Ramón Margalef (eruptive phase) and R/V Angeles Alvariño (quiescence period); these two last research vessels are twins. The following section describes the technical characteristics of the equipment used and the procedures of data acquisition and processing.

2.1 **Multibeam data acquisition**

2.1.1 **Pre-eruptive stage surveys**

Bathymetric information available prior to the 2011–2012 eruption were gathered under the Spanish Exclusive Economic Zone (EEZ) program, using R/V Hespérides, and the periodic updating of the Spanish cartographic plan, using R/V Malaspina.

The EEZ program was initiated in 1995 by the IHM-IEO to systematically map and study the Spanish EEZ. From 1997 to 2001 the EEZ program moved to the Canaries from the Iberian Peninsula, surveying much of the Canary Islands’ EEZ (Figure 1).

R/V Hespérides equipped with Simrad multibeam echosounders EM1000 and EM12, covered 100% of the seabed with a 30% overlap between lines. The EM-12 echosounder operates at a frequency of 13 kHz and provides sweeps up to 3.5 times the water depth. Its accuracy is about 0.25% of the water depth. The EM1000 echosounder operates at a frequency of 95 kHz and was used for depths shallower than 200 m. The raw data from both echosounders and the navigation telegram were stored on a Sun workstation using Merlin software. Further processing and post processing was made using Neptune, Cflor and IberGIS among other software. Processed data were gridded to a 30 m bin size in order to create a Digital Elevation Model (DEM) (Figure 1).

The positioning and navigation system used was based on two navigators GPS Trimble 4000DL differential GPS with continuous differential corrections provided by the Omnistar and Skyfix systems.

The surveys to update the cartography of the area took place in 2010 with the Hydrographic vessel Malaspina, equipped with a multibeam system Kongsberg EM302. The overlap between lines was again 30%. EM302 operates at a nominal frequency of 30 kHz, covering approximately four times the water depth, and was used for depths between 80 and 200 meters to overlap with the Hespérides survey. The processing was performed using HIPS from CARIS, with a bin size of 1 meter. The attitude and navigation system used was Seapath 200, and the differential corrections (RTCM) were received from the Omnistar system through a Trimble AgGPS 132.

2.1.2 **Eruptive phase surveys**

After 13 days of the underwater eruption, the R/V Ramón Margalef began a series of oceanographic cruises called BIMBACHE1011 (Table 1) six of which were planned to achieve bathymetric and geomorphologic objectives (IEO Survey team et al., 2011). BIMBACHE1011-Leg01 was the first acoustic survey cruise carried out on the submarine volcano.

The brand-new R/V Ramón Margalef has a multibeam echo sounder Kongsberg EM-710 (0.5° × 1°) and a scientific multi frequency echo sounder EK60 (18, 38, 70, 120, 200 and 333 kHz) that were used in the geophysical cruises.

The EM 710 operates at sonar frequencies in the 70–100 kHz range. The transmit fan is divided into three sectors to maximize range capability, but also to suppress interference from multiples of strong bottom echoes. A high-density beam operating mode provides up to 400 soundings per ping; 200 beams to starboard and 200 to the port side (Kongsberg, 2011).

Other auxiliary equipment included: an attitude and position signal integration system SEAPATH 200, a Motion Reference Unit, a sound velocity gauge for measuring sound speed
at the transducer depth in real time while surveying, and a sound velocity profiler SV-Plus (Applied Microsystems), used to measure the full water column and correct refraction of sound when needed.

Because of the poor condition of the water column due to the volcanic activity, the survey procedure had to be modified in order to achieve maps with the resolution and data quality needed to identify hazards and assess the risks.

Temperature, pH, dissolved ions and other physico-chemical parameters influence the way sound travels across the water column and these were very different from ordinary values (Figure 3). Anomalies in the sound velocity profile produce ray bending in the acoustic signal beams due to refraction. These artifacts in bathymetry data hinder correct interpretation of geomorphology and undergoing geologic processes. To minimize this kind of artifact it was required to analyze the sound velocity profiles more often than usual in order to counteract the strong gradients aggravated by the quick changes due to turbulence.

Another major problem was the presence of gas bubbles and suspended solids (pyroclasts and cinder) that blocked the signal on its way through the water column. Density differences between sea water and gas, and sea water and rock, drastically alters the acoustic impedance which has the effect of increasing signal reflectance significantly impairing the performance of the echo sounder and even masking wide seabed areas. Although gas bubbles and large pyroclasts had the most unfavorable influence, that influence was locally restricted to the emission spots because its ascent was vertical or sub vertical; straight up to ocean surface. Furthermore rock fragments sunk straight to the bottom as soon as they cooled and degassing in about one minute (Figure 2c).

Ash and minor grain size pyroclasts also reflect and absorb acoustic energy but hopefully not as much as required to completely mask the seabed. Nevertheless, those particles were arranged in layers at certain depths covering wide areas where echo sounder coverage and range were reduced. Through the use of the EK60 and EM710 Water Column module it was possible to detect these layers in the echogram at certain frequencies (Figure 4). We can then infer that the
volcano reach, in terms of volume increase, should extend farther than the area plotted on the present map although this impact due to sediment deposition is not detectable using acoustic techniques. Only video imagery and sediment sampling could detect such low sedimentation rates.

In order to alleviate the important problem of water column conditions, the number of planned survey lines was increased by more than two times the standard density in an ordinary survey. So in good weather and the proper conditions the overlap between lines is about 30% (15% per side) while during the eruption monitoring the overlap between passes was 60%. Even with such density, emission spots remained uncovered because of the presence of gas, large rocks of variable-buoyancy and suspended sediment masking the seabed (Figure 4). To prevent this masking effect, emission spots were insonified by the outside beams of the swath avoiding the vertical ascension of gas, sediment and blocks (Figure 3), and in addition, passes were spaced out in time. As the eruptive pattern fluctuated between high and low activity over time, this procedure decreased the probability of coincidence between a lava pulse emission and a survey pass. Depending on the intensity of volcanic activity at each survey, overlap between lines was adjusted in those specific areas. Up to 300% overlap was needed in some surveys. The last survey conducted in BIMBACHE1011-Leg12 (February 2012) showed morphology of the new volcano consisting of a conic edifice of more than 200 m height. Because the type of eruption was a fissural one, the summit presents a longitudinal axis crest oriented 336° instead of a single crater.

Repeated BIMBACHE1011 cruises have allowed, by comparison with successive surveys, the average volume and the partial and total rate of material emitted (Rivera et al., 2013)

2.1.3 Quiescent period surveys

On 5 March 2012 IGN officially declared the end of the eruptive phase of the underwater volcano of El Hierro, with earthquakes decreasing in number and intensity.

From 6 to 8 December 2012, R/V Ángeles Alvariño, the sister ship of R/V Ramón Margalef, undertook a new oceanographic survey of the new submarine volcano area.

The cruise, named HIERRO-AA-1212, counted among its scientific team hydrographers from the IHM in order to establish the current bathymetric status of the new volcano without the noise and physico-chemical problems found in surveys conducted in the eruptive phase. As eruptive processes had finished (degassing was significantly present during the February cruise) the survey tasks were much easier. Vessel speed was increased up to 7 kn instead of 4–6 kn sailed in the eruptive phase, thanks to better conditions. However, line overlapping remained as high as 100% in the survey area in order to keep a high sounding density that allowed us to obtain a better final surface despite increased processing time. Thanks to this redundancy in data gathering, it was possible to achieve an average sounding density of 62.51 soundings inside a 12 × 12 m tile, with a sounding density standard deviation (STD) of 49.51. Such a high STD is due to the depth range of the surveyed area (from 13.9–2002 m) which implies a very high sounding density in shallow water but as low as just a few soundings per 12 × 12 m tile in the deep zone. To avoid interpolation in deep areas when creating the DEM, a 12 by 12 m cell size was chosen. This gives a DEM resolution suitable for use with a 1:25,000 scale map.

3. Conclusions

In this paper, we present the final bathymetric state of the new submarine volcano located south of El Hierro Island (Canary archipelago) as a result of the 2011–2012 submarine eruption. In addition, we provide a detailed description of the procedures conducted in order to reduce the problems of surveying an area affected by a submarine volcanic eruption through the use of multi-beam echo sounders, which is uncommon but essential in case a civil emergency like this occurs.
Repeated follow-up cruises for monitoring the morphological evolution of the new volcano in its eruptive phase has allowed us to understand, in real time, the mechanism and processes that occur in shallow submarine eruptions, as well as to provide civil protection authorities a useful tool for the mitigation of geological hazards and management of a volcano crisis. It is worth noting the importance that cartography had in this particular case, as the DEM presented in this map had been the only way to infer the reach of a risk hidden by the ocean.

**Software**

The multibeam bathymetric data for our study area was acquired from SIS-Seaﬂoor Information System (Kongsberg Maritime) and processed and gridded using the hydrographic software Hips&Ships v7.2.1 (CARIS). ASCII grids were rendered in Fledermaus v7.0 (QPS) for interpretation and virtual fly through movie creation. ArcGIS v10.0 (Esri) has been used for analysis and map editing.

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