Earth-Science Reviews 150 (2015) 168–200

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

The 2011–2012 submarine eruption off El Hierro, Canary Islands: New lessons in oceanic island growth and volcanic crisis management

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ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form 9 June 2015
Accepted 25 June 2015
Available online 2 July 2015

Keywords:
El Hierro
Submarine eruption
Ocean islands
Magmatic underplating
Island growth and evolution
Volcanic crisis management

ABSTRACT

Forty years after the eruption of the Teneguía volcano on La Palma, 1971, the last volcanic event in the Canary Islands, a submarine eruption took place in 2011 off-shore El Hierro, the smallest and youngest island of the archipelago. In this paper, we review the periods of seismic unrest leading up to the 2011–2012 El Hierro eruption, the timeline of eruptive events, the erupted products, the wider societal impacts, and the insights garnered for our understanding of ocean island growth mechanisms and hazard management. Seismic precursors allowed early detection of magmatic activity and prediction of the approximate location of the eruption. White coloured "floating stones" ("xeno-pumice") were described within the first few days of the events, the origin of which were hotly debated because of their potential implications for the character of the eruption. Due to epistemic uncertainty derived from delayed flow of scientific information and equivocal interpretations of the "floating stones", the El Hierro 2011–2012 events were characterised by cautious civil protection measures, which greatly impacted on the residents' lives and on the island's economy. We therefore summarise the scientific lessons learned from this most recent Canary Island eruption and discuss how emergency managers might cope with similar situations of uncertainty during future eruptive events in the region.

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http://dx.doi.org/10.1016/j.earscirev.2015.06.007
0012-8252/

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1. Introduction

A dramatic account entitled “How not to handle a volcanic eruption”, was published on Oct. 31, 2011 in El País, the most influential newspaper in Spain. It stated (translated from spanish): “*Since July 19, residents of the Canary island of El Hierro have been preparing for a possible eruption of a volcano a few kilometres out at sea. Scientists headed to the area, the regional government of the Canary Islands put in place preparations for a possible sea and air evacuation, and the Spanish military moved in. Measures taken to protect El Hierro's population (11,000), however, have been criticised by the residents as more disruptive than the volcano itself. Many residents are now wondering if the authorities had any real idea of what was going on with the volcano, and whether there was any real danger to human life in the first place*”. This commentary was followed by another article in “El País” on Jan. 19, 2012, entitled: “El Hierro: 100 days of volcanic eruption and the economic ruin of the island”, in which the economical and societal consequences of the eruption management were yet more critically summarised. In this review, we outline the geological history of the island, the recorded eruptive phenomena, and the timeline of the geological and societal aspects related to the 2011–2012 eruptive events, with the overall aim of placing the lessons learned into a wider volcanological and hazard management context.

1.1. Geology of El Hierro

The Canary archipelago comprises an East–West aligned chain of seven islands of which El Hierro is the westernmost and youngest. The ages of the oldest subaerial rocks on each island indicate that the chain youngs westward from ca. 22 Ma in Fuerteventura to ca. 1.2 Ma in El Hierro (Carracedo et al., 1998), which is widely thought to be the result of an underlying mantle plume (e.g. Carracedo et al., 2001; Geldmacher et al., 2005). The Canary island chain is predated by a group of seamounts trending NW from the archipelago, the oldest of which is dated at ~68 Ma (Lars Seamount; Geldmacher et al., 2005). The archipelago and the seamounts together form the Canary Volcanic Province (CVP). An older episode of magmatism is preserved in the south of the CVP (Klügel et al., 2011; van den Bogaard, 2013), as exemplified by the Cretaceous Henry seamount and similar seamount complexes located further to the south-west (van den Bogaard, 2013). These older edifices appear to be aligned to magnetic anomaly M25 and lack an internal age-progression, which suggests that they are not related to the volcanism that produced the Canary Islands (Zaczek et al., 2015).

The shape and structure of El Hierro is controlled by a three armed rift system. Ridges extend from the centre of the island in a characteristic “Mercedes star” geometry (Carracedo, 1994; Walter and Troll, 2003; Carracedo and Troll, 2013) (Fig. 1), a pattern that is not uncommon in the Canary Islands. With reference to similar rift geometries at, e.g., Mt. Erebus in Antarctica or Mauna Kea volcano on the island of Hawaii, this three-armed rift arrangement was a key argument for Teide National Park on Tenerife being selected as a UNESCO world heritage site (Carracedo and Troll, 2013). The triple-armed configuration of El Hierro is enhanced by the scars of several massive gravitational landslides that truncate the flanks of the island, but is of a similar type to that of Tenerife (e.g. Guillou et al., 1996; Day et al., 1997; Carracedo et al., 2001, 2011a,b; Manconi et al., 2009). The collapse of the north flank, which left behind the spectacular El Golfo embayment with a 1400 m-high and almost vertical escarpment, is thought to be the youngest giant landslide in the Canary archipelago, although its exact age is still debated, with estimates ranging from between 130 ka and ~39 ka, and even up to as recent as 13 ka (Watts and Masson, 1995; Guillou et al., 1996; Carracedo et al., 2001; Longpré et al., 2011).

Gravity inversion modelling on El Hierro by Montesinos et al. (2006) provided information on the mass distribution within the island, and correlated several volcanic structures with the distribution of the gravity field sources. The characteristic triple-arm rift system is associated with low-density extensional areas, while a high-density and likely large intrusive body lies at the centre of the island at a depth of between 6 and 10 km (Montesinos et al., 2006).

Palaeomagnetic (geomagnetic reversals) and geological mapping in combination with radiometric dating allowed a broad reconstruction of the volcanic history of the island (Guillou et al., 1996; Carracedo et al., 2001; Manconi et al., 2009) and three main volcano-stratigraphic units were defined. These are i) the basaltic shield volcanoes, ii) the differentiated lavas (volumetrically subordinate trachybasalt to trachyte flows and block-and-ash deposits at the terminal stages of the El Golfo volcano at about 176 ka), and iii) the recent basaltic, picritic and ankaramitic rift volcanism. These main episodes of growth are separated by gravitational collapse events (Carracedo et al., 2001), which provide useful stratigraphic boundaries in the field (Fig. 1).

In addition to being prominent topographic features above sea level, and hosting the majority of geologically recent volcanic eruptions, the volcanic rift zones of El Hierro continue below sea level as extensive ridges (Fig. 2). The south rift zone, for example, extends as a submarine ridge for more than 40 km and hosts a high density plutonic body of likely mafic character. This dense body has been postulated to represent remnants of an older seamount (Gee et al., 2001; Montesinos et al., 2006) and dredged volcanic rocks from this area have indeed recently been dated to a Cretaceous age (133 Ma; van den Bogaard, 2013). A differentiation has therefore been made between the submarine continuation of the El Hierro south rift zone and the much older pre-island edifice in that region (Fig. 2; e.g. Gee et al., 2001; Zaczek et al., 2015).

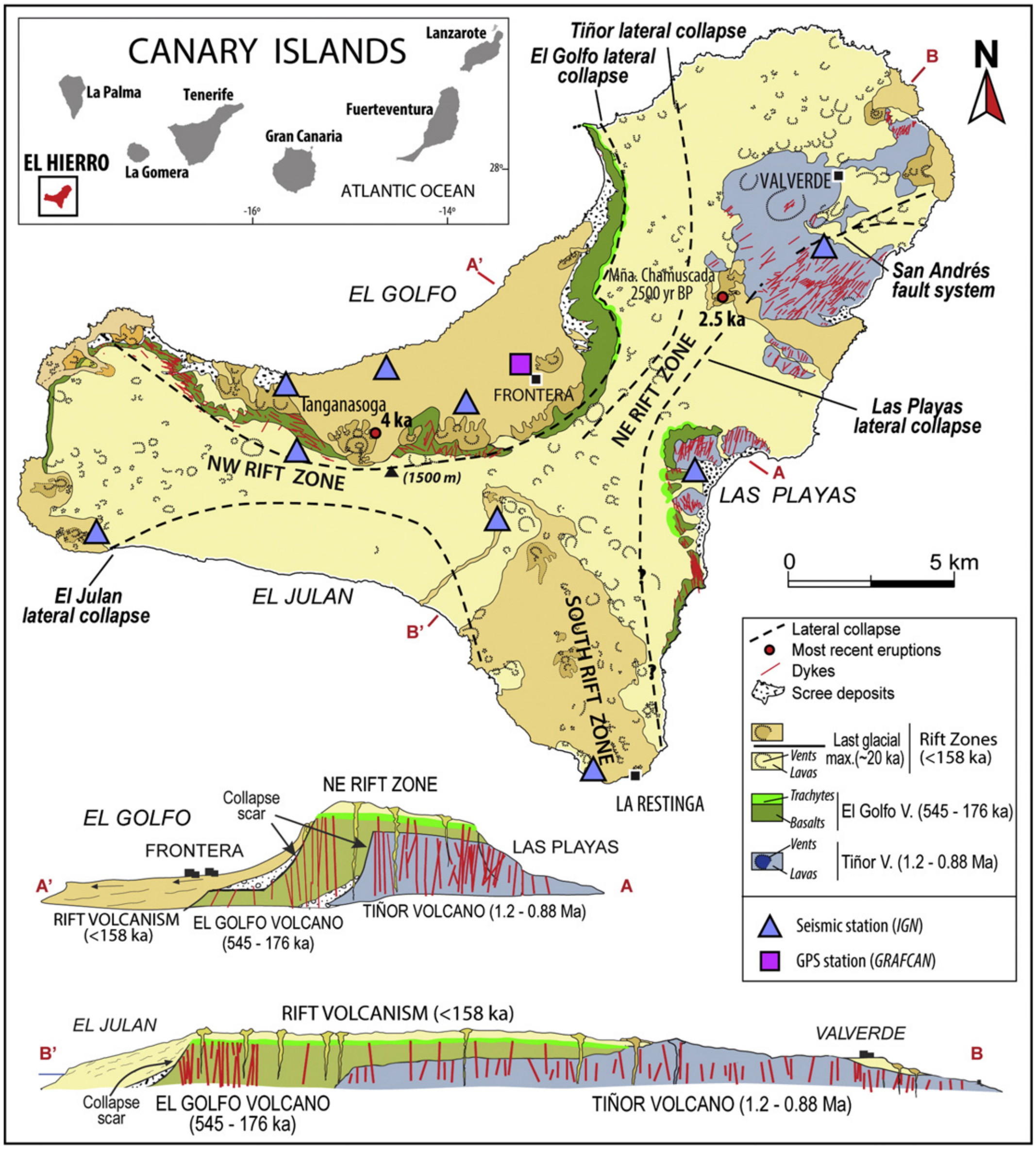

Fig. 1. Map of the Canary archipelago, and a geological map and cross-sections of El Hierro (modified after Day et al., 1997; Carracedo et al., 2001; Gee et al., 2001; Manconi et al., 2009). Note the triple-arm geometry of the island and the landslide embayments in-between the rift arms. Recent volcanism emanates from the rifts and is concentrated in the El Golfo embayment. The village of La Restinga is located at the southernmost tip of the island. The location of operational GPS and seismic stations are highlighted. For more details on the geology and stratigraphy of El Hierro, see Guillou et al. (1996) and Carracedo et al. (2001).

1.2. The 2011–2012 eruption

After several months of seismic unrest that started in July 2011, which was associated with vertical and lateral magma movement, the submarine eruption off the southern coast of El Hierro commenced on Oct. 10th, 2011 (for a detailed timeline, see Section 4.1). The eruption involved several months of submarine volcanic activity lasting until Mar. 2012 (e.g. Carracedo et al., 2012). Subsequent episodes of seismic unrest in June–July and Sept. 2012 ended without eruptions. The 2011 eruption and its scientific and societal impacts brought about the opportunity to investigate several issues related to volcanic crises, such as socio-economic impacts and hazard management, but also allowed for new lessons to be learned regarding the geological development of the Canaries. These geological lessons include improved understanding of i) intrusive growth of the islands, ii) the construction of rift zones, iii) the timing and duration of submarine seamount construction, and iv) the crustal structure underneath the island edifices. Our insight into the latter point has profited from the remarkable occurrence of floating, highly vesiculated xenoliths (termed "xeno-pumice") and basaltic lava balloons, the likes of which have only rarely been observed during previous submarine eruptions (Gaspar et al., 2003; Kueppers et al., 2012; Troll et al., 2012; Schmincke and Sumita, 2013).

El Hierro, the youngest Canary Island, is thought to be located directly above the thermal anomaly (hotspot) that controls the growth of the archipelago (Carracedo et al., 1998; Geldmacher et al., 2005). The 2011 eruption occurred on the southern rift of El Hierro, demonstrating that submarine volume addition may add considerably towards ocean island growth, by strengthening the structural backbone of the island (Walker, 1992; Carracedo, 1994; Urgeles et al., 1998; Carracedo et al., 2001). Importantly, the 2011 El Hierro eruption represents the first time a submarine eruption has been observed and monitored in the Canaries right from its early precursors to eventual termination. In addition to the new geological lessons learned, the 2011–2012 eruption represents a valuable opportunity to assess the present capabilities to monitor, predict, and manage the consequences of volcanic eruptions in the Canaries, and their respective epistemic uncertainties (see Section 6.5.2).

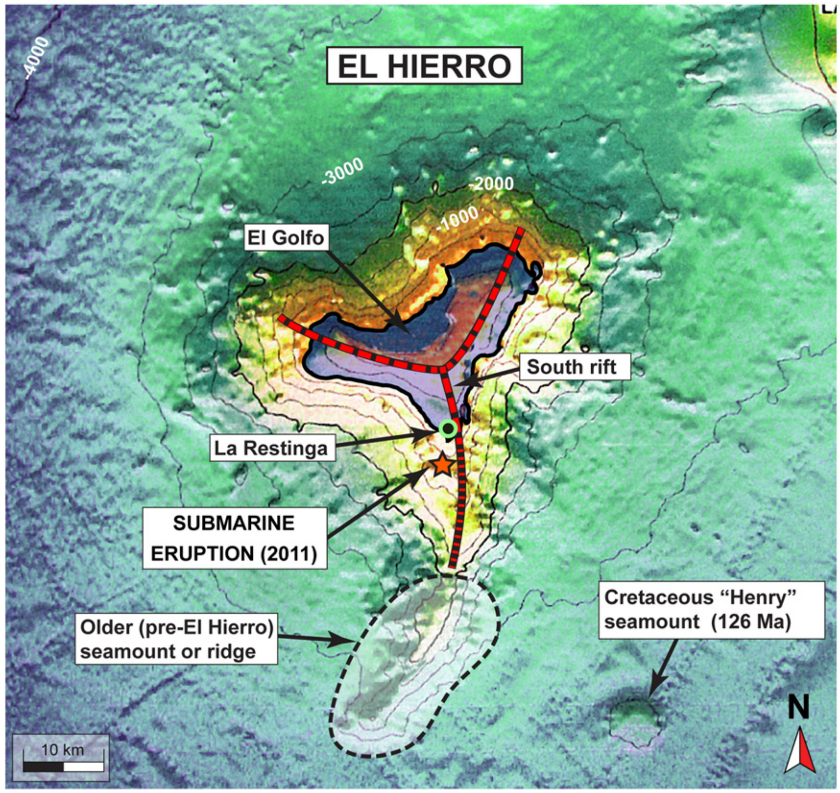

Fig. 2. Colour shaded relief image of El Hierro (modified after Masson et al., 2002). The subaerial and submarine parts of the south rift, and the location of the 2011–2012 submarine eruption are indicated. The apparent "extension" of the south rift was identified as an older (pre-El Hierro) structure (cf. Masson et al., 2002; van den Bogaard, 2013).

2. Historic to recent seismic and eruptive activity in the Canary Islands

Submarine eruptive activity and seismic unrest were first reported in detail during the 1730–1736 fissure eruption on Lanzarote (Carracedo et al., 1992). Recent activity of submarine volcanoes in the Canaries are known from swath bathymetry surveys, for example between Tenerife and Gran Canaria at the Hijo de Tenerife submarine edifice (Krastel and Schmincke, 2002), or the Las Hijas seamounts ~100 km SW of El Hierro (Rihm et al., 1998). The existing evidence from historical events on Lanzarote, Tenerife and La Palma (Table 1) also points to frequent multi-vent eruptions (Day et al., 2000; Carracedo et al., 2001), which would allow magma to bypass solid obstacles and exploit existing structural weaknesses.

El Hierro is presently in an early phase of shield-building, but recent Holocene subaerial eruptive activity on the island is scant when compared with the neighbouring islands of La Palma, Tenerife, and Gran Canaria (Guillou et al., 1996; Carracedo et al., 2001; Rodriguez-Gonzalez et al., 2009; Pérez-Torrado et al., 2011), or other well-studied ocean islands such as Hawaii or Réunion. While six eruptions took place on La Palma in historical times (i.e. after 1492), subaerial activity on El Hierro has probably been limited to one eruption in the last 2.5 ka (Guillou et al., 1996) (Fig. 1). Although it has been proposed that the centre of the Canary Island hotspot presently lies beneath El Hierro (Carracedo et al., 2001), the relative scarcity of recent eruptions on El Hierro as compared to La Palma has also been used to discuss a division of the Canary Island chain into two island trends (Carracedo et al., 1998), comparable to the dual lines of Kea and Loa in the Hawaiian islands (Hieronymus and Bercovici, 1999) or the dual trend observed in the Cape Verde archipelago (e.g. Barker et al., 2012). Indeed, a possible alternation of growth pulses of either island and relative eruptive quiescence on the other has been considered, which would mean that the two islands might be coupled volcano-tectonically, possibly in an "on–off" sequence (Carracedo, 1999). The occurrence of the 2011 El Hierro event as a submarine eruption, now suggests a further possibility, i.e. instead of long eruptive gaps at El Hierro, intense and frequent eruptive activity in recent and even historical times may have taken place below sea-level, and may thus have remained largely undetected by human observation. Submarine vents located deeper than a few hundred metres would likely have remained unnoticed, especially in the absence of recently developed technological surveying methods. The possibility also exists that local observations in historical times may not have been recorded, or were widely known but subsequently forgotten.

An upshot of limited subaerial activity on El Hierro is that only little local volcanological experience and expertise has accumulated (which indeed applies to the Canaries in general). Given the relatively small population and the fact that an entire generation passed between each of the most recent historic events on La Palma and El Hierro (e.g. 1949–1971–2011), the transfer of first-hand local knowledge beyond an individual human lifetime becomes a difficult task (Derex et al., 2013; Richerson, 2013). Systematic instrumental recording of seismic activity on El Hierro commenced only as recently as 1989 (www.ign.es; Carreño et al., 2003), highlighting a very likely information gap on similar phenomena on the islands in historical and pre-historical times. Indeed, indirect evidence for abundant submarine activity prior to the 2011 event was revealed, for example, by the 1998 German research cruise METEOR 43/1, wherein fresh lava samples were dredged from the submarine prolongations of the southern rifts of La Palma and El Hierro (e.g. Schmincke and Graf, 2000). El Hierro samples taken close to the 2011–2012 eruptive site (<3 km distance) include fresh picrites and alkali-basalts and variably altered lapilli stones and hyaloclastites. Further dredging along the submarine northwest and northeast rift zones during the RV Poseidon cruise 270 in 2001 recovered fresh alkali basalts from 21 young volcanic cones around El Hierro at depths of between 800 and 2300 m (e.g. Stroncik et al., 2009). Notably, ocean bottom sediments with a pronounced volcaniclastic component (Troll et al., 2012) and fragments of ancient volcanic rocks (van den Bogaard, 2013) were also recovered

Table 1
Historical eruptions in the Canary Islands.

Ad	Duration		Volume (km^3)	Area (km^2)	Island	Eruption name	Eruption precursors
	(Years between eruptions)	(Days)					(with data from Romero Ruiz, 1991)
1492					Tenerife	Boca Cangrejo (Columbus report and C-14)	–
1585	93	84	0.016	3.7	La Palma	Tajuya–Jedey	Abundant and strong seismicity several months before the eruption
1646	61	78	0.029	7	La Palma	Martín	Seismic activity and underground noise days before the eruption
1676–1677	30	6	0.025	4.5	La Palma	Fuencaliente	Seismic activity and deep underground roar 4 days before the eruption
1704–1705	27	13	0.027	6.7	Tenerife	Siete Fuentes–Fasnia–Arafo	Strong seismic activity a week before the eruption and underground noises
1706	1	9	0.066	6.5	Tenerife	Montaña Garachico	Strong seismic activity a year before the eruption and underground noises
1712	6	56	0.02	10.2	La Palma	El Charco	Seismic activity and deep underground roar 5 days before the eruption
1730–1736	18	2000	1	150	Lanzarote	Timanfaya (Montañas del Fuego)	Strong earthquakes just before the eruption onset
1793	57	1	0.02	0.5	El Hierro	Uncorrelated submarine volcano in El Golfo	Seismic activity and deep underground roar from March 27 to the end of June, 1793. No eruption on the island (submarine?)
1798	5	92	0.012	4.7	Tenerife	Chahorra	Seismic activity 3 years before the eruption
1824	26	90			Lanzarote	Volcán Nuevo–Tinguatón–Tao	Seismic activity 11 years before the eruption
1909	85	10	0.011	1.5	Tenerife	Chinyero	Seismic activity more than 1 year before the eruption
1914–1917	5				Fuerteventura	Pájara	Seismic activity, underground noise and fumaroles (aborted eruption?)
1949	32	38	0.021	4.8	La Palma	San Juan	Seismic activity, underground noise and ground fractures since 1936
1971	22	25	0.04	3.1	La Palma	Teneguía	Seismic activity and underground noise 9 days before the eruption
2011	40	>90	0.329	~5	El Hierro	Submarine vent off La Restinga	Seismic activity 83 days before the eruption

from the southern El Hierro ridge during that cruise, implying that young volcanism is superimposed on an older and at least in part volcanogenic basement. Moreover, the spatial density of young volcanoes on El Hierro's submarine rifts is broadly consistent with the record on land, emphasising the significant role of submarine eruptions in the growth of oceanic islands and the fact that new eruptive vents likely follow one of the main triple-armed axes displayed by the island (Day et al., 2000; Walter et al., 2005).

2.1. A possible eruption off El Hierro in 1793

References to a possible submarine eruption off El Hierro in 1793 appear in the works of Bory de St. Vincent (1804), von Humboldt (1815), and Darias Padrón (1929), the latter of which includes detailed eyewitness accounts that describe an apparent seismic crisis on the island of El Hierro in that year. From Mar. 27 to June 15, 1793, strong earthquakes were reported to have shaken the island. Damaged buildings raised public alarm, and prompted the authorities to prepare the first known Canary Island evacuation plan in 1793 (Bethéncourt-Massieu, 1982).

The 1793 seismicity was initially restricted to the El Golfo area, but was later felt throughout the island. Nevertheless, seismicity eventually declined in intensity and frequency and finally ceased, without any documented manifestations of subaerial volcanic activity anywhere on the island. Indeed, available reports point out that an evacuation would have been carried out "*had volcanism ruined the island*", which thus makes it improbable that a potential subaerial eruption went unnoticed. The reports therefore imply that this particular episode of unrest either ended without an eruption, or that the eruption was submarine, but unfortunately, no eyewitness reports on any surface manifestation of a submarine eruption off El Hierro are available from 1793. In contrast, Hernández Pacheco (1982) considered the 1793 seismicity to relate to the subaerial basaltic eruption of Lomo Negro, in NW El Hierro, based on a ^{14}C age for this eruption of 1800 ± 50 AD. However, the dated sample consisted of unburnt plant material found under the lava flow and, as conceded by the author, is not ideal for ^{14}C dating, thus rendering the obtained age highly unreliable.

2.2. Witnessed Canary eruptions prior to the 2011–2012 events

In total, sixteen historical volcanic eruptions are known from the Canaries (Table 1), but thankfully human fatalities are rare, with one death reported in 1677 and two deaths in 1971 (both on La Palma). Eruption management in the Canary Islands has had only one real test case, however, — the Teneguía eruption of La Palma in 1971. During the Teneguía event, conditions were likely more adverse than at El Hierro in 2011, because the eruptive vents opened onshore and very close to the village of Fuencaliente, which had 1700 inhabitants back then. Monitoring facilities and disaster prevention contingency plans were virtually absent at the time. The crisis was managed by a team of volcanologists from the Department of Petrology and Geochemistry at the Complutense University in Madrid as part of an open collaboration with other Spanish and international scientists. The Teneguía eruption ended without evacuation or major traffic restrictions and in fact created a measurable increase in tourism during and after the event itself, despite the two fatalities which were caused by asphyxiation. In contrast, the moderate seismicity associated with the submarine eruption at El Hierro was monitored by state of the art instrumental facilities, but key information, such as vent depth, was unavailable to the scientific board at times. In combination with concerns on potential large-scale explosive events, the authorities opted for the implementation of cautionary measures which were not universally popular on the island, and which are discussed further below. Indeed, the repeated evacuations on El Hierro were a serious source of distress to the population and had significant economic impact (see Sections 1 and 6.5).

2.3. Canary Island volcano monitoring

A Royal Decree on June 18th, 2004, just after the 2004 crisis on Tenerife, commissioned the *IGN* with the responsibility of monitoring volcanic activity and associated hazards in mainland Spain and the Canary

Islands. Management and civil protection decisions before and during the 2011 El Hierro eruption were the responsibility of the Civil Protection Department of the Canarian Government, which had set up a programme for eruptive hazard prevention in the year before the 2011 eruption (*Plan Especial de Protección Civil y Atención de Emergencias por riesgo volcánico en la Comunidad Autónoma de Canarias, PEVOLCA*, www.gobcan.es/boc/2010/140/006.html, Emergency Response Organisation to Volcanic Risk in the Canary Islands). The task of the scientific advisory committee was assigned to the *Comité Científico de Evaluación y Seguimiento de Fenómenos Volcánicos* (*CCES*), the same administrative body that had been in charge of the 2004 unrest on Tenerife. In other words, *PEVOLCA* represents the political executive committee of the Canarian government, while *CCES* is a scientific advisory board to *PEVOLCA*. The final decisions taken before and during the eruption were, therefore, effectively political (governmental) decisions (Fig. 3). The *Instituto Geográfico National* (*IGN*), in turn, also provides open geodetic data for the islands of Tenerife and La Palma (www.ign.es/ign/layoutIn/geodesiaEstacionesPermanentes.do).

2.4. Seismicity on El Hierro and the Canary Islands before the 2011–2012 eruption

Several periods of unrest recently occurred in the Canaries, but only those in 2011 on El Hierro ended in an actual volcanic eruption. The 2011 events thus provide insights into the causes for the previous episodes of unrest and, in part at least, for their failure to culminate in an eruptive event. Prior to seismic reawakening in 2011, activity on El Hierro was low, earthquakes tended to cluster in discrete swarms separated by long periods of quiescence, and only individual events reached magnitudes of $M_L > 3$ (Fig. 4). Remarkably, a seismic swarm recorded between 2003 and late 2005 contained an M_L 5.0 event, which notably exceeded the highest magnitude earthquake recorded during the 2011 submarine eruption (*IGN*; *Catálogo y Boletines Sísmicos*).

In addition to the 1793, 2003–2005, and the 2011–2012 episodes of seismic unrest on El Hierro, which continued in May 2015 (www.ign.es/ign/resources/volcanologia/HIERRO.html), a number of increased seismicity events without volcanic manifestations had also been felt and reported on some of the other Canary Islands (Darias Padrón, 1929). The first seismic station in the Canary Islands was deployed in 1964 on Tenerife, and it was only in 1975 that three more stations were installed on Tenerife, La Palma, and El Hierro. All estimates regarding seismic activity prior to these dates are therefore based entirely on eyewitness accounts and media reports. For example, strong seismicity (estimated to VII on the Mercalli scale) is reported from Fuerteventura between 1914 and 1917. The entire island and the southern part of Lanzarote were affected, houses were damaged and the population experienced widespread concern (Monge, 1980; Romero Ruiz, 1991). Indeed, two events in 1915 and 1917, with an intensity of VII MSK (Medvédev–Sponheuer–Kárník macroseismic intensity scale; Medvedev et al., 1964, which is similar to the Mercalli scale), are included in an inventory of seismicity in the Iberian Peninsula and the Canaries (Galvis, 1940). Similar seismic unrest occurred on La Palma between 1936 and 1939, ten years before the 1949 eruption, causing slumps, rock falls, and damage to houses (Martel San Gil, 1960; Romero Ruiz, 1991).

A more recent unrest event that drew scientific and international media attention was the brief increase in seismic activity on Tenerife in early 2004, the first episode of seismic unrest since the island's last volcanic eruption in 1909 (Chinyero). The first seismic station on the island was not deployed until 1964 (in Santa Cruz, the capital of the island on the NE coast of Tenerife; Monge, 1980), and the first station located in the centre of the island was installed only as recent as 1975 (Mezcua et al., 1990). Therefore, the origin of the 2004 earthquakes sparked substantial controversy within the scientific community. Some scientists claimed that precursory warning signals for volcanic activity were present, such as occasional emissions of "visible gas plumes" from the central peak of Teide volcano (3718 m) and the opening of fumaroles in the Orotava Valley (García et al., 2006; Martí et al., 2009). Other authors contested the presence of major volcanic manifestations, demonstrating that the gas plume from Teide and the fumaroles in the Orotava Valley had meteorological and anthropogenic origins, respectively (cf. Carracedo and Troll, 2006). In this case, a deep magmatic intrusion was alternatively suggested as the cause for the seismicity (e.g. Gottsmann et al., 2006; Almendros et al., 2007). Notably, ground deformation detected in the NW part of Tenerife in 2004 using InSAR and GPS networks was correlated with groundwater pumping (Fernández et al., 2005), meaning that the ground deformation may thus have been a partly non-magmatic affair. Nevertheless, similarities between the 2004 Tenerife unrest and the 2011 volcanic eruption at El Hierro indicate that deep magmatism was nevertheless the most plausible cause for the 2004 Tenerife events also.

A significant amount of cumulated seismic energy was released between Sept. 22nd, 2011 and the eventual initiation of the submarine eruption at El Hierro on Oct. 10th, 2011 (Fig. 5). While the El Hierro June to Sept. 2012 unrest and the Tenerife 2004 events may both have been related to a deep magma injection (cf. Carracedo and Troll, 2006; Gottsmann et al., 2008), the lower magnitude seismicity ($M_L < 2.6$) and the lack of comparably accelerated ground deformation on Tenerife in 2004 would imply a relatively deep and low volume magma batch that was arrested during ascent. This possibility appears reasonable when compared to the unrest that occurred in summer 2012 at El Hierro (Fig. 5D). At that time, five $M_L > 4.0$ earthquakes, a sharp increase in cumulated seismic energy, and significant ground deformation did not result in an eruption. In contrast, the 2011 El Hierro events saw magma migrate with sufficient pressure to utilise a weak spot in the southern rift where it eventually reached the surface, probably due to exploitation of the extensional regime that usually opposes large-scale landslides (the 'passive rift arm'; e.g. Walter and Troll, 2003; Walter et al., 2005). The repetitive periods of unrest and the 2011–2012 submarine

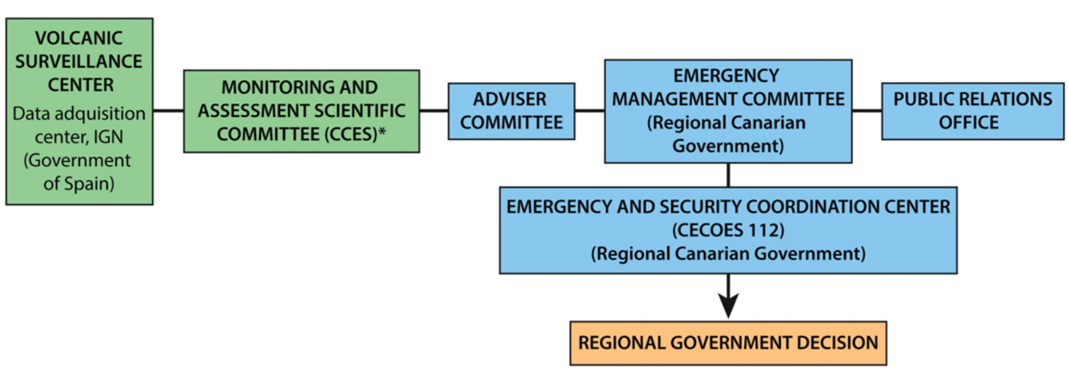

Fig. 3. *PEVOLCA* organisational chart. *PEVOLCA* consists of a technical and scientific committee (*CCES*) that reports to regional authorities (Canarian Government) and to decision makers. The scientific committee (*CCES*) was limited to scientists from mainland Spain during the initial stages of the crisis, but was eventually opened to input from a wider scientific arena, including local scientists of the Estación Vocanológica de Canarias (*CSIC*) and both Canarian Universities, Las Palmas (*ULPGC*) and La Laguna (*ULL*) on Nov. 14th, 2011.

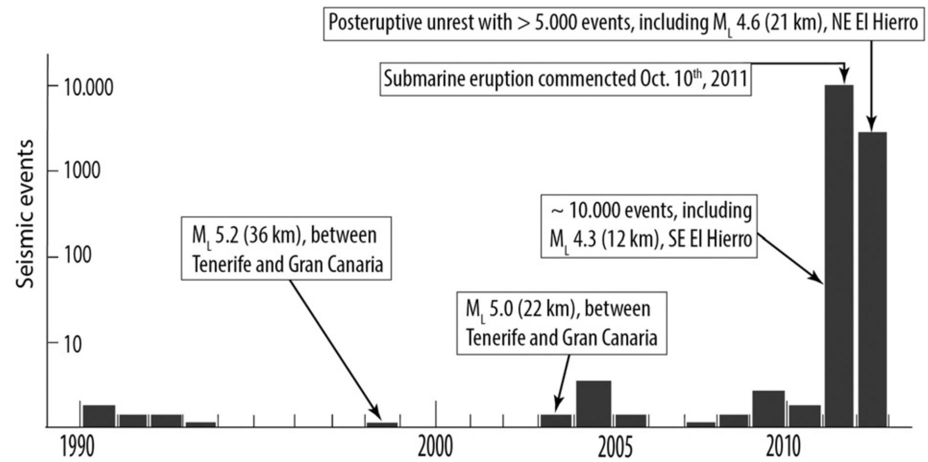

Fig. 4. Number of annually recorded earthquakes in the Canary Islands in the 20 years prior to the 2011–2012 El Hierro events. Note the sharp increase in recorded seismic activity in 2011 (data from *IGN*).

eruption at El Hierro, thus imply that seismic unrest *can* culminate in an eruption, but may not lead to surface volcanic manifestations if the volume of magma is insufficient. However, the 2004 seismic unrest on Tenerife comprised only 261 recorded low-intensity events, 14 of which were $M_L > 2.0$, with a maximum magnitude of M_L 2.6 (*IGN*; *Catálogo y Boletines Sísmicos*), and only some of them were felt in the NW of the island around the town of Icod de los Vinos (IGN, 2004 catalogue). Despite the relatively low seismic intensity, a volcanic eruption on

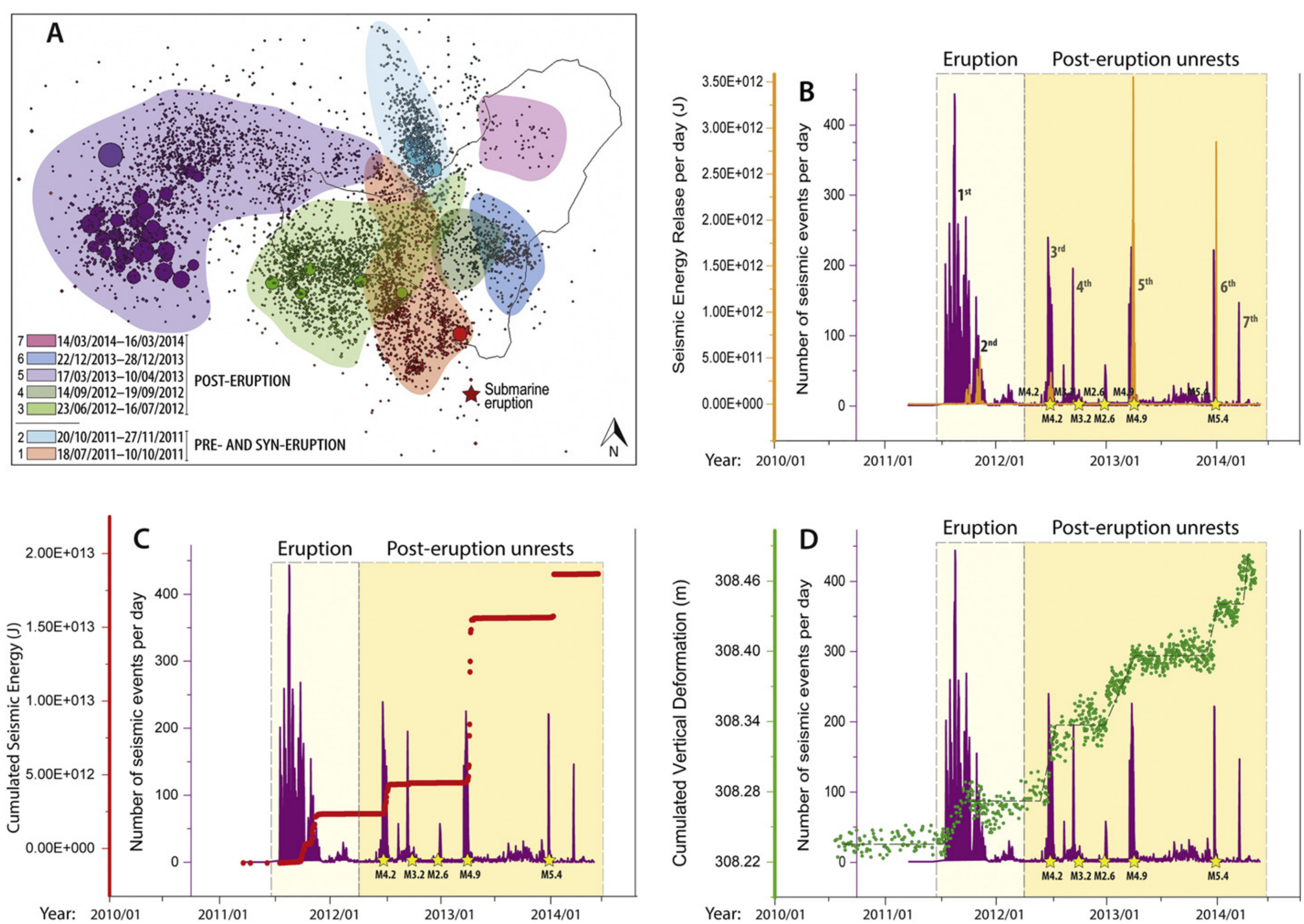

Fig. 5. Plot A. shows seismic clusters during the seismic unrest episodes and number of earthquakes. The sizes of the symbols correspond to earthquake intensities, B. seismic energy released per day, C. accumulated seismic energy, and D. accumulated deformation for the periods of unrest during and following the 2011 submarine eruption. Five successive periods of unrest are recorded. The occurrence of the maximum intensity seismic events is marked by yellow stars (data from *IGN*). Ground deformation (vertical) data from *GRAFCAN*. The M_L 5.4 earthquake of December 27, 2013 coincided in location, but not in the time of occurrence, with unrest no. 6. This M5.4 event was very similar to the highest earthquake previously recorded in the Canaries, which is the M_L 5.2 event on May 9, 1989, which had its epicentre between Tenerife and Gran Canaria.

Tenerife was forecast for Oct. 2004 from as early as the spring of that year (i.e. several months in advance; García et al., 2006). This ultimately false prediction raised both local and international alarm and adversely affected the tourism-based economy of Tenerife. However, since no eruption actually occurred, the situation resulted in a general loss of faith in scientific volcanology by many of the islanders (Carracedo and Troll, 2006).

On the other hand, analysis of seismic and ground deformation parameters in the successive periods of unrest at El Hierro in 2011 and 2012 show some interesting correlations to each other. Seismic event distribution shows that each episode of unrest formed essentially a discrete cluster, potentially corresponding to individual batches of magma exerting pressure at depth. Paradoxically, post-eruptive episodes of unrest at El Hierro released more seismic energy and caused greater ground deformation than the unrest preceding the 2011–2012 submarine eruption and the eruption itself. A plausible explanation may be that the eruption released cumulated energy as an “open system”, while during the post-eruptive unrest episodes injections of magma

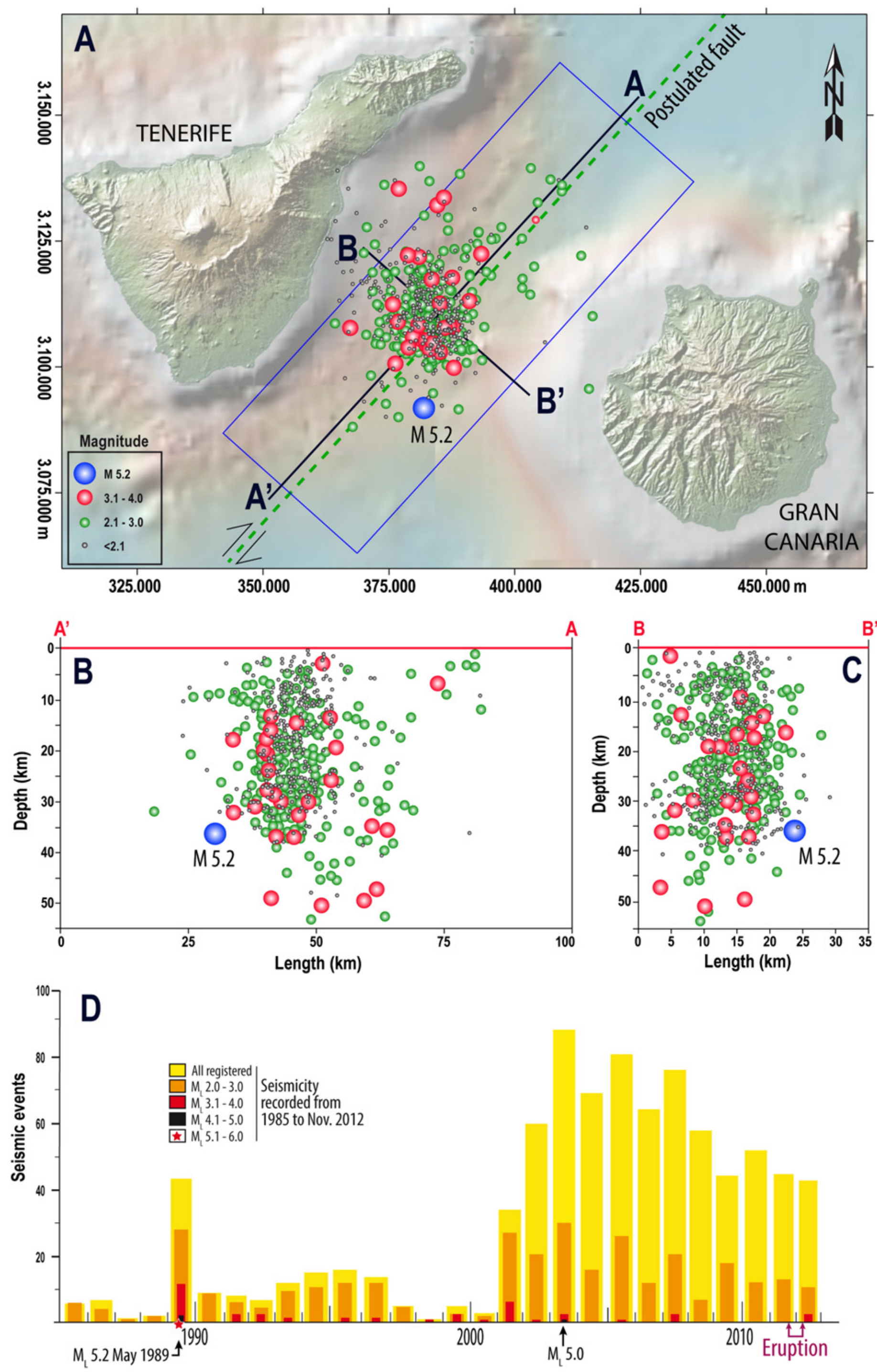

Fig. 6. A–C. Epicentral and hypocentral distribution of seismicity associated with a persistent seismogenic source located between Tenerife and Gran Canaria (1986 to 2013). Note the absence of any linear feature and the normal distribution of earthquake sources making it more likely related to a magmatic intrusion (data from the *IGN* seismic catalogue). D. Number of earthquakes per year recorded between Tenerife and Gran Canaria since 1986. Earthquakes occur in discrete temporal pulses, in a similar pattern as in the 2011–2012 eruption off El Hierro (data from the *IGN* seismic catalogue www.ign.es/ign/layoutIn/sismoFormularioCatalogo.do).

were unable to create a pathway to the surface, thus forming a seismically "closed" system. This explanation could account for the scattered distribution of seismicity during the different unrest episodes. Successive failed attempts by magma intrusions to open a conduit to the surface are thus suggested to be responsible for the persistent seismicity and its considerable seismic magnitudes displayed after the actual eruption.

Another example of recent to ongoing seismic activity is located between Tenerife and Gran Canaria, where a M_L 5.2 earthquake was recorded on May 9th, 1989 (Fig. 4), which was followed by frequent seismic unrest since that time. Initially, this area was thought to coincide with a possible regional fracture (Dash and Bosshard, 1969; Mezcua et al., 1992), however, the seismic sections of the area (along and perpendicular to the postulated fault plane) lack the offset geometry that would be expected from fault-related seismicity (Fig. 6). In contrast, the epicentres cluster in a Gaussian rather than a linear distribution (Fig. 6), which is indicative of a point-source, such as a volcanic conduit (cf. Krastel and Schmincke, 2002; Carracedo et al., 2011a,b). Indeed, these epicentres (Fig. 6) coincide with a small group of submarine vents, several of which are likely active, with the largest of them widely referred to as "Hijo de Tenerife" (Schmincke and Rihm, 1994; Schmincke and Graf, 2000). A regional fracture in the oceanic crust in this particular spot is unlikely, in turn, as some degree of seismicity occurs at a depth of 50 km below this site, indicating a deep and spatially focussed volcanic feeder system.

3. The onset of the 2011–2012 eruption

The opening of a submarine vent on Oct. 10th, 2011 was heralded by changes in seismic signals (see Section 2.4; Fig. 5), however, direct evidence for the exact location of the vent and hence for the potential of a submarine eruption was not available at the time. First estimates of the distance from the vent to the coast (and hence to the town of La Restinga) varied from kilometres to less than 100 m. The actual depth of the vent was also unknown, which is a crucial parameter with respect to the likelihood of Surtseyan explosions during a submarine eruption. Indeed, estimates of the vent depth ranged from 2 to 3 km to only a few metres below sea level, testifying to the great uncertainties regarding the nature of the eruption at that time.

The first visible manifestation of the eruption was a roughly circular, grey, bubbling area on the sea surface on Oct. 12th, 2011 (Fig. 7). This area of discoloured seawater was observed in high-resolution satellite images, and was locally known as "*la mancha*" ("the stain"), visible on the surface of the Mar de Las Calmas (Fig. 7A). This water discoloration was interpreted as a rising plume of dissolved magmatic gases and suspended matter in the water column. Rock material brought up by this underwater plume, together with abundant dead marine biota, was found floating ~1.5 to 2 km off the south coast of El Hierro. At times, strong bubbling and degassing reflected the NE–SW alignment of the underwater vents (Fig. 7B, C), which in combination with floating frothy pyroclasts on Oct. 15th, 2011, indicated that the eruption was initially fed by a fissure at depth. Although this initial eruptive fissure was visible in early satellite images (see Fig. 7), by the time the first bathymetry was conducted on Oct. 23rd, 2011, the eruptive vents grouped in a more spatially restricted area (Figs. 8 and 9; Table 2). A detailed timeline description of pre- and post-eruption events can be found on the official website of the Canarian Government (www.gobiernodecanarias.org/dgse/alertas/sismoElHierro/noticias_sismo_hierro.html).

4. Available data on the 2011–2012 submarine eruption

The 2011 El Hierro eruption is the first example of a volcanic event in the Canaries that was continually monitored from initial unrest to eventual termination (e.g. López et al., 2012; Pérez-Torrado et al., 2012; Gonzales et al., 2013; Longpré et al., 2014). Prior to the first visible plume of discoloured water ("the stain"), voluminous gas exhalations,

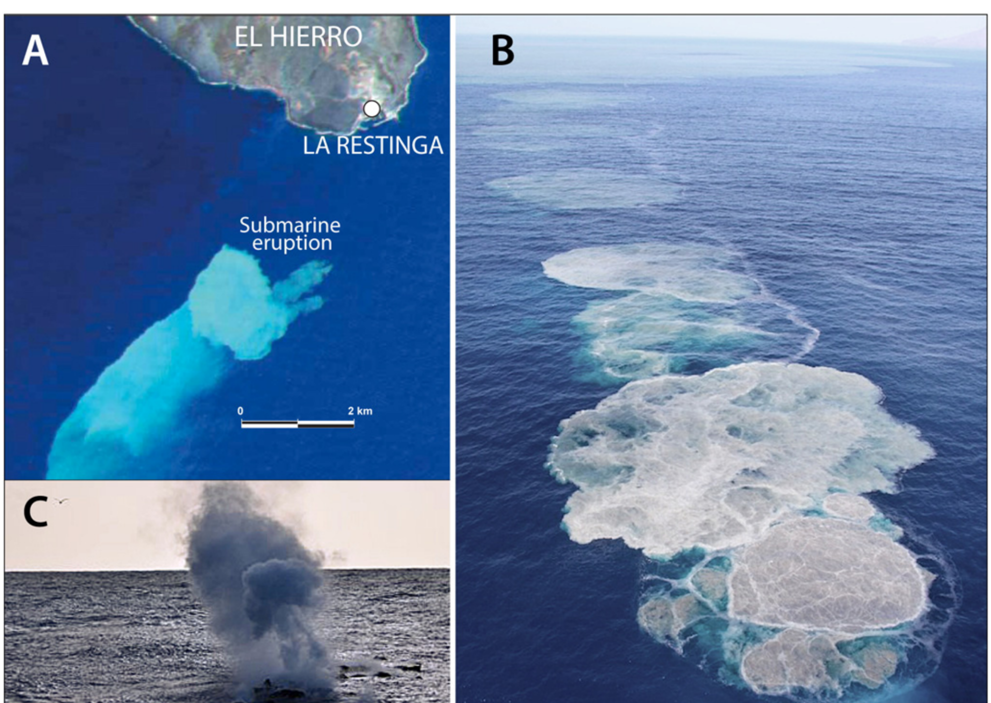

Fig. 7. A. Photographs of "La Mancha" ("the stain") caused by dissolved magmatic gases and suspended matter that produced bright green discolouration of the seawater, which commenced on Oct. 10, 2011 and extended initially for several kilometres to the south-west, eventually drifting off into the Atlantic (satellite image by RapidEye). B. Plumes of gas on ocean surface showed an initial N–S alignment, indicating a submarine eruptive fissure. C. Pulses of strong degassing brought up abundant rock fragments and generated large bursting 'bubbles' on the sea surface, some of them 10–15 m-high (Nov. 8, 2011).

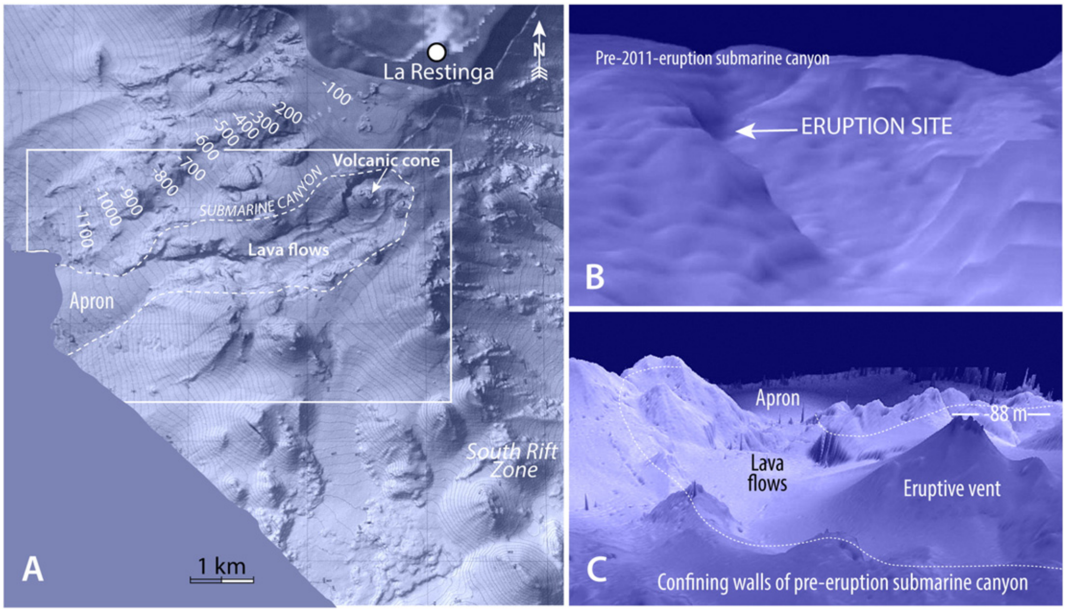

Fig. 8. Oblique views of the affected area during the 2011–2012 submarine eruption off El Hierro (images from *IEO*). A. A general view of the area of the eruption site. B. The pre-eruptive submarine canyon where the 2011 eruption nested. C. The submarine cone and lava flows. Images taken by the RV Hespérides, 1998; *IEO*.

or floating lava bombs, indication of an impending submarine eruption was provided by seismic and ground deformation data, recorded by *IGN* and *GRAFCAN*, respectively. Seven bathymetric surveys were also carried out by the *Instituto Español de Oceanografía* (*IEO*). Notably, *IGN* and *IEO* openly provided near-real-time online access to the collected data based on the initiative of the Canary government's official hazard management committee *PEVOLCA*. Here we focus on the seismic and ground deformation data published by *IGN* (e.g. López et al., 2012), and the swath bathymetric data published by *IEO* (e.g. Rivera et al., 2013).

4.1. Seismological observations from 2011 to 2012

Prior to the 2011 events, the stable seismic baseline at El Hierro was defined by ~2.6 events per year over the previous 5 years and by 3 events in the first half of 2011. In sharp contrast, from July 19th, 2011 onwards, hundreds of earthquakes were recorded per day around El Hierro (*IGN*; *Catálogo y Boletines Sísmicos*). The majority of these events were insignificant from a hazard point of view, but as they heralded the eventual volcanic eruption, they thus provided valuable preparation time for monitoring teams (Fig. 4).

Initially, deep and low-magnitude earthquakes ($M_L < 3.0$; depths of 10–15 km) north of the island suggested magma was being mobilised from below the Mohorovičić discontinuity (Moho), consistent with the then known magma storage depth from microscopic fluid inclusion work on mafic and ultramafic mantle xenoliths, and barometry on phenocrysts in recent rift lavas from El Hierro (Hansteen et al., 1998; Stroncik et al., 2009). The hypocentres then migrated southeast, increasing in depth (12–17 km) and intensity reflecting magma transit in a north–south direction (Figs. 10A and 11A; Domínguez Cerdeña et al., 2014). On Sept. 27, seismic events increased yet again in frequency and magnitude (up to M_L 3.8), but hypocentres became shallower (12–14 km). On Oct. 8, 2011, an M_L 4.3 earthquake, distinctly felt by residents, was recorded at ~12 km depth and 1.5 km offshore the town of La Restinga (Figs. 10A and 5). Following this strong earthquake, swarms of low magnitude shallow events ($M_L < 2.0$, 1–6 km depth) complemented the on-going deeper seismicity (15 km depth; Fig. 11A). Finally, on Oct. 10, a harmonic tremor was recorded by all seismic stations on the island (start at 05:15 GMT), with the highest amplitudes offshore La Restinga (López et al., 2012). This harmonic tremor marked the opening of a submarine vent, and hence the start of the submarine eruption. The harmonic tremor continued with amplitude variations until the end of the eruption on Mar. 5, 2012.

The number of volcanic earthquakes during the precursory stages to volcanic activity can provide useful constraints on the mechanisms and evolution of volcanic events (e.g. McNutt, 1996), as evident from the relationship between the daily number of volcanic earthquakes and accumulated seismic energy on El Hierro (Fig. 5C). The greater part of the recorded earthquakes occurred from June to mid-Sept., although the associated seismic strain release was small due to the low magnitude of the events. Remarkably, when the seismic energy release per day is plotted (Fig. 5B), the sharp increase in daily seismic strain release does indeed accurately pin-point the onset of the submarine eruption to Oct. 10 (Fig. 5). After Nov. 2011, a second episode of seismic activity below the northern coast led to a number of higher intensity events (M > 4) and associated energy release (Figs. 5B, 10B). The amount of energy released (total and per day) during the episodes of post-eruptive unrest (i.e. Oct. 2011, June 2012, Sept. 2012, Mar. 2013, Dec. 2013, and Mar. 2014; Table 3) compared with the seismic energy released in the period that directly preceded the eruption (i.e. early Oct. 2011), shows that energy release dropped after the eruptions, with the exception of Mar. 2013, when seismic energy release was 5 times higher than in Oct. 2011 (see Table 3 and Fig. 5B). However, the occurrence of earthquakes up to M_L 4.9 during this unrest did not bring about any response from the authorities, who by this time seem to have accepted that unrest does not automatically lead to eruption.

During the eruption, intermittent seismicity also continued elsewhere on the island, but mainly in the northern El Golfo embayment. There, a tight cluster of earthquakes (including $M_L > 4.0$ events), and the highest magnitude event of the eruption to that day occurred ($M_L > 4.6$, 21 km depth, Nov. 11th, 2011; see Figs. 10B, 11B), which caused the released cumulated energy to jump sharply from 3.3×10^{12} to 5×10^{12} J (Fig. 5C). Speculation that another vent may have opened to the north of El Hierro or later to the west of El Hierro was not confirmed as *IGN* data only indicated a single source for the harmonic tremor, i.e. the one at the southern rift of the island.

The available seismic data are therefore consistent with emplacement of magma starting from mid-July, 2011. Initial activity clustered below the El Golfo embayment at a depth of between 10 and 25 km,

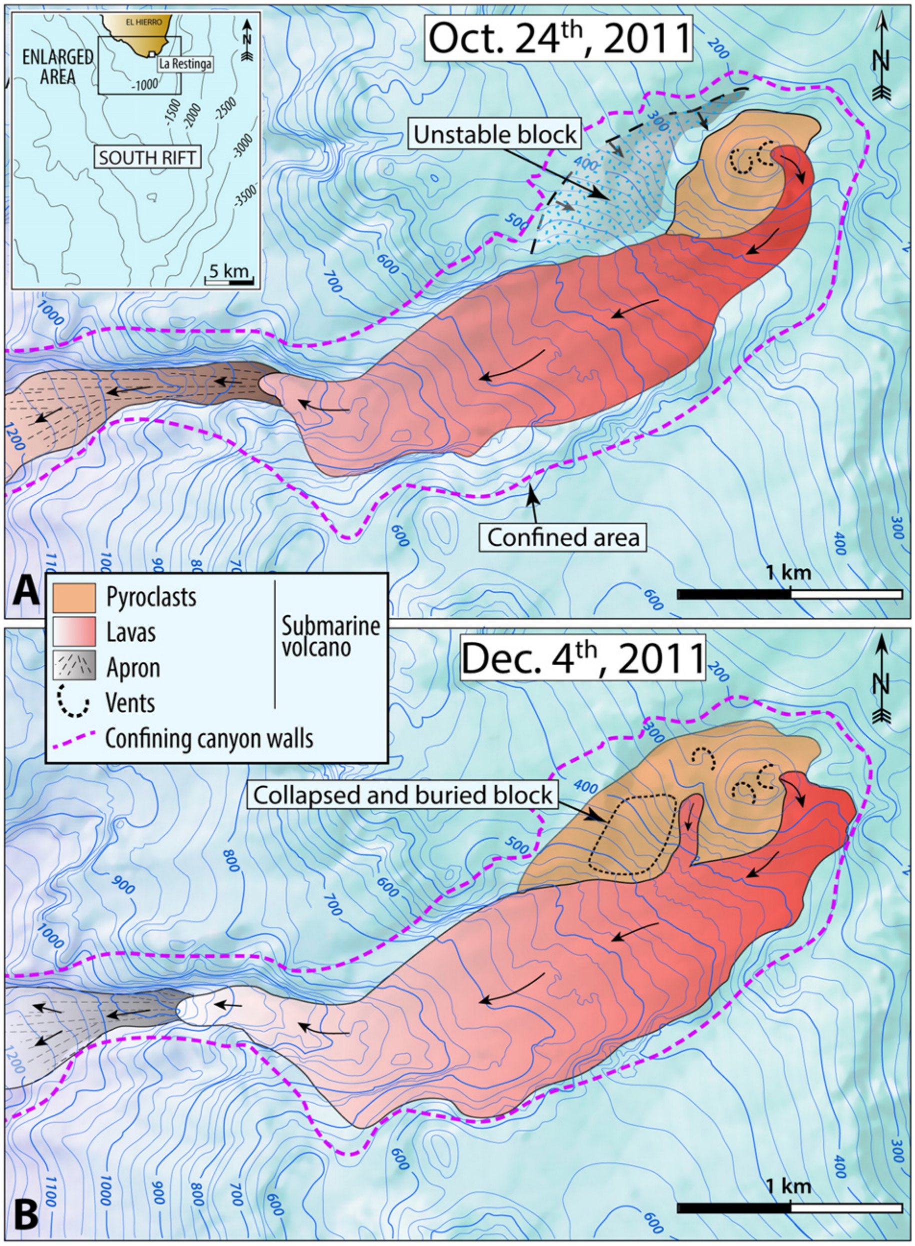

Fig. 9. A. Simplified geological map of the submarine eruption area from the first bathymetry obtained on Oct. 24, 2011 by the RV Ramon Margalef. B. Geological sketch map of the same area on Dec. 4, 2011.

but activity subsequently migrated from deeper to shallower levels and then towards the final eruption site on the southern rift of the island (Gonzales et al., 2013; see also Section 6.1).

Table 2
Dates of the bathymetric surveys and key observations (see also Figs. 8 and 9).

Dates of surveys	Observations
Oct. 23–25, 2011	Build up of 650 m wide volcanic cone within a canyon, summit 220 m below sea level
Oct. 28–31, 2011	Collapse of SW flank of the cone, summit ~260 m b.s.l.
Nov. 12–13, 2011	Collapse of NW wall of the canyon, block of 300 × 500 m was detached
Nov. 29–Dec. 3, 2011	Re-growth of cone summit to 160 m b.s.l.; Downslope flow of erupted material (presumably hyaloclastites)
Jan. 10–11, 2012; Feb. 7–8, 2012; Feb. 23–24, 2012	Maximum height of cone: ~88 m b.s.l. in Feb 2012

4.2. Ground deformation

Open access information about ground deformation on El Hierro can be obtained from the permanent global navigation satellite system (GNSS) network operated in the Canary Islands by *GRAFCAN*, whose records are publicly available (www.grafcan.es/2012/10/acceso-a-los-datos-de-las-estaciones-gnss). Additionally, five continuous GPS recording stations were deployed by *IGN* on El Hierro in July 2011 to record three-dimensional displacement in time, but these data are not available publicly. The first indication of activity was a north-eastward displacement at one of the eastern GPS stations on July 7th 2011 (López et al., 2012). After July 19th, seismicity increased and deformation began to be recorded at all GPS stations. At this point, the western stations recorded movement to the north and northwest, while the eastern stations moved northeast. In Sept. 2011, deformation increased again, and all GPS stations recorded northward movement. At the end of Sept. 2011, northward deformation accelerated, exceeding an accumulated total of 5 cm after the M_L 4.3

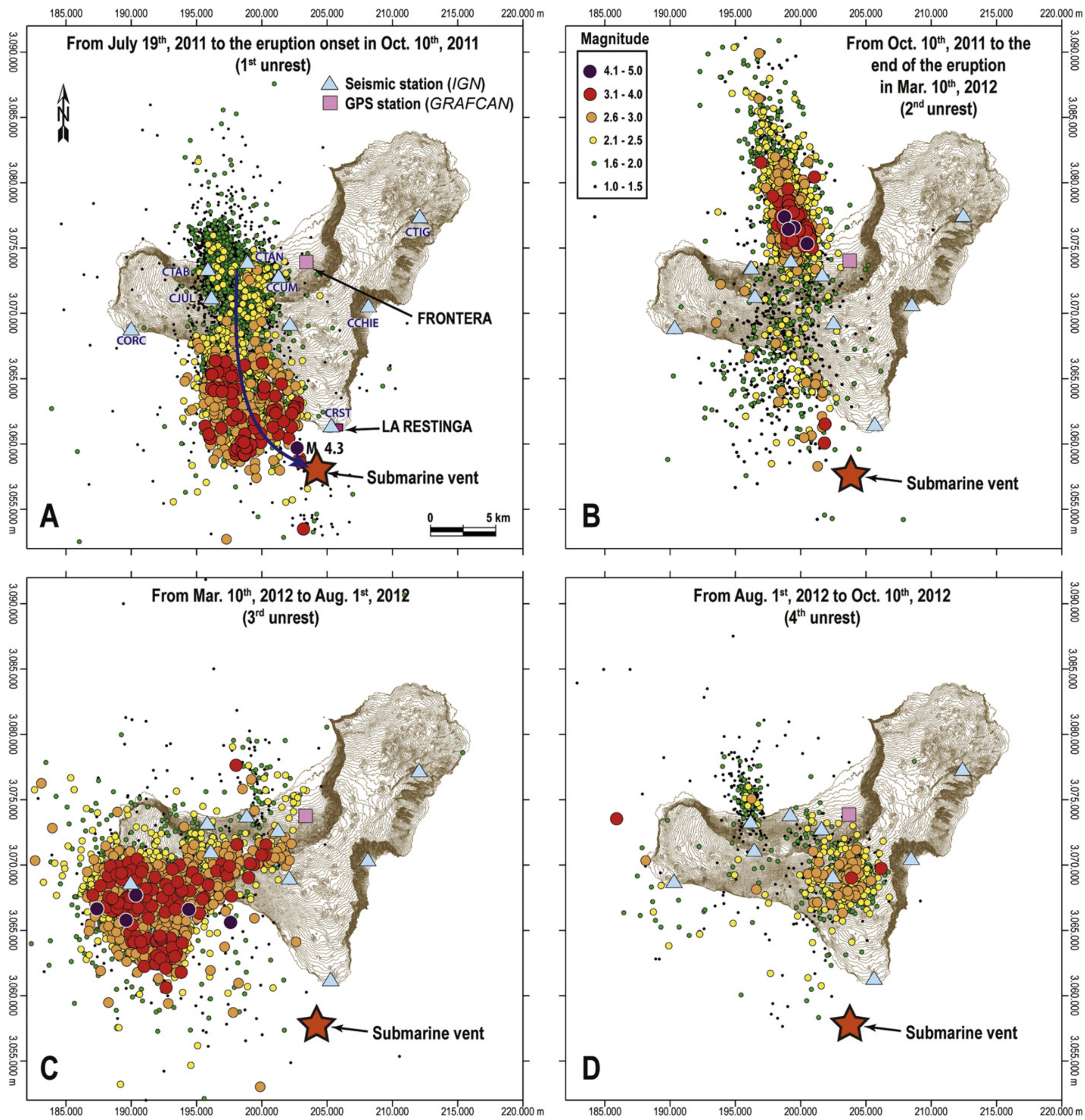

Fig. 10. Distribution of epicentres beneath El Hierro between July 2011 and Oct. 2012, indicating the intensity and locations of the seismic events. A. From July 19, 2011 to the eruption onset on Oct. 10, 2011 (1st unrest). B. From Oct. 10, 2011 to the end of the eruption in Mar. 10, 2012 (2nd unrest). C. From Mar. 10, 2012 to Aug. 1, 2012 (3rd unrest). D. From Aug. 1, 2012 to Oct. 10, 2012 (4th unrest). The location of GPS and seismic stations are highlighted. Data from *IGN*.

earthquake on Oct. 8th, i.e. immediately prior to the onset of the 2011 eruption.

Notably, the *GRAFCAN* GNSS station in Frontera started recording changes long before the onset of the eruption. Indeed, the stable positioning of 303.24 m (July 2011) underwent steady inflation, peaking at 303.29 m (i.e. 5 cm overall inflation) at the onset of the eruption (Fig. 5D). This was followed by a period of deflation, which lasted until Dec. 2011 and caused the island edifice to approach the pre-eruption level of June 2011. Subsequently, renewed inflation in 2012 restored the peak vertical displacement of the first phase of unrest prior to the eruption (Fig. 5D). Notably, these subsequent periods of unrest (i.e. June and Sept. 2012; 3rd and 4th unrest in Fig. 5) ended without eruption and the significant accumulated inflation remained as semi-permanent vertical uplift of the island of at least 10 cm at the end of 2012 and of ~22 cm by revision of the manuscript (June 2015).

4.3. Bathymetric surveys

Prior to 2011, most bathymetric information regarding the offshore prolongation of El Hierro's southern ridge came from multibeam sonar

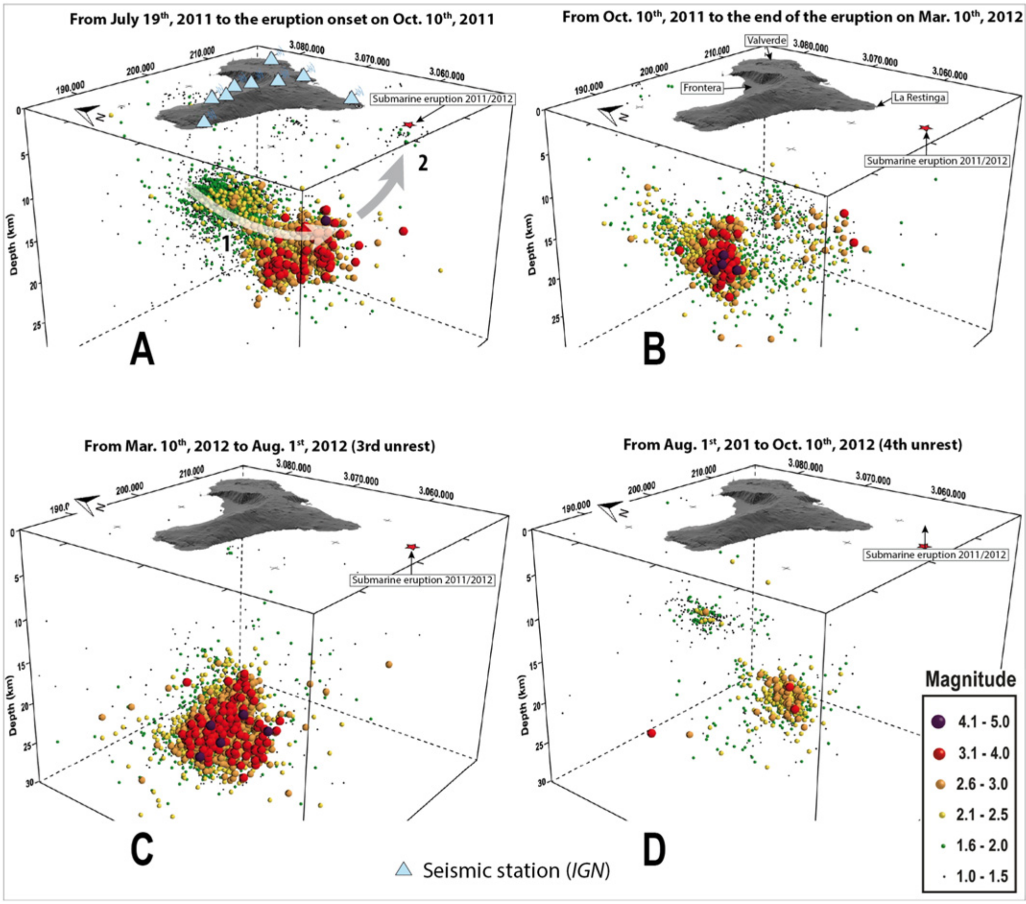

Fig. 11. 3D projection of hypocenter distribution beneath the island of El Hierro in the same temporal intervals as in Fig. 10. Data from *IGN*.

mapping by the R/V Charles Darwin (Gee et al., 2001) and from previous high-resolution seafloor mapping by the Spanish R/V Hespérides in 1998 (Fig. 8A). During the eruption, the Ramón Margalef oceanographic vessel of the *IEO* carried out multiple surveys of the eruption site (Table 2; Fig. 8B–C). The first survey of Oct. 23rd to 25th, 2011 revealed a nascent 650 m wide volcanic cone nested inside a canyon on the western flank of the southern rift at 220 m below sea level. In the 1998 survey, this site was at about 360 m depth. Several additional surveys were subsequently carried out with the aim of monitoring the activity of the eruptive vent, and between Oct. 28th and 31st, 2011, the cone summit was 40 m deeper, presumably due to collapse of the SW flank of the evolving cone. Between Nov. 12th and 13th, 2011 another collapse, this time of the NW wall, and a detached block of 500 × 300 m was detected (Fig. 9). Between Nov. 29th and Dec. 3rd, 2011 and during the following surveys in 2012, re-growth of the cone summit was recorded to a height of 88 m below sea level (Fig. 12; Table 2). A gas plume in the water column also continued to be active with variable intensity until Mar. 2012.

Growth rates and volumes were calculated from the results of the successive bathymetric surveys. The total volume of volcanic materials produced during the eruption was ~329 × 10^6 m^3 of non-dense rock equivalent (NDRE). Notably, this volume is within the range identified for data on 221 pre-exiting cones in the submarine part of El Hierro (Rivera et al., 2013), that show volumes of 50 to >1000 × 10^6 m^3 NDRE. The possibility of further vents opening onshore was considered early in the eruption, but was discarded after the first bathymetry was carried out. The vents grouped as a tight cluster, the knowledge of which removed many of the uncertainties from before the oceanographic survey that prompted cautionary restrictions to be implemented by the authorities (i.e. evacuations, road and tunnel closures; see below). Although the role of the vessel in assessing the eruption was initially considered to be “not important” by the scientific adviser committee (*CCES*), the information it delivered transpired to be critical during the ongoing eruption. Once open to a wider background of expertise (Nov. 14th, 2011), the main request of *CCES* was the long-term presence of an oceanographic vessel and frequent

Table 3
Successive episodes of unrest before, during, and after the 2011–2012 El Hierro eruption.

Unrest no.	Date	Location	Duration (days)	Number of events	Mag. 2–3	Mag. 3–4	Mag. 4–	Energy per day
1	18/06/2011–10/10/2011	S Restinga	114	10,076	1540	100	1	1.27×10^{12}
2	20/10/2011–27/11/2011	N Frontera	29	1760	949	71	4	2.02×10^{12}
3	23/06/2012–16/07/2012	SW Orchilla	24	2372	1634	151	5	1.98×10^{12}
4	14/09/2012–19/09/2012	SW Pinar	6	589	325	4	0	8.03×10^{10}
5	17/03/2013–10/04/2013	W Verodal	20	2251	1633	639	32	1.11×10^{13}
6	22/12/2013–28/12/2013	S Pinar/W Verodal	3	585	382	6	1	2.93×10^{12}
7	14/03/2014–16/03/2014	SW Valverde	5	425	78	1	0	1.60×10^{10}

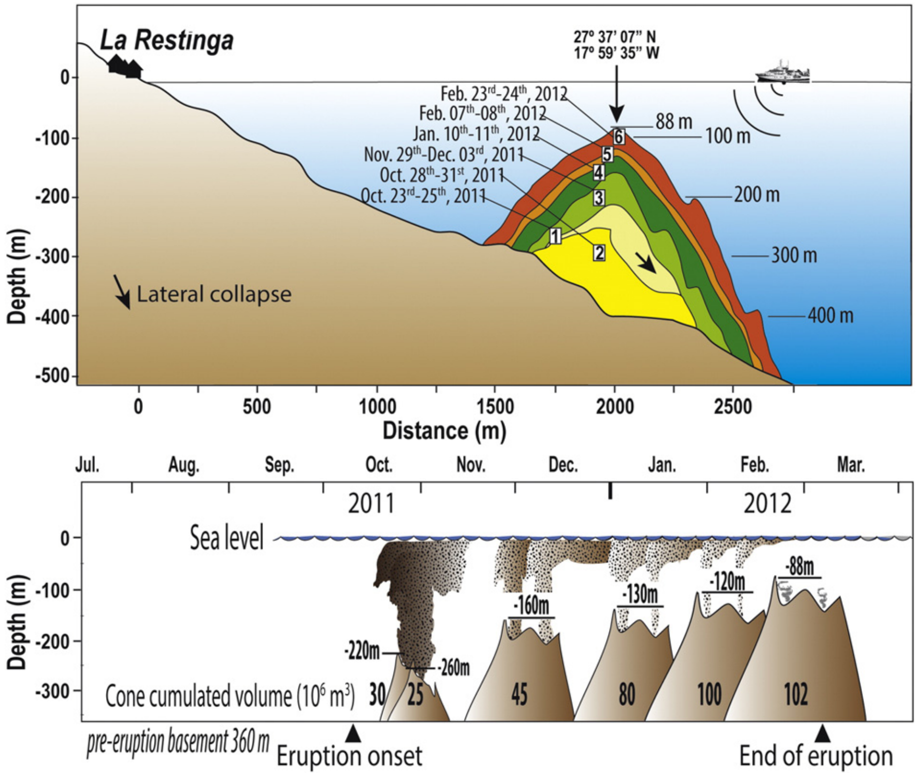

Fig. 12. Progressive development of the submarine volcanic cone of the 2011 eruption based on successive bathymetries of the *IEO* vessel Ramon Margalef. Note the decrease in the height of the cone from the first to the second bathymetry campaign was caused by a summit collapse of the rapidly growing cone (data *IEO*).

bathymetric surveys to monitor the evolution of the ongoing eruption vent. The vessel was a high-priority information gathering tool, despite the risk posed by the eruption, as sadly documented by the loss of the Japanese research vessel "5 Kaiyo-maru", in which all 31 personnel on board perished during the Myojin reef eruption in the Izu Islands in 1952 (Morimoto, 1960). However, during the crucial initial phases of the El Hierro eruption, most of the measures taken were based on inferences, and may therefore be compared to "flying blind". In hindsight, information could have been obtained right from the onset of the eruption, for instance by employing a remotely operated vehicle (ROV), deployed from a mother vessel at a safe distance from the vent area.

4.4. Eruptive products

4.4.1. Magmatic products

Similar to the "lava balloons" described from the submarine eruptions of, e.g., La Serreta, Terceira Island, Azores (Gaspar et al., 2003; Kueppers et al., 2012), Socorro Island, Mexico (Siebe et al., 1995), Pantelleria Island, Italy (Riccò, 1892), and the island of Hawaii, USA (Moore et al., 1985), hollow basanite lava balloons were erupted during the El Hierro 2011–2012 events. The petrology of the basanite eruptives is described in detail by Martí et al. (2013a) and Longpré et al. (2014). Both author teams report that the basanite is highly vesiculated and contains a mineral assemblage including olivine, clinopyroxene, chromite, and ulvöspinel, as well as rare plagioclase microlites. Remarkably, the bulk basanite that erupted in the later phases of the eruptive events was enriched in MgO compared to the early basanite eruptives, whereas little variation is displayed in the matrix glass.

4.4.2. Xeno-pumice

Abundant rock fragments reached the ocean surface during the first days of the eruption (Fig. 13). Besides the basanite lava balloons (Fig. 13F), many of the rock fragments consisted of light-coloured, highly vesicular, and glassy material, surrounded by dark basanite (termed "xeno-pumice"; Fig. 13A–E; Troll et al., 2011, 2012). Xeno-pumice shows mingling and mixing textures between their light-coloured cores and the enveloping dark basanite, resulting in a full spectrum of light and medium grey to cream colours in the cores of the samples. The porosity of xeno-pumice is comparable to magmatic pumice, and hence they float on water. Heterogeneous distribution of vesicle sizes throughout the sample suite is documented, and remnant sedimentary domains and partly intact sedimentary relicts are frequently observed. These relicts show features such as folded protolith bedding (Figs. 13 and 14) and remarkably, the sedimentary relicts have been found to contain nannofossils of Cretaceous to Pliocene age, making a strong case for xeno-pumice being dominantly of sedimentary derivation (see Section 6.4.3; Zaczek et al., 2015).

Within days of the first occurrence of xeno-pumice at El Hierro, major and trace element and XRD data were available, which revealed a mineral assemblage similar to sedimentary rock compositions (Figs. 13–15), including clear and rounded quartz grains (Fig. 14A, B), clay, jasper, carbonate, and contact metamorphic minerals such as illite and wollastonite (Troll et al., 2011, 2012). Normal igneous minerals usually present in Canarian magmas, such as olivine, pyroxene, amphibole, and feldspar, were notably absent in the XRD spectra of xeno-pumice interiors (Table 4; Troll et al., 2012). Silica contents of xeno-pumice are, in turn, high, ranging from 68 to 71 wt.% in the bulk analyses and up to 90 wt.% in glass (Fig. 15A). With respect to their trace element abundances, xeno-pumice specimens show a wide range of Zr concentrations, while their Ti concentrations and Rb/Sr ratios differ remarkably from known El Hierro magmatic rocks (Fig. 15C, D). Available oxygen isotope ratios of xeno-pumice (9.1–12.7‰; Troll et al., 2012; Rodriguez-Losada et al., 2015; Table 4) fall exclusively within the range of globally recorded sedimentary rocks (e.g. Savin and Epstein, 1970a,b) and S-type granitic melts (Harris et al., 1997, 2000). The first analyses were obtained and published within weeks after the onset of the eruption (Troll et al., 2011).

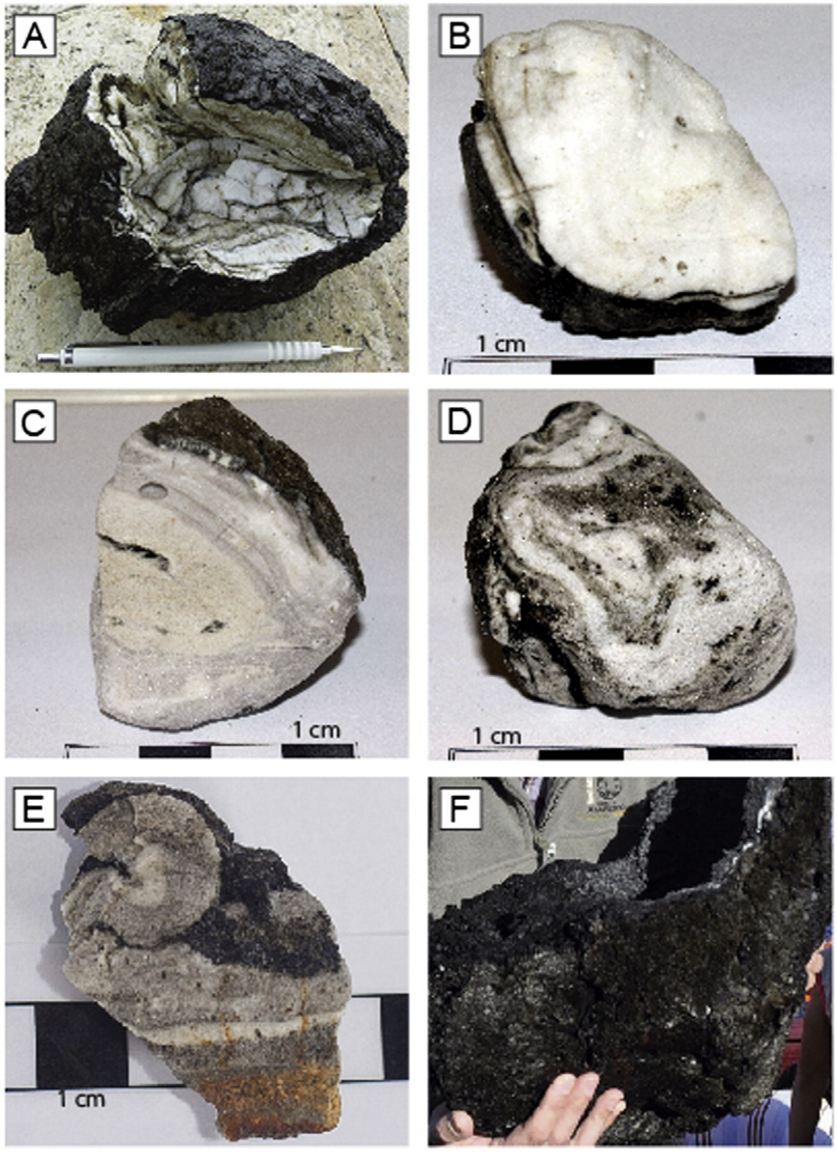

Fig. 13. 'Floating rocks' observed in Oct. 2011 off El Hierro. A. Xeno-pumice bomb displaying white interior infiltrated with basanite veins and surrounded by basanite. B. White xeno-pumice fragment with basanite coating. C. Xeno-pumice sample with basanite coating and a vesiculated inner domain, reflecting different thermal reactions of layers during magma-sediment interaction. D. Xeno-pumice that displays intense mingling of white high-silica glass and black basanite material. Note the grey portions of the sample, which are likely sedimentary structures that were also affected by plastic deformation during transport. E. Xeno-pumice with basanite coating and original lithological layering and intensely folded bedding. Note the quartz-rich white portions of the sample between the two grey bands. F. Hollow basanite lava balloon of the later stages of the eruption, with no associated xeno-pumice.

Xeno-pumice ceased to erupt a few days into the 2011–2012 El Hierro eruption, and entirely basanitic and hollow balloons were then erupted exclusively (Pérez-Torrado et al., 2012; Fig. 13F). The geological and hazard implications of xeno-pumice are particularly important and are discussed in further detail in Section 6.4.3.

5. Unrest episodes from 2012 to 2013

In the course of the events at El Hierro that commenced in July 2011, seven periods of unrest were recorded, and five of them occurred subsequent to the eruption, i.e. after Mar. 2012 (Fig. 5). Despite a number of speculations and warnings, no further eruption site was confirmed for the subsequent unrest episodes.

The post-eruptive episodes of unrest were characterised by increased seismicity and vertical displacements, repeating the pattern of unrest that preceded the submarine eruption. Epicentre distributions show that the earthquakes of the unrest episodes clustered in separate groups, with sources scattered beneath the western, central and eastern parts of the island, as well as in an extended region offshore the west of the island (Fig. 5A). The number of seismic events is not directly correlated with the amount of energy released, and for example more earthquakes were recorded in episode 3 ($n = 2372$) than in episode 5 ($n = 2251$), although the total seismic energy released in episode 5 (1105×10^{13} J) was by an order of magnitude greater than in episode 3 (1978×10^{12} J) (Fig. 5B and Table 3). A similar relationship is observed between the number of seismic events and the cumulated seismic energy (Fig. 5C), or the cumulated vertical deformation (Fig. 5D). Remarkably, current records yield up to 22 cm uplift in the GPS station located at Frontera.

5.1. June 2012 to September 2012

The end of the initial eruption in Mar. 2012 was followed first by several months of very low levels of seismicity, but from June to late July 2012 a swarm of earthquakes occurred, totalling 2500 individual seismic events (Figs. 5, 10C, 11C). The recurrent unrest in June 2012 was

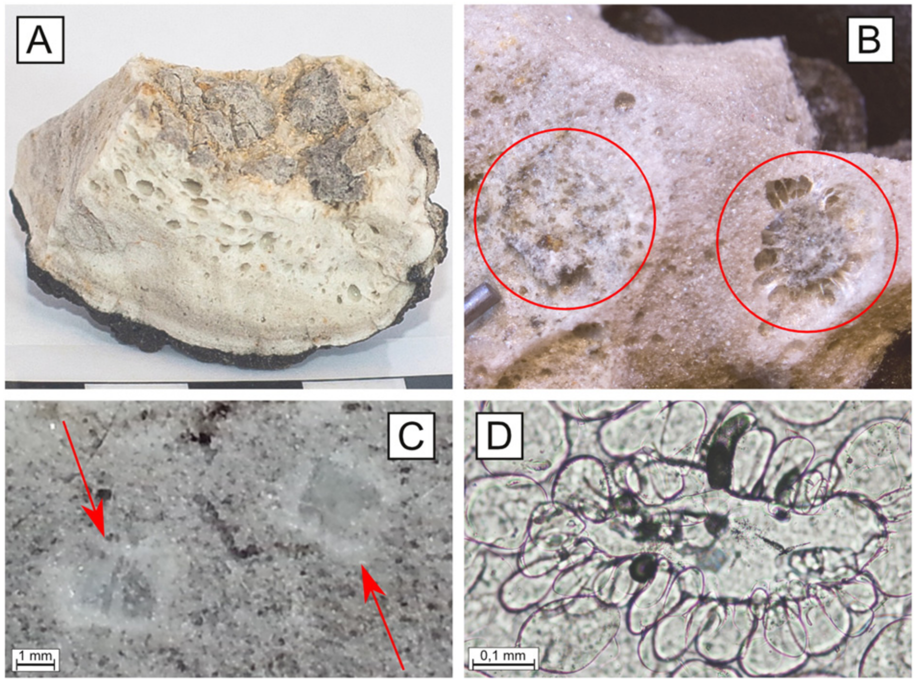

Fig. 14. Photos of A. A sedimentary relict in the core of a xeno-pumice sample. Note that the relict is surrounded by a glass layer that displays large vesicles up to 2 mm in size. A finely vesicular glass layer follows and meets the basanite crust. B. Two examples of sedimentary relicts, surrounded by vesicles that formed from degassing around the now relict material. C. Large quartz grains in glassy xeno-pumice (red arrows). Note that primary magmatic quartz does not occur in the western Canary Islands. D. Quartz grain in a thin section, surrounded by vesicles, indicating quartz grain degassing (cf. Vasiloi et al., 1985).

characterised by a relatively sudden increase in seismic activity and ground deformation (Fig. 5). Magnitudes of $M_L > 3.0$ were frequent (138 events), while five of the events were $M_L > 4.0$. A renewal of the 2011–12 eruptive process was anticipated, because both the cumulated energy release and ground deformation sharply increased in a fashion similar to the seismic intensity changes preceding the 2011–12 eruption, but over a significantly shorter time interval (Fig. 5; Prates et al., 2013). At that point, seismicity focussed mainly along the southern flank of the NW rift zone and at a depth of 25 to 15 km (Fig. 11C). This prompted the authorities to once more raise the alarm level to yellow (in a three-level colour code: green, yellow and red). However, no evacuations were carried out at that stage. By mid-July 2012 seismic activity progressively waned to background levels, while ground deformation stabilised after attaining a maximum vertical deformation of 5 to 6 cm relative to pre-June 2012.

Seismic activity sharply increased again in Sept. 2012 (Figs. 5, 10D, 11D) in a fourth period of unrest. This time, the majority of the earthquake epicentres clustered beneath both the NW rift zone and the centre of the island, although at greater depths (20 to 30 km) than during the June–July 2012 unrest period (Fig. 11D). A smaller, shallower (5 to 10 km), and probably independent seismic swarm focused off the northern coast near the town of Sabinosa. The additional ground deformation associated with this episode (about 2 cm) raised the accumulated inflation of the island to between 10 and 12 cm (see Fig. 5D). At the time of writing (June 2015), the ground levels remain elevated relative to the pre-2011 levels (~22 cm), suggesting permanent uplift of the island edifice. Notably, the June–July and Sept. 2012 periods of unrest showed similar characteristics to, and even greater ground deformation accelerations than the initial pre-eruptive 2011 unrest, but, in contrast, the Sept. 2012 events involved the imposition of fewer direct cautionary measures. This differing response to unrest potentially reflects the accumulation and application of newly-gained experiences on the part of the emergency-response team. However, on July 3rd, 2012, a member of the scientific committee predicted the occurrence of large ($M > 4.4$) earthquakes on the island, while another interpreted heavy surf as a new eruptive plume during a survey flight over the southern coast of the island on July 4th, 2012. Both predictions prompted *PEVOLCA*'s scientific committee to once more raise the alert level to yellow, but no eruption followed. These actions were met with angry responses from the El Hierro Employers Association, claiming that the island was "being used as an experimental laboratory by some scientists". At this stage, hotel reservations had dropped from 60% to 10% (Asamblea de la Pequeña y Mediana Empresa; APYME, July 19th, 2012), which represented a devastating blow to the island's strongly developed tourism sector. Remarkably, no further civil protection measures were taken during the following period of unrest in Sept. 2012. Because seismic and deformation signals were equally alarming in 2012 as they were in autumn 2011, the question remains whether the scientific approach by *PEVOLCA* had significantly changed by September 2012, or if public pressure became so strong that cautionary and disruptive measures were simply suppressed. Another possibility is that a general assumption was adopted wherein the lack of an eruption following the summer 2012 seismic crisis reinforced the idea that sequential seismic crises may not lead to an eruption either. This latter kind of assumption would not generally be considered consistent with volcanic hazard management strategies, however.

5.2. Unrest episodes after March 2013

Another episode of seismic unrest occurred between Mar. 18th and Apr. 10th, 2013 (Fig. 5). Some 2000 seismic events were recorded, reaching a maximum of M_L 4.9 on Mar. 30, the strongest recorded since the beginning of the events in 2011. This seismic swarm was recorded 10 to 15 km off the NW coast of the island, and the majority of the seismicity was located at 15 to 20 km depth (*IGN*). Associated vertical deformation reached over 10 cm in a very short time, accelerating at a higher rate than during the pre-eruption phase in 2011. However, after a crisis meeting of *PEVOLCA* on Mar. 26th, 2013, the alert level continued to stay green (normal), except for the implementation of traffic limitations along certain cliff roads, due to the danger of rock falls. On

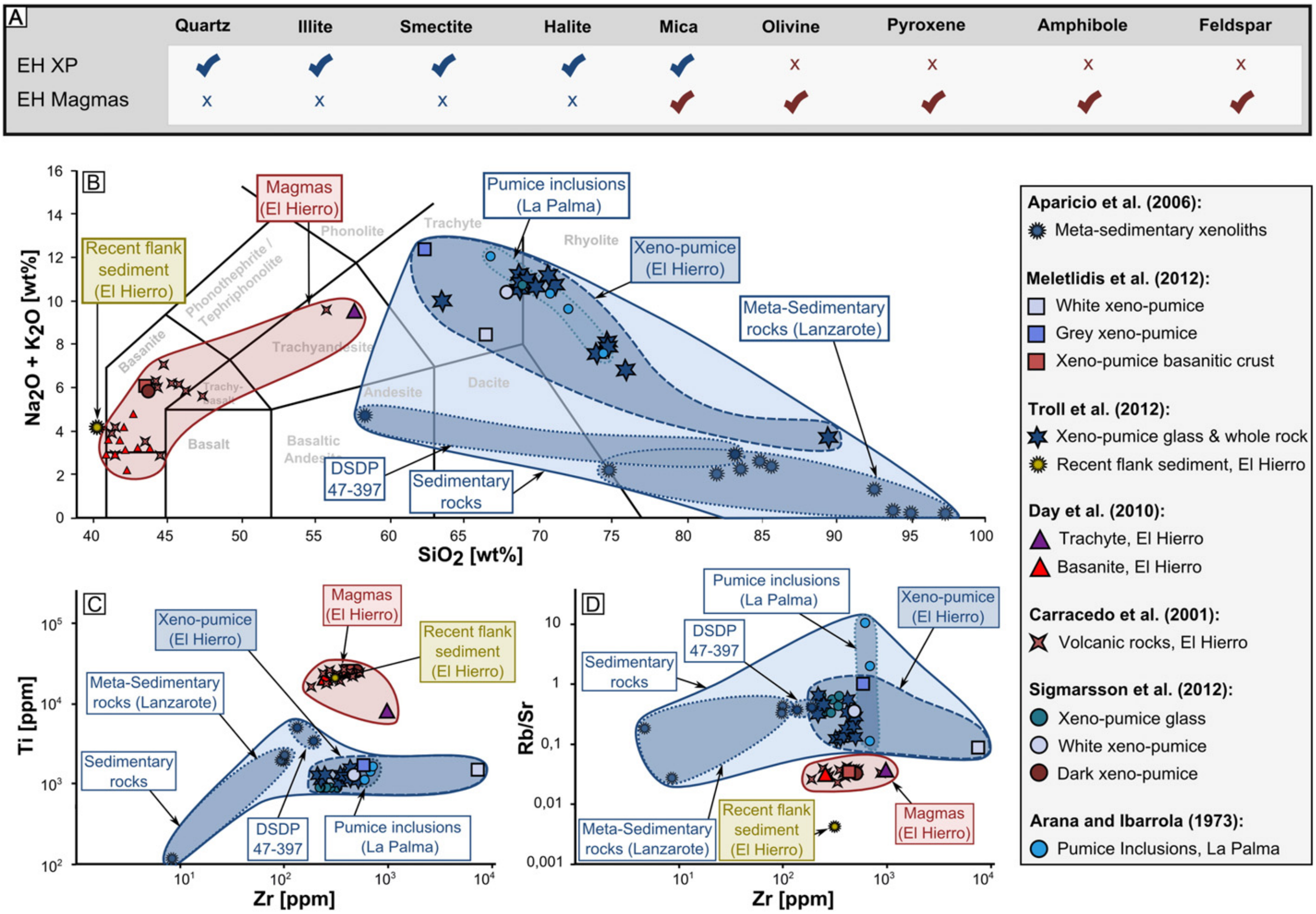

Fig. 15. A. Comparison of the mineralogy of El Hierro xeno-pumice (EH XP) and El Hierro magmas (after Troll et al., 2012). Note the almost complete absence of magmatic minerals within the xeno-pumice samples. B. Total-Alkali-vs.-Silica (TAS) diagram with a recent El Hierro flank sediment, El Hierro magmatic rocks and xeno-pumice from El Hierro, "pumice inclusions" from La Palma, DSDP 47–397 sedimentary rocks and meta-sedimentary rocks from Lanzarote shown for comparison (Araña and Ibarrola, 1973; Carracedo et al., 2001; Aparicio et al., 2006; Day et al., 2010; Troll et al., 2012; Meletlidis et al., 2012; Sigmarsson et al., 2013). The majority of the xeno-pumice samples fall within the rhyolite field, but tend towards low alkali concentrations with increasing SiO_2. C, D. Variation diagrams of Ti and Rb/Sr against Zr with the same sample suite as in B. The magmatic and sedimentary rocks form distinct areas on both plots. C. Xeno-pumice forms a wide field of Zr to Ti concentrations that does not overlap with the narrow El Hierro magmatic range. D. The Rb/Sr ratios of xeno-pumice covers a wide compositional range, while the magmatic rocks from El Hierro display a distinct field that does not overlap with the xeno-pumice field or other sedimentary rocks from the region.

December 27th, 2013, a new M_L 5.1 event occurred west of the island, in the same area where unrest 5 occurred and where sporadic seismic activity continues to the present day.

At this late post-eruption stage, claims of large or explosive eruptive phenomena, that were frequent and influential at the time of the 2011–2012 eruption, did not continue and no significant public responses followed. This change of behaviour on the part of the authorities was likely due to the substantial public and media pressure that was a strong factor in post-eruptive decision making (see also Section 5.1). It seems probable that the Emergency Management Committee had assimilated the geological experiences, as well as the population and mass media opinions at that point, as no further preventive measures were taken. This change of practice notably occurred despite the fact that earthquakes in the post-erosion unrest periods attained greater magnitudes than during the 2011 eruptive crisis, for example 32 events of $M > 4$ occurred during unrest 7, including a single M_L 5.1 event on Dec. 27th, 2013 west of Frontera, the highest magnitude earthquake recorded in all of the successive unrest periods.

6. Discussion

In the following discussion we focus on the geological events and hazard mitigation in the wake of the 2011–2012 El Hierro eruption, during the eruption itself, and in the periods of unrest that occurred after cessation of the eruption. We furthermore discuss the long-term geological implications of the data recorded during these events, as well as the social and economic impact that the eruption and it's management had on the local population. Finally, the lessons learned for hazard management and preparation for possible future volcanic crises in the Canary Islands are addressed.

6.1. Pre-eruptive unrest July to September 2011

The interpretation of the main processes involved in the 2011 El Hierro events from the earliest signs of unrest to eventual eruption were facilitated by a wealth of instrumental data provided by *IGN* and *GRAFCAN* (seismic and GPS measurements), and by *IEO* (bathymetric surveys). Seismic data were particularly helpful to monitor lateral and vertical transport of magma prior to eruption, thus helping to anticipate the eventual location of the eruptive vent.

The available seismic data are consistent with slow emplacement of a batch of magma at depth, starting July 19th, 2011, when a period of low magnitude seismic events began. Activity concentrated at the northern end of the island, below the El Golfo embayment, and was located at a depth of between 10 and 25 km. The majority of the events took place at 9.5 ± 4 km depth (see Fig. 16; Gonzales et al., 2013), which corresponds to the depth of the Moho (mantle–crust transition) in this area (Watts, 1994; Ranero et al., 1995; Ye et al., 1999). Around the same

Table 4
Features of xeno-pumice compared to Canary Island magmatic pumice sorted after first, second and third order observations[a].

	Means of analysis	Critical observation	Fresh Canary Island magmatic pumice	El Hierro xeno-pumice
First order observations	Handlens, naked eye, field Raman device, XRD	Vesicularity	High	High
Field petrology onsite, available within		Sedimentary relicts	Uncommon	Common
minutes to hours		Plutonic/volcanic relicts	Common	Absent
		Clear, rounded quartz grains	Absent	Common
		Magmatic minerals[b]	Present	Absent
		Clay minerals[c]	Absent	Common
		Contact-metamorphic minerals[d]	Absent	Common
Second order observations	Microscopy, textural analysis, XRF, ICP-MS	Magmatic minerals[b]	Present	Absent
"Simple" analytical means, available within		Sedimentary minerals[c]	Absent	Frequent
days of eruption		Nannofossils	Not usually	Present
		High silica content	Present	Common
		Low trace element abundances[e]	Unusual	Common
		High U concentrations[e]	Unusual	Very possible
Third order observations	Stable isotope techniques	Oxygen isotope ratios	5.7–6.2‰	>9.1‰
Long-term scientific understanding, available	ICP-MS/TIMS	Radiogenic isotope ratios	tbd	tbd
within weeks to months	LA–ICPMS, 3D tomography	Element maps, detailed characterisation	tbd	tbd
	Further methods		tbd	tbd

tbd = to be determined.
[a] Based on the time-frame of the theoretical and actual availability of the data (Troll et al., 2011, 2012).
[b] i.e. olivine, pyroxene, amphibole.
[c] Illite, smectite.
[d] Illite, wollastonite.
[e] Compared to Canary Island volcanic rocks.

time, a linear increase in vertical displacement of the island surface commenced (Figs. 5D and 17A). Previous thermobarometric analyses of mineral phases in basanites from recent El Hierro submarine cones indicated that the main storage and fractionation level of magma is within the uppermost mantle (Hansteen et al., 1998; Stroncik et al., 2009), consistent with the seismic observations in summer and autumn of 2011 that indicated the addition of magma at this level (i.e. at 10 to 12 km).

From beneath the El Golfo embayment, these early hypocentres then migrated southeast towards the south rift zone, but were now located slightly deeper than before (12 to 17 km). This observation implies that resistance of the island crust was initially not overcome, but that magma was instead forced to migrate southward towards the Mar de Las Calmas, probably due to an edifice loading effect (e.g. Pinel and Jaupart, 2004; Figs. 16, 17B). INSAR data imply that magma migration involved a reservoir at 9.5 ± 4 km (Gonzales et al., 2013), from which magma moved upwards through two successive stress regimes; first a deep upper mantle one, and then a shallow one, that is controlled mainly by the edifice itself (e.g. Walter and Troll, 2003; Fig. 18). At El Hierro, a decompressive regime at mantle depth grades into a more compressive regime underneath the El Golfo landslide scar, i.e. in between the enveloping rift-arms, while the third rift-arm, i.e. the one opposed to the sliding sector, would undergo passive extension (e.g. Walter and Troll, 2003; Walter et al., 2005; Manconi et al., 2009). We postulate that once the ascending magma entered the increasingly compressional near surface regime in the El Golfo area, it began to migrate towards the passive third rift arm opposite the landslide scar (i.e. towards the

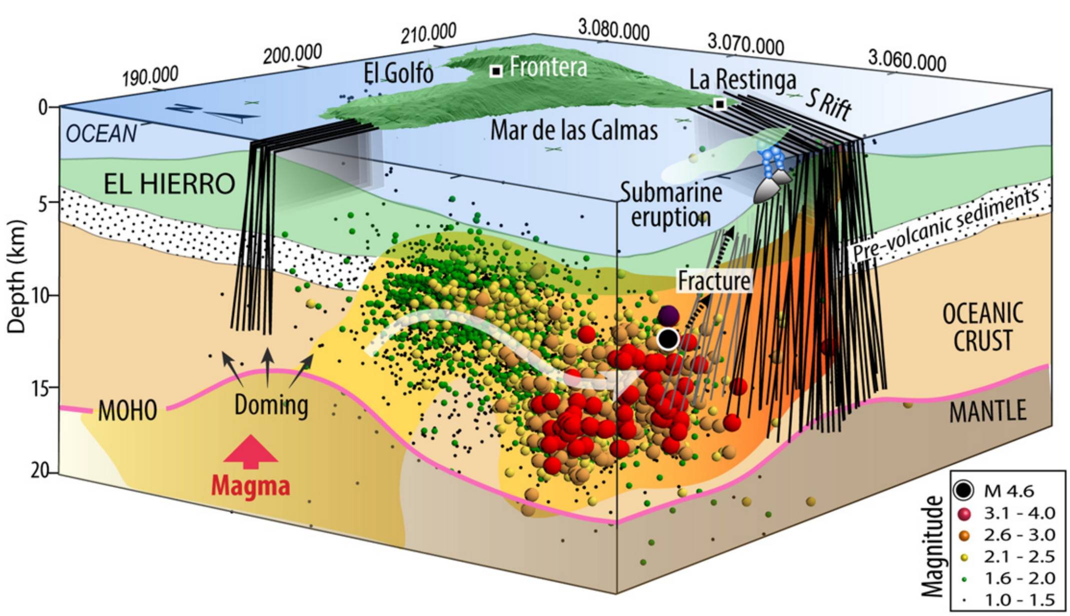

Fig. 16. Hypocentres of seismic events beneath El Hierro between July 19 and Oct. 10, 2011, just at the onset of the submarine eruption. Hypocentres migrated from beneath the NW rift towards the South rift zone of the island, where they became shallower and eventually led up to the eruption. In the weeks before the eruption, seismicity remained at the base of the oceanic crust, seemingly unable to create a vent, until migration into the S-rift allowed magma to break through to the ocean floor (seismic data from *IGN*, www.ign.es/ign/resources/volcanologia/html/eventosHierro.html).

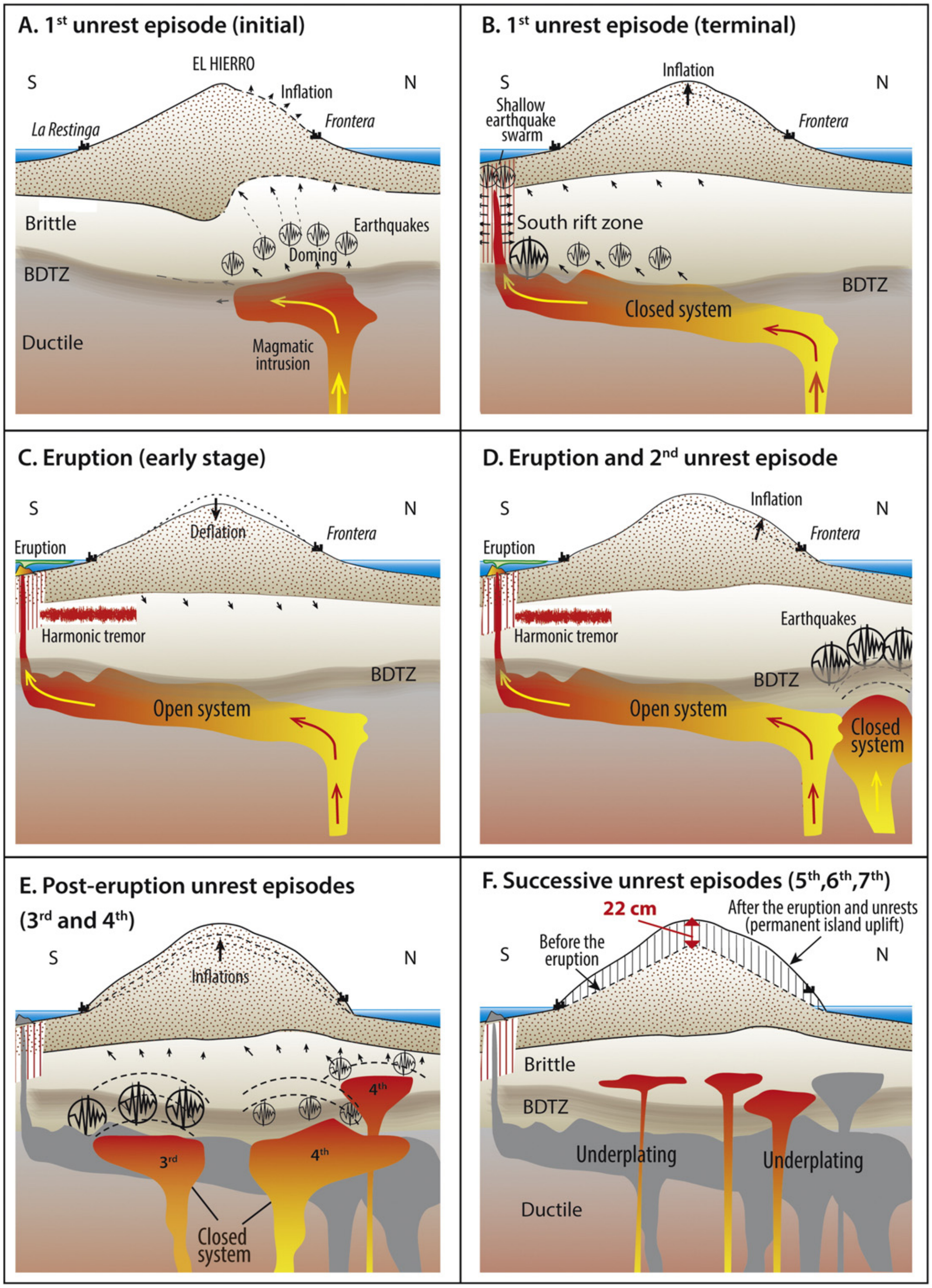

Fig. 17. Cartoon sequence illustrating the successive magmatic intrusions (pulses) of the 2011–2012 unrest at El Hierro. Note that strong seismicity and inflation correspond to closed system intrusions (A, B, E). Once the eruption started (C), the seismicity changed to that of an open system (C & D) by shifting to a harmonic tremor that was associated with overall deflation of the system. In D, the eruption continued on the S-rift, but a new intrusion below the northern coast caused additional seismicity and inflation. Additional intrusions in the summer of 2012 increased inflation once more and renewed the seismic activity (E), causing a persistent uplift of the island on the order of between 10 and 12 cm at that time (D), which is likely a result of magmatic underplating at the brittle–ductile transition zone (BDTZ, panel F).
Seismic data from *IGN* and deformation data from *GRAFCAN*.

southern rift of El Hierro; Gonzales et al., 2013). These observations are consistent with a high-density body at a depth between 6 and 10 km underneath the centre of the island identified by Montesinos et al. (2006), and which likely forced the magma to take the alternative route of lesser resistance.

Lateral magma migration is furthermore consistent with observations from extinct rift zones in, e.g. the Anaga massif on Tenerife (Walter et al., 2005), where an initially linear rift axis developed a large landslide and subsequently a third, largely passive rift-arm. This realisation implies that decompression from landslides might initially facilitate preferential magma ascent in the deep plumbing system (from up to ~35 km depth; Longpré et al., 2009; Manconi et al., 2009). If magma supply is not vigorous, however, magma may gradually migrate either into the fault-controlled area of the landslide scar and/or into the extensional rift-arm behind the collapse embayment when eventually exposed to the mainly edifice-controlled near-surface stress-environment (e.g. Walter and Troll, 2003; Walter et al., 2005; Manconi et al., 2009; Carracedo et al., 2011b; Gonzales et al., 2013). In fact, this scenario appears to explain why rift-arms have developed so strongly on El Hierro during successive stages of island growth. As landslides are known to have occurred in between all rift arms, intrusive diversion into passive rift-arms would have facilitated the 'rotational' propagation of different rift arms throughout the recent geological evolution of the island.

6.2. The 2011 to 2012 eruption

On Oct. 8th, 2011, the southwards migrating seismic swarm reached the thoroughly fractured southern rift of El Hierro, which is an extensional environment characterised by rift-parallel dyke swarms (cf. Walker, 1992; Carracedo, 1994, 2011; Walter and Troll, 2003; Delcamp et al., 2010, 2012; Carracedo et al., 2011a,b). The seismic data allowed detailed monitoring of magma migration into the south rift zone and predicted the final eruption site in the Mar de las Calmas, offshore the south of El Hierro. The 12 km deep, M_L 4.3 earthquake of Oct. 8th, 2011, the highest magnitude event prior to the eruption, coincided with ascent of seismic activity below the rift zone. This seismic event probably recorded final rupture of the crust by magma pressure, which would have occurred via the opening of a hydraulic fracture that then quickly propagated towards the surface (500 m/h; López et al., 2012). The occurrence of a swarm of shallow (1 to 6 km deep), low magnitude earthquakes ($M_L < 2$) some 5 km off the south coast of the island on the following day is consistent with upward propagation of such a fracture (Figs. 17B, 19A). Most likely, the migrating magma utilised existing dykes in the rift zone that comprises the upper regions of the plumbing system of the southern rift region, as for example spectacularly exposed in the "Cumbre Dorsal" on Tenerife (e.g. Fiske and Jackson, 1972; Swanson et al., 1976; Carracedo, 1994; Delcamp et al., 2010, 2012; Deegan et al., 2012). Such a dyke-fed rift system on El Hierro is the result of magma migration into a region of least resistance (i.e. likely reflecting the strongest extension in the El Hierro triple-armed rift system; cf. Walter and Troll, 2003; Walter et al., 2005). Following the onset of the 2011 eruption on Oct. 10th, 2011, earthquakes returned to deeper levels, and generally remained deep during subsequent seismic unrests (Fig. 19B).

6.3. Post-eruptive unrest

The June–July 2012 seismicity was deep (20 to 30 km) and strong, with 5 events of $M > 4.0$ that focused in the southern flank of the NW rift zone (Fig. 19C). This pattern recurred during a short period of unrest in Sept. 2012 (Fig. 19D), although with lower earthquake intensity ($M < 4.0$). Post-eruptive unrest was likely the result of independent intrusions that led to renewed magmatic overpressure and thus continued to contribute to island uplift. The Mar.–Apr. 2013 seismicity was characterised by the strongest seismic events to date, with earthquake intensities up to M_L 5.1. The epicentres were focussed about 10 to 15 km off the westernmost edge of the island at ca. 20 km depth. This activity, which did not progress to an eruption, also resulted in no major emergency responses by the authorities, suggesting either desensitisation or adaptation on the part of the authorities in charge (see Section 6.5).

6.4. Implications for underplating and island growth

The temporal distribution of earthquakes at El Hierro between 2011 and 2013 appears to be characterised by discrete swarms separated by periods of relative quiescence. This compares well with the information available from the 1793 seismic unrest period, and implies that some minor swarms may have passed unnoticed prior to the first seismic network being deployed in the islands in 1989. It therefore appears that deep seismicity is usually associated with batches of magma that migrate at depth and cause deformation along the brittle/ductile interface at the base of the oceanic crust (López et al., 2012; Gonzales et al., 2013). This situation generates updoming stress and increasingly shallow seismicity would then indicate upward magma migration that can eventually break through as an eruption. Intermittent seismicity without associated eruptions is hence compatible with the view that extrusion frequency at El Hierro is considerably lower than intrusion frequency and that episodes of unrest will not always lead to an eruption (e.g. Newhall and Dzurisin, 1988; Bailey and Hill, 1990). In the Canary Islands, episodes of unrest that ended without volcanic activity (besides the 1793 and 2012 unrests on El Hierro) include the 1914 to 1917 unrest episode on Fuerteventura, the 1936 to 1939 unrest on La Palma (e.g. Klügel et al., 1999), and the 2004 seismic unrest on Tenerife (e.g. Carracedo and Troll, 2006). These events most likely represent episodes when intrusive material was added to the islands' cores (e.g. by underplating and intrusion).

Notably, during the 2011 El Hierro events, the long-term vertical ground displacement recorded during pre-eruptive unrest was 4 to 5 cm, which equilibrated to about 2 cm of total uplift directly after the

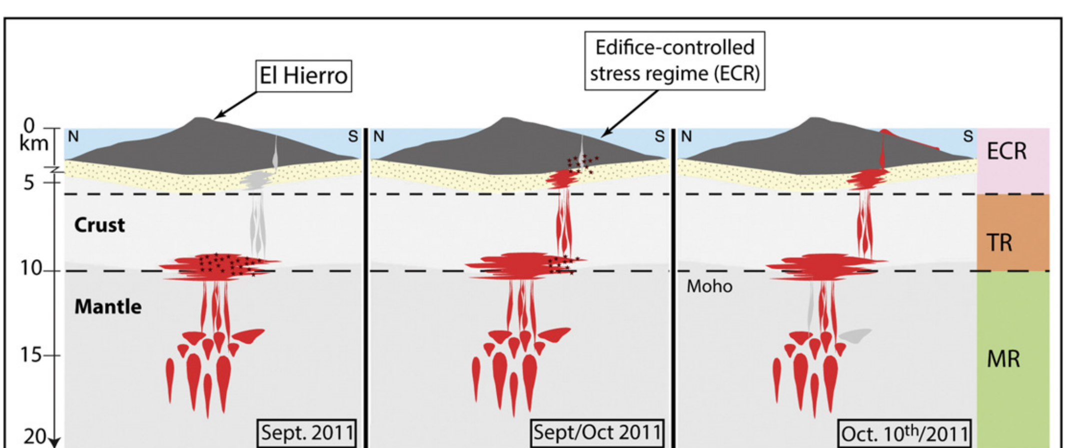

Fig. 18. Magma ascent history leading up to the Oct. 2011 eruption (modified after Gonzales et al., 2013). A mantle stress regime (MR) grades through a transition zone (TR) into the shallow, edifice-controlled stress regime (ECR). Note the lateral transport components along i) the Moho level (Martí et al., 2013a,b; Longpré et al., 2014), and ii) along the sedimentary layers that cover the ocean crust (Troll et al., 2012; Gonzales et al., 2013).

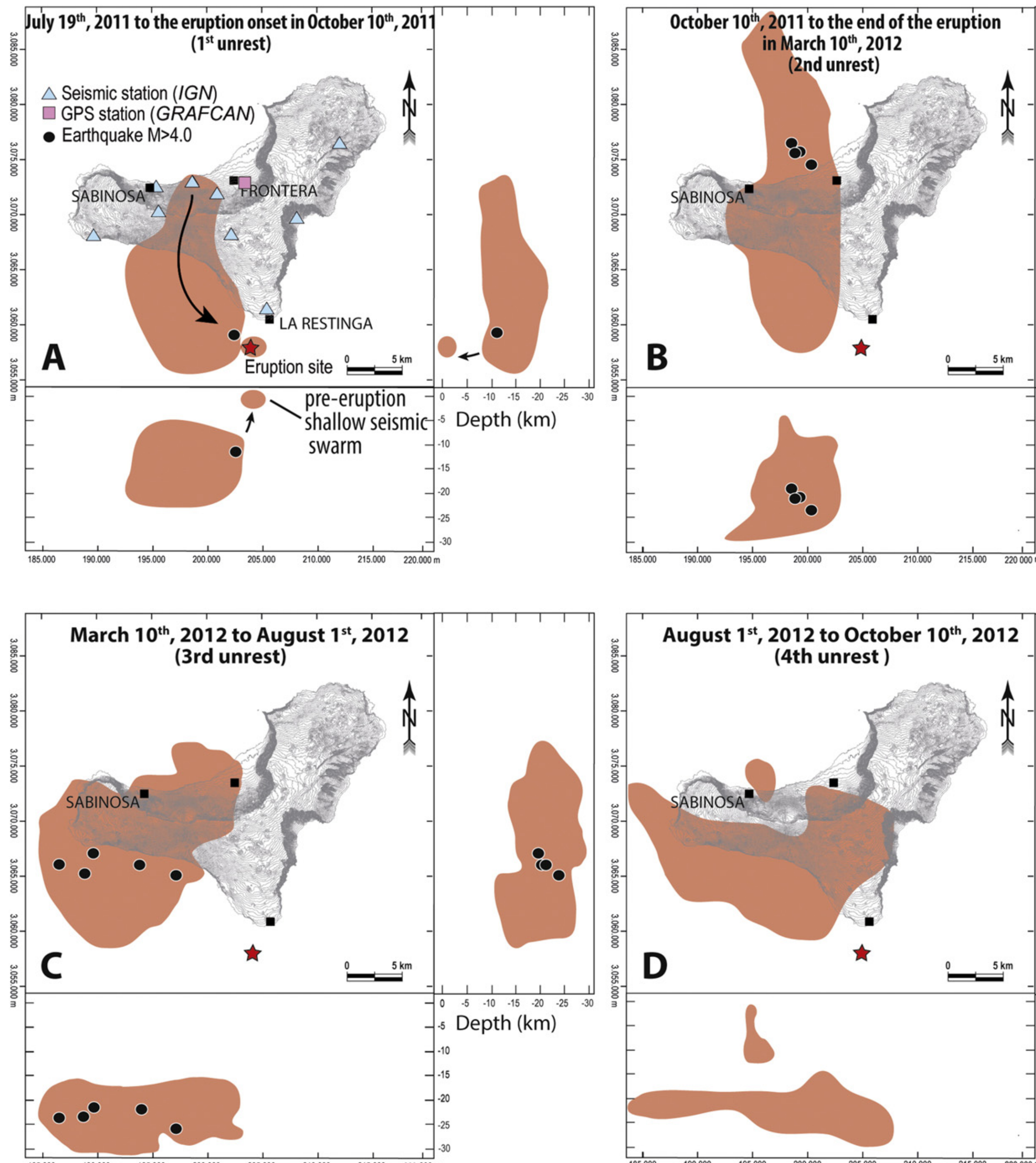

Fig. 19. Changes in the distribution of earthquakes in the four main phases of unrest associated to the 2011–2012 events. A. Closely preceding the onset of the eruption, seismicity sharply migrated upward from about −15 km to only a few km below the surface. This migration was associated with an M 4.3 earthquake. The initial ascent of the magma from beneath the El Golfo embayment was diverted and magma migrated into the SE rift arm of the island (see text for details). B. Immediately after the eruption, seismicity concentrated mainly below the north of the island, with 4 deep (20–25 km) events with magnitudes over 4.0, likely indicating resistance of the oceanic crust and overlying edifice to magma ascent in this part of the island. C and D. Successive unrests in the summer of 2012 were derived from deeper seismicity that focused beneath the NW rift zone.
Seismic data from *IGN*.

eruption (see Fig. 5D). Island uplift was even greater during the subsequent 2012 and 2013 unrests (6 to 7 cm), equating to a total uplift of around 22 cm, that remains at the time of writing. This observation probably indicates lasting growth of the island by repeated episodes of magma injection into the shallow lithosphere, likely centred around the Moho discontinuity and the lower island crust (e.g. Hansteen and Troll, 2003). However, a percentage of long-term “deflation” is to be expected, when the intruded magma cools down and contracts (e.g. Prates et al., 2013; Carracedo and Troll, 2013). Remarkably, pillow lavas and marine sediments crop out on the SE shore of El Hierro, similar to pillow lava outcrops on other islands, including Fuerteventura, Gran Canaria, and La Palma. These uplifted units suggest that intrusive uplift occurred in El Hierro's past and is likely a key process for island growth. We note that the volume required for 22 cm of uplift on El Hierro would be on the order of 0.01 km^3.

If the recorded patterns of vertical deformation do indeed reflect periods of magmatic underplating and associated updoming, then the formation or widening of fractures would be expected to occur. The thousands of low-magnitude earthquakes that preceded the 2011 eruptive event had little effect on the accumulated seismic energy released, but were instead related to a stage of inflation (Fig. 17A, B). In contrast, high magnitude seismic events that occurred after the eruption onset (Oct. 10, 2011) caused a sharp increase in the energy released, but had little effect on vertical deformation (inflation), and even registered a short period of deflation (Fig. 17C). The accumulated stresses caused by pre-eruptive magma updoming (during a period of low-magnitude seismicity) were hence potentially released after the eruption onset and expressed as high-magnitude earthquakes. Inflation resumed again in June to Sept. 2012, when seismic frequency, energy release, and inflation increased once more due to new intrusion pulses and emplacement of associated magma batches (Fig. 17D, E).

6.4.1. Implications for the origin of the Canary Islands

The currently accepted model for the Canary Islands is one of a thermal anomaly in the mantle (a hotspot), which leads to a high production rate of magma (cf. Morgan, 1971). This model is consistent with the observed age progression of the islands' oldest erupted rocks from east to west and with the point-source nature of seismicity and a seismic anomaly (e.g. Carracedo et al., 1998; Montelli et al., 2004; Geldmacher et al., 2005; Zaczek et al., 2015), which indicates a volcanic rather than plate-tectonic origin of the earthquakes (e.g. Carracedo et al., 1998).

Some authors nevertheless prefer a regional tectonic fracture model for the origin of the Canary archipelago, either associated with the Atlas fault system, or with oceanic structures like Mid-Atlantic Ridge transform faults (Hernández-Pacheco and Ibarrola, 1973; Anguita and Hernán, 1975, 2000). Recently, Geyer and Martí (2010) postulated that the Canaries are located along a major lithospheric fracture several thousand kilometres in length, which they interpreted to represent the boundary between the Moroccan and African (Nubian) microplates. However, tectonic models involving fractures cutting through the lithosphere to cause the Canarian volcanism have several difficulties. Firstly, they cannot account for the large volumes of magma generated in the Canary Volcanic Province (cf. McKenzie and Bickle, 1988; White and McKenzie, 1989). Secondly, they cannot explain the pronounced age progression of the Canary Islands from east to west (Abdel-Monem et al., 1971, 1972; Carracedo et al., 1998; Geldmacher et al., 2001, 2005), that is supported by further evidence from El Hierro (see Section 6.4.3), and which stands in stark contrast to the random age distributions of demonstrably fracture-controlled archipelagos such as the Azores (i.e. Féraud et al., 1980; Navarro et al., 2009; Larrea et al., 2014). Thirdly, fracture-related models offer no explanation for why the magmatism is concentrated only around the Canary Islands and not along the full length of this alleged structural continuity.

In contrast, the hotspot model (Carracedo, 1979, 1994, 1996, 1999; Schmincke, 1982; Hoernle et al., 1991; Holik et al., 1991; Hoernle and Schmincke, 1993; Carracedo et al., 1998; Geldmacher et al., 2001, 2005; Longpré et al., 2009; Deegan et al., 2012) is largely independent of lithospheric fractures. With respect to the observed patterns of seismicity in and around the Canaries, the hotspot model appears more plausible, because the frequent Gaussian-distributed point-source seismicity is inconsistent with the linearly arranged hypocentres observed in fault-controlled seismic regions (Ito, 1995; Borges et al., 2007; Larrea et al., 2014). Furthermore, no evidence has been found for the existence of a major fault connecting the Atlas with the Canaries in any detailed geophysical study of the Canary archipelago (Watts, 1994; Funck et al., 1996; Watts et al., 1997; Urgeles et al., 1998; Krastel et al., 2001; Krastel and Schmincke, 2002; Martínez and Buitrago, 2002). Lastly, sustained seismicity like in the area between Tenerife and Gran Canaria over such a long interval of time (>23 years, Fig. 6), together with recurrent periods of high magnitude seismicity, more closely resemble the behaviour of an active volcanic point-source rather than that of a regional fracture system (see also Krastel and Schmincke, 2002).

The 2011 eruption at El Hierro has therefore shed new light on these repeated and spatially focused periods of seismic unrest in the region and shows that this form of seismic pulsing is characteristic of mafic volcanism in the Canaries. The similarities in the distribution of seismicity on El Hierro between 2011 and 2013 with the persistent and frequent small earthquakes that occur between Tenerife and Gran Canaria, and that are grouped in discrete swarms separated by long periods of quiescence (Fig. 6), suggests a common underlying process.

6.4.2. Detailed aspects of underplating

Intrusive additions lifted the entire island edifice of El Hierro by approximately 10 cm during the 2011–2012 events (Fig. 17F), while the increase in total volume and height of El Hierro by expulsion of volcanic material was modest and highly localised (329×10^6 m^3; Rivera et al., 2013). Indeed, periods of unrest associated with intrusion and underplating do not always result in eruption, indicating that eruption frequency is not a direct proxy for the rate of island growth. In contrast, analyses of fluid inclusions and mineral–melt equilibria from Canary basaltic rocks have shown that underplating of primitive magmas is likely very frequent in the Canary Islands, and by extension, in other ocean islands too (Gurenko et al., 1996, 1998; Hansteen et al., 1998; Klügel, 1998; Krastel and Schmincke, 2002; Hansteen and Troll, 2003; Klügel et al., 2005; Galipp et al., 2006; Longpré et al., 2008, 2009; Stroncik et al., 2009; Weis et al., 2015).

A significant part of ocean island growth may therefore be related to intense underplating, which would not be expressed in the observable eruptive record (Hansteen et al., 1998; Klügel, 1998; Hansteen and Troll, 2003; Klügel et al., 2005; Longpré et al., 2008, 2009; Stroncik et al., 2009). Ground deformation, which reached up to 22 cm on El Hierro by 2014, may instead show how the Canary Islands grow by a combination of intrusive and extrusive activity, as observed in the Hawaiian Islands. Ratios of intrusive to extrusive volumes of 5 to 1 for oceanic localities (Crisp, 1984) may therefore not be unrealistic, despite more recent suggestions of only ≤30% of intrusive components in ocean islands (Flinders et al., 2013).

Evidence for underplating in the Canaries is also found in form of a chaotic seismic facies at the northern end of the archipelago that Holik et al. (1991) interpreted as volcanic in origin. These authors also detected a low-velocity anomaly at the base of the crust, which they proposed to reflect the signature of thermal rejuvenation and associated underplating of earlier activity of the Canarian hotspot (e.g. around 60 Ma). Watts and Masson (1995) and Watts et al. (1997) questioned underplating in the Canaries based on seismic evidence from the vicinity of Tenerife, whereas seismic evidence from elsewhere in the archipelago led many authors to suggest magmatic underplating as major growth process for the Canary Islands (e.g., Funck et al., 1996; Ye et al., 1999; Krastel et al., 2001).

Specifically, the seismic and GPS data recorded during the recent El Hierro eruption and subsequent unrest episodes now document magma migration and ponding around Moho- or lower crustal levels, and thus support the notion of large-scale magmatic storage (underplating) of primitive magmas in the region. Recurrent intrusive episodes likely account for the relatively frequent periods of seismicity felt in the various islands that did not result in subaerial eruptions (e.g. 1793 on El Hierro, 2004 on Tenerife). Some of these periods of unrest may have ended in submarine eruptions at depths too great to allow direct observation and it is possible that the 2011 to 2012 submarine eruption would have passed largely unnoticed where it not for the relatively recently installed instruments. Conceivably, other episodes of seismic unrest may build up to larger events, as for example on Lanzarote where 11 years of noticeable seismicity preceded the eventual small-scale eruption of 1824 or on La Palma, where unrest commenced in 1936 prior to the eventual eruption of 1949 (Klügel et al., 1999; Day et al., 2000).

6.4.3. Erupted products and the significance of xeno-pumice

The petrology of 2011–2012 El Hierro basanites was described in detail by Martí et al. (2013a) and Longpré et al. (2014) (see Section 4.4.1). Martí et al. (2013a) imply that slightly evolved basanite magma was erupted during the first ~7 weeks of the events, while subsequent replenishment of the system with primitive basanite magma led to a drop in tremor activity. Longpré et al. (2014) propose that mixing of different basanite magmas occurred already in the mantle and produced a hybrid basanite magma that was subsequently erupted. Both author teams agree on magma storage and late-stage crystal growth at a depth of 20 to 25 km and 17 to 24 km (Martí et al., 2013a; Longpré et al., 2014, respectively), and earthquake hypocentres (i.e. López et al., 2012) imply vertical as well as lateral magma migration from the deep reservoir. Shallow lateral migration occurred initially in the upper mantle and again once the magma reached the transition from ocean crust and overlying sediments to the volcanic edifice (Gonzales et al., 2013), indicating both a deep (mantle-controlled) and a shallow (edifice-controlled) stress regime that guided magma ascent at El Hierro (Fig. 18).

The relatively deep magma reservoirs that feed the rift zones at El Hierro distinguish it from the Hawaiian volcanoes, which generally feature a two-storey system of magma storage (Ryan, 1987). Hawaiian rift zones appear to be fed systematically from levels as shallow as 2 to 4 km depth beneath the volcano crest (e.g. Decker et al., 1987; Dieterich, 1988), which is itself supplied by magma residing in the upper mantle (e.g. Nakamura, 1980; Clague, 1987). In contrast, the majority of Canary Island rift zones appear to be fed from Moho depths, with intermediate storage occurring only in a few cases (e.g., Klügel et al., 2005; Galipp et al., 2006; Longpré et al., 2008; Stroncik et al., 2009; Deegan et al., 2012). The recent El Hierro events have now allowed us to trace out the petrologically predicted storage dynamics by means of seismic activity (e.g. Longpré et al., 2014).

The initial confusion regarding the origin of the white xeno-pumice stemmed from the fact that on first glance, xeno-pumice shares a visual similarity with igneous pumice. On closer inspection, it was revealed that some trace element concentrations of xeno-pumice overlap with basaltic igneous rocks from the Canaries, while silica and alkali element concentrations are similar to felsic (high-silica) rocks from the archipelago. These observations led Meletlidis et al. (2012) and Sigmarsson et al. (2013) to consider a magmatic origin for xeno-pumice, while Troll et al. (2012) proposed that xeno-pumice derived from interaction of ascending magma with layers of sedimentary rocks from the oceanic crust. The latter model is based on mineralogical observations, major and trace element systematics, oxygen isotope ratios, and comparative evidence elsewhere in the Canaries (e.g. Hoernle, 1998; Gurenko et al., 2001; Troll and Schmincke, 2002; Hansteen and Troll, 2003; Aparicio et al., 2006, 2010; Deegan et al., 2012; Rodriguez-Losada et al., 2015; and Section 4.4.2; Table 4).

One key observation is the presence of quartz grains of considerable size in xeno-pumice (1–2 mm; Fig. 14), which is noteworthy because the silica-undersaturated magmatic rocks in the western Canary Islands are not reported to contain quartz as a free mineral phase. A likely source of the quartz crystals found in El Hierro xeno-pumice are sand grains that were transported from continental Africa as aeolian matter or marine sediment (e.g. Stillman et al., 1975; Robertson and Stillman, 1979a,b; Criado and Dorta, 1999; Gee et al., 1999; Collier and Watts, 2001; Aleon et al., 2002; Georgiopoulou et al., 2010). Wind-blown sediments are usually very fine-grained (below silt-size), which rules out a simple aeolian transport for the mm-sized quartz crystals found in the early El Hierro xeno-pumice samples. Instead, the sedimentary rocks of layer 1 of the pre-El Hierro ocean crust (Fig. 20) have been found to consist of material transported from Africa by both wind and turbidity currents (cf. Georgiopoulou et al., 2009, 2010). Layer 1 of the oceanic crust is usually formed by deep-sea sedimentary rocks and, near continents, by terrigenous, turbidite type facies. This is very much in line with uplifted Cretaceous to Miocene silicic and carbonate sedimentary strata exposed in the basal complex of Fuerteventura, and the sedimentary successions drilled from DSDP sites 47–397 and 41–369 (Lancelot et al., 1978; Robertson and Stillman, 1979a,b; von Rad et al., 1979; Steiner et al., 1998) that contain detritus from Africa, including large quartz crystals and a considerable variety of sedimentary facies (such as almost pure quartz beds, heavy mineral sandstones, mixed calcareous and silicic beds). Another crucial observation is that xeno-pumice was recently shown to contain Cretaceous and Pliocene nannofossils (Zaczek et al., 2015). This finding renders a sedimentary, and hence xenolithic, origin for xeno-pumice as the most likely hypothesis. The preservation of nannofossils in xeno-pumice is remarkable, and allows for speculation on the timing of the onset of volcanic activity in the vicinity of present day El Hierro. The youngest overlapping age assemblage is <2.5 Ma, therefore supporting the plume-model for the origin of the Canary Islands by verifying the youngest pre-volcanic sedimentary material to underly the west of the archipelago (e.g. Carracedo et al., 2001; Zaczek et al., 2015; see Section 6.4.1), hence supporting the overall east to west age progression within the Canaries.

In combination with their distinct sedimentary mineralogy, oxygen isotope compositions, and the lack of geophysical evidence for a shallow magmatic source reservoir, it thus appears most plausible that sub-island sedimentary strata were picked up as xenoliths and heated by the ascending magma, causing much of the sedimentary material to melt and vesiculate on decompression. An aspect in need of more detailed consideration, however, is the volatile content of such sedimentary compositions and their potential to contribute to the dynamics of an eruption. The high silica content of most xeno-pumice samples, together with relics of dominantly siliciclastic sedimentary materials (e.g. bedded layers and quartz, clay, gypsum and jasper components), implies that pore and mineral waters were important volatiles present. This realisation is in line with reported relicts of dissolved zircons (e.g. Meletlidis et al., 2012), underlining the dominantly siliciclastic nature of the protolith (cf. Mesozoic zircon sands exposed on Fuerteventura; Robertson and Stillman, 1979a,b; see section below). Gluyas and Cade (1997) suggest that porosities up to 20% are possible in siliciclastic sedimentary basins at a depth of ~5 km, providing pore space for H_2O or other fluids. Assuming this pore space translates to ~10 wt.% H_2O in a sedimentary rock at this depth, and assuming a sediment/magma mixture of 10:90%, with basanite nominally set at ca. 1 wt.% H_2O, then the resulting 1.9 wt.% H_2O implies doubling of the original magma (basanite) H_2O content ($0.9 \times 1 + 0.1 \times 10$), which could have played a role in driving the early stages of the eruption. Structurally bound (mineral-) water will be released on complete sediment melting also, thereby adding extra bursts of H_2O to the system. The occurrence of gypsum and contact-metamorphic phases like wollastonite imply that a component of carbonate and other chemical sediments were present also, but perhaps in smaller proportions. Assuming a CO_2 content of 0.5 wt.% for the 2011 El Hierro magma, and a $CaCO_3$ component of 5 wt.% from the sub-island sediment, and a 43 wt.% CO_2 proportion in $CaCO_3$, then >2.63 wt.% CO_2 ($0.95 \times 0.5 + 0.05 \times 43$) from combined magmatic and sedimentary sources could have been associated with the initial pulses of magma. Importantly, at such shallow levels in the crust, H_2O and CO_2 are not soluble in magma, but would form a free volatile phase (Holloway and Blank, 1994) and thus contribute to the gas content of the initial pulse of the eruption. This may help explain the "Jacuzzi" effect described in the first weeks (Fig. 7) and the strong bubble outbursts observed on repeated subsequent occasions (cf. Blythe et al., 2015), and is moreover consistent with the textural evidence for multi-generation bubble distribution observed in microprobe images of El Hierro xeno-pumice (Fig. 21).

A key factor in the assessment of the potential for explosive (Surtseyan-type) submarine eruptions, is the depth of the vent (e.g. Colgate and Sigureirsson, 1973; Wohletz, 1983; Wohletz and Sheridan, 1983; Kokelaar, 1986; Clarke et al., 2009). Expansion of bubbles increases with decreasing water depth, with the volume ratio of steam to fluid water reaching critical explosive levels at depths of about 100 m below sea level (Schmincke, 2004). Although the initial controversial interpretation of xeno-pumice as high-silica magma evoked fear of a pending explosive volcanic eruption, we note that sedimentary strata could have conceivably also contributed to temporarily elevated gas fluxes. This process could occur at even greater depths if additional

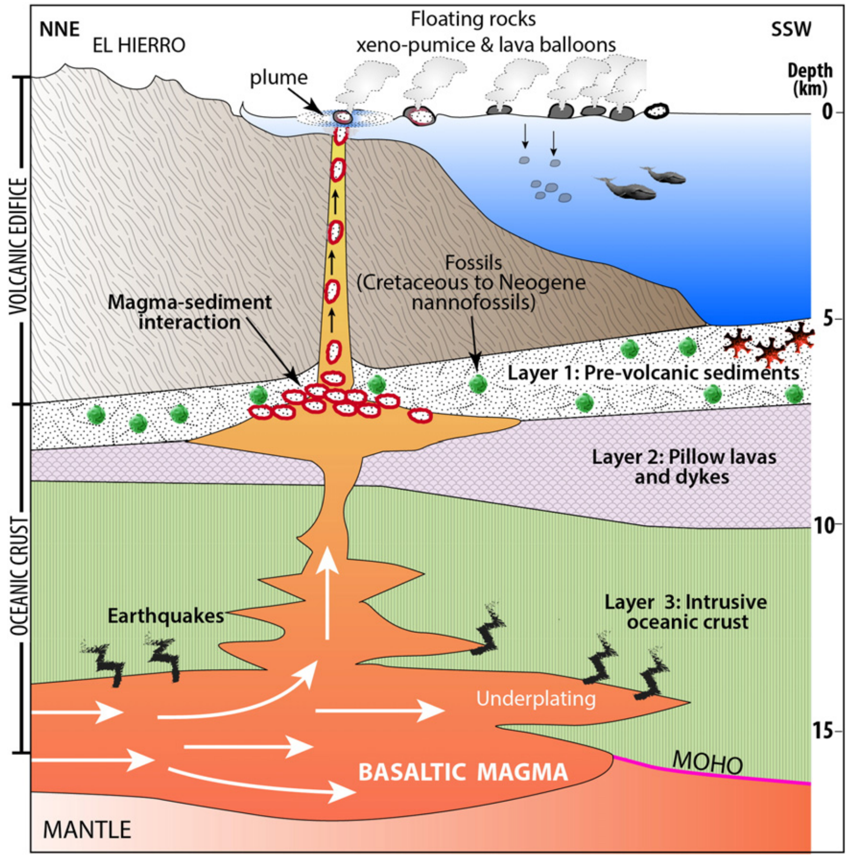

Fig. 20. Sketch cross-section showing the structure of the island of El Hierro and the location of activity during the 2011 events. Sub-horizontal magma migration in the ocean crust, from north to south, led to ascent below the south rift and allowed the rising magma to interact with pre-volcanic sedimentary rocks. The white floating rocks found at El Hierro during the early days of the eruption are likely the products of magma–sediment interaction beneath the volcano. These 'xeno-pumice' fragments were carried to the ocean floor during eruption and melted and vesiculated while immersed in magma. Once erupted onto the ocean floor, they separated from the erupting lava and floated on the sea surface due to their high vesicularity and low density. Modified from Troll et al. (2012).

volatiles from dissolution of water-saturated xenoliths are added to the mixture, thus enhancing the volatile-pressure within the magmatic system (cf. Gardner et al., 2013). However, virtually all forms of phreatomagmatic eruptions in the Canaries are of local effect only (cf. Clarke et al., 2009), which we will discuss on the basis of regional geological examples below (Section 6.4.4). In addition, and maybe the most fundamental aspect here, we have now also learned that a first order provenance determination of xeno-pumice is in many cases possible using classic petrographic observations directly in the field, and through swiftly accessible microscopic assessment, which may prove useful for future eruptive hazard management in the Canary Islands (Table 4).

6.4.4. Regional occurrence of xeno-pumice

The occurrence of sedimentary xenoliths in the volcanic rocks of the Canaries is relatively infrequently reported, but not uncommon (Fig. 22), even though relatively few workers seem to have fully appreciated this phenomenon. Eruption products similar to El Hierro xeno-pumice are known from pre-historic and recent volcanic events in the Canary archipelago and, for example, frothy quartz-bearing xenoliths were found in the 1949 eruptions on La Palma (Klügel et al., 1999; Fig. 22A) and in eruption products of the submarine volcanic edifice Hijo de Tenerife (offshore between Gran Canaria and Tenerife; Schmincke and Graf, 2000). Partially melted sandstone xenoliths are also known from Holocene basanite eruptives on Gran Canaria (Hansteen and Troll, 2003; Fig. 22B) and Lanzarote (Araña and Bustillo, 1992), and Aparicio et al. (2006, 2010) describe silica-rich xenoliths (Fig. 22C) as well as fossil-bearing limestones and shales from the lavas of the 1730–1736 Timanfaya eruption on Lanzarote. Moreover, uplifted pre-island sedimentary rocks in the Basal complex of Fuerteventura are also quartz-rich, and are interlayered with clays and minor carbonates (e.g. Stillman et al., 1975; Robertson and Stillman, 1979a,b; Steiner et al., 1998) (Fig. 23). In fact, the link between the frothy sedimentary xenoliths on Lanzarote and the uplifted sediments on Fuerteventura was already suggested some forty years ago by petrological pioneers (e.g. Rothe and Schmincke, 1968). In this context, the 1730–36 Timanfaya eruption on Lanzarote could be taken as a blueprint for large-scale mafic events in the Canaries, where xeno-pumice likely contributed extra volatiles to drive the eruption (see Section 6.4.3). Notably, xeno-pumice fragments on Lanzarote occur particularly frequently in explosive lapilli beds rather than in lava, suggesting a link between their occurrence and eruptive explosivity. However, xeno-pumice is evidently not an indication for the presence of a large volume of evolved and "highly explosive" phonolite, trachyte, or rhyolite magma at depth as was suggested at El Hierro, especially since the seismicity before and during the 2011 events gave no cause to consider the existence of a silica-rich magma pocket. In contrast, an analogy may be drawn to other marine eruptions like those of, e.g., Anak Krakatau in Indonesia, where xeno-pumice inclusions occur frequently amongst the andesitic lavas and scoria deposits. Similar to El Hierro xeno-pumice, the Anak Krakatau samples contain sedimentary and meta-sedimentary mineral assemblages, as well as elevated oxygen isotope ratios (e.g. Mandeville et al., 1996; Gardner et al., 2013), while no large silicic magma reservoir has been detected at present (Jaxybulatov et al., 2013).

El Hierro xeno-pumice thus represent clues from depth that help us to better understand the history of the islands, as well as the interaction between ascending magma and the crust underlying the island edifice. The sedimentary portion of the ocean crust under El Hierro has

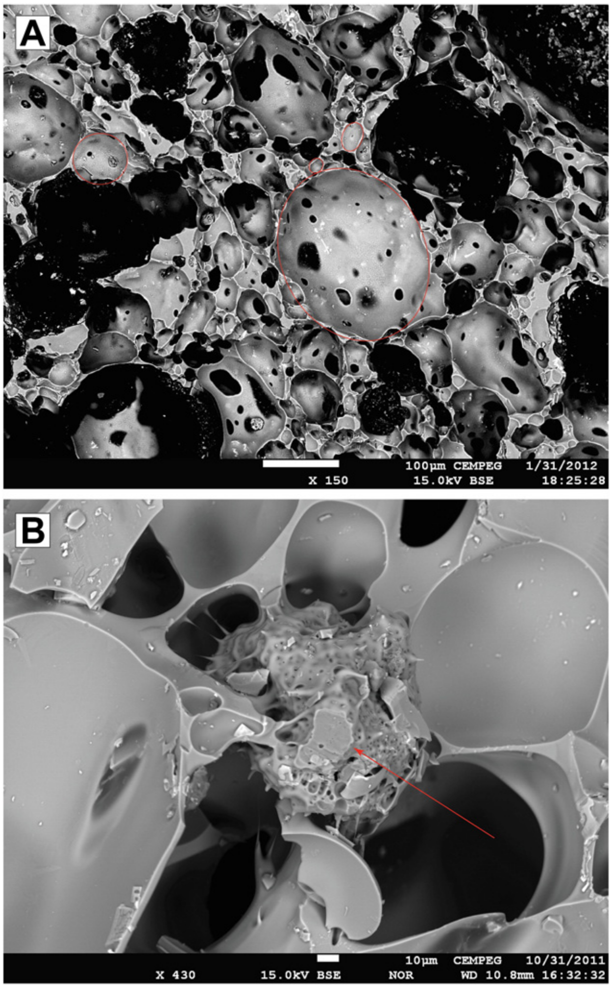

Fig. 21. A. BSE image of heterogeneous vesicle distribution throughout the high-silica glass of El Hierro xeno-pumice (exemplified by red circles), which points to various degassing episodes (e.g. pore water, volatile bearing minerals and the release of CO_2 from heat-induced chemical reactions); and B. BSE image of a sedimentary relict in El Hierro xeno-pumice with a quartz grain in its centre (red arrow), surrounded by vesicles. The gasses released during melting likely contributed to the volatile fraction of the basanite during the onset of the eruption.

previously been established to have a thickness of >0.5 km (Collier and Watts, 2001; Gonzales et al., 2013), remnants of which were found preserved in xeno-pumice. Remarkably, some of these sedimentary rock relicts were found to contain preserved nannofossil remains. The nannofossils are predominantly Cretaceous in age, and reach up to the Upper Pliocene (Zaczek et al., 2015), while recent nannofossils are absent, thus ruling out contamination of the investigated samples in the water column during the eruption or the presence of short-lived vent biota. The youngest (Pliocene) fossils now provide an age constraint for the onset of eruptions that formed the base of the El Hierro island edifice in the vicinity of the 2011 submarine vent. Specifically, the remains of the original pre-island sedimentary strata brought to the surface by magmatic activity constrain the timing of the earliest submarine seamount growth to ≤2.5 Ma, a phenomenon that is hardly dateable by any other means (see Section 6.4.3; Zaczek et al., 2015). Using this datum and estimate of the volume of El Hierro (~10.500 km^3), a mass eruption rate of ≥4.2×10^3 km^3/Ma is derived. This value is in line with estimates established for the other Canary Islands, which range between 4 and 9×10^3 km^3/Ma (Schmincke and Sumita, 1998).

Another interesting aspect regarding the evolution of the crustal structure beneath ocean islands is the combination of intrusive island growth and the occurrence of xeno-pumice at El Hierro. Material comprising the original (sedimentary) oceanic crust was evidently removed during the El Hierro 2011 events and presumably replaced by solidifying magma (see Burchardt et al., 2012). The sub-island crustal structure may thus gradually mature by becoming increasingly "ocean island-like" in its nature, a process that will only fully come to conclusion in long-lived and matured ocean island systems.

6.5. Emergency management of the submarine eruption

The volcano monitoring system on El Hierro was deployed only one year before the 2011 eruption by the Instituto Geográfico Nacional (*IGN*), and allowed *IGN* geophysicists to analyse and interpret seismic precursors, thus permitting early detection of the timing and approximate location of the eruption. Open access geophysical data from the eruption (seismicity, energy release, deformation) was provided via the *IGN* webpage in near real time (www.ign.es/ign/resources/volcanologia/HIERRO.html). This open access policy received great local and international publicity and is an admirable step towards transparency. However, information afforded by earthquake frequency alone can be equivocal if the number of earthquakes is reported without direct indication of their magnitude, especially when read and interpreted by lay scientists. Media reports commenced three months before the actual crisis was apparent, i.e. from the beginning of the seismic unrest in July 2011. Graphics of thousands of earthquakes at El Hierro, often lacking both magnitude data and detailed scientific explanations, caused widespread alarm and significant, likely avoidable, economic losses due to a steep decline in international visitors at that time (e.g. "Diario de Avisos", Nov. 5, 2011: "Frustración en La Restinga"; "El País", Jan. 9, 2012: "Una economía hundida por el volcán").

The first official civil protection measure was taken on Sept. 23, 2011 after two months of sustained seismicity (and media attention). The volcano alert level was raised to yellow (green-yellow-red colour code) as some of the seismic events were felt by the population and increasing surface deformation was registered at that point (Fig. 24A). Southwards magma migration made it increasingly likely that an eruption would occur and that it would manifest itself to the south of El Hierro (e.g. López et al., 2012; Gonzales et al., 2013). Given the depth of the seismicity, the data pointed to an offshore and hence submarine outbreak, implying limited direct hazard potential to the population onshore.

A major road tunnel which constitutes a bottleneck for cross-island traffic was closed soon thereafter (from Sept. 27th to Nov. 23rd, 2011). The purpose of the closure was to minimise impact from large (> M_L 5) earthquakes that might occur along regional faults, and to mitigate the risk for seismically induced rock falls. The decision to close the road tunnel was questioned by many members of the local population, as tunnels should have been built in an earthquake-proof fashion (see also Section 6.5.2). This additional uncertainty on construction standards led to further distress for the island's population by considerably slowing down the local economy and causing people to worry about the safety of their own dwellings, as well as that of other public buildings and constructions.

During the post-eruption unrest episodes, seismicity was even stronger (up to M_L 5) than during the actual eruption, and in fact caused severe and large rock falls, that, by contrast, did *not* lead to any road or tunnel closures on El Hierro. This change in policy illustrates a change in decision making rationale regarding hazard proportions and impacts. However, the key question that now arises is whether the construction of major roads in volcanically active regions should adhere to particular safety standards so that an island's core transport and communications infrastructure can reliably withstand a certain degree of seismic activity, irrespective of epistemic (scientific) uncertainties (i.e. the exact cause for the seismicity; see also below). This approach would moreover ensure that evacuation and supply routes remain available to populations in more remote settlements during a possible future event, when they

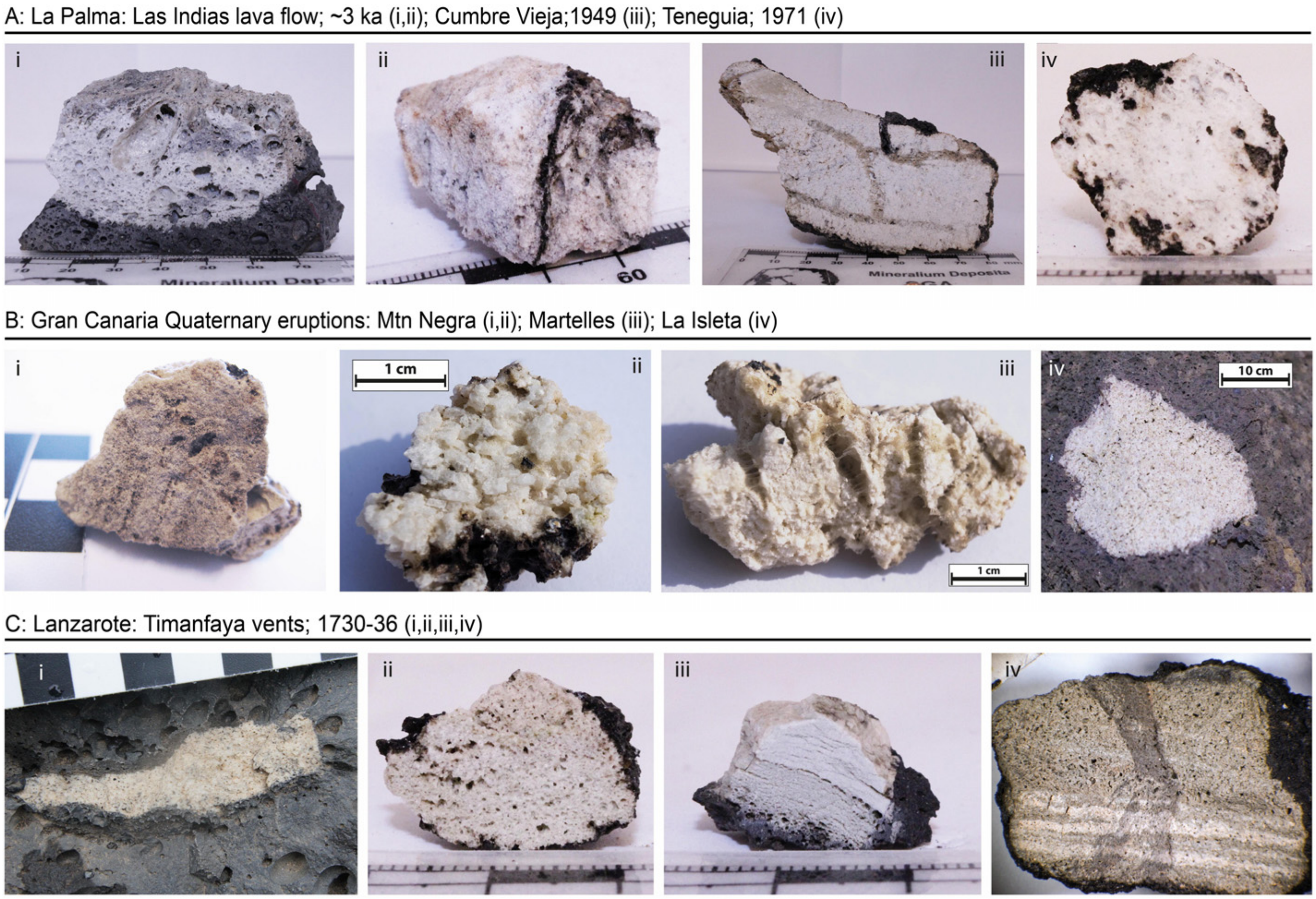

Fig. 22. Examples of xeno-pumice in historical and recent eruptions from; A. La Palma (ca 3 ka, 1949, 1971), B. Quaternary Gran Canaria (i.e. ≥1900 BP), and C. Lanzarote (i.e. El Golfo vent and 1730–1736), displaying intense vesiculation, relicts of sedimentary structures, mingling, and folding due to plastic deformation. Note the strong similarity to xeno-pumice from El Hierro (Fig. 13). The regional occurrence of xeno-pumice throughout the Canary Islands supports the inclusion of these remarkable rocks into the petrological repertoire for future hazard management considerations in the archipelago, and beyond (e.g. Gardner et al., 2013).

are most needed (i.e. Wilson et al., 2014). This would remove an element of uncertainty for the authorities and the local population alike and help build robust and reliable emergency plans.

Another issue that arises from the El Hierro crisis pertains to the release of monitoring data and the limited number of official scientific advisors involved. This situation can place those scientists who are not involved in official data interpretation committees in a dilemma — if they present alternative interpretations or a critique of the "official line" of information they may be viewed as acting in a manner that is inconsistent with the general guideline that states that the scientific community should speak to the public through one conduit alone (e.g. Newhall, 1999). If, in contrast, a scientist remains silent, he or she is understood by the public to implicitly endorse the official interpretations. This aspect leads us to discuss improved approaches towards epistemic uncertainty because mechanisms to handle dilemmas of this nature are required for future occasions (see Section 6.5.2).

6.5.1. Bathymetry and risk of Surtseyan explosions

The scientific advisory committee (*CCES*) initially declared the deployment of an oceanographic vessel as "not-essential", despite the detection of a near-surface vent and the occurrence of lava balloons and xeno-pumice floating on the sea surface. In hindsight, this decision may have been sub-optimal with respect to the events that subsequently unfolded. Unfortunately, bathymetric information concerning the state of the submarine eruption and the development of the eruptive (and non-explosive) vent became available only weeks into the eruption when the oceanographic vessel was eventually deployed (Fig. 24B). The lack of bathymetric information during the initial weeks of the crisis was probably a major factor in the road closures and evacuations of the initial eruptive phase due to the very high uncertainties at that point (Fig. 24C). The uncertainties were only alleviated when the depth of the submarine vent was located after the first *IEO* bathymetric survey on Oct. 24th (over two weeks into the eruption). This survey revealed a volcanic cone ~2.2 km off the coastline of La Restinga, with its summit at 220 m below sea level (Fig. 24D). Following determination of the depth and main features of the submarine volcano, civil protection measures became more aligned with the population's daily routines and the widespread public opinions on the events. Although we realise that the risk for oceanographic research vessels may be considerable (e.g. Morimoto, 1960), a remotely operated vehicle (ROV) may be a way forward in future, albeit a more costly one. Utilising an ROV and its mother vessel (from which the ROV is operated) would reduce the risk of losing the mother vessel and its crew in the event of a disaster, and would replace this risk with a purely financial one in the event of loss of the ROV.

We now know that the explosivity of the submarine eruption never reached a critical level, although the summit of the vent complex grew to a height of about 88 m b.s.l. at one point, but the eruption was, however, waning at that stage (Fig. 24D) (Feb. 24th, 2012). Furthermore, wall collapses of the submarine vent complex (Table 2) neither triggered tsunamis, nor led to enhanced explosivity due to loss of overburden pressure and/or possible exposition of an underlying hydrothermal system. Fluctuating intensity of gas outbursts at the sea surface likely

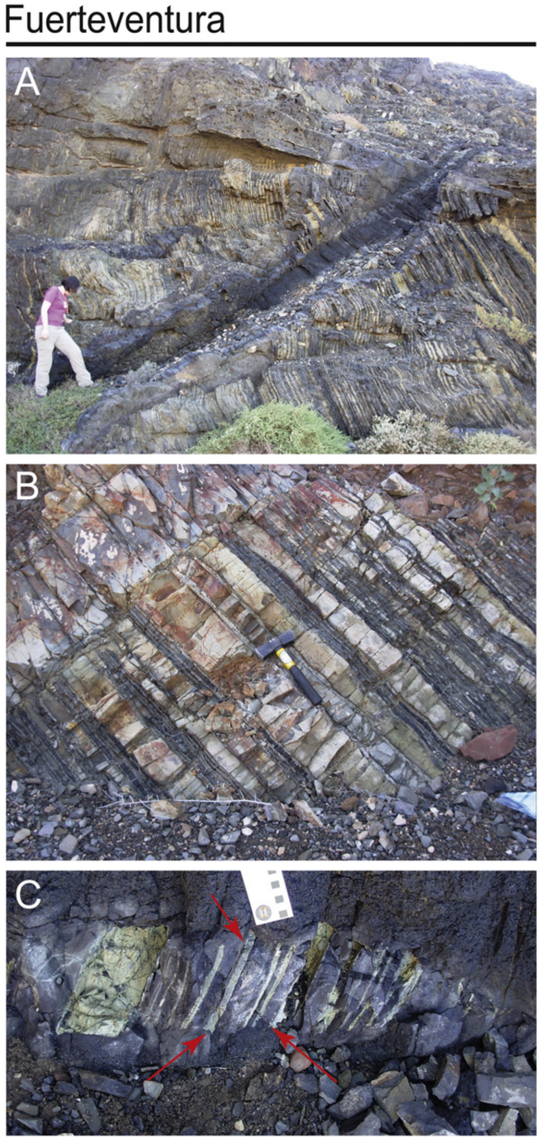

Fig. 23. Photos of the Mesozoic sedimentary rock sequence in the basal complex on Fuerteventura. A. An ankaramite dyke cross-cuts an uplifted and internally deformed portion of Mesozoic sedimentary rocks. B. Uplifted and tilted interbedded sequence of clay, silt-, and sandstones, cross-cut by an inclined dyke in the top left of the image. Hammer for scale. C. Screen of sedimentary strata, enclosed in cross-cutting ankaramite dyke, testifying to replacement of sedimentary strata by magmatic activity. Note the visible thermal cracking and alteration at the rim of the xenolith (red arrows).

correlated to vent degassing, caused by episodic large gas exhalations. Indeed, phreatomagmatic explosions in the Canaries are usually very localised (e.g. Clarke et al., 2009) and may in themselves not represent a threat for the bulk of an individual island's population. In this context, we must accept that it is not yet possible to determine precisely where new eruptive vents will open and how many of them will form (Carracedo et al., 1992; Day et al., 1997; Klügel et al., 1999). Although vents on El Hierro cluster along the rifts and the El Golfo collapse scar (Carracedo et al., 2001; Manconi et al., 2009), off-rift vents are not uncommon in the Canaries (e.g. Clarke et al., 2009). An accurate prediction of eruption sites is therefore difficult and associated with large epistemic uncertainties (see Section 6.5.2; and Clarke et al., 2009; Becerill et al., 2014). From this point of view, most areas of El Hierro were effectively at risk of being directly affected, with few possible exceptions, yet evacuations were very much localised only.

During the initial period of the eruption at El Hierro, and in spite of the unknown vent depth, members of the scientific advisory committee also considered an imminent, explosive eruption involving highly differentiated magmas (trachyte or rhyolite). These theories were based on the occurrence of high silica pyroclasts erupted during the first week of the submarine eruption (xeno-pumice). The first in-depth analytical evidence suggested that the white cored bomb interiors might actually be of sedimentary derivation rather than representing highly evolved magmatic liquids at depth (e.g. Troll et al., 2011), but conclusions of the origin and implications of xeno-pumice remained equivocal (see also below). In combination with the absence of a detectable shallow reservoir in the area that could host high-silica magma, the interpretation of an explosive high-silica magma chamber was rather unlikely. This is especially true since no white-coloured material was erupted after the first week of the events, suggesting that only a finite amount of this material was available to the eruption, consistent with a model of sedimentary rock protoliths for the xeno-pumice samples. Yet, a particularly large gas outburst on Nov. 5th, 2011, combined with the continuing uncertainties regarding the potential involvement of "explosive" high silica magma, prompted the authorities to order the second evacuation of La Restinga (see Figs. 24C, E). The presence of high silica, rhyolitic magma below El Hierro was questioned by a team of international scientists at that point (including two of the current authors, Juan Carlos Carracedo and Vicente Soler), and a report was sent to *PEVOLCA* scientists in early Nov. 2011. Chemical analyses of quartz crystals and high SiO_2 concentrations in glass (>80%) suggested the white cored bomb interiors to be dominantly recycled sedimentary rocks (Troll et al., 2011, 2012), similar to the common occurrence of the frothy sedimentary xenoliths elsewhere in the Canaries (e.g. Rothe and Schmincke, 1968; Klügel et al., 1999; Schmincke and Graf, 2000; Hansteen and Troll, 2003; Aparicio et al., 2006, 2010). However, this interpretation was not discussed by the authorities in any official statement (see also next section).

6.5.2. Managing epistemic uncertainty

In situations of volcanic crisis, where many parameters that contribute to the prediction of the outcome of a given situation are naturally unknown, predictive uncertainty becomes a serious issue (e.g. Sobradelo et al., 2015). Moreover, it is part of human nature to filter what we see through previously gained knowledge and experience. It is therefore difficult to assess data in a truly objective way, as individuals tend to be biased in terms of expectation (Bond et al., 2007). "Epistemic uncertainty" (the "unknown"; Doyle et al., 2014a,b) therefore becomes a challenging problem to manage in crisis situations, especially in localities where crises are infrequent. In these cases, the level of individual responsibility tends to be ill-defined, and media and public pressure is often intense (cf. Marrero et al., 2015; Sobradelo et al., 2015).

Post-eruption reflection indicates that the instrumental data acquisition and interpretations by *IGN* and *IEO* were of high quality, allowing early detection and determination of the approximate location of the eruption. This demonstrates the preparedness and capacities of both institutions to monitor onshore and offshore volcanic eruptions in the Canary Islands. An aspect that raised concern, however, was the relatively limited number of scientists that comprised *PEVOLCA*. Another issue was that during the crisis, sampling permissions were officially restricted to this group alone (Pérez-Torrado et al., 2012; "El País", Jan. 9, 2012: "Una economía hundida por el volcán"; "El País", Jan. 19, 2012: "El Hierro: 100 días de volcán y de ruina económica para la isla"). The police at the airport (*Guardia Civil*) were ordered to oversee that no "illegal" eruptive material was taken off the island, by consequence restricting the involvement of international research teams (Carracedo et al., 2011c, 2012; Pérez-Torrado et al., 2012). This approach likely limited the pool of expertise available to support decision-making at critical points during the crisis. The decision to withhold a survey vessel that could have provided detailed information on submarine activity right from the onset of the eruption was another point of serious concern

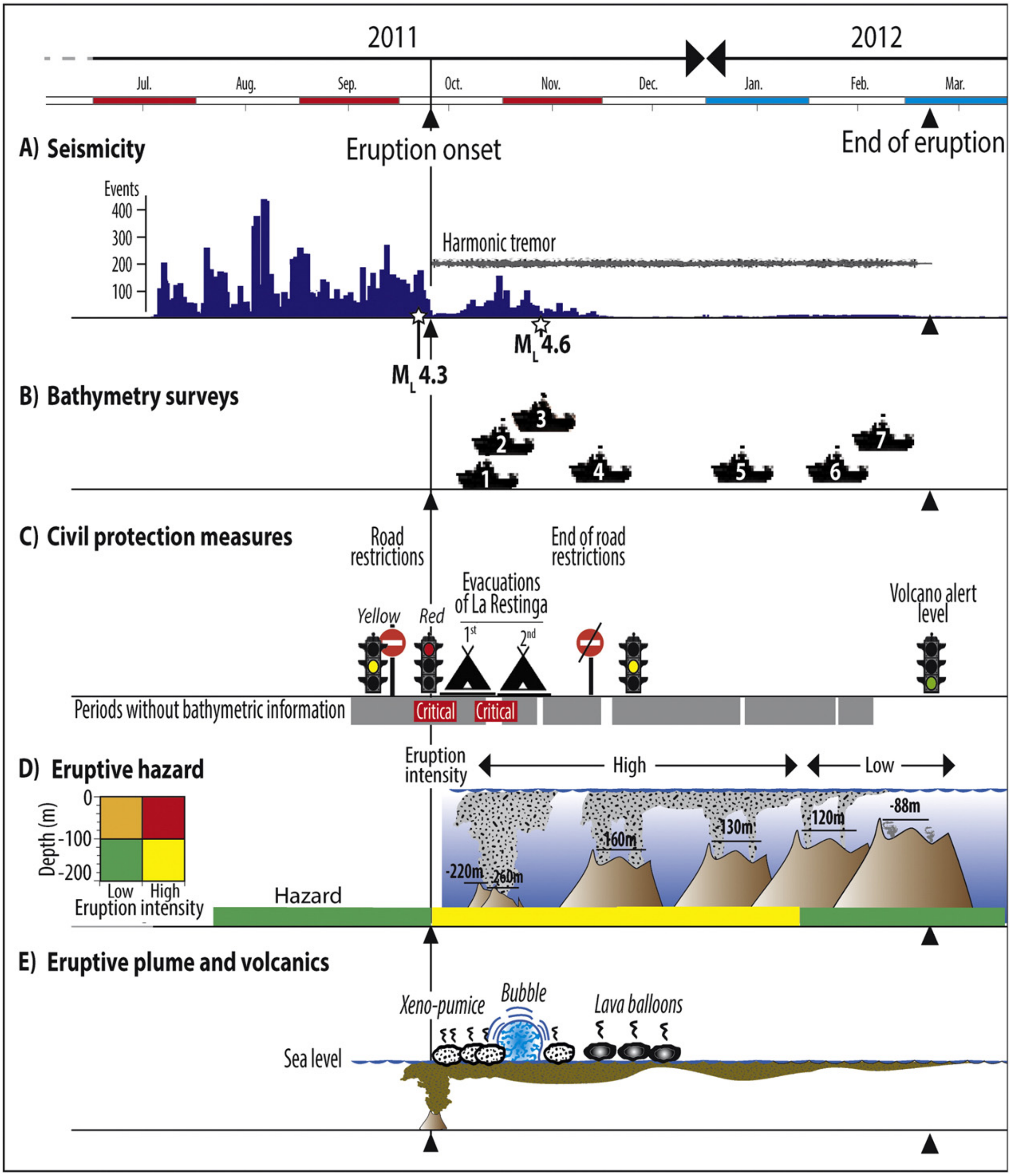

Fig. 24. Scientific information available during the 2011 submarine eruption on El Hierro and civil protection measures taken (see text for details).

for many observers (e.g. Carracedo et al., 2011c, 2012; Pérez-Torrado et al., 2012). The first evacuation of La Restinga prior to deployment of the oceanographic vessel was likely ordered because insufficient information on the distance and depth of the submarine vent or the exact compositions of magmas involved necessitated a higher level of caution than was perhaps necessary. The lack of on-site data via non-deployment of a survey vessel at the beginning of the crisis to provide constraints on the depth of the eruption vent was probably, in hindsight, a serious underestimation of the full range of possible scenarios that may unfold. Public opinion was particularly critical of this point as a small vessel of the *Guardia Civil* had already been surveying the area of "la mancha" in early Oct. 2011. The uncertain nature and unfolding controversy on xeno-pumice (see Section 4.4.2) is another factor that added to the complexity of possible situations to be considered. Much-needed constraints on the potential explosivity of the eruption via either Surtseyan or high-silica magma-driven explosions were ill-defined and a holistic view of evidence was unavailable for decision-making. This made balanced, timely, and effective scientific advice during critical points of the crisis very difficult and was likely a factor in civil protection measures that were viewed by many as prohibitive, and were in hindsight probably unnecessary (e.g. Pérez-Torrado et al., 2012; Marrero et al., 2015; Sobradelo et al., 2015; "El País", Jan. 19, 2012: "El Hierro: 100 días de volcán y de ruina económica para la isla").

It is worth noting, however, that just over a year previous, the Eyjafjallajökull eruption on Iceland in 2010 intersected a shallow felsic magma pocket which is believed to have initiated the explosive phase of the 2010 events (Sigmundsson et al., 2010). However, the possibility of shallow felsic magma at El Hierro lacked seismic supporting evidence, as no shallow magma reservoir was detected prior to, or during the eruption. This is in stark contrast to the situation at Eyjafjallajökull, where the presence of a shallow magma pocket was seismically detected, with violent magma mixing eventually ensuing in the later stages of the eruption (Sigmundsson et al., 2010). The recent, and probably very vivid, impression of the Eyjafjallajökull eruption in 2010, and the subsequent strong media and research interests at the time, may have created the impression that it was best to prepare for an Eyjafjallajökull-style event, especially because of the large uncertainties. The evacuation of La Restinga seems to have hence been a dominantly reactive decision. Seismicity was also strong under El Golfo at times, yet the much more populous villages in the El Golfo region were not at any point evacuated. Civil protection measures taken in La Restinga during the 2011 submarine eruption off El Hierro therefore seemed disproportionate for many (i.e. "Diario de Avisos", Nov. 5, 2011: "Frustración en La Restinga"; "El País", Jan. 9, 2012: "Una economía hundida por el volcán"; "El País", Jan. 19, 2012: "El Hierro: 100 días de volcán y de ruina económica para la isla") especially in the sense of Schiermeier (2010), who warns: "Every ounce of extra prevention is counterproductive in a crisis situation as it reduces the overall credibility of the system". This lesson was learned at several places around the globe over the last few decades, where geophysical unrest did not always lead to eruption (e.g. at Campi Flegrei, Italy or Mammoth lakes, USA; Bailey and Hill, 1990; Gottsmann et al., 2003). Effective crisis-management strategies therefore need to develop towards a fine-tuned management of information and consequent actions. Crisis management teams should be able to digest multiple information input sources and still instigate coordinated and systematic actions and responses. Ideally, these responses would satisfactorily cover most of the probable crisis developments anticipated, while at the same time an open dialogue with the general public to ensure their support during protective measures would be maintained (c.f. Doyle et al., 2014a,b). During the 2011 El Hierro events, civil protection measures at La Restinga (600 residents) seemed to many to involve unorganised closures and reopening of sections of the island's main road tunnel, as full explanations of the reasons for these decisions were not communicated. As a result, residents felt increasingly confused, and intensely frustrated. The civil protection measures were criticised to have been proportional to a scenario of an impending large explosive eruption (see Pérez-Torrado et al., 2012), and are widely viewed to have resulted in partial collapse of the island's tourism-based economy (i.e. "El País", Jan. 9, 2012: "Una economía hundida por el volcán"). The financial damage, the uncertainty, the distress to local communities, and the inconveniencies from protective measures eventually resulted in intense public dismay when large explosive activity did not materialise at any point during the 2011–2013 events (i.e. "El País", Jan. 19, 2012: "El Hierro: 100 días de volcán y de ruina económica para la isla").

6.5.3. Preparing for the next Canary eruption

Extensive risk mitigation measures were undertaken during the 2011–2012 volcanic crisis, to a much greater extent than for previous eruptions in the Canary Islands, with the aim of preventing harm from earthquakes and eruptions to the population and economy of the island.

Instrumentally detected micro-seismicity, even at very low magnitude, is an important tool to investigate the internal structure of oceanic volcanic systems and provides a valuable precursory signal to eruptions. However, the analysis of S-wave travel times to define the presence of potential eruptible magma requires long recording periods for comparison (i.e. a stable baseline). The strategic deployment of seismic stations in the Canaries was initially not aimed at volcanic activity, however (e.g. Mezcua et al., 1989). This is because the Canary seismic network was originally designed to record tectonic earthquakes, in the sense of continental mainland networks. It was only after the intense media coverage of the 2004 unrest on Tenerife that seismicity detected in the archipelago was widely accepted to be dominantly of magmatic rather than tectonic origin, and consequently, the number of seismic stations around volcanic vent areas was increased to improve monitoring and early detection of volcanic activity. This was legally reinforced by the Royal Decree of June 18th, 2004, just after the 2004 crisis in Tenerife, commissioning the *IGN* with the responsibility of monitoring volcanic activity and associated hazards in Spain, including the Canary Islands. It appears now that this was a wise move, as it created a modern instrumental network that was fully operational for the 2011–2012 El Hierro events.

For comparison, the Hawaiian Volcano Observatory deploys a seismic network that has been at the estimated optimum density of stations since 1984. The resulting long-term records provide the crucial baseline to define periods of abnormal activity and thus to sensibly mitigate eruptive risks (Tilling, 2008). The wealth of seismic data, including S-wave travel times that are associated with natural seismic activity only and are not reproducible in active seismic experiments, allowed a detailed reconstruction of the internal structure of the main active volcanoes on Hawaii from the three-dimensional distribution pattern of earthquakes (Ryan, 1987). Although *IGN* increased the density of seismic stations after 2004, the number is still far from sufficient to build a database that compares to that of Hawaii, Réunion, or the Azores. The internal structures of the most active Canarian volcanoes such as the Teide and Pico Viejo volcanic complex on Tenerife, the Cumbre Vieja volcano on La Palma, and the island of El Hierro are not particularly well defined (e.g. Carracedo and Troll, 2013). It is therefore encouraging that *IGN*, the institution officially tasked to monitor seismic and volcanic hazards in the Canaries, now focusses on magmatic processes as the source of seismicity and ground deformation, and highlights the need for specific and denser seismic and ground deformation networks for each of the Canary volcanoes. In a summary of the efforts by *IGN* on the identification and monitoring of the 2011 El Hierro submarine eruption, López et al. (2012) state "*the main lesson learned from post-eruption critical analysis is that global coverage of the area should be accomplished as soon as possible in order to have a real-time characterization of possible lateral magma migrations or new areas of magma injection*".

In this context, we also need to consider human perception versus statistical probabilities. Considering the historical eruptions in the last 500 years, there were 13 eruptions in the Canaries as a whole (6 on La Palma, 5 on Tenerife, and 2 in Lanzarote), and remarkably none on El Hierro, unless they were offshore (such as e.g. the possible 1793 events, as discussed in Section 2.1). Using statistical predictions based on historical eruptions in the Canaries, La Palma and Tenerife emerge as the most probable locations of a future eruption in the archipelago (e.g. Sobradelo et al., 2011). However, many local residents consider Lanzarote most active, probably because of collective memories of the devastating 1730–36 eruption. El Hierro was hence not considered the prime candidate for an eruption by either approach. The probability distribution of eruptions in the Canary archipelago should now be re-examined and will have to include the additional modelling parameters provided by the 2011 eruption.

Another critical aspect is that of the handling of epistemic uncertainty (e.g. Rougier and Beven, 2013) during the course of immediate events at El Hierro in 2011 and 2012. A limited set of expertise is a critical issue in this respect, as it is well established that we are more likely to "see what we already know" (Bond et al., 2007). Relying on a limited set of scientists on site is therefore not advisable, especially as small groups of experts are prone to knowledge deterioration (Derex et al., 2013; Richerson, 2013), thus making an open scientific board a desirable component during the handling of crisis events such as an eruption. It may indeed be advantageous to adopt solutions similar to those increasingly used in crisis management such as employing neutral scientists within the emergency management organization whose job is specifically to assess and evaluate the data and interpretations provided by different scientific groups or experts, and to balance the different views for emergency managers (e.g. the 1985 Nevado del Ruiz eruption, Columbia; Voight, 1990).

For example, the epistemic uncertainties that existed prior to and during the onset of the 2011–2012 El Hierro eruption might have been reduced by seeking advice from neutral assessors who could mediate incoming views, information, and requests with local scientists of the advisory board. Perhaps in the long run, "defeasible argument software" that can balance various models against each other (within the given input parameters) will analyse a situation on a purely factual basis (e.g. Sobradelo et al., 2015). Such tools are increasingly used in medicine, where critical decisions are often made under extreme time- and emotional pressure and where expert opinions frequently differ due to differential diagnoses (e.g. Fox et al., 2007). Such an approach, if it were adopted by volcanology, might avoid both over- and under-reactions and thus might regulate cost, uncertainty, and unnecessary effort and distress on future occasions. Detailed emergency management plans are thus of limited value without an accompanying continuous, well-integrated scientific monitoring effort and a strong and independent national and international expert pool that can be consulted on demand.

To underscore the importance of these lessons, let us briefly consider the possibility of an El Hierro-style eruption near Las Palmas de Gran Canaria or Santa Cruz de Tenerife instead of the relatively sparsely populated island of El Hierro. Assuming unrest in either of these places would have caused enormous public alarm, the hazard management steps as taken at El Hierro would have led to large-scale disruption of daily life in these key population centres, and thus indeed throughout the islands as a whole. This thought experiment represents a real possibility, because ~6 km from Las Palmas de Gran Canaria a suite of young (≤2000 years) volcanic cones exist that previously produced phreatomagmatic ash deposits. These notably also contain xeno-pumice and spread towards the present-day city for a few kilometres (e.g. the Bandama vent; Hansen et al., 2008). In preparation for such a scenario, increased interaction between the general public and the authorities would be highly relevant and proper management of such a situation (with or without a final onshore eruption), would present a formidable challenge for the authorities. Educational efforts by the authorities therefore appear to be a real need to advance preparedness of the population in these regions of the archipelago also (e.g. Doyle et al., 2014a,b; Marrero et al., 2015).

The El Hierro 2011–2012 events therefore underline the need to analyse volcanic crisis situations carefully, to optimise the use of scientific methods, and to exercise the appropriate employment of instrumental and human resources available. The handling of the El Hierro eruption thus highlights lessons that will also have to be considered for crisis management guidelines in general (e.g. *International Association of Volcanology and Chemistry of the Earth's Interior* (*IAVCEI*) guidelines; Newhall, 1999). Indeed, *IAVCEI* or national authorities may need to incorporate the fact that conceptual advice should be moderated by body of neutral experts that can be called to aid in times of unrest and crisis to provide an assessment of the degree of epistemic uncertainty and judge from the perspective of an outsider, independent of national or local politics, societal pressures, or economical dependencies.

7. Closing remarks

The compiled data on the 2011–2012 El Hierro events reviewed here allow us to now consider a number of geological phenomena in a new light. These include i) appreciation of the significant role of intrusive activity and underplating in Ocean Island growth, ii) an improved understanding of island structure, magma plumbing, and migration pathways in Atlantic oceanic islands, iii) the definition of "xeno-pumice" and its addition to the volcanic lexicon, and iv) the opportunities for improving hazard assessment and responses in a regional Canary context. The most important aspects learned from the 2011–2012 El Hierro submarine eruption concerning the management of the volcanic crisis include a) the need for rapid-response (submarine) survey capacities, either by mother vessel or by the employment of a remotely operated vehicle (ROV), b) the need for a formal organisational framework that can openly handle future eruptions and ensure transfer of the organisational knowledge gathered during this event for future crisis situations (i.e. Garcia et al., 2014; Scarlato et al., 2014; Marrero et al., 2015), c) the need for enhanced communication strategies and structures, including the employment of outside expertise to control epistemic and public uncertainty and a formalised strategy for public information and data release. The latter aspect would also include communication with, and education of, wider societal circles in the Canary Islands and beyond.

Acknowledgements

JCC, VRT and KZ contributed in approximately equal proportion to the current article. We are indebted to the Instituto Geografico Nacional, in particular to Carmen López and Maria José Blanco, for valuable information and discussion. The Consejo del Medio Natural, Cabildo de El Hierro, kindly permitted us to take the samples of the "floating stones" of the eruption, and Paola C. Agnew collected xeno-pumice samples of the initial days of the eruption. We furthermore thank A.K. Barker, A. Klügel, S. Burchardt, S. Wiesmaier, U. Kueppers, C. Harris, B. Dahren, L. S. Blythe, F. J. Perez-Torrado, T. H. Hansteen, C. Freda, D. A. Budd, E. M. Jolis, E. Jonsson, F. C. Meade, S. E. Berg, L. Samrock, T. Mattsson, O. Sigmarsson, L. Mancini, and M. Polacci for valuable input and discussions on the El Hierro xeno-pumice samples. We also thank J.A. Gamble and an anonymous reviewer for constructive criticism that helped to improve the quality of the manuscript. Lastly, we are grateful to the Royal Swedish Academy of Science (KVA), the Swedish Science Foundation (VR project 2013-5628), the Centre of Natural Disaster Science (CNDS) at Uppsala University, the Canarian Government, and CSIC for generous financial support (projects PN785/2012, MEC CGL2011-25494, CGL12-33430, and SolSubC200801000047).

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