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Floating sandstones off El Hierro (Canary Islands, Spain): the peculiar case of the October 2011 eruption

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Abstract

The eruption that started off the south coast of El Hierro, Canary Islands, in October 2011 has emitted intriguing eruption products found floating in the sea. These specimens appeared as floating volcanic “bombs” that have in the meantime been termed “restingolites” (after the close-by village of La Restinga) and exhibit cores of white and porous pumice-like material. Currently the nature and origin of these “floating stones” is vigorously debated among researchers, with important implications for the interpretation of the hazard potential of the ongoing eruption. The “restingolites” have been proposed to be either (i) juvenile high-silica magma (e.g. rhyolite), (ii) remelted magmatic material (trachyte), (iii) altered volcanic rock, or (iv) reheated hyaloclastites or zeolite from the submarine slopes of El Hierro. Here, we provide evidence that supports yet a different conclusion. We have collected and analysed the structure and composition of samples and compared the results to previous work on similar rocks found in the archipelago. Based on their high silica content, the lack of igneous trace element signatures, and the presence of remnant quartz crystals, jasper fragments and carbonate relicts, we conclude that “restingolites” are in fact xenoliths from pre-island sedimentary rocks that were picked up and heated by the ascending magma causing them to partially melt and vesiculate. They hence represent messengers from depth that help us to understand the interaction between ascending magma and crustal lithologies in the Canary Islands as well as in similar Atlantic islands that rest on sediment/covered ocean crust (e.g. Cape Verdes, Azores). The occurrence of these “restingolites” does therefore not indicate the presence of an explosive high-silica magma that is involved in the ongoing eruption.

1 Introduction

On 10 October 2011, a submarine eruption began off the south coast of El Hierro (ca. 27°37′ N; 18° 0′ W), the westernmost and youngest (1.12 Ma; Guillou et al., 1996)

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island of the Canaries. Surface expressions of this eruption, the first to be witnessed at El Hierro, included green discolouration of seawater (locally known as “la mancha”) and strong bubbling and degassing. In addition, abundant rock fragments resembling lava bombs on a decimetre scale, and characterised by glassy basaltic crusts and white to cream coloured interiors, were found floating on the ocean surface during the first days of the eruption. The interiors of these floating rocks are glassy and vesicular (similar to pumice), and mingling between the pumice-like interior and the enveloping basaltic magma is often observed. These floating rocks have become locally known as “restingolites” after the nearby village of La Restinga. Their nature and origin remain elusive however, with suggestions from the scientific community including: (i) that the “restingolites” are in fact juvenile and potentially explosive high-silica magma, (ii) that they are fragments of marine sediment from the submarine flank of El Hierro, and (iii) that they are relatively old, hydrated volcanic material (see e.g. Coello, 2011; Gimeno, 2011). However, none of these interpretations provides a satisfying fit to the available observations, since, for instance, high-silica volcanism is uncommon on El Hierro, and magmatic minerals (either grown in magma or as detritus from erosion) are entirely absent in the “restingolites”. Given that the involvement of highly evolved, high-silica magmatism would have implications for the explosive potential of the eruption, it is important to clarify the nature of the “restingolites” in order to fully assess the hazards associated with the ongoing El Hierro eruption. Furthermore, in the case where the “restingolites” can be shown not to originate from high-silica magma, unravelling their genesis will provide unique insights into the volcano-magma system beneath El Hierro. We collected samples of the floating “restingolites” on 21–25 October and 28 October of 2011 for textural, mineralogical, and elemental analysis. The results lead us to conclude that the “restingolites” from El Hierro are crustal xenoliths that originate from the layer of pre-island sedimentary rocks (layer 1 of the oceanic crust) underneath the Canary Islands.

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2 Analytical methods

2.1 Imaging and micro-analysis: electron probe micro analyser

Scanning electron microscopy (SEM) imaging and micro-analysis of the "restingolites" was carried out in the Centre for Experimental Mineralogy, Petrology and Geochemistry (CEMPEG) at Uppsala University, Sweden, using a JXA-8530F JEOL HYPERPROBE field emission electron probe micro-analyser (FE-EPMA). The FE-EPMA is equipped with four wavelength–dispersive spectrometers (WDS) and secondary and backscattered electron detectors. Microprobe EDS analyses were performed using an accelerating voltage of 15 kV, a beam current 5 nA, and a beam diameter of 5 µm for glass and 1 µm for mineral analyses.

2.2 Mineralogy: XRD

Samples of "restingolites" were crushed to mm-sized chips and separated from the enclosing lava by hand-picking the pumice chips for pristine appearance. The clean chips were then pulverised to a fine powder using an agate mill at CEMPEG, Uppsala University. The mineral assemblage of the El Hierro "restingolite" rock powders was subsequently determined by X-ray diffraction (XRD) using a Siemens/Bruker D5000 diffractometer at the Geological Survey of Sweden (SGU) laboratory in Uppsala, Sweden.

2.3 Major and trace elements: XRF and LA-ICP-MS

The major and trace element composition of four representative "restingolites" were determined by X-ray fluorescence (XRF) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Bremen, Germany. For XRF analyses, hand-picked pumice chips were cleaned in an ultrasonic bath and pulverise in an agate mill. Loss on ignition at 1000 °C was determined gravimetrically. About 3 g of powder was mixed with wax, pressed into a pellet and analysed using a

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Philips PW1400. LA-ICPMS analyses were carried out on clean pumice chips using a NewWave UP193ss LA-ICP-MS coupled to a Thermo Element2. Analytical conditions included a laser beam diameter of 75 µm, a pulse rate of 5 Hz, an irradiance of ca. 1 GW cm^{-2}, and 0.66 l min^{-1} He as a sample gas. NIST612 glass was used for quantification with Ca as the internal standard element; data quality was monitored by analysing BHVO-2G glass.

3 Results

3.1 Textural observations

The cores of the "restingolites" that were erupted offshore El Hierro stand in a sharp contrast to their glassy, basaltic crusts (Fig. 1). They range in colour from white and cream to medium and dark grey and exhibit a foam- (or pumice-) like texture (Fig. 2) and a glassy matrix. This results in extremely low densities that enable them to float on water, in spite of carrying a dense basaltic crust. Individual vesicles may be up to several mm in size, but typically they are on the sub-mm level (Fig. 3). The vesicles are heterogeneously distributed throughout the rock, occurring in bands, individually or as clusters (e.g. Figs. 1–3). In particular, some of the "restingolites" show physical mingling textures with the basaltic magma expressed as flow folds and schlieren structures (e.g. Fig. 1e, f and Fig. 2e). Layering that is identified as primary by changes in colour, which is also frequently folded, indicates a ductile deformation episode (e.g. Fig. 1d–f).

3.2 Mineral and glass phases

All samples are glassy and light in colour and most samples are macroscopically crystal-free, however, occasional quartz crystals, jasper fragments, gypsum aggregates, and carbonate relicts have been identified in hand specimen (Fig. 2a–c). X-ray diffractograms indicate the presence of principally quartz, biotite and/or illite, and glass.

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The occurrence of halite documents the influence of sea water. There is a notable absence of primary igneous minerals from the XRD data (Table 1). A comparatively significant phyllosilicate peak at ca. 10 Å probably reflects thermal decomposition of smectites (Appendix Fig. A2, A3).

SEM and Energy-Dispersive X-ray (EDX) analysis has revealed the largely glassy and pervasive vesicular nature of the samples (Fig. 3; Table 2). Microscopic quartz crystals have also been identified and analysed by FE-EPMA (Fig. 3c; Table 2).

3.3 Major and trace element composition

The major element composition of glass and crystal phases in the "restingolites" obtained by EDX is given in Table 2. Major and trace element data obtained by XRF on three representative "restingolites" are presented in Table 3. For comparison, the following representative data are also given in Fig. 4 and Table 3: (i) siliciclastic crustal xenoliths from Gran Canaria and Lanzarote (Hansteen et al., 1998; Hansteen and Troll, 2003; Aparicio et al., 2006), (ii) ocean floor dredged sediment (Berg, 2011), (iii) basanites and trachytes from El Hierro (Pellicer, 1979; Carracedo et al., 2001), (iv) trachytes and rhyolites from Gran Canaria (Troll and Schmincke, 2002), and (v) basanites and phonolites from Tenerife (Wolff and Palacz, 1989; Wiesmaier, 2010).

The composition of glass in the "restingolites" and bulk white core samples is dominated by SiO_2 (70 to 80 wt. %) (Tables 2 and 3). In fact, the glassy coating on the sedimentary restite in Fig. 3c contains 89 wt. % SiO_2, while the crystal in the centre of this image yields 100 wt. % SiO_2 (i.e., it is quartz). Aside from silica, other major constituents are Al_2O_3 (up to 18 wt. %), Na_2O (up to 6 wt. %), and K_2O (about 5 wt. %), while FeO and CaO contents are very low (Tables 2 and 3). The concentration of some trace elements is also remarkably low (e.g. Sr, Zr; Table 3; Fig. 4), given the high SiO_2 content.

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The chemical data thus underline that "restingolites" are highly atypical for Canary magma compositions. Chemically, they resemble known sedimentary xenoliths and pre-island sedimentary compositions if their full major and trace element compositions are considered.

4 Similar rocks from elsewhere in the Canary Islands

Eruption products similar to the samples from El Hierro are known from historic and Holocene volcanic activity on the Canary Archipelago. Araña and Ibarolla (1973) report "rhyolitic pumice" erupted during the 1971 eruption of Teneguía on La Palma that are of similar composition (their analysis No. 2, white pumice) and thus likely to be of similar origin to our samples. Xenoliths of similar nature were also found in the 1949 eruptions on La Palma (Klügel et al., 1999) and in eruption products of the submarine volcanic edifice Hijo de Tenerife offshore between Gran Canaria and Tenerife (Schmincke and Graf, 2000). Furthermore, partly melted sandstone xenoliths were found in Holocene basanite eruptives of Gran Canaria (Hansteen and Troll, 2003), and Aparicio et al. (2006, 2010) describe similar xenoliths, some including fossil-bearing limestone and shale 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 carbonates (cf. Stillman et al., 1975).

We have analysed samples of such xenoliths from Gran Canaria, La Palma, and Lanzarote that have undergone heating, degassing, and expansion. In particular, a suite of samples of white, vesicular sandstone xenoliths from Gran Canaria strikingly resemble the "restingolites" from El Hierro in texture, composition and general appearance. The Gran Canaria sandstone samples are glassy, strongly vesicular (Fig. 2d and e; Fig. 3g–i), and contain variable amounts of strongly altered quartz crystals. Based on their "frothy" texture, we term these and other vesicular xenoliths "xeno-pumice", because they are pumice-like in appearance but xenolithic in origin. Xeno-pumice from

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Gran Canaria exhibits density values as low as 0.54 g cm^{-3} and open porosity values of 78 %. X-ray µ-CT imaging reveals vesicle networks and pipelines, through which gas could leave the xenoliths.

5 Discussion: Nature and origin of the "restingolites"

The high silica content coupled with overall low incompatible trace element concentrations, the occurrence of mm-sized relict quartz crystals and the lack of igneous minerals, plus the occurrence of carbonate, clay, jasper, and gypsum relicts are all incompatible with a purely igneous origin for the cores of the floating stones (cf. Table 1). In fact, El Hierro igneous rocks are generally silica undersaturated, and the most evolved igneous rock reported from El Hierro barely reaches silica concentrations of 65 wt. % (Pellicer, 1979). Igneous rocks on El Hierro do not contain any free (primary) quartz crystals (nor do igneous rocks on any of the other Canary Islands).

A potential source of the quartz crystals found in the floating rocks from El Hierro could be sand plumes that originate from large sand storms in the Sahara desert that can transport considerable quantities of aeolian sediment that is deposited in the Canarian Archipelago (e.g. Criado and Dorta, 1999). These recent wind-blown sediments are very fine-grained, which rules out a purely aeolian transport for the mm-sized quartz crystals found in the "restingolites". Instead, the sedimentary rocks of layer 1 of the pre-island ocean crust consist of material transported from Africa by both wind and turbidity currents (cf. Criado and Dorta, 1999; Ye at al., 1999; Gee et al., 1999; Krastel and Schmicke, 2002), intermixed with "regular" oceanic background sedimentation. These sedimentary rocks of layer 1 are thus likely to contain larger quartz crystals and a variety of different sedimentary facies. The absence of any igneous minerals, such as pyroxene, amphibole or accessory phases, such as titanite or zircon, in the "restingolites" and their trace-element chemistry demonstrate that the "restingolites" are neither derived from a typical evolved Canary magma, nor from sediments on the submarine slopes of El Hierro, as both would contain igneous minerals. In the former case, they

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would have grown from the magma and in the latter they would have been concentrated due to the considerable detrital input of eroded igneous minerals from the island (cf. Sumita and Schmicke, 1998). The absence of igneous minerals, in turn, suggests that the sedimentary protolith to the "restingolites" was formed before any igneous influence affected the sedimentation around El Hierro, i.e. they formed before the island was built, otherwise igneous minerals would still be expected in 'melted' xeno-pumice, especially given that relict clays (low melting temperature) are still observed in places. We therefore propose that it is these pre-island sedimentary rocks of ocean crust layer 1 that have been brought up as "restingolites".

The features of the El Hierro xeno-pumice samples described above indicate that they became heated, melted and eventually vesiculated during their transport in magma. The mingling textures and the often sharp contact to the enclosing basalt indicates that these samples came in contact with the magma only shortly (hours) prior to eruption, whereas complete assimilation and blending/hybridisation would require a somewhat longer time (cf. Perugini et al., 2010; McLeod and Sparks, 1998; Sparks, 1998). Thermal conductivity values of typical rocks show that a basaltic magma would heat up a fist-size sedimentary xenolith in about half an hour (Hansteen et al., 1998), a time during which significant mingling of melts may already occur. We propose that this melting and the associated vesiculation of the sedimentary rock fragments leads to a) a dramatic density decrease of these xenoliths, giving them sufficient buoyancy in the magma and in sea water, but also b) progressive degassing of the xenolith melt. This raises its melting temperature and viscosity again, which results in limited mingling as observed and probable partial "freezing" of the melt (cf. Sparks, 1998; Hammer et al. 1999). Both processes, degassing and freezing, thus have likely contributed to an effective detachment of the xeno-pumices from the erupted lava to rise as "floating bombs" during the early phase of the eruption. The large quantities of "restingolites" during the early eruption phase and their disappearance during the later stages of the eruption is a likely consequence of the establishment of a relatively stable conduit, the formation of which required clearing the way for the ascending magma through the sedimentary rocks of layer 1 (Fig. 5; also compare IGN, 2011). In contrast, fragments of the oceanic crust layer 2 and 3 (pillow lavas, sheeted dykes, and layered gabbro) would not rise buoyantly to the sea surface due to protracted melting of basaltic rocks and significantly lower volatile contents.

We therefore conclude that the "floating rocks" of El Hierro originate from the sedimentary rocks of layer 1 of the oceanic crust beneath the Canary Islands. Beneath El Hierro, the pre-island sediments are likely to be less voluminous (and probably more fine-grained) than under, e.g., Gran Canaria, and may reside at depths of approximately 5 to 6 km below sea level (Collier and Watts, 2001; Hansteen and Troll, 2003; Fig. 5). Seismicity at El Hierro prior to and in the early phase of the eruption clustered between 7 and 17 km depth, i.e. within the igneous ocean crust and at the base of crustal layer 1 (IGN, 2011).

6 Conclusions

The "floating rocks" observed in October 2011 off El Hierro, Canary Islands, originate from pre-island sedimentary rocks, in particular quartz-rich sand- and mudstones, from layer 1 of the oceanic crust beneath El Hierro. The xenoliths are messengers from depth that attest to the importance of magma-crust interaction beneath the Canary Islands. This is likely to be most pronounced in young edifices in their main shield-building stage and may also play a role in the volatile budget of the initial phases of such eruptions. The occurrence of these high-silica rocks does, however, not indicate a high explosivity potential of the eruption as a whole.

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Table 1. Minerals present in restingolite samples from XRD analysis. For individual analytical spectra see Appendix Figs. A2 and A3.

Sample	Olivine	Pyroxene	Amphibole	Feldspar	Mica	Quartz	Illite	Halite	Smectite
EH-XP-1	x	x	x	x	✓	✓	✓	x	✓
EH-XP-2	x	x	x	x	✓	✓	✓	✓	✓
EH-XP-3	x	x	x	x	✓	✓	✓	x	x

x = not detected, ✓ = presence confirmed

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Table 2. Representative EDS analysis of El Hierro restingolite glasses.

Sample I.D.:	EH-XP3	EH-XP4	EH-XP5	EH-XP9	EH-XP11	EH-XP11	EH-XP312	EH-XP13
SiO_2	73.86	74.62	74.58	75.75	71.99	63.34	89.43	100
Al_2O_3	16.39	17.53	17.33	17.41	18.03	18.017	6.877	–
Fe_2O_3	–	–	–	–	–	–	–	–
MgO	–	–	–	–	–	–	–	–
CaO	2.06	–	–	–	–	–	–	–
Na_2O	1.45	2.37	3.83	2.39	4.77	11.66	1.61	
K_2O	6.24	5.47	4.26	4.44	5.21	7	2.09	
SO_3	–	–	–	–	–	–	–	–

Major elements are given as wt. % oxide.

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Table 3. Major and trace element composition of El Hierro "floating rocks". Data for Gran Canaria and Lanzarote crustal xenoliths, ocean floor sediment, and representative Canary Island magmatic rocks are shown for comparison.

	Restingolites			Crustal Xenoliths		Flank Sediment	Representative Magmatic Rocks			
Sample I.D.:	H12110 [1]	EH2510-1 [2]	EH2110-2 [3]	HAT917C [4]	ANG-58 [5]	SED174-1-1 [6]	C1H102 [7]	EH21 [8]	Al-MCa [9]	CAB [10]
SiO_2	69.19	71.03	68.61	86.7	83.48	32.35	56.43	59.96	69.27	60.88
TiO_2	0.22	0.18	0.21	0.4	0.36	3.44	1.26	0.91	0.68	0.70
Al_2O_3	15.76	15.10	15.43	4.9	7.05	11.61	19.30	19.38	14.47	19.42
Fe_2O_3	0.73	0.69	0.71	2.5	2.35	12.29	5.60	4.11	3.56	3.30
MnO	0.01	0.02	0.02	0.06	0.05	0.21	0.28	0.24	0.15	0.16
MgO	0.31	0.12	0.55	1.3	2.25	9.98	1.33	0.85	0.29	0.41
CaO	0.48	0.31	0.47	1.2	1.31	5.95	5.73	4.30	0.36	0.97
Na_2O	6.09	6.11	6.52	0.8	0.76	2.61	7.23	7.14	6.58	8.37
K_2O	4.88	4.73	4.78	0.9	1.5	0.92	2.43	2.90	4.39	5.46
P_2O_5	0.07	0.04	0.05	0.06	0.09	0.94	0.41	0.19	0.06	0.10
LOI	1.19	1.06	1.00	1.57	0.6	19.3	–	–	–	0.31
Sum	98.93	99.39	98.35	100.38	99.80	99.74	100.00	100.00	99.81	100.08
Ba	436.05	543.60	495.99	131	330	114	801	868	693	527
Co	1.10	1.02	0.63	–	5.29	49	4	37	< 4	0.6
Cr	5.65	0.52	1.11	–	62.9	166	2	9	< 18	5.5
Cu	9.71	2.61	6.43	65.1	10.2	104	–	–	–	< 3
Nb	72.51	56.21	56.05	6.5	6.78	78	172	214	148	185
Ni	2.08	1.66	10.30	–	25.6	91	6	–	–	< 4
Pb	7.26	14.25	7.14	3.89	–	5.69	–	4	7	17.6
Rb	42.98	49.34	48.29	31.7	56.8	1.8	68.4	93	100	151
Sr	90.44	79.39	135.03	113	127	444	2099	1465	30	34.2
Th	5.53	7.58	6.93	3.62	–	3.5	15	23	19	26.2
U	23.90	11.80	3.28	0.52	–	1.2	–	–	–	6.89
V	0.99	0.47	1.51	–	57.5	193	34.6	37	31	11.7
Zn	21.54	37.40	38.01	28.4	36.0	142	186	149	159	101
Zr	236.83	219.96	211.50	25.6	98.2	310	857	1191	1037	960
Rb/Sr	0.48	0.62	0.36	0.28	0.45	0.00	0.03	0.06	3.33	4.42
U/Th	4.32	1.56	0.47	0.14	–	0.34	–	–	–	0.26
Zr/Nb	3.27	3.91	3.77	3.94	14.44	3.97	4.98	5.56	7.01	5.19
Y	9.98	5.78	4.67	8.57	13.7	32	58.5	53	–	26.3
La	29.23	28.84	34.57	14	14.5	43.9	151	149	93	91.6
Ce	77.76	62.95	85.16	28	29.72	98.66	305	302	397>	153
Pr	7.19	7.55	7.99	3.23	3.61	11.7	36.23	30	–	14.4
Nd	23.85	21.26	25.52	12	13.87	50.1	–	–	–	44.1
Sm	4.14	4.74	4.15	2.49	2.76	8.4	–	–	–	6.75
Eu	0.76	0.80	0.82	0.53	0.64	2.4	–	–	–	1.68
Gd	2.63	2.38	2.49	2.26	2.47	7.0	–	–	–	5.1
Tb	0.39	0.30	0.30	0.31	0.365	0.9	–	–	–	0.82
Dy	2.13	1.57	1.56	1.61	2.248	5.6	–	–	–	4.75
Ho	0.37	0.27	0.22	0.28	0.507	1.0	–	–	–	0.90
Er	0.97	0.62	0.52	0.78	1.3	2.1	–	–	–	2.64
Tm	0.18	0.09	0.09	0.11	0.212	0.3	–	–	–	0.41
Yb	1.15	0.60	0.65	0.64	1.441	1.8	–	–	–	2.91
Lu	0.17	0.08	0.09	0.09	0.26	0.3	–	–	–	0.45
Hf	5.83	6.84	7.24	0.66	–	5.81	–	–	–	16.4
Ta	3.93	4.81	4.79	0.53	-	3.9	-	–	–	12.4

Major elements are given as wt. % oxide; trace elements are given in ppm; "–" indicates that no data is available.

Notes: [1–3] Samples of restingolites collected off-shore El Hierro, October 2011. Major elements analysed by XRF; trace elements by LA-ICP-MS at the University of Bremen, Germany. [4] HAT917C is a siliclastic sedimentary xenolith from Gran Canaria (Hoernle, 1998; Hansteen and Troll, 2003). [5] ANG-58 is a siliclastic sedimentary xenolith from Lanzarote (Aparicio et al., 2006). [6] SED 174-1-1 is an El Hierro submarine flank sediment (Berg, 2011). [7] Trachytes from El Hierro (Carracedo et al., 2001). [8] Trachytes from El Hierro. Data obtained by XRF. [9] A1-MCa is a rhyolite from Gran Canaria (Troll and Schminke, 2002). [10] Phonolite from Tenerife (Wiesmaier, 2010).

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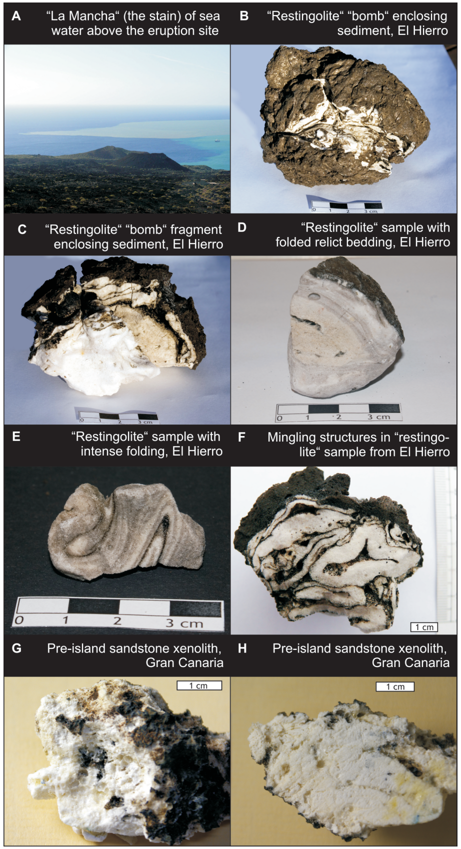

Fig. 1. Overview of features of “restingolite” samples from El Hierro. **(A)** Ocean surface above the offshore eruption. Note the changed colour of the water (locally referred to as “la mancha”, i.e. “the stain”) that occurred early during the eruption. **(B–F)** “Restingolite” samples displaying typical features, such as a crust of basalt, primary sedimentary bedding, folding, high vesicularity, and mingling structures. **(G and H)** “Xeno-pumice” samples from Gran Canaria that resemble the “restingolites” from El Hierro and have been demonstrated to originate from pre-island sandstone. For additional sample images of the “restingolites” see Appendix Fig. A1.

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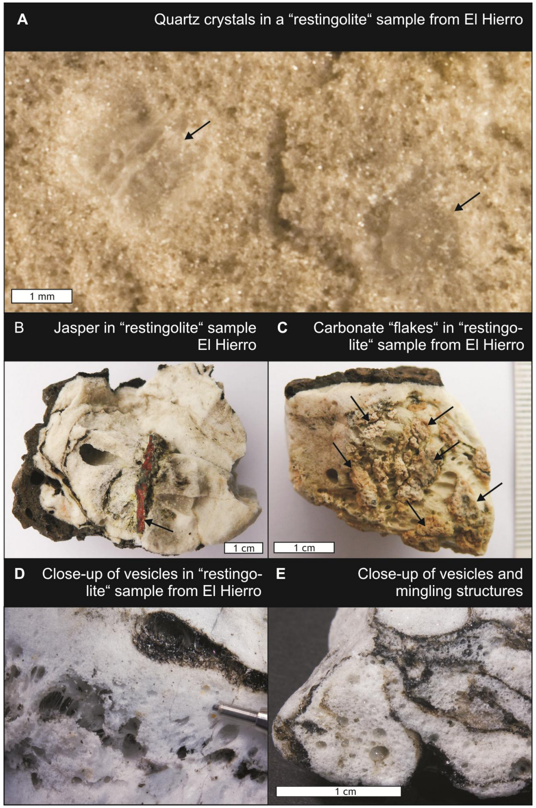

Fig. 2. Overview of small-scale features of "restingolites" samples from El Hierro. **(A)** mm-size quartz crystals. **(B)** Jasper inclusions **(C)** Carbonate "flakes". **(D and E)** Vesicles.

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Floating sandstones off El Hierro (Canary Islands, Spain)

V. R. Troll et al.

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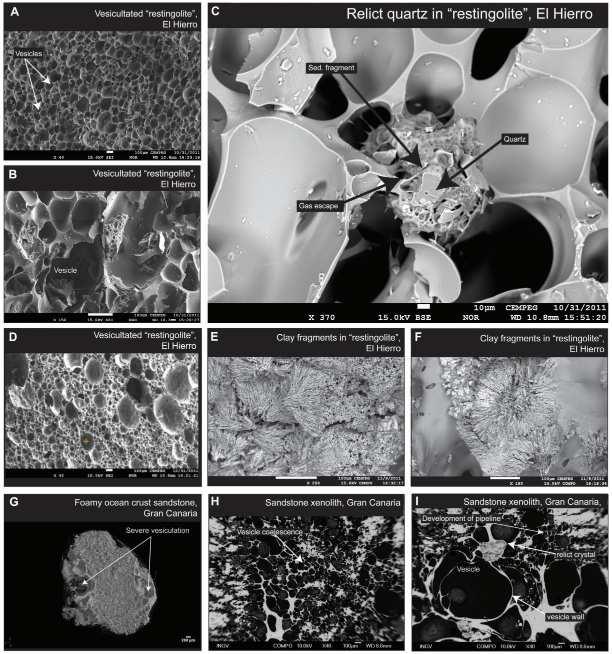

Fig. 3. SEM images of "restingolites" **(A–F)** and comparative images of Gran Canaria ocean crust sediment xenoliths **(G–I)**. **(A)** Pervasive micro-vesicularity in restingolite. **(B and D)** Details of vesicle distribution and vesicle wall textures. **(C)** High resolution image of sedimentary fragment in restingolite that has not yet fully melted. The melt surrounding the fragment has SiO_2 of 89 % and a several-tens-of-microns large quartz crystal is seen in the centre of the image (compare Table 2). **(E and F)** Remnants of clay aggregates found in "restingolites". Note in F these relicts are surrounded by glass. **(G)** Synchrotron X-ray computed micro-tomography image of a vesicular sedimentary xenolith from Gran Canaria, showing similar textures and compositions to the "restingolites" (compare Table 3). **(H and I)** SEM images of vesicular sedimentary xenoliths from Gran Canaria with relict quartz crystals and thin vesicle walls, i.e. they display very similar textures to the El Hierro "restingolites".

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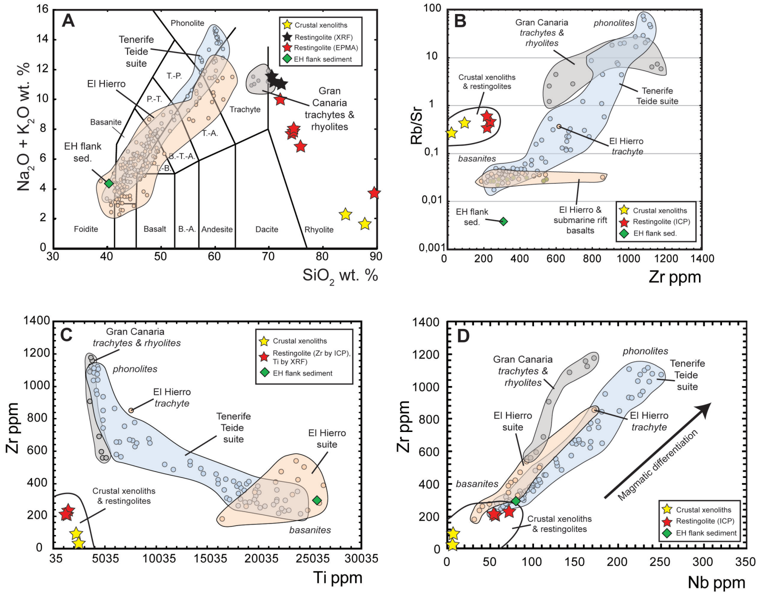

Fig. 4. Geochemical plots of "restingolites" and comparative data for El Hierro, Gran Canaria, Tenerife, and Canary Island crustal xenoliths. **(A)** Total alkalis versus silica (TAS) plot showing the alkaline Canary Island magma suites. The "restingolites" plot within the trachyte to rhyolite fields, however, they do not follow a typical Canary Island magmatic trend. Note that known crustal xenoliths from Gran Canaria (Hansteen and Troll, 2003) and Lanzarote (Aparicio et al., 2006) also plot as rhyolites. **(B)** Rb/Sr versus Zr plot. The most evolved Canary Island magmas again plot to the top right of the diagram. The "restingolites" and crustal xenoliths form a distinct group from both the least and most evolved magmatic samples. **(C)** Zr versus Ti (ppm) plot, showing the main magmatic trends (Tenerife, El Hierro and Gran Canaria) and the composition of the "restingolites". Note that the magmatic trends and the "restingolites" and sedimentary xenoliths form distinct groups that do not overlap. **(D)** Zr versus Nb plot. Canary Island suites show strong magmatic differentiation trends, with the most evolved samples plotting to the top right of the diagram (i.e., at high Zr and Nb concentrations). In contrast to the TAS plot, "restingolites" plot near the least evolved magmatic samples. The chemical data thus underline that "restingolites" are highly atypical for Canary magma compositions and chemically resemble known sedimentary xenolith and pre-island sedimentary compositions once the full major and trace element compositions are considered. Reference data fields El Hierro (Pellicer, 1979; Carracedo et al., 2001), Gran Canaria (Troll and Schmincke, 2002; Hoernle, 1998), Tenerife (Wiesmaier, 2010).

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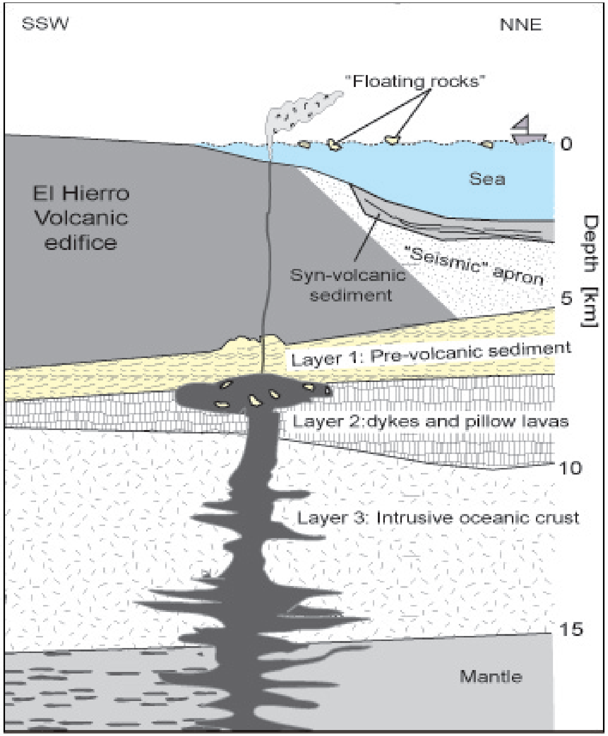

Fig. 5. Sketch showing the structure of El Hierro Island. Ascending magma that, according to the distribution of seismic events prior to eruption, moved sub-horizontally from north to south in the oceanic crust, is interacting with the pre-volcanic sedimentary rocks, and we suggest that the floating rocks found at El Hierro are the products of magma-sediment interaction beneath the volcano. The "restingolites" 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 (i.e. their low density).

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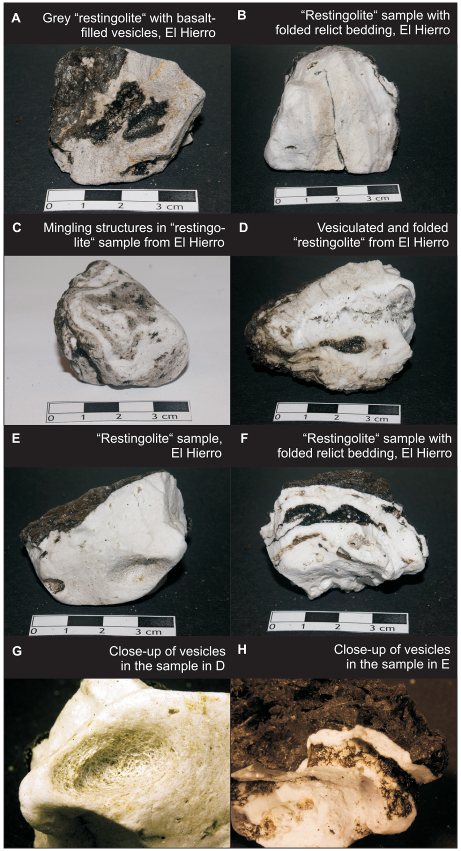

Fig. A1 Features of “restingolite” samples from El Hierro, displaying typical features, such as a rind of basalt, layering, folding, vesicularity, and mingling structures.

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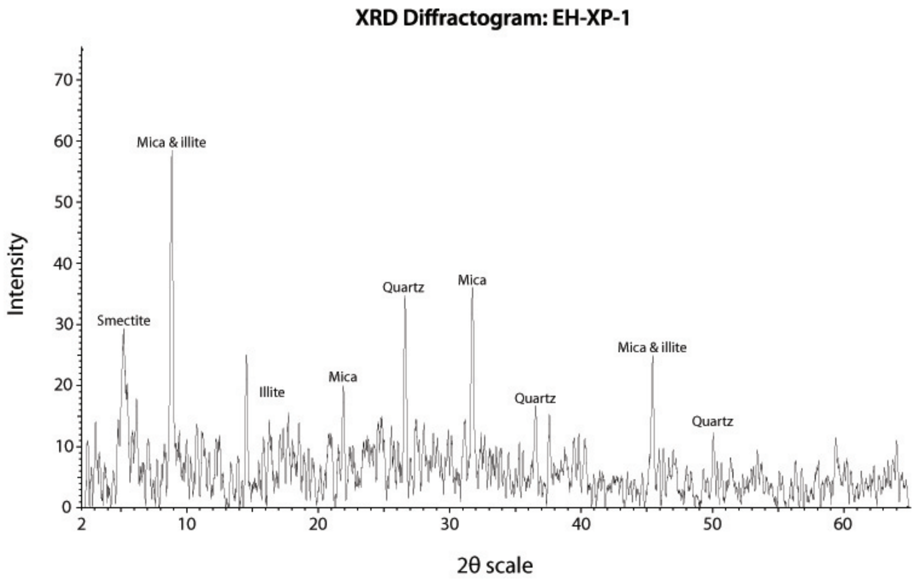

Fig. A2 XRD analysis of sample EH-XP-1 summarised in Table 1. Notably, the comparatively significant ca. 10 Å phyllosilicate (mica & illite) peak could wholly or in part represent the illite-type structure characteristic of thermal decomposition products of major primary clay minerals.

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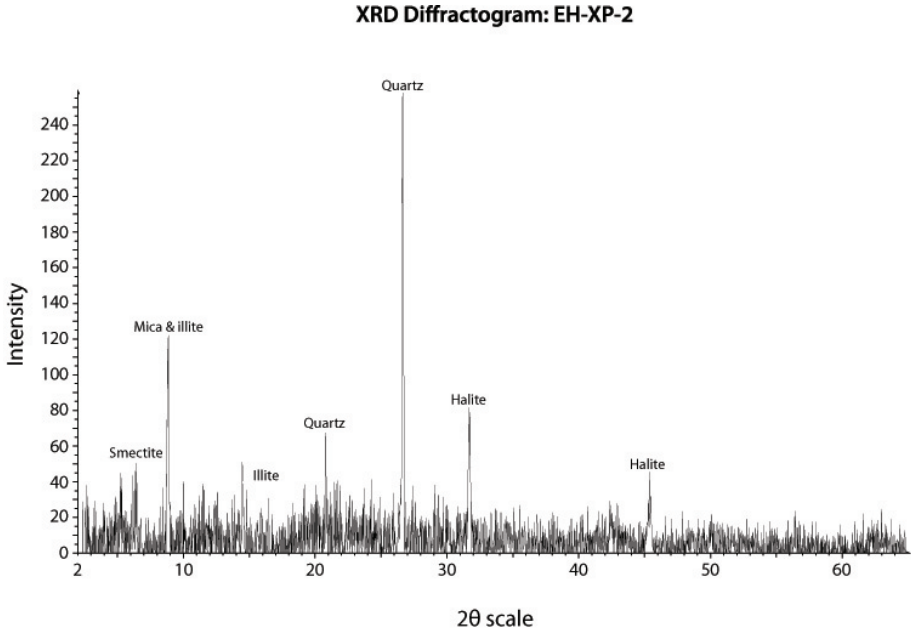

Fig. A3 XRD analysis of sample EH-XP-2 summarised in Table 1. Notably, the comparatively significant ca. 10 Å phyllosilicate (mica & illite) peak could wholly or in part represent the illite-type structure characteristic of thermal decomposition products of major primary clay minerals.

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