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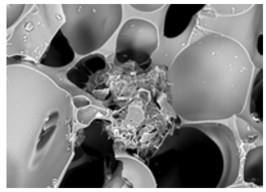

Nannofossils: the smoking gun for the Canarian hotspot

The origin of volcanism in the Canary Islands has been a matter of controversy for several decades. Discussions have hinged on whether the Canaries owe their origin to seafloor fractures associated with the Atlas Mountain range or to an underlying plume or hotspot of superheated mantle material. However, the debate has recently come to a conclusion following the discovery of nannofossils preserved in the products of the 2011–2012 submarine eruption at El Hierro, which tell us about the age and growth history of the western-most island of the archipelago. Light coloured, pumice-like 'floating rocks' were found on the sea surface during the first days of the eruption and have been shown to contain fragments of pre-island sedimentary strata. These sedimentary rock fragments were picked up by ascending magma and transported to the surface during the eruption, and remarkably retained specimens of pre-island Upper Cretaceous to Pliocene calcareous nannofossils (e.g. coccolithophores). These marine microorganisms are well known biostratigraphical markers and now provide crucial evidence that the westernmost and youngest island in the Canaries is underlain by the youngest sediment relative to the other islands in the archipelago. This finding supports an age progression for the onset of volcanism at the individual islands of the archipeligo. Importantly, as fracture-related volcanism is known to produce non-systematic age-distributions within volcanic alignments, the now-confirmed age progression corroberates to the relative motion of the African plate over an underlying mantle plume or hotspot as the cause for the present-day Canary volcanism.

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The ocean floor of the central-east Atlantic is littered with seamounts, but only four continuous volcanic island chains exist. These are the Azores, Madeira, the Canary, and the Cape Verde archipelagos, also known as the Macaronesian islands (from the greek *makárôn nêsoi* = 'islands of the fortunate'; Fig. 1). These four island chains share similar natural features, including their climate, flora, fauna, and also their principal geology. With the exception of the Azores, which are located on the Mid-Atlantic Ridge, the other three island chains cluster along the northwest African coast. They developed approximately simultaneously, and each of these three island chains is known to show an internal age progression among the oldest onshore volcanic rocks from the individual islands. Isotope geochemistry, in turn, confirms that each of the island groups has a different mantle source, which suggests similar processes contribute to the origin of the Macaronesian islands. Indeed, following the introduction of the concept of plate tectonics, these three island chains were widely considered to represent hotspot tracks associated with upwelling mantle plumes. An average volcanic age progression of about 1.2 cm/yr is then required, which, for the Canary and Madeira islands, is consistent with the rotation of the African plate of ~0.2°/Ma around a common Euler pole located at the southern tip of Greenland.

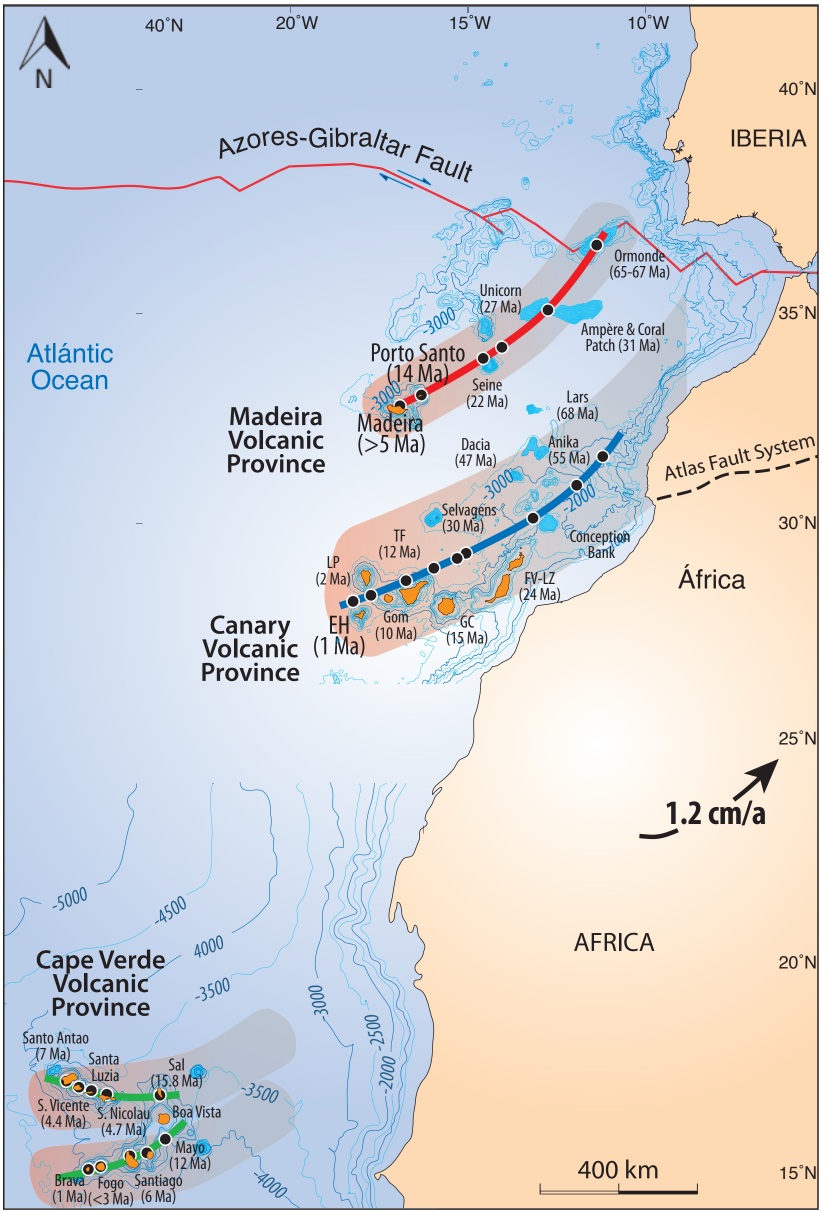

Fig. 1. Bathymetric map of the Macaronesian archipelagos. The Canary Islands (blue), Madeira (red), and the Cape Verde (green) volcanic provinces and associated seamounts are shown. The ages of onshore rocks imply an east to west age progression for these three archipelagos. The different island chains are contemporaneous and are aligned roughly parallel to each other, following a similar curved trend. Formation of the islands is consistent with the rotation of the African plate with a rotation (Euler) pole located south of Greenland (ages after Geldmacher *et al.*, 2005 and Holm *et al.*, 2008).

The conventional hotspot model was initially developed for the Hawaiian Islands, however, the Hawaiian chain demonstrates significant geotectonic differences to the Macronesian islands. As a result, some difficulties have been encountered in adapting the hotspot model to the Macaronesian islands, especially in the Canary archipelago, as the Atlantic plate moves much slower than the Pacific one. Problematic features of the Canaries include the protracted volcanic history of the islands, the long interruptions in volcanic activity (quiescence periods), and, particularly, the occurrence of historic eruptions in the oldest parts of the archipelago (e.g. the 1730 and 1824 eruptions on Lanzarote). While a mantle plume model received greater acceptance for the Madeira and Cape Verde archipelagos, these observations, as well as their proximity to the northwest African coast and the Atlas Mountain range, initiated a four-decade-long debate on the origin of the Canary Islands.

Models for the origin of the Canary Islands

Two models were proposed in 1975 to account for the origin and structural evolution of the Canary Islands. Anguita & Hernán advocated that Canary magmatism arises as a result of a propagating fracture from the Atlas system. This model is based upon structures that cut through the lithosphere, which in doing so, are thought to initiate and control the location of Canary volcanism. Around the same time, Carracedo postulated an upwelling mantle plume for the origin of the islands, a model which is largely independent of lithospheric or regional tectonic structures. The debate concerning the origin of the Canary Islands has persisted to the present day, with numerous studies carried out over the last four decades citing evidence in support of either of the two hypotheses, as well as arguments against the other.

Opponents of the propagating fracture model have argued that this concept is unable to account for the large volumes of magma required to develop the Canary Volcanic Province (CVP). Being aware of this shortcoming in the fracture model, some 15 years ago Anguita & Hernán eventually considered the existence of an upwelling mantle plume under the Canary Islands. They argued that a mantle plume may exist, but that ascending material is guided in the lithosphere by a fracture system associated with the Atlas Mountains, which thus facilitates and controls the ascending plume magmas of the CVP. However, this variation of the propagating fracture model, like its predecessor, lacks detailed regional geophysical evidence for the existence of a major fault system connecting the Atlas and the Canaries. Despite this limitation, the fracture model has in 2013 received renewed support by van den Bogaard, who discovered Cretaceous volcanic rocks dredged from the ocean floor near the western-most island of El Hierro. If these Cretaceous volcanic rocks are confirmed to be

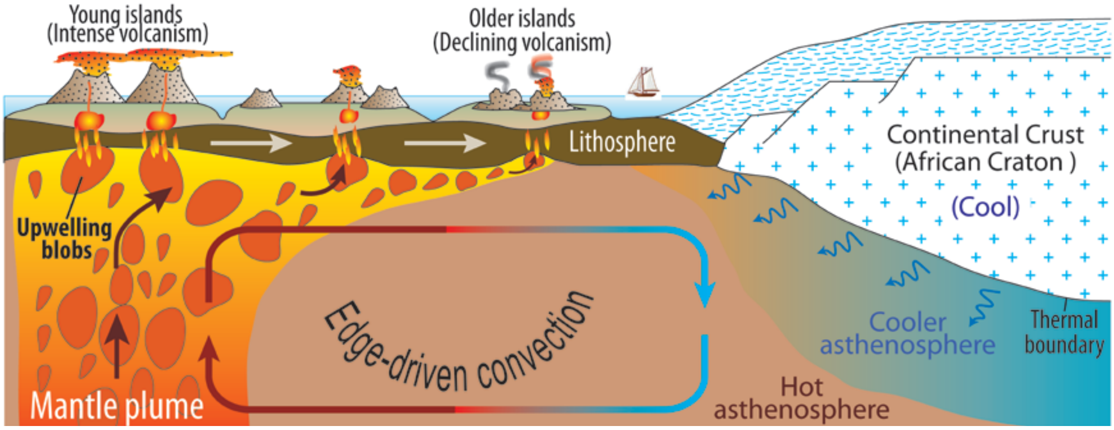

Fig. 2. One of the most frequently cited features that conflicts with the conventional hotspot model is the persistence of volcanism throughout the CVP (e.g. historical eruptions on El Hierro, La Palma, Tenerife, and Lanzarote). A feasible explanation is the combination of a blob-type plume supply column (proposed by Hoernle and Schmincke, 1993) and the occurrence of edge-driven convection processes around the cold African craton, which is thought to interfere with the Canary mantle plume. This general model is based on suggestions by King & Anderson (1998) and King & Ritsema (2000) on geophysical grounds and by Gurenko and co-workers (2010) on geochemical grounds.

part of the CVP (*sensu stricto*), then they would indeed challenge the apparently systematic age-progression within the islands. This is critical, because non-systematic age distribution of the islands would be a key tenet of any fracture-centric model, since fracture systems usually generate magmatism at several places simultaneously, as known from, e.g. the Azores or the Cameroon volcanic line. Moreover, an upwelling mantle plume that intersects a lithospheric fracture system should simultaneously generate active volcanic islands, intense and strong seismicity throughout the archipelago, and islands that show visibly elongated shapes along these underlying lithospheric fractures (as, for example, in the Azores).

Some features of the CVP that are frequently used to build an argument against conventional hotspot models include the irregular spatial distribution of the islands and seamounts (Fig. 1), and the persistence of volcanism in the older end of the archipelago. This was met with explanations from plume proponents involving the interaction of the Canary plume with upper mantle edge-driven convection processes, as proposed by King & Anderson and King & Ritsema a little over a decade ago (Fig. 2). Older seamounts in the region (e.g. the Cretaceous Henry seamount, ~120 Ma), however, appear to align with Atlantic ocean floor structures. This would imply that these older seamounts belong to a much older and entirely unrelated magmatic episode (see below) as underlined by Zazcek and coworkers earlier this year.

On the other hand, abundant evidence in favour of a hot spot model for the origin of the CVP has also been published. Strong support for a mantle plume was provided by the observed temporal cyclicity in the chemistry of erupted rocks. For example, Hoernle and Schminke expounded a modification of the classic plume model in the early 90s to explain geochemical cycles in the CVP. They proposed that individual cycles of volcanism in the archipelago represent discrete blobs of plume material and that periods of volcanic quiescence reflect the entrainment of cooler material in the melting zone beneath the islands (Fig. 2). Most of the recent geochemical studies undertaken also support the plume model, such as the investigations of Gurenko and co-workers and Deegan and colleagues, albeit with modifications regarding the exact chemical processes and temporal changes at play. Independent evidence for a mantle plume as the underlying source for all the Macaronesian islands was recently also put forward using a different approach, namely finite-frequency tomographic images of S-wave velocity. Montelli and co-workers imaged a series of anomalies in the East Atlantic which they relate to the presence of deep mantle plumes beneath the Azores, the Canary, and the Cape Verde archipelagos (Fig. 3). However, doubts about the reliability of this method and even of the existence of mantle plumes continue to be an issue.

Another approach to resolving the fracture versus plume controversy over the last two decades focused on systematically dating the oldest erupted lavas in the Canaries to check the consistency of the islands' age progression. Hundreds of radiometric (K/Ar and $^{40}Ar/^{39}Ar$) ages have been produced for the CVP,

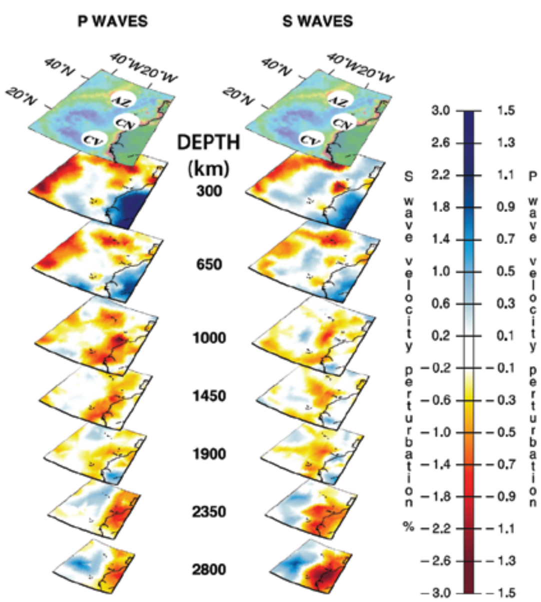

Fig. 3. Three-dimensional view of the plumes beneath the Azores (AZ), the Canary (CN), and the Cape Verde (CV) archipelagos as resolved in both P-wave (left) and S-wave (right) tomographic models. Note that the anomalies beneath the Canaries, Madeira, and the Cape Verdes are traceable down to the core-mantle boundary, implying a deep-seated mantle anomaly such as a hot spot or a plume (image from Montelli *et al.*, 2004).

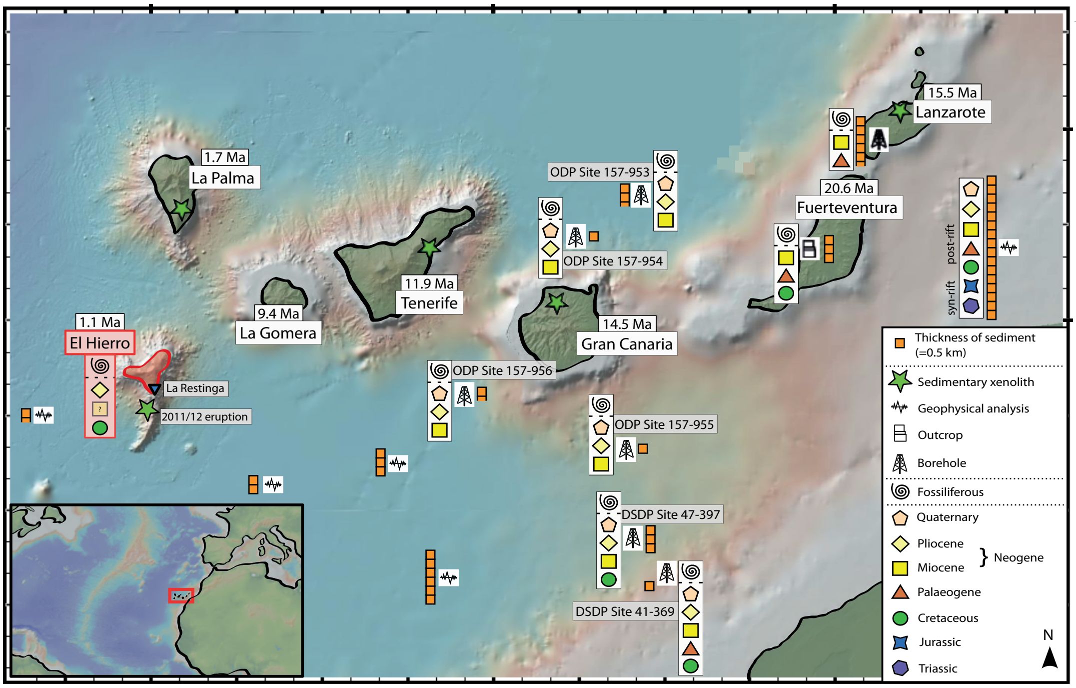

Fig. 4. Map of the Canary archipelago with ages of oldest volcanic rocks, occurrence of sedimentary relicts ('xenoliths'), thickness of sedimentary layers, and deterministic techniques indicated. The sedimentary strata underneath the eastern Canaries is well characterised from onshore exposure, drilling campaigns, and seismic investigations, while the age and nature of the sedimentary strata underneath the western Canaries lacks direct constraints. The eruption of nannofossil-bearing sedimentary relicts at the westernmost island of El Hierro in 2011 now defines the age range of the sedimentary layers beneath El Hierro to between Cretaceous and Pliocene and confirms that El Hierro is the youngest Canary Island (image modified after Zaczek *et al.*, 2015).

which together make the Canaries one of the world's best dated oceanic archipelagos. However, the ages of CVP volcanic rocks were obtained by numerous research groups working in different laboratories, and, most significantly, contrasting sampling criteria were applied. The latter is a particularly crucial aspect in determining the oldest formations of the islands. For example, K/Ar dating by Ancochea and co-workers a little over a decade ago suggests that the island of La Gomera started the seamount stage in the Lower Miocene, which would make it contemporaneous with the island of Fuerteventura, and it would thus belong to the oldest part of the CVP. The implication would be that no consistent age progression exists, which would then effectively negate the idea of a systematic Canary hotspot track. Later workers, however, pointed out that some dated samples contained xenoliths (i.e. foreign and older material from the Jurassic oceanic crust under the island), thus producing an artificially mixed age of no geological relevance. The controversey concerning an age progression in the Canary Islands is still not resolved, becuaes of such uncertainties in dating the initiation of volcanism on each island. Indeed, it seemed as though the debate reached a stalemate recently and only fresh evidence could move the matter forward. Fortunately, this evidence has now been delivered during the 2011–2012 eruption at El Hierro.

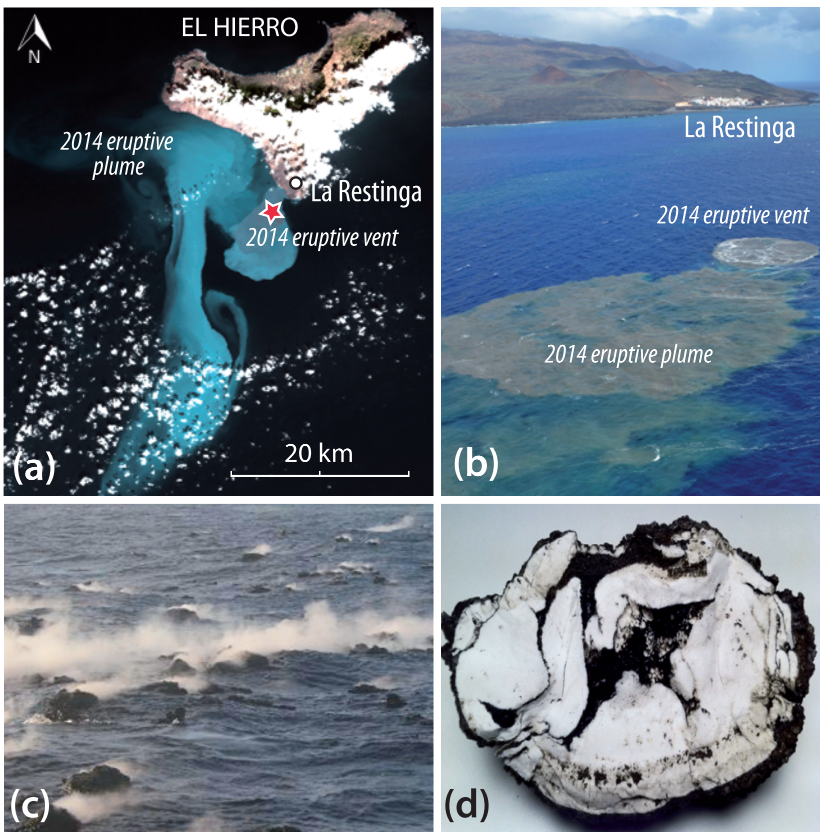

Fig. 5. a. Satellite image of the 'stain' ('la mancha') caused in late 2011 by dissolved magmatic gases and suspended matter that produced bright green discolouration of the seawater (image courtesy of NASA). **b.** Closer view of the eruptive plume (image courtesy of Guardia Civil). **c.** 'Floating stones' observed in October 2011 off El Hierro. **d.** Xeno-pumice bomb cracked open to display the white folded interior, as well as black veins of the surrounding basanite crust (images in C and D are from Carracedo *et al.*, 2012).

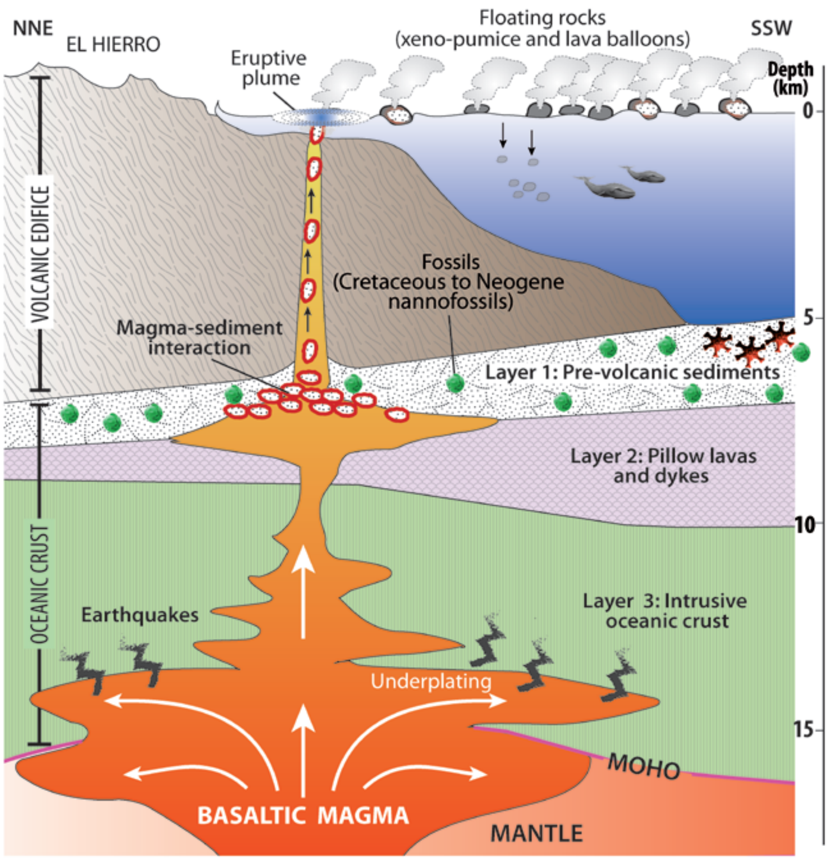

Fig. 6. Cartoon showing the approximate internal structure of El Hierro Island during the 2011 events. According to the distribution of seismic events prior to eruption, the ascending magma moved sub-horizontally from north to south at the level of the oceanic crust, thus allowing intense interaction with the pre-volcanic sedimentary rocks. The white-cored floating rocks found at El Hierro ('xeno-pumice') are hence the products of magma–sediment interaction beneath the volcano. These xeno-pumice samples 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. Remarkably, some relict material from their sedimentary protoliths survived the journey through the volcano to now provide us with a glimpse into the sub-island geology (image modified after Troll *et al.* 2011, 2012).

Dating the pre-island sedimentary strata in the Western Canary Islands

If a mantle-plume is indeed responsible for the Canaries, the onshore volcanic age-progression should be coupled with progressively younger pre-island sedimentary strata towards the west of the archipelago. Fragments of pre-island sedimentary rocks were erupted in the 2011–2012 submarine event at El Hierro, i.e. the westernmost extent of the CVP, and now afford new and independent data to test if an age progression in the CVP exists.

Bathymetric and seismic reflection studies suggest that up to 8 km of sedimentary rock exists below the western Canaries, whereas only 0.5 to 1 km of sedimentary strata underlies the eastern part of the archipelago. Detailed records of the pre-Canary Island sedimentary environment are presently restricted to the east and central part of the archipelago where onshore exposures, drill cores (e.g. DSDP), and extensive xenolith suites are available. In contrast, direct age information on the pre-island sedimentary rocks underlying the western-most and apparently youngest islands of El Hierro and La Palma has been critically lacking (Fig. 4).

The most recent eruption in the Canary Islands commenced in October 2011 along the southern submarine rift zone of El Hierro. This event lasted until March 2012, and occurred about 2 km offshore with a vent depth that ranged from 350 to 100 m b.s.l. (Fig. 5A). The onset of the submarine eruption was associated with visible surface phenomena, such as a plume of discoloured seawater, which produced a large 'stain', locally known as 'la mancha' and that contained abundant floating rock fragments comprising lava balloons and frothy xenolith bombs (Fig. 5A–D). Later in the eruption, voluminous gas exhalations were also observed (Fig. 5C). Notably, abundant decimetre-sized bombs or fragments of light-coloured, highly vesicular material with glassy textures enveloped in dark, glassy, basanitic material, reached the ocean surface during the first days of the eruption (Figs 5, 6). These frothy white fragments were termed 'xeno-pumice' by Troll and co-workers due to their apparently non-magmatic origin (from the greek *xenos* = 'foreign' or 'strange'), but vesicular and hence pumiceous appearance. It is these xeno-pumice specimens from the first week of the 2011–2012 El Hierro eruption that contained semi-intact sedimentary relicts of jasper, gypsum, clays, zeolites , rounded detrital quartz and also the critical nannofossils (Figs 6, 7). Xeno-pumice ceased to erupt after about one week to 10 days into the eruption, and hollow, entirely basanitic bombs subsequently comprised the only erupted materials. These basaltic bombs are notably similar to the 'lava balloons' described from other submarine eruptions, e.g. that of La Serreta, Terceira Island, in the Azores described by Gaspar and colleagues or those near Socorro Island in Mexico studied by Siebe and his team.

Xeno-pumice, in turn, was initially considered to signal the presence of high-silica magma beneath El Hierro by the authorities, which evoked fear of a pending explosive volcanic eruption, similar to the events at Ejyafjallajökull on Iceland just the year before. Thorough investigations on-site, however, using classic petrographic approaches, revealed that these rocks contained mm-sized transparent quartz crystals

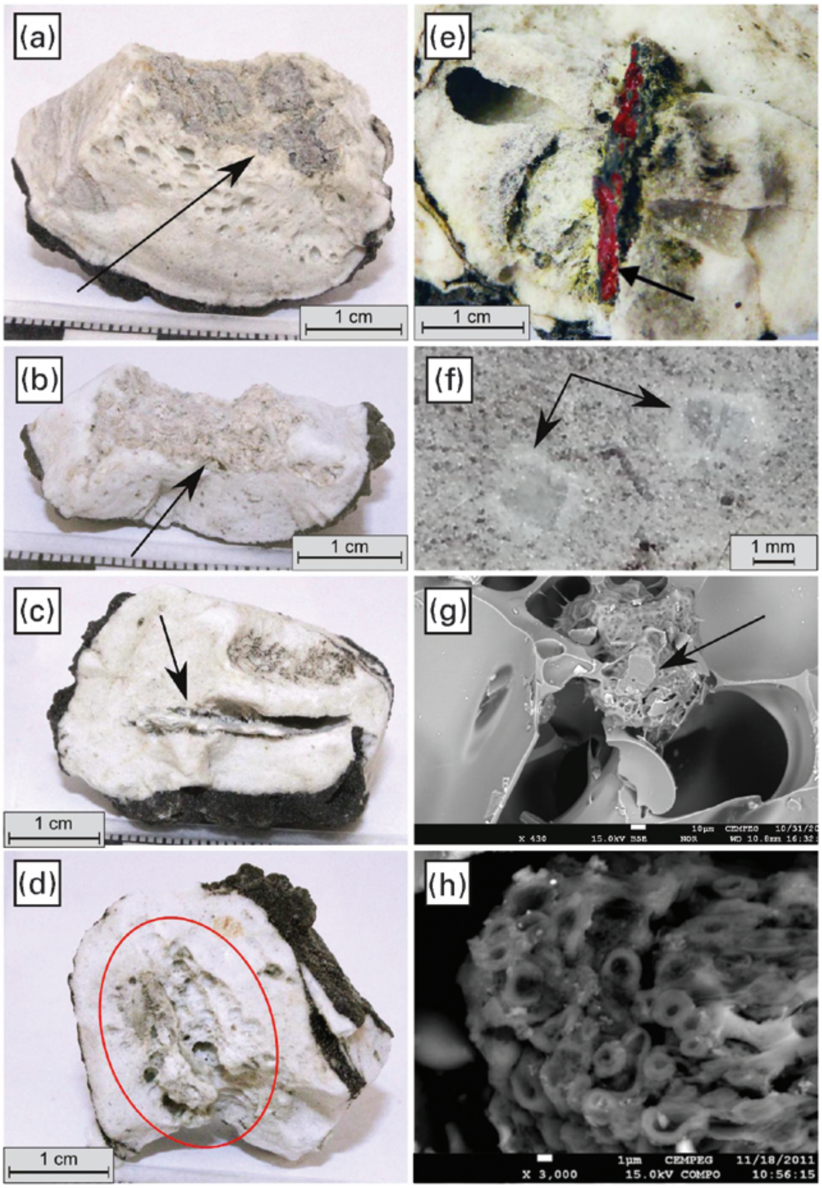

Fig. 7. Photographs of representative xeno-pumice samples from the 2011 El Hierro eruption, including sedimentary relicts that contain fossil remains. **a.** The core of this xeno-pumice contains clay-type sedimentary material, surrounded by vesicles up to 2 mm in size and a finer vesicular layer near the margin. **b.** Silty sedimentary material in the core of a xeno-pumice sample, surrounded by a finely vesicular outer rim. **c.** Clay-rich sedimentary fragment in xeno-pumice surrounded by a gas cavity. **d.** Xeno-pumice with highly vesicular inner domain around a sedimentary fragment that was 'caught in the act' of degassing and inflation upon melting and pre-eruptive decompression. **e.** Jasper fragment, partially dissolved in xeno-pumice (note the large vesicle in the upper left part of the sample, which indicates intense degassing). **f.** Large relict detrital quartz grains in a xeno-pumice sample. **g.** Scanning Electron Microscopy (SEM) image of quartz grain within a sedimentary relict in xeno-pumice. The quartz is surrounded by large vesicles and glass films. **h.** Backscattered electron (BSE) image of a cluster of coccoliths, typical of oceanic biogenic sediment, preserved inside an El Hierro xeno-pumice (images in A–G are from Troll *et al.*, 2012 and Zaczek *et al.*, 2015).

(Fig. 7D), quite unlike any other igneous rock on the western Canary Islands. On the other hand, quartz is frequently found in the Canary Islands in marine and aeolian sediment derived from the African continent. In combination with cm-sized flakes of jasper, gypsum, clay aggregates, and abundant cm-sized sedimentary rock relicts with remnant sedimentary bedding in a considerable number of samples, a magmatic origin for xeno-pumice seemed highly improbable (Fig. 7). Additional geochemical evidence, especially oxygen isotopes, subsequently confirmed a sedimentary origin for xeno-pumice and a thorough comparison of xeno-pumice textures, mineralogy, and chemistry to other known sedimentary xenoliths from Gran Canaria, Lanzarote, and La Palma is currently underway. At this stage, it has already become clear that sedimentary rock-derived xeno-pumice represents a regional phenomenon in the Canaries rather than being a local peculiarity or signifying localised pockets of evolved magmatic liquids.

One of the most interesting aspects of xeno-pumice, however, is the presence of sedimentary relicts that must then originate from below the island. The composition of xeno-pumice notably contrasts recent flank sediments from El Hierro and La Palma, which contain abundant volcanic detritus. This observation, together with the lateral migration of magma along the island's base just prior to the eruption described by, for example, Lopez and colleagues and Gonzales and co-workers, further supports the idea that the erupted El Hierro xeno-pumice is derived from the pre-island sedimentary rock layers. After careful microscopic investigation, Zaczek and colleagues recently showed that the sedimentary relicts preserved in xeno-pumice contain Cretaceous to Pliocene marine nannofossils, consistent with a dominantly sedimentary origin for these rocks (Fig. 8A). Calcareous nannofossils are the tiniest (less than 60 µm) routinely studied micro-palaeontological group and were recognized in 50 percent of the investigated sedimentary relicts that were selected from a large suite of xeno-pumice samples. The recovered nannofossils comprise mainly coccolithophores, which are one of the major open ocean phytoplankton groups and quite abundant in oceanic oozes. Their geological record extends back to the Late Triassic and shows rapid evolutionary diversification, but also significant extinctions, making them reliable stratigraphical biomarkers. Taxonomic identification of coccoliths following established classification schemes defines a dominant group of fossils found in El Hierro xeno-pumice as Upper Cretaceous in age (*c.* 100 Ma), consistent with the age of the ~8 km thick Jurassic to Miocene

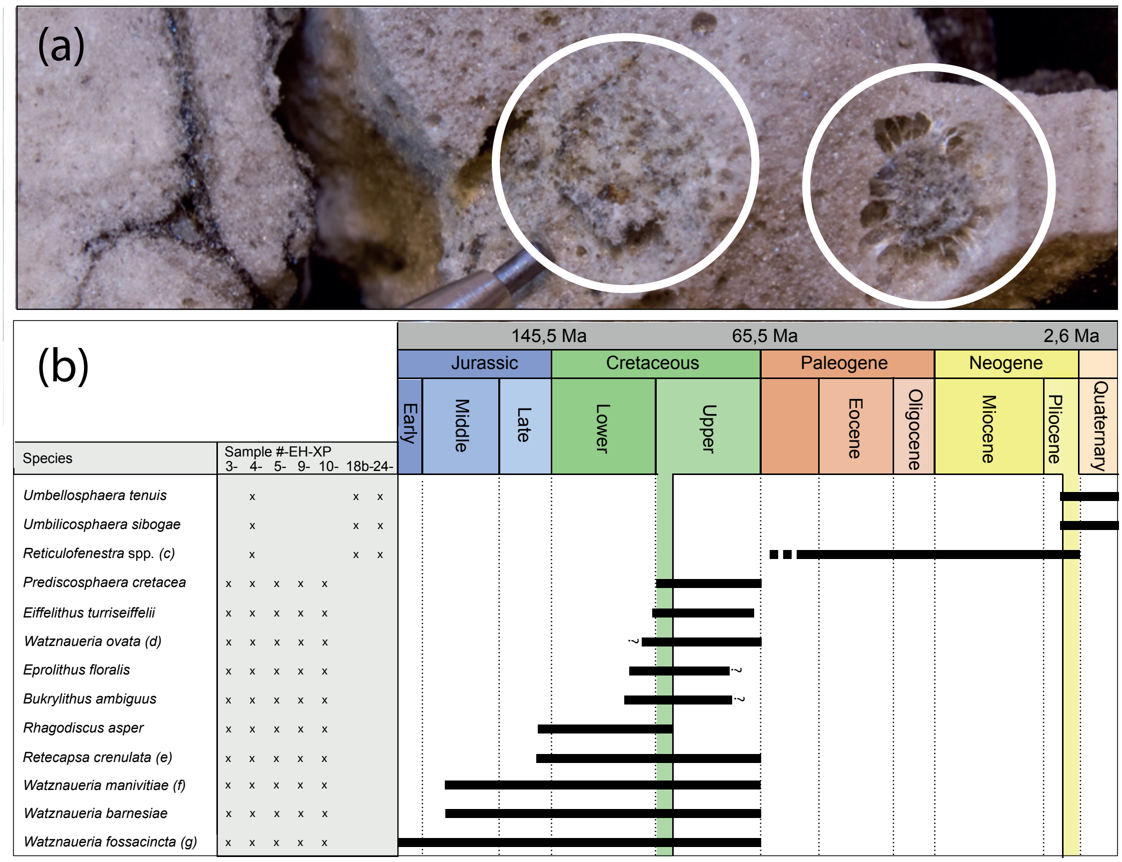

Fig. 8. a. Close-up of sedimentary relicts in El Hierro xeno-pumice. Note the bubble corona on the example to the right hand side. **b.** Temporal record of Calcareous nannofossils recovered from the xeno-pumice suite at El Hierro. Out of 14 samples, four contain Jurassic to Cretaceous nannofossil species that define a common Albian/Cenomanian age (~ 100 Ma). This implies that the island of El Hierro started to form around that time (i.e. ≤2.5 Ma) thereby dating the youngest pre-island sedimetary relects to ~2.5 Ma. The older Cretaceous volcanic rocks from the vicinity of El Hierro show, in turn, an age progression of ≥ 130 Ma and hence predate the sedimentation period recorded by the new fossil evidence (image modified after Zaczek *et al.* 2015).

sedimentary successions under the eastern Canary Islands (Fig. 8B). In contrast, the youngest fossil age recovered from xeno-pumice, ~2.5 Ma, is in agreement with previous estimates for the onset of shield building at El Hierro, inferred to be Pliocene to Quaternary (~2 to 3 Ma) on the basis of seismic reflection data. As the white El Hierro xeno-pumice samples contain no obvious volcanic or volcaniclastic material, the youngest fossil specimens must reflect some of the latest pre-island sediments before the present volcanic island of El Hierro started to grow. Thus, these samples provide a critical constraint for bracketing the change from a sedimentary depositional to a volcanic environment that terminated regular marine sedimentation below El Hierro at ≤2.5 Ma.

The erupted El Hierro sedimentary relicts thus provide crucial support for an east-west age progression for the onset of volcanism in the CVP by demonstrating unequivocally that the youngest pre-island sedimentary rocks in the Canary archipelago are located beneath El Hierro (Figs 4, 9). These findings also imply that the Cretaceous seamounts in the region (~ 125 to 145 Ma), which are notably oriented almost perpendicular to the curved Canary trend and parallel to the magnetic ocean floor anomalies (e.g. M25), must predate Canary volcanism. The Cretaceous seamounts in the Canary region thus relate to earlier, spreading and fracture-controlled magmatic episodes during the opening of the Atlantic Ocean and thus seem unrelated to the genesis of the present-day Canary archipelago.

The fossil evidence from El Hierro therefore provides the crucial 'smoking gun' evidence for a Canary mantle plume having pierced through the Jurassic ocean crust, the overlying Cretaceous to Pliocene sedimentary cover, and older volcanic rocks in the region, to form a classic hot-spot alignment that is consistent with the motion of the Atlantic plate. The new evidence therefore concludes the current debate on the origin of the Canary Islands. The remarkable fossil data from xeno-pumice now provide independent support for an age-progression and therefore a mantle-plume as the most plausible cause of the current volcanism in the CVP, and by extension, for the other Macaronesian islands as well.

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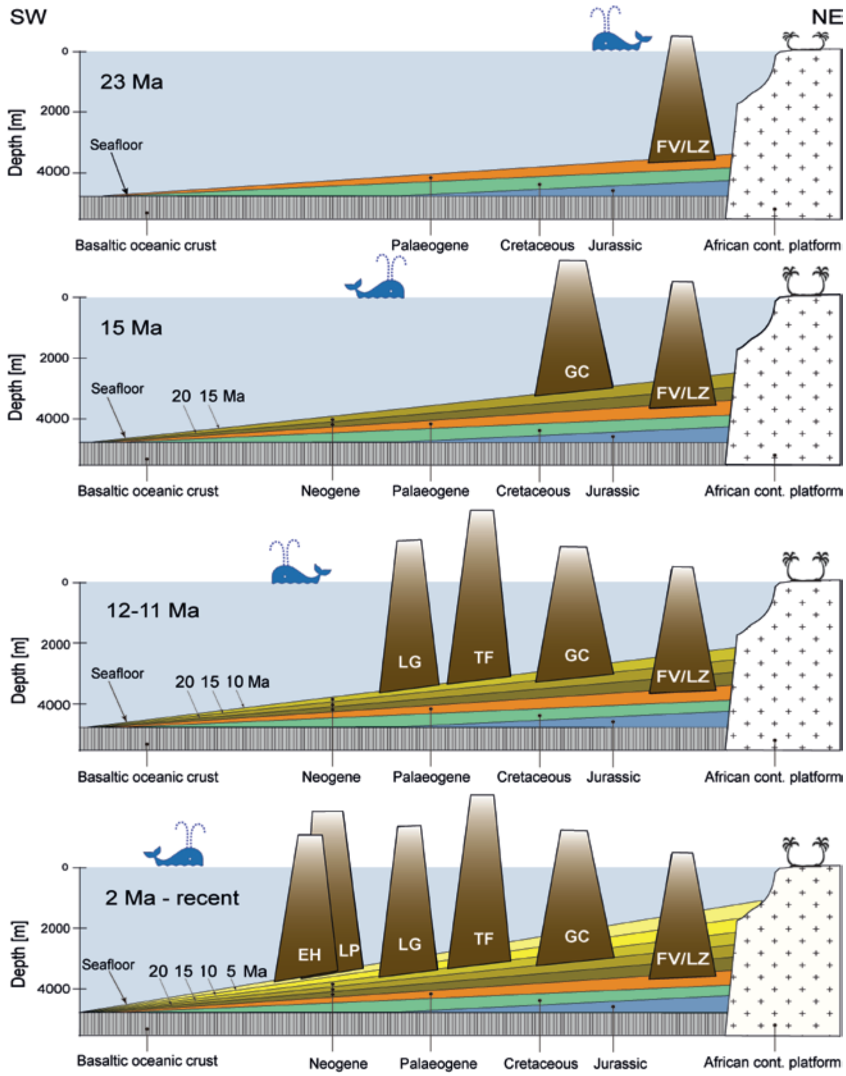

Fig. 9. Evolutionary sketch for the Canary Islands in four schematic SW-NE cross-sections through the archipelago (vertically exaggerated). The El Hierro nannofossils now identify the youngest sub-volcanic sedimentary strata (~2.5 Ma) in the west of the archipelago and so confirm the onshore age progression via independent fossil evidence from the pre-island sedimentary record (image modified after Zaczek *et al.* 2015).

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Suggestions for further reading

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