North-East Atlantic Islands: The Macaronesian Archipelagos

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The Central-East of the North Atlantic: Geological and Geodynamic Context

The eastern central North-Atlantic Ocean is situated between approx. 38°–15°N and 45°–15°W, an area with an average width of about 2700 km and a surface area of about 8000 km^2. The larger part of the Central-East Atlantic has a depth of ~4000–5000 m and can reach 5500 m in some places, as recorded in the Madeira and Canary Abyssal Plains (Fig. 1). The eastern central North-Atlantic formed following Middle to Late Triassic rifting, and separation of North America and Africa began at ca. 185 Ma (Withjack et al., 1998). This rifting and spreading episode created new oceanic crust and caused progressive separation of the African and American continents. This development created the Central-East Atlantic Ocean basin, which is bounded to the north by the Azores-Gibraltar fracture zone. The Azores fracture zone then joins the Mid-Atlantic Ridge in the Azores triple junction where the African, Eurasian and North American plates meet (see Fig. 1). The western boundary to the Central-East Atlantic is the active Mid-Atlantic Ridge, which is offset by numerous transform faults. The transform faults at the ridge extend eastward as fracture zones for many hundreds of kilometers, reaching into the Madeira and Canary Abyssal Plains. Several fracture zones also originate at the African continental region and have a similar trend. These are the result of the deformation induced by the differential eastward displacement of the Eurasian and African plates (see Fig. 1). Lastly, the eastern boundary of the Central-East Atlantic basin is the African coast, which forms a passive, aseismic margin separating the Atlantic oceanic crust from the African continental plate. In this region, the African continental plate is made up of the West African Craton to the south, and the Moroccan Meseta to the north. These two regions are divided by the High Atlas Mountains (see Fig. 1), bounded to the south by the South Atlas Fault Zone. The western end of this fault system, which lies close to and within the apparent prolongation of the Canary Archipelago, has previously been proposed to account for the origin of the Canary Islands, giving rise to early speculations that magmatism was perhaps linked to a propagating fracture from the Atlas Mountain system (Anguita and Hernán, 1975).

The Central-East North Atlantic Seamounts and Island Groups

The uniformity of the regular seafloor of the oceanic basin formed by expansion from the Mid-Atlantic Ridge is interrupted by several shallower regions and island groups such as the Azores Plateau and the Cape Verde Rise (Fig. 2). Although seamounts litter the ocean floor of the Central-East Atlantic, only four continuous volcanic island chains exist; the Azores, Madeira, the Canary Islands, and the Cape Verde archipelago (Table 1). These four island groups are also widely known as the Macaronesian islands (from the Greek *makárôn nêsoi* = "islands of the fortunate"). Notably, all four archipelagos reside on oceanic crust and show many

 https://doi.org/10.1016/B978-0-08-102908-4.00027-8

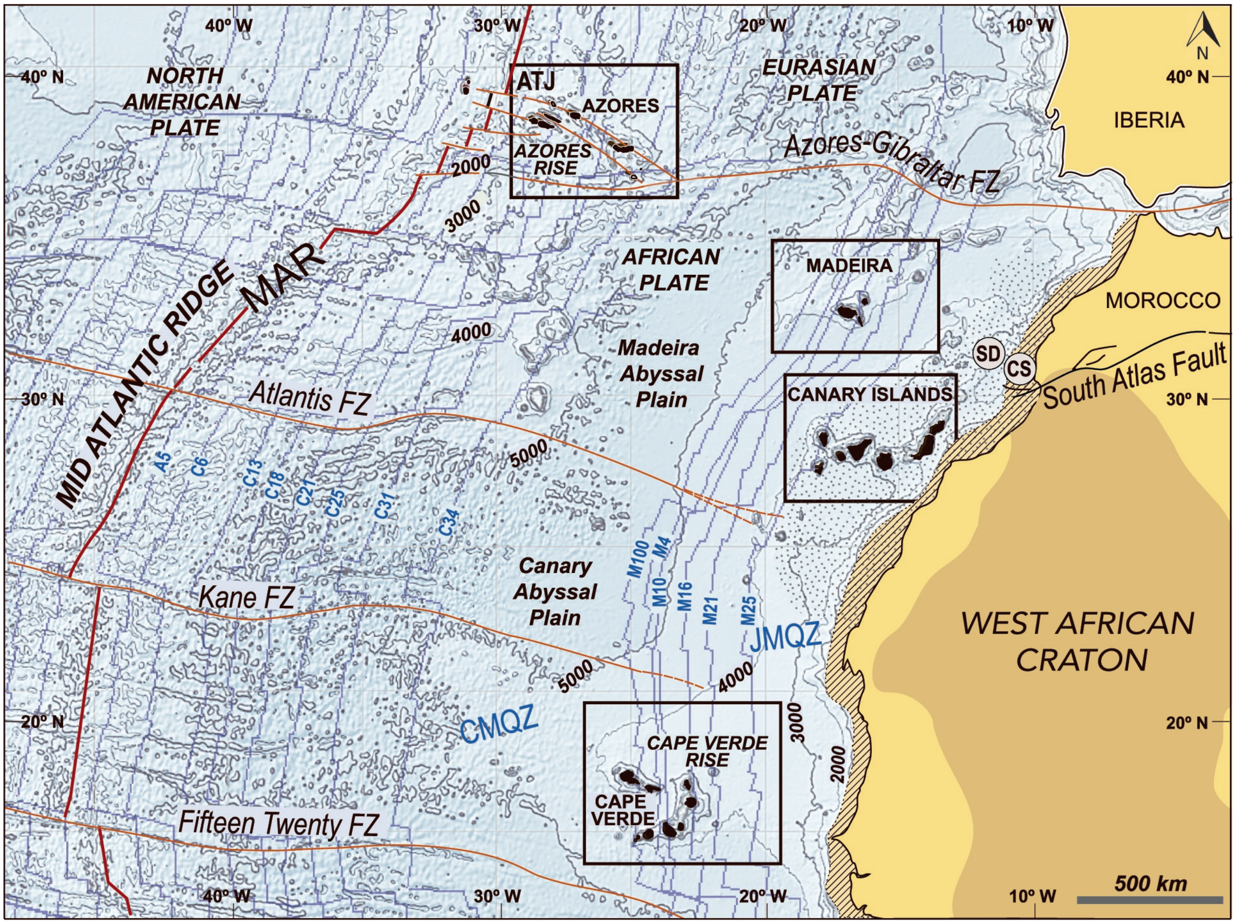

Fig. 1 Map highlighting the geological and geodynamic features of the Central-East Atlantic region with the four Macaronesian archipelagos (inside the black squares). CS: Coastal shelf or passive margin offshore. SD: Pelagic and terrigenous sediments and Mesozoic evaporites (Acosta et al., 2003). Magnetic anomalies in Ma (Bird et al., 2007). See Table 1 for details of the main geographic features of the islands. Full details on Coastal shelf and passive margin offshore are found in Hafid et al. (2006); Benabdellouahed et al. (2017), and Fekkak et al. (2018). Pelagic and terrigenous sediments and Mesozoic evaporites are described in Acosta et al. (2003) and the magnetic anomalies in Ma in Bird et al. (2007). Bathymetry: NOOA GLOBE 1 km.

similar natural features, including climate, flora, fauna, and also to a reasonable extent their principal geological origins and evolutionary histories, but also some significant geological particularities. Except for the Azores, which are located close to the Mid-Atlantic Ridge on relatively young crust (<50 Ma old), the other three island chains rest on old oceanic crust and cluster along the north-west African coast (see Fig. 1). In particular, the Canary Islands are situated on top of some of the oldest oceanic crust in the Atlantic Ocean. This oceanic crust under the Canaries formed in the earliest stages of the opening of the Atlantic, corresponding to Mesozoic Chrons M41–M26 (156–185 Ma) and form the present-day Jurassic Magnetic Quiet Zone (JMQZ in Fig. 1) (Bird et al., 2007).

A wealth of geological information is available regarding the individual Macaronesian archipelagos, but fewer papers focus on the comparative analysis of these island groups (e.g., Schmincke, 1973; Geldmacher et al., 2005; Jeffery and Gertisser, 2018). The comparison can be instrumental, however, especially for clarifying the various geological scenarios that are required to explain the main features exhibited by these island groups as well as their diversities, comprising, e.g., the size and shape of the islands, the age and distribution of volcanism, the compositional ranges of their eruptive products, and the possible association of volcanism and seismicity with regional fractures. This comparative analysis can now help to test how these features relate to different models proposed for the generation of magmatism that ultimately caused the development of these oceanic island groups.

The Macaronesian archipelagos, moreover, differ in the number of islands, their size and population, the oldest subaerial rocks, and their seismic and eruptive hazards (Table 1). The different highest altitude of the islands of these archipelagos are an indication of their age as this corresponds to their eruptive growth vs. erosive decay. Spain colonized the Canary Islands from 1483 and at present it is the most populated of the Macaronesian archipelagos (over 2.2 million inhabitants). The Azores (~0.25 million inhabitants) and the Madeira (~0.26 million inhabitants) archipelagos, both autonomous regions of Portugal, were colonized by the Portuguese commencing in 1443 and 1420, respectively. Cape Verde (~0.55 million inhabitants) was also first settled by the Portuguese (starting in 1460), but has been an independent Republic since 1975.

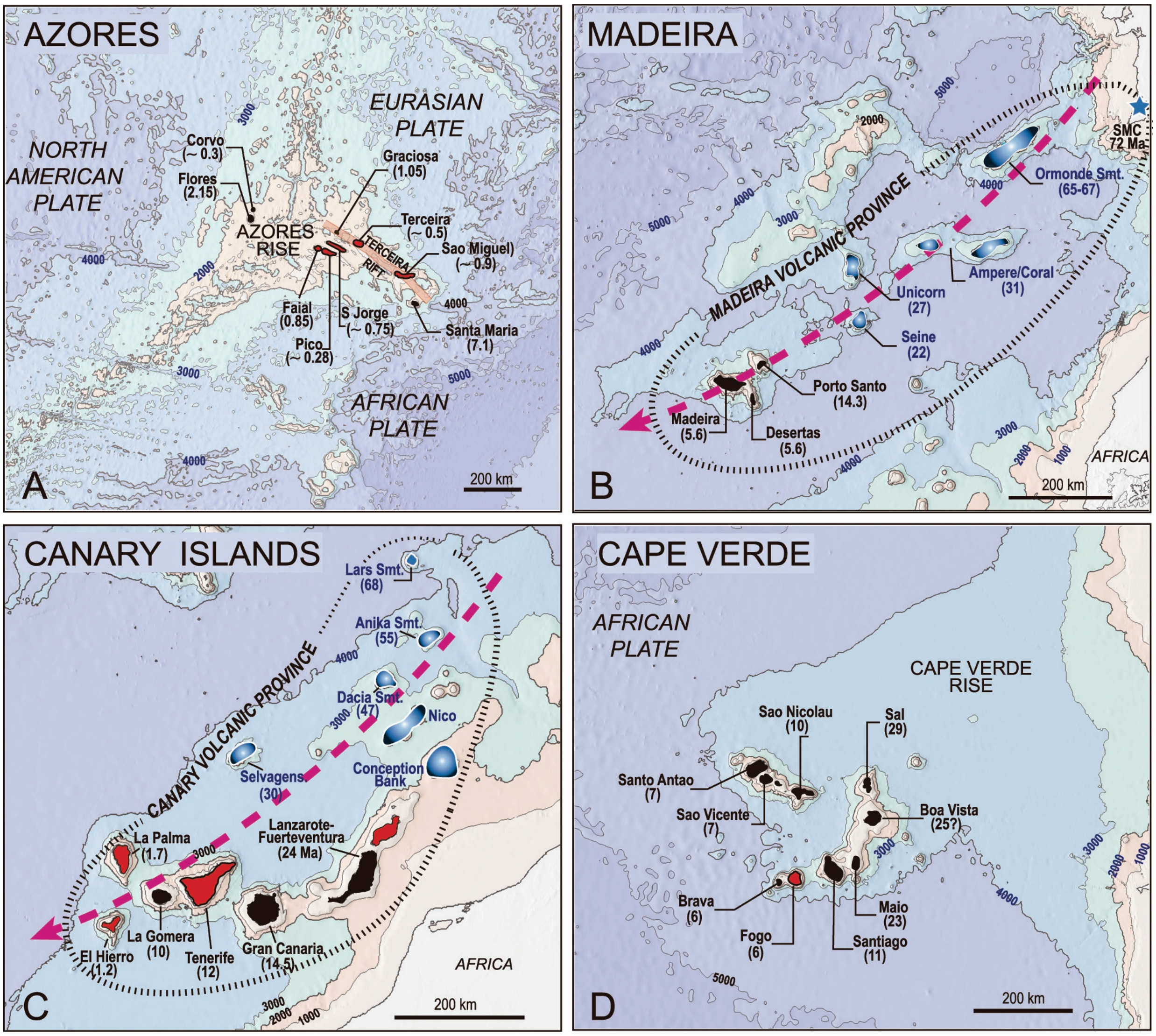

Fig. 2 Detailed bathymetry of the Azores and Cape Verde rises and the Madeira and the Canary Islands volcanic provinces (Black squares in Fig. 1). The oldest radiometric ages (Ma) for the oldest subaerial lavas of each island are indicated. Red islands are those with historical eruptions. *SMC*, Sierra de Monchique volcanic complex. Bathymetry data from NOAA GLOBE.

Age and Distribution of Volcanism

In the Central-East North Atlantic, oceanic archipelagos originated by a fixed mantle plume acting on a lithospheric plate (c.f., the Hawaiian Islands type model). Except for the Azores, the islands are usually constructed sequentially, increasing progressively in age. This distribution of the islands in time and space observed in the Canary, Madeira and Cape Verde volcanic provinces confers systematic changes from southwest to northeast in their evolutionary stage (Figs. 1 and 2). As the volcanoes age, they originally go through a constructive phase of evolution in which growth of the edifice through volcanic activity outpaces its destruction through mass wasting (e.g., landsliding) and erosion. The morphology of the islands thus reflects their evolutionary stage. In addition, the determination of the age of the successive eruptions that build up oceanic islands allows us to define their time of emersion, and thus a critical reference point in the evolution of each island. Once established, this reference point helps to correlate exposed volcanic formations and define a detailed volcanic stratigraphy, and so permits an assessment of approximate eruptive rates. Except for the Azores archipelago, which sits on a tectonic triple-junction and where the islands are all relatively young (predominantly of Quaternary ages), the other three Macaronesian archipelagos show considerably longer volcanic life spans, with growth periods exceeding 14 Ma in Madeira and the Cape Verde, and over 24 Ma in the Canary Islands (see recent summary in Jeffery and Gertisser, 2018). In this regard, it is particularly valuable to determine the oldest subaerial volcanism in a volcanic chain and to test for possible age patterns, e.g., age progression of emergence amongst the successive islands. However, this is a difficult task because

Table 1 The Macaronesian archipelagos by island.

Archipelago	*Island*	*Area km²*	*Highest elevation (m asl)*	*Oldest subaerial rock (Ma)*	*Historical eruptions (* Submarine)*
AZORES	Corvo	17	770 (Monte Gordo)	~0.3	–
	Faial	172	1043 (Cabeco Gordo)	0.85	1957, 1958, 1672
	Flores	142	914 (Pico Alto)	2.15	–
	Graciosa	60	402	1.05	–
	Pico	447	2351 (Montanha do Pico)	~0.28	1562, 1718, 1720
	Santa María	97	590 (Montanha do Pico)	7.1	–
	Sao Jorge	243	1053 (Pico da Esperanza)	~0.75	1580, 1808/1902, 1964*
	Sao Miguel	747	1113 (Pico da Vara)	~0.9	1439, 1562, 1563, 1564, 1630
	Terceira	400	1022 (Serra Sta. Barbara)	~0.5	1761, 1867, 1998*
MADEIRA	Islas Desertas	14	442 (Boqueiro Norte)	5.6	–
	Madeira	801	1862 (Pico Ruvio)	5.6	–
	Porto Santo	42	517 (Pico de Facho)	14.3	–
ISLAS CANARIAS	El Hierro	268	1510 (Malpaso)	1.2	2011*
	Fuerteventura	1660	807 (Janda)	~24	–
	Gran Canaria	1560	1949 (Pico Las Nieves)	14.5	–
	La Gomera	370	1487 (Garajonay)	10	–
	La Palma	708	2423 (Roque Muchachos)	1.7	1480, 1585, 1646, 1677, 1712, 1949, 1971
	Lanzarote	846	671 (Peñas del Chache)	15.6	1730, 1824
	Tenerife	2034	3718 (Teide)	12	1492, 1705, 1706, 1798, 1909
CABO VERDE	Boa Vista	620	387 (Monte Estancia)	~25	–
	Brava	67	976 (Monte Fontainhas)	<3	–
	Fogo	476	2829 (Monte Fogo)	<2	1680, 1712, 1769, 1785, 1799, 1816, 1847, 1852, 1857, 1951, 1995, 2014
	Maio	269	436 (Monte Penoso)	12	–
	Sal	216	216 (Monte Grande)	16	–
	Santiago	991	991 (Pico da Antonia)	6	–
	Santo Antau	779	1979 (Tope de Coroa)	7	–
	Sao Nicolau	388	1340 (Monte Gordo)	<5	–
	Sao Vicente	227	725 (Monte Verde)	<4.5	–

Summary of the combined dataset used in this study.

* *Offshore eruption.*

Data from Guillou H, Carracedo JC, Pérez Torrado FP and Badiola ER (1996) K-Ar ages and magnetic stratigraphy of a hotspot-induced, fast grown oceanic island: El Hierro, Canary Islands. *Journal of Volcanology and Geothermal Research* 73: 141–155; Torres P, Madeira J, Silva L, Brum da Silveira A, Serralheiro A and Mota Gomes A (1997) *Carta Geológica das erupções históricas da Ilha do Fogo: Revisão e actualização.* Ministério da Ciencia e da Tecnologia, Instituto de Investigação Científica Tropical, pp. 421; Geldmacher J, Hoernle K, Van den Bogaard P, Duggen S and Werner R (2005) New Ar-40/Ar-39 age and geochemical data from seamounts in the Canary and Madeira volcanic provinces: Support for the mantle plume hypothesis. *Earth and Planetary Science Letters* 237: 85–101; Holm PM, Grandvuinet T, Friis J, Wilson JR, Barker AK and Plesner S (2008) An 40Ar-39Ar study of the Cape Verde hot spot: Temporal evolution in a semistationary plate environment. *Journal of Geophysical Research* 113: B08201; Madeira J, Brum da Silveira A, Mata J, Mourão C and Martins S (2008) The role of mass movements on the geomorphologic evolution of island volcanoes: Examples from Fogo and Brava in the Cape Verde archipelago. *Comunicações Geológicas* 95: 93–106; Ramalho RA (2011) *Building the Cape Verde Islands.* Berlin: Springer Science and Business Media. https://doi.org/10.1007/978-3-642-19103-9; Gaspar JL, Guest J, Queiroz G, Pacheco A, Pimentel A and Gomes R (2015) Eruptive frequency and volcanic hazards zonation in São Miguel Island, Azores. In: Gaspar JL, Guest JE, Duncan AM, Barriga FJAS and Chester DK (eds.). *Volcanic Geology of São Miguel Island (Azores Archipelago).* Geological Society: London, Memoirs 44, pp. 155–166; Jeffery AJ and Gertisser R (2018) Peralkaline felsic magmatism of the Atlantic Islands. *Frontiers in Earth Science* 6: 145.

hydrothermal alteration in the oldest rocks can limit their use for radiometric age determination and has previously given rise to contradictory results (see discussion in Guillou et al., 1996, 2004). The Azores archipelago seems to lack a distinct age pattern in the distribution of the oldest subaerial (emergence) rocks of the different islands, thus contrasting the other three Macaronesian archipelagos (Fig. 2). There, age progressions appear systematic, particularly in the Madeira and Canary archipelagos, and especially when considering not only islands but also the associated seamounts of the region (Geldmacher et al., 2005; Troll et al., 2015).

The presence or absence of an age progression in oceanic island chains has crucial geological implications for the origin of these islands and has been the subject of prolonged controversy. This debate has been particularly long-lived and lively in the Canary Islands, where different authors, using different sampling and laboratory methods, frequently obtained different ages for the stratigraphically oldest formations (e.g., Abdel-Monem et al., 1971, 1972; Guillou et al., 1996; Fúster et al., 1993; Paris et al., 2005; Ancochea et al., 2006). In recent years, however, geophysical and palaeontological determinations have provided crucial supporting data for a continuous easterly increase in age along the Canary Archipelago. For instance, Funck and Schmincke (1998) showed by using high-resolution reflection seismic data that the flank of Tenerife onlaps the steeper and older flank of Gran Canaria, which, in turn, rests on the older apron of Fuerteventura (Fig. 3A), implying that the islands are progressively younger towards the west.

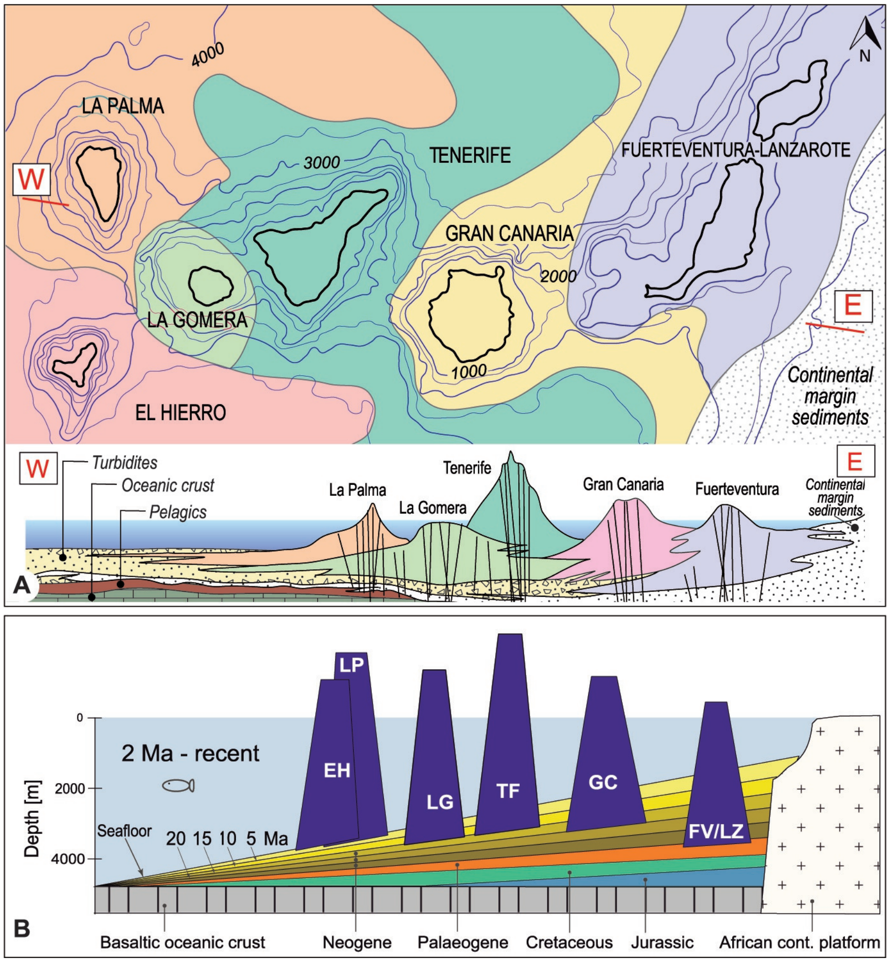

Fig. 3 (A) Progressive W-E onlap of island aprons in the Canary archipelago deduced from seismic reflection data. (B) Schematic cross-section through the Canary archipelago and the African continental margin (thicknesses of sedimentary layers not to scale). Nannofossils in El Hierro eruptives now demonstrate, in agreement with available radiometric ages of the oldest subaerial lavas, that progressively younger pre-volcanic sediments are present under the islands in the west of the archipelago, in support of the previously established onshore age-progression of the islands. (A): After Urgelés R, Canals M, Baraza J and Alonso B (1998) Seismostratigraphy of the western flanks of El Hierro and La Palma (Canary Islands): A record of Canary Island volcanism. *Marine Geology* 146: 225–241; (B): After Zaczek K, Troll VR, Cachao M, Ferreira J, Deegan FM, Carracedo JC, Soler V, Meade FC and Burchardt S (2015) Nannofossils in 2011 El Hierro eruptive products reinstate plume model for the Canary Islands. *Scientific Reports* 5: 7945.

In addition, Urgelés et al. (1998) obtained seismostratigraphic evidence on the Western Canaries that implies the successive overlapping of the Tenerife, La Palma and El Hierro aprons (see Fig. 3A). Moreover, sedimentary rock fragments picked up by ascending magma during the 2011 submarine eruption of El Hierro retained specimens of pre-island calcareous nannofossils (Zaczek et al., 2015; Troll et al., 2015). The El Hierro frothy sedimentary fragments (xenopumice) that contain the nannofossils were originally deposited as ocean floor sediment from the Mesozoic up to shortly before island growth started, which terminated regular background sedimentation. This is confirming the youngest sub-island sediment age within the Canary archipelago, and thus a consistently diminishing age of the pre-island sedimentary strata from Fuerteventura to El Hierro (Fig. 3B). The palaeontological evidence is consistent with the onshore age progression for the individual islands within the archipelago (Troll et al., 2015), corroborating a plume model for the Canary Islands.

The Azores differ in this regard, and distribution of volcanism within the Azores archipelago shows clear differences from the other three Macaronesian archipelagos. Volcanic centers in the Azores tightly cluster along fractures typically related to the Mid-Atlantic Ridge and the Terceira Rift (see Fig. 1), while volcanic vents and dykes in the Canaries and Madeira form independent rifts and chains without any apparent predominant direction (see Figs. 1 and 4).

Many portions of the Macaronesian archipelagos are classified as volcanically active and historical volcanism is recorded in the islands of Faial, Pico, Terceira, Sao Jorge and Sao Miguel in the Azores, on Fogo in the Cape Verde archipelago, and on El Hierro, La Palma, Tenerife and Lanzarote in the Canary Islands (Fig. 4; Table 1). Volcanic activity poses risks for the population of many regions of these islands.

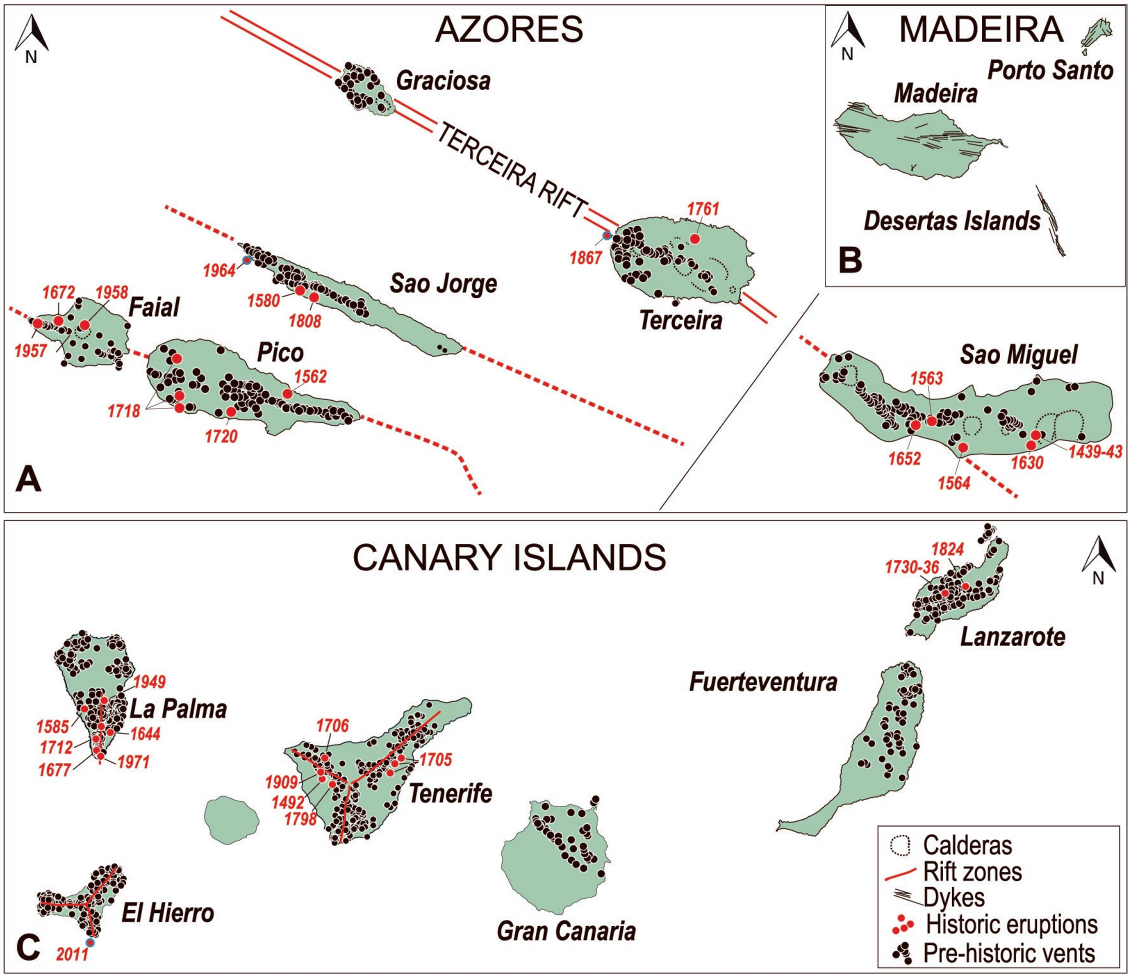

Fig. 4 Structural features and distribution of vents in the Azores (A), Madeira (B) and Canary Islands (C). Note the close relationship of the islands and their earthquakes with active regional fractures (broken red lines) in the Azores, a feature that is largely absent in Madeira and the Canary Islands.

Seismicity and Seismic Hazard in the Macaronesian Islands

The Central-East Atlantic basin is for most parts aseismic, and only scant and scattered earthquakes occur except at the direct plate boundaries and beneath the Macaronesian islands themselves (Fig. 5A). The occurrence of high magnitude earthquakes in the Azores islands is related to their location in the vicinity of the active fracture zones of the Mid-Atlantic Ridge (Fig. 5B). Strain adjustments derived from dynamics of the Azores triple junction have resulted in up to 33 high-intensity earthquakes ($M > 7$) since the 15th century, causing more than 6000 deaths and widespread destruction (Caldeira et al., 2017). From 1915 to 1998 (Nunes et al., 2004), and for the period 1999 to 2011 (Sousa and Martins, 2000), the seismic records in the Azores contain 9214 earthquakes, of which 5456 register on the Richter-scale (Rodrigues and Oliveira, 2013). These authors used the number of events recorded in this period and their maximum magnitude to identify seven zones with significant differences in seismicity (red lines and figures in Fig. 5B). Zones 1, 3 and 7 are considered background zones, while zones 4 and 5 show very high seismicity, with magnitudes reaching up to $M = 6–7$. Zone 6, related to the Gloria Fault, displays the highest earthquake magnitudes ($M = 8.2$) of all zones.

In contrast, seismicity in the intraplate island groups, i.e., Madeira, the Canary and Cape Verde archipelagos, is generally (directly or indirectly) related to volcanism, and is thus usually of relatively low magnitude. Exceptions would be those rare events that are associated to catastrophic gravitational collapses or caldera-forming eruptions, but those have not yet been witnessed in historical times.

The idea of relating the orogenic pulses of the Atlas tectonism with fractures extending towards the Canarian archipelago has had a long and persistent influence (e.g., Anguita and Hernán, 1975, 2000). The review of the Moroccan seismicity map and adjacent regions for the 1901–2010 period (Medina and Cherkaoui, 1992; Cherkaoui and El Hassani, 2012) now shows that the seismic activity is concentrated in two domains: the High Atlas fault on the one side, and the area of the Canary Islands on the other, which

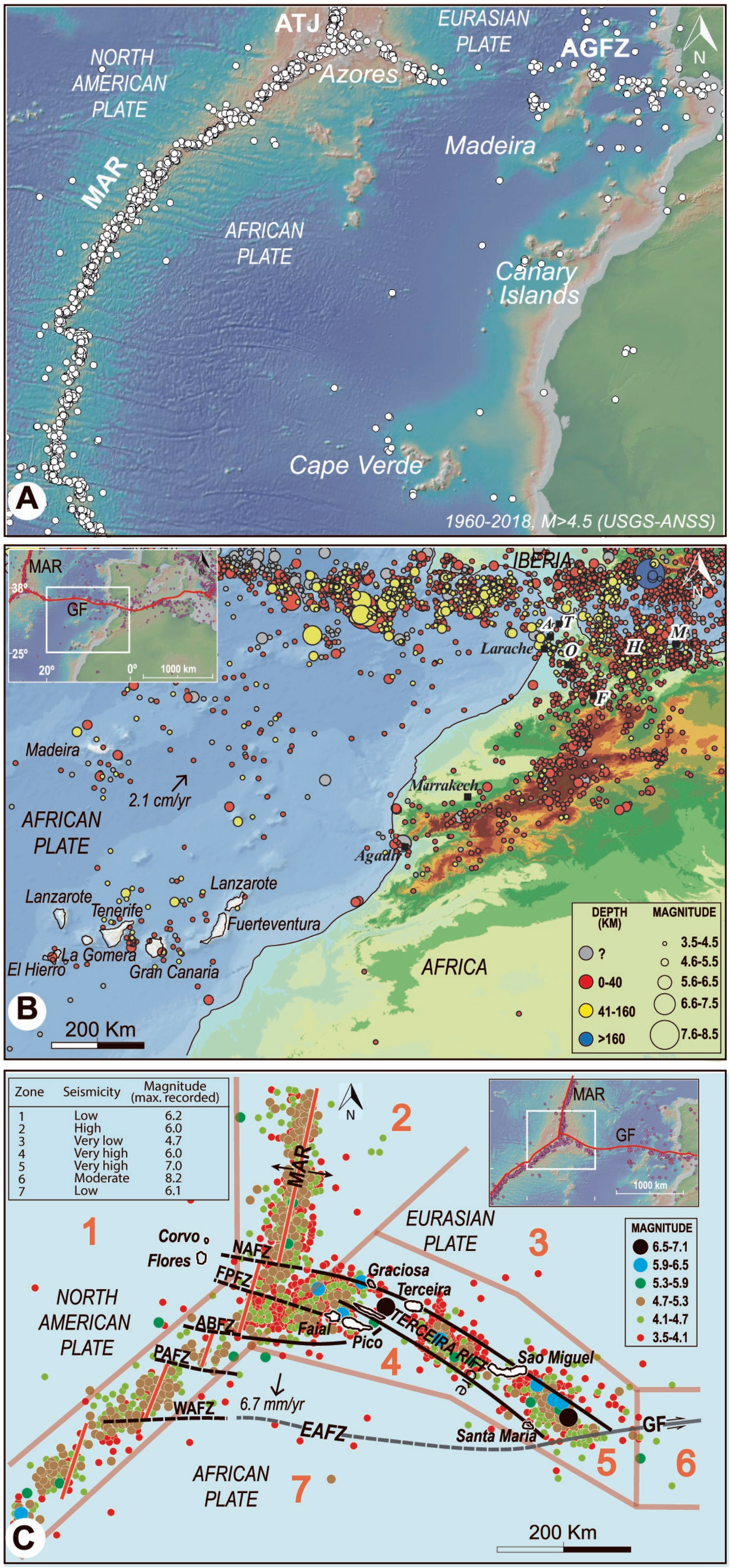

Fig. 5 (A) Distribution of M > 4.5 earthquakes recorded in the Central-East Atlantic (1960–2018, USG-ANSS). Note the numerous events associated with the Mid-Atlantic Ridge and the Azores on the one side, and plate boundary faults on the other. In contrast, the interior of the Central-East Atlantic is essentially aseismic, except for moderate seismicity in the area of the Madeira and Canary archipelagos, predominantly related to magmatic and volcanic processes. (B) Main tectonic features of the Azores region and associated seismicity (M > 3.5) for the period 1926 to 2017. Seven zones with significant differences in seismicity (red lines and numbers) have been identified from their maximum magnitude (see text for further explanation). Zones 4 and 5 show very high seismicity, with magnitudes reaching up to M = 6–7. The highest earthquake magnitude (M = 8.2) is related to the Gloria Fault. (C) Location of the Moroccan seismicity and adjacent regions for the period 1901–2010 (Medina and Cherkaoui, 1992; Cherkaoui and El Hassani, 2012). This seismicity is concentrated along the High Atlas fault and in the area of the Canary Islands but is separated by a distinct gap, likely related to the arrest or termination of the Atlas fault line off the coast of Agadir (Benabdellouahed et al., 2017; Fekkak et al., 2018). After Caldeira B, Fontiela J, Borges JF and Bezzeghoud M (2017) Grandes terremotos en Azores. *Física de la Tierra* 29: 29–45; Rodrigues MCM and Oliveira CS (2013) Seismic zones for Azores based on statistical criteria. *Natural Hazards and Earth System Sciences* 13(9): 2337–2351.

are separated by a distinct aseismic gap (Fig. 5C). The gap in seismicity between the Canary Islands and the continent implies the arrest or termination of the Atlas fault near the coast off Agadir (Benabdellouahed et al., 2017; Fekkak et al., 2018).

The Origin of Volcanism of Central-East Atlantic Island Groups

The processes capable of generating magma with sufficient volume and duration to build the different island edifices of the east-central Atlantic archipelagos need to be addressed within the structural and volcanic framework described above. Following the introduction of plate tectonics, two initial hypotheses were proposed to explain the genesis of the Hawaiian Islands: (1) A propagating fracture model proposed by McDougall (1971), and (2) A fixed heat anomaly in the mantle, i.e., a hotspot (Wilson, 1963). The latter was thought to represent the surficial expression of a narrow, quasi-stationary anomalously hot and thermally buoyant plume of mantle material rising from the core-mantle boundary (Morgan, 1971). Despite an early application of the fracture model to the Canary Islands (Anguita and Hernán, 1975), the East-Central North Atlantic archipelagos are today widely considered to represent hotspot tracks associated with upwelling mantle plumes (Carracedo, 1979; Holik et al., 1991; Hoernle and Schmincke, 1993; Carracedo et al., 1998; Geldmacher et al., 2001, 2005). However, doubts in the applicability of a classic mantle plume origin persist in the case of the Azores, which are located close to the Mid-Atlantic Ridge and are thus affected by regional fracture systems. More recently, the propagating fracture concept was re-applied to the Canary Islands, combining the role in the archipelago of a thermal anomaly in the mantle, but suggesting a critical role for the onset of volcanism being a regional fracture, possibly a prolongation of the continental Atlas Fault (Anguita and Hernán, 2000). The critical issue to be clarified was, therefore, whether these archipelagos require structures that cut through the lithosphere to cause and to control the location of the volcanism, or they are fed from a deep mantle source and are then largely independent of the lithosphere (Hoernle and Carracedo, 2009).

Magmatism in the Azores, as in Iceland, appears instead to be a characteristic example of hotspot-ridge interaction (Schilling, 1975; Cannat et al., 1999; Escartín et al., 2001; Gente et al., 2003; Madureira et al., 2005; Silveira et al., 2006; Yang et al., 2006). The Azores Plateau, an area of thickened oceanic crust, is likely the result of sustained magmatic uplift, which supports the existence of a mantle plume (Silveira et al., 2006; Schilling, 1975; Zhang and Tanimoto, 1992; Montagner and Ritsema, 2001; Montelli et al., 2004). In addition, the Azores are strongly influenced by lithospheric faults and rifts that control the location of the volcanism, as well as the shape and structure of the individual islands and their seismicity (see Figs. 1, 2, 4A and 5B). Lithospheric fractures are also at the core of the lack of a consistent age progression in the Azores archipelago, which is more typical of fracture-related "hotspot-type" intraplate archipelagos (e.g., Cameroon Volcanic Line). In contrast, for Madeira, the Canaries and the Cape Verde islands, the observed age progression most probably represents a hotspot track associated with upwelling mantle plumes that pierce a moving lithosphere above, thus giving rise to Hawaiian-style hotspot tracks (Fig. 6). The intense seismic activity in the Azores archipelago is, in contrast, further influenced by the dynamics of the Azores triple junction plate boundary and the numerous associated faults and rifts in that region (Fig. 5B).

The Cape Verde Archipelago overlies the Cape Verde Rise, an extensive area that is elevated by up to >2 km above the surrounding seafloor (see Figs. 1 and 2), traditionally interpreted to represent a hotspot swell (Crough, 1982). The lack of a comparable bathymetric anomaly is sometimes used to question a hotspot origin for the Madeira and the Canary Islands groups. However, this apparent contradiction may be related to the different plate environments, which are notably semi-stationary in Cape Verde (Holm et al., 2008; Ramalho et al., 2010) compared to relatively fast-moving plate velocities in the regions of the Madeira and the Canary Islands (Holik et al., 1991; Carracedo et al., 1998; Geldmacher et al., 2001, 2005). Persistent magmatic uplift and underplating acting at the Cape Verde Rise is thus "less dispersed," clustering around the stationary plume source. In the Canary and Madeira volcanic provinces, volcanic pulses are thus considerably more strung out along a longer hotspot track (see Figs. 2 and 6).

To summarize so far, an early hypothesis linked the origin of the Canaries with magmatism resulting from decompression melting along a leaky transform fault or propagating fractures cutting through an old (Mesozoic) section of the lithosphere. This concept has, by now, been largely abandoned in favor of an upwelling mantle plume. However, some authors (Anguita and Hernán, 2000) maintain a possible connection between the Canaries and the Atlas Fault. These authors argued that even if a mantle plume exists, the ascending material is guided in the lithosphere by a fracture system associated with the Atlas Mountains, which thus "controls" the ascending plume magmas, similar to the Azores. Fault-controlled magma ascent is usually accompanied by an absence of systematic ages along fault lines, as seen in the Azores, but also along, for instance, the Cameroon Volcanic Line and the Rhine graben. The postulated fracture hypothesis for the Canary Islands thus conflicts with the systematic internal age-progression observed. An upwelling mantle plume that intersects a lithospheric fracture system should generate simultaneously active volcanic islands, intense and persistent seismicity throughout the archipelago, and visibly elongated island shapes due to the underlying lithospheric fractures. These features are apparent in the Azores, but generally absent in the Canaries and Madeira archipelagos (see Figs. 4 and 5A). Furthermore, there is no evidence for such faults in the Canary or Madeira volcanic provinces or suture zones in these areas (Martínez del Olmo and Buitrago, 2002; Acosta et al., 2003). Moreover, movements along structures cutting thick Mesozoic lithosphere (McKenzie and Bickle, 1988) would not generate sufficient volumes of melt to construct these archipelagos as a result of the passive upwelling of normal asthenosphere mantle. Dyke swarms in Fuerteventura and orientation of uplifted marine strata could come from faults, but these are parallel to the oceanic anomalies, i.e., are self-parallel oceanic faults unrelated to the Atlas system (Gutiérrez et al., 2006).

Strong additional support for the existence of a mantle plume comes from the orientation of the Madeira and Canary volcanic archipelagos, following roughly parallel curved trends (see Figs. 2 and 6), consistent with the rotation of the African plate with a

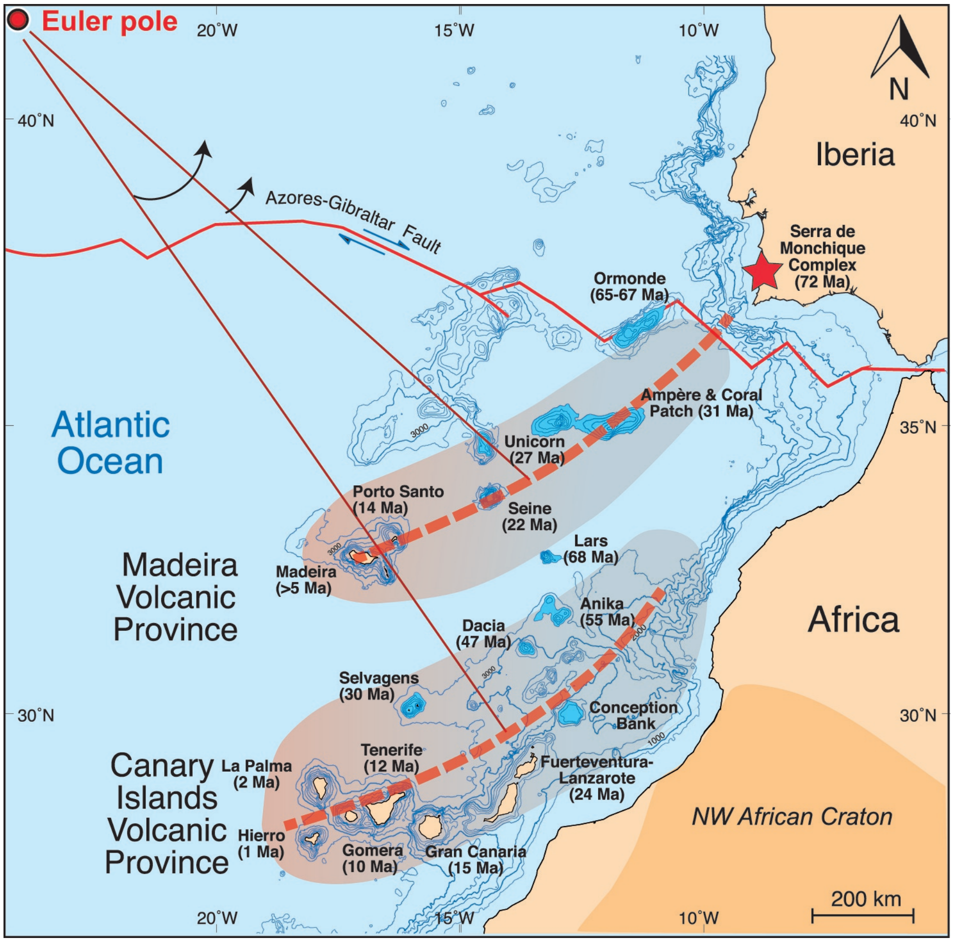

Fig. 6 The Canary and Madeira Volcanic Provinces (comprising the main islands and the associated seamounts) began to form roughly at the same time and developed at a similar rate. The two volcanic chains follow a parallel and curved trend with a common Euler rotation pole, consistent with the displacement of the African plate above two stationary melting anomalies. Modified after Geldmacher J, Hoernle K, Van den Bogaard P, Duggen S and Werner R (2005) New Ar-40/Ar-39 age and geochemical data from seamounts in the Canary and Madeira volcanic provinces: Support for the mantle plume hypothesis. *Earth and Planetary Science Letters* 237: 85–101; Troll VR, Deegan FM, Burchardt S, Zaczek K, Carracedo JC, Meade FC, Soler V, Cachao M, Ferreira J and Barker AK (2015) Nannofossils: The smoking gun for the Canarian hotspot. *Geology Today* 31(4): 137–145.

rotation (Euler) pole located south of Greenland (Geldmacher et al., 2005; Troll et al., 2015). The coeval but isotopically different archipelagos were constructed along parallel curved paths and developed at the same average rate for at least the last 70 million years, likely corresponding to deep mantle plumes that independently feed the Madeira, Canary Islands, Cape Verde, and the Azores archipelagos.

These geological arguments are further supported by finite-frequency tomographic images from seismic wave velocities that have now also confirmed the existence of deep mantle plumes below a large number of known island clusters and chains, including the Macaronesian islands (Montelli et al., 2004, 2006). This concept has been recently corroborated using whole-mantle seismic imaging techniques (French and Romanowicz, 2015). In these studies, the three Macaronesian plumes (Canaries, Azores and Cape Verde) appear as robust deep mantle anomalies (Fig. 7), extending as isolated anomalies down to >1000 km depth, and are thus sourced from very deep in the Earth's mantle (Montelli et al., 2004, 2006).

Geochemical Evidence in Support of a Plume Origin for the Macaronesian Islands

The compositional spectrum of erupted products in the Macaronesian islands is relatively wide, but generally of an alkaline basaltic nature with variously voluminous alkaline felsic derivative compositions that take the form of trachytes, phonolites and highly alkaline rhyolites (e.g., Schmincke, 1973, 1976; Troll and Schmincke, 2002; Jeffery and Gertisser, 2018). Close to the African continent, several islands contain somewhat larger volumes of rhyolitic or phonolitic eruptives (e.g., Gran Canaria and Tenerife), which may be related to the large sedimentary fan deposits on which these islands are constructed. Regarding the basaltic evolutionary magmatic suites present in the Azores, the Madeira, the Canary, and the Cape Verde Islands, they can generally be

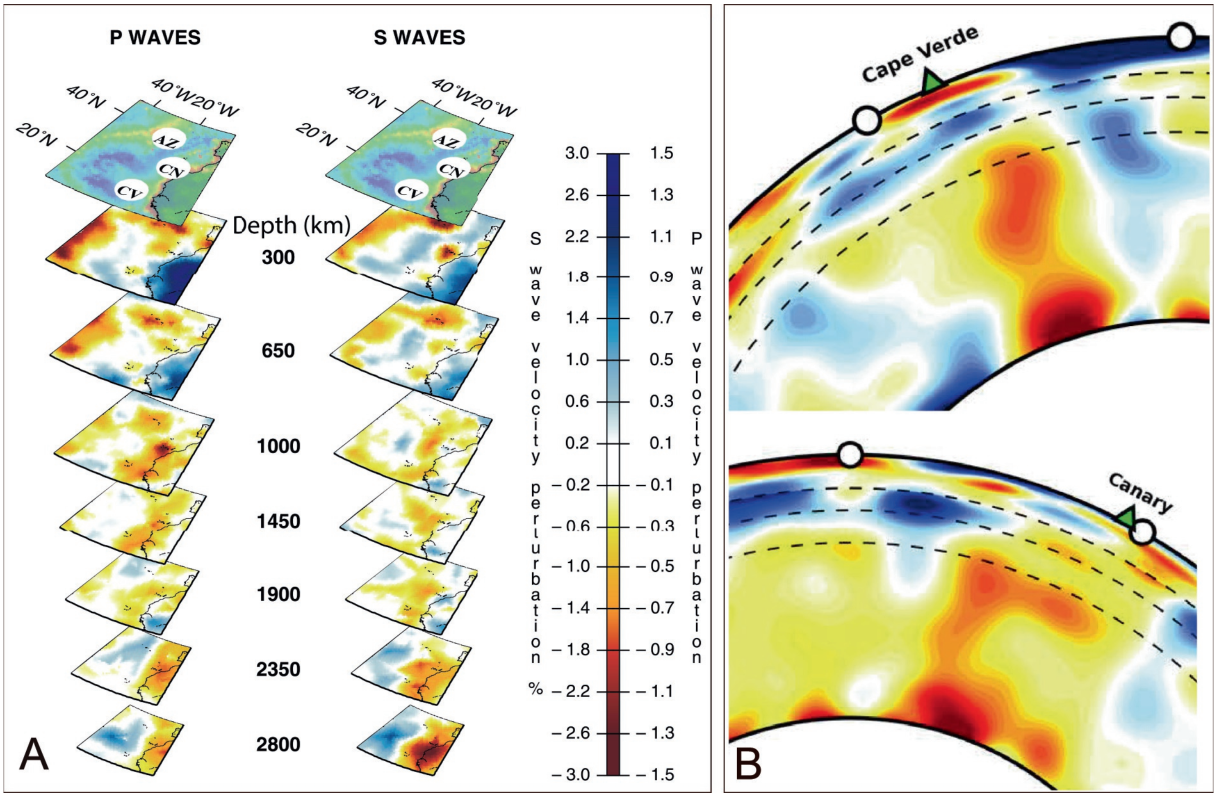

Fig. 7 (A) Three-dimensional view of the melting anomalies (plumes) beneath the AZ (Azores), CN (Canary), and CV (Cape Verde) archipelagos in both (left) P-wave and (right) S-wave tomographic models. Note the anomalies are traceable all the way to the core-mantle boundary. (B) Whole-mantle depth cross-sections of relative shear-velocity variations in model SEMUCB-WM14, in the vicinity of Cape Verde and Canary Islands hotspots. Green triangles mark the locations of hotspots. (A): From Montelli R, Nolet G, Dahlen FA, Masters G, Robert Engdal E and Hung SH (2004) Finite-frequency tomography reveals a variety of plumes in the mantle. *Science* 303 (5656): 338–343; (B): After French SW and Romanowicz B (2015) Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. *Nature* 525: 95–99.

classified as "Ocean Island Basalt" Series (OIB). This Series is characterized by higher alkalinity at similar SiO_2 than standard tholeiitic Mid-ocean ridge-type (MORB) basalt. Moreover, while the archipelagos appear to differ in their precise isotopic compositions, an OIB-type origin has been identified in all four archipelagos on the basis of trace elements and especially radiogenic and stable isotope geochemistry (e.g., Hoernle and Schmincke, 1993; Widom et al., 1997; Christensen et al., 2001; Geldmacher et al., 2006a,b; Millet et al., 2008; Beier et al., 2010). In particular, a HIMU (high mother Uranium) recycled deep mantle component has been postulated by many of these authors based on radiogenic isotopes to contribute to the source chemistry of the erupted lavas of the four Macaronesian island groups. Moreover, noble gas studies have shown that higher proportions of primordial helium is present in melt inclusions in magmatic minerals compared to what is typical for MORB-type rocks (e.g., Moreira et al., 1999; Hilton et al., 2000; Christensen et al., 2001), implying a primitive deep mantle component in their mantle sources. An enriched mantle component (EM1) appears present in some islands but is not seen in all of them, defining an element of inter-archipelago differences.

The HIMU mantle component detected in the Macaronesian archipelagos is believed to represent formerly subducted near-surface materials that have a more crustal U-Pb composition and which would be more radiogenic than both the deep and the shallow mantle domains. The higher rates of radioactive decay in these "high mother uranium" mantle components are likely a key reason for these compositions to heat up and become buoyant again, thus constituting a possible key driver for some hotspot volcanic regions. This contrasts with the high primordial helium ratios since crustal helium values are rather low, while deep in the Earth primordial helium is still present at higher abundance. Elevated helium isotope values beyond the range typical for upper mantle-derived rocks (MORB) imply that mantle melting in such regions liberated some of the remaining primordial helium stored in the lower mantle. The elevated helium ratios found in the Azores, Canaries and Cape Verde islands relative to MORB-type values are thus a critical observation in favor of a deep "plume" or "hotspot" origin for these island groups. Ascending components from the deep mantle then mix with ambient depleted upper mantle during their ascent, but there is locally an additional enrichment with an "enriched mantle component," usually referred to as the EM1 component. This component was initially considered to derive from greater depth as well, but has been increasingly associated with subcontinental lithospheric peridotite material. The

Canaries and the Cape Verde Islands, the islands closest to Africa, seem to display this geochemical feature in particular. It has been suggested that the EM1 component represents melts from sub-African mantle lithologies that might have detached from the sub-continental lithosphere beneath Africa, e.g., during opening of the Atlantic, and became subsequently entangled and intermixed with ascending plume materials (cf. Gurenko et al., 2009, 2010; Barker et al., 2012). This concept has also been applied to those islands in the Azores that also display an EM1 component, and it has been suggested that portions of subcontinental lithospheric mantle that originally resided beneath northwestern Africa (or perhaps Iberia) may in part be responsible for the locally enriched magma chemistry of some Azores eruptives (c.f., Widom et al., 1997). It has thus been argued that fragments that broke off from beneath Africa may still be present as shallow and localized contaminants in the upper mantle beneath the Azores, the Canaries and the Cape Verde islands, and can so create a compositional imprint on the magmas produced (e.g. Gurenko et al., 2009; Barker et al., 2012).

In addition to the general acknowledgment that the magmas of the Macaronesian archipelago contain deep plume components that comprise a primitive lower mantle component and also a recycled high-U deep mantle component, temporal variations within islands also exist. This is well displayed in the long-lived examples from the Canary Islands, e.g., on Gran Canaria and Tenerife, where several cycles of activity have been observed over the exposed geological history. The blob model has been a popular way to explain the apparent pulsing of volcanic activity (i.e., the observed evolutionary stages or cycles) (e.g., Hoernle and Schmincke, 1993; Thirlwall et al., 2000; Gurenko et al., 2009; Deegan et al., 2012). In this framework, blobs of variably fertile mantle materials rise and initiate melting in the upper mantle. This leads to bursts (cycles) of activity that alternate with periods of magmatic quiescence throughout the history of individual islands. The plume-derived HIMU component is widely considered to represent ancient and formerly subducted high-level (crustal) material that occurs in the deep mantle as nuggets or streaks and which may rise buoyantly after a considerable residence in the deep mantle due to prolonged heating from radioactive decay of, e.g., U and Th, and may represent the ultimate driving force for some Atlantic ocean island magmatism. The upper mantle, in turn, is depleted MORB, while the EM1 component may reflect subcontinental lithosphere domains dispersed in the upper mantle from the fragmentation of Africa during the opening of the Atlantic, before the formation of any of the four Macaronesian island groups. Finally, claims for magma-crust interaction have multiplied for the Macaronesian ocean islands over the last two decades, including the Canaries, the Azores and also the Cape Verdes, and have been identified through oxygen isotopes in particular (e.g., Wolff et al., 2000; Hansteen and Troll, 2003; Barker et al., 2012; Deegan et al., 2012; Genske et al., 2013).

The Geology of the Macaronesian Archipelagos

The Azores

The Azores archipelago comprises nine islands, but only seven of them are located in the Central-East Atlantic, east of the Mid-Atlantic Ridge (see Figs. 2A, 4A and 8A). The islands form the emerged part of the Azores micro-plateau, a triangular-shaped bathymetric shallow region bounded by three tectonic fracture systems that mark a triple junction that separates the North-American, Eurasian and African plates (see Figs. 2A and 5B).

The Azores plateau, oceanic crust and archipelago make up the youngest of the four Macaronesian island-groups and differ from the other three archipelagos in the apparent lack of consistent island age progression (see Fig. 2A). A distinctive feature of the Azores is the ESE elongate trend of the island group (and individual islands) consistent with the active regional fractures with which they are aligned (Fig. 8A). Except for the oldest and intensely eroded island of Santa Maria, the Azores show distinct volcanic landforms, relatively high elevations, very active seismicity, and lively volcanic histories with frequent historical eruptions (Gaspar et al., 2015; Kueppers and Beier, 2018; Table 1).

The majority of the subaerial magmas of the Azores archipelago are mafic in composition (predominantly basalts), while felsic magmas are less abundant. The rarer felsic eruptives are often associated with explosive eruptions (e.g., Plinian), frequently from central vents of various volcanic centers or complexes (e.g., Gertisser et al., 2010; Jeffery and Gertisser, 2018; Pimentel et al., 2015) and their lava domes and coulées (e.g., Self, 1974, 1976; Booth et al., 1978; Pimentel, 2006).

The tectonic framework strongly influences the shapes of the islands. This feature is most apparent in the island of Sao Jorge, where a chain of basaltic volcanic cones aligns along the main WNW-ESE axis of the island's ridge, configuring eight times longer than wide dagger-shaped island (inset in Fig. 8A). However, the construction of central volcanoes along with such fractures frequently modifies the configuration of the islands to a somewhat more rounded shape (e.g., Faial and Pico islands, see inset in Fig. 8A). Moreover, the island of Sao Miguel comprises four felsic coalescent central volcanoes and calderas: Sete Cidades, Fogo, Furnas and Povoação (Fig. 8B and C) that define the island's shape and geometry. Pico Volcano is the most spectacular volcano in the Azores and also constitutes the highest elevation of the archipelago (Nunes, 1999; França et al., 2009). It gave its name to the island (Fig. 8D), and is a 2351 m-high basaltic stratovolcano with a recent crater (1 in the inset of Fig. 8D), that is partially filled with lavas (2 in the inset of Fig. 8D), and culminates in the Piquinho lava cone (3 in the inset of Fig. 8D).

The location of the Azores archipelago on an active plate boundary is, however, also affected by a mantle plume, which results in frequent seismic and eruptive activity. This combined action of important regional active tectonism and plume magmatism renders the Azores different from the other Macaronesian archipelagos. For instance, the Madeira, Canaries and Cape Verde islands show much less frequent and much lower magnitude earthquakes and eruptions in historical times (Kueppers and Beier, 2018). The number of seismic events with $M > 3$ recorded between 1926 and 2017 in the area of the Azores archipelago is 9420 (International Seismological Centre, 2019). High magnitude earthquakes repeatedly occurred in and around the islands at shallow depths since

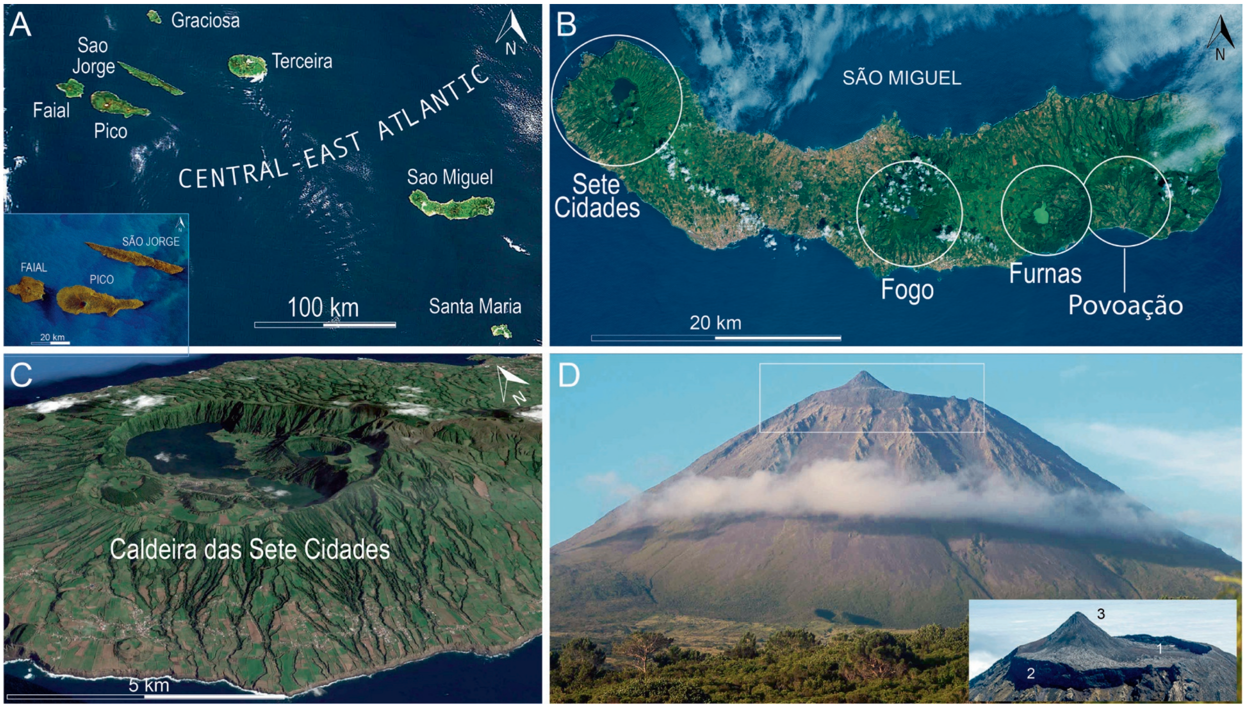

Fig. 8 (A) Map of the Azores archipelago located in the Central-East Atlantic. Note the NW to SE orientation of the islands, in accordance with the main active regional tectonic fractures. The elongated shape of the islands is pointing in the same direction, particularly strong for the island of Sao Jorge (lower inset). (B) The Azores islands are constructed by lineations of basaltic eruptive vents and central volcanoes. The island of Sao Miguel comprises four felsic coalescent volcanoes (image Google Earth). (C) Google Earth image of Sete Cidades central volcano and caldera on Sao Miguel. (D) Pico Volcano, the highest elevation in the Azores, gave its name to the island of Pico. The volcano is a 2351-m-high basaltic stratovolcano, culminating in the Piquinho lava cone (lower inset). Images courtesy of Google Earth and Geoparque Azores, via Panoramio.

the archipelago was colonized in the mid-14th century (Madeira and Brum, 2003). Although, in general, the predominant seismicity in the Azores is of low magnitude and shallow depth, comparable to that of the other Macaronesian archipelagos, the significant difference is the additional occurrence of higher magnitude ($5 \leq M \leq 7$) earthquakes in the Azores, causing great damage and thousands of victims, e.g., in 1522 on Sao Miguel (~5000 victims), 1614 on Terceira (~200 victims), 1757 on S. Jorge (>1000 victims), 1980 on Terceira (>60 victims), (Fig. 9A), and in 1998 on Faial (8 victims) (Caldeira et al., 2017).

Abundant volcanism has also been observed in historic times in the Azores and also offshore between the main islands (see Fig. 4A), comprising basaltic to trachytic magmas and from mild Hawaiian/Strombolian eruptive styles to explosive Plinian eruptions. The most recent eruption at the Azores occurred in 1998 at sea off Ponta de Serreta, near the island of Terceira. The eruptive plume of bright discolored seawater, with gas bubbles and floating, gas-filled lava balloons observed in this submarine event occurred in similar form also in the 2011 submarine eruption off El Hierro (see Fig. 13B). However, in the 1998 eruption, the

Fig. 9 (A) Ruins of the Nossa Senhora da Ajuda church (17th century) that was destroyed after the 1998 earthquake in the island of Faial. (B) Capelinhos eruption (at the westernmost point of Faial, September 1957), a typical shallow submarine (Surtseyan) eruption evolving to magmatic (Strombolian). The eruption eventually formed a stable volcanic edifice that connected to the main island. Images courtesy of Ralf Gertisser.

floating lava balloons (frothy lava bombs) show basanite compositions only (Kueppers et al., 2010). The last onshore eruption at the Azores occurred in 1957/58, also at the westernmost part of Faial, in front of the Capelinhos lighthouse (Ribeiro and Brito, 1957). This type of volcanism, starting as a characteristic hydromagmatic (Surtseyan) eruption and changing to a magmatic (Strombolian) event at the final stages of the eruption (Fig. 9B), is not uncommon on the Azores, and is known from other Macaronesian archipelagos as well (e.g., Clarke et al., 2009).

Madeira

The Madeira archipelago comprises three main islands (Fig. 10), that are located in the eastern Central Atlantic region, ~700 km west of the African coastline and ~400 km north of the Canary Islands. The islands sit upon 140 Ma old oceanic crust (Pitman and Talwani, 1972), and rise ~4 km from the seafloor. The Madeira archipelago marks the emerged south-western end of a northeast-southwest-trending alignment of seamounts (Geldmacher et al., 2005), which extends for ~700 km to the northeast (Figs. 2B and 6). This chain stretches from mainland Portugal to the Madeira archipelago and exhibits a crude age progression from the 72 Ma Sierra de Monchique igneous complex in Iberia to the island of Madeira itself (see Fig. 2B), which is typically interpreted as a hotspot track and hence as evidence for an underlying mantle plume (Morgan, 1971; Geldmacher et al., 2005).

Together, Madeira and the Desertas islands are often considered to represent a single, predominantly basaltic (Mata, 1996) volcanic system (see Fig. 18), dated at ~5.6 Ma (Watkins and Abdel-Monem, 1971; Feraud et al., 1981; Ferreira et al., 1988; Geldmacher et al., 2006a,b). The E-W-trending Madeira Rift formed at an angle of ~110° with the NNW-SSE oriented Desertas rift arm.

Similarly to the uplifted seamount of La Palma (see Fig. 14A), Madeira island likely emerged by uplift during its initial stages of island-building, possibly driven by magmatic underplating and successive basal intrusion, rather than by dominantly volcanic activity (Carracedo et al., 2015; Ramalho et al., 2015). The bulk of Madeira's subaerial shield edifice lies unconformably over the eroded remains of the volcanic seamount, and forms about 99% of the subaerial volume of the island, the more significant part erupted from ~3.9 to 4.6 Ma in successive rift phases (Geldmacher and Hoernle, 2000). Basaltic pyroclastic deposits and minor lava flows that are profusely cut by dykes crop out in the highlands of the central part of Madeira island (Fig. 11A). At its eastern end, the central highland massif gently dips and forms the Ponta de S. Lourenço peninsula (Fig. 11B). The geomorphological features of

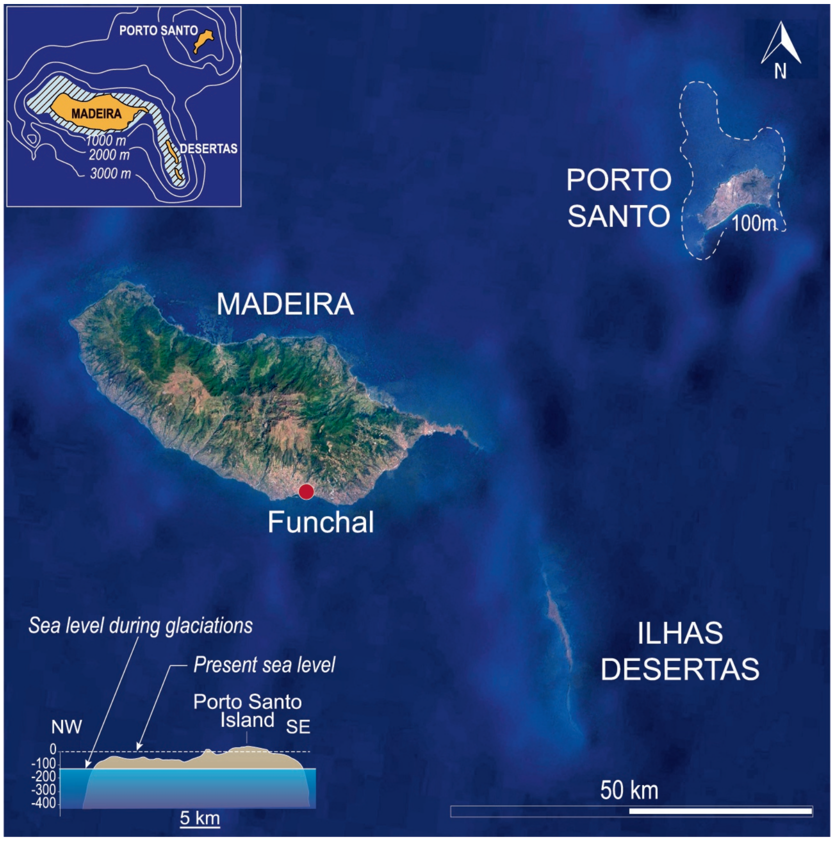

Fig. 10 The Madeira archipelago comprises the islands of Porto Santo, Madeira and Desertas. Upper inset: Ocean depths <500 m between the islands of Madeira and Desertas suggest that both islands likely form a single volcanic edifice. Lower inset: Schematic section showing the larger subaerial extent of the island of Porto Santo during the last glaciation. From Ribeiro ML and Ramalho MM (2010) *A Geological Tour of the Archipelago of Madeira*. ISBN: 978-989-675-008-4.

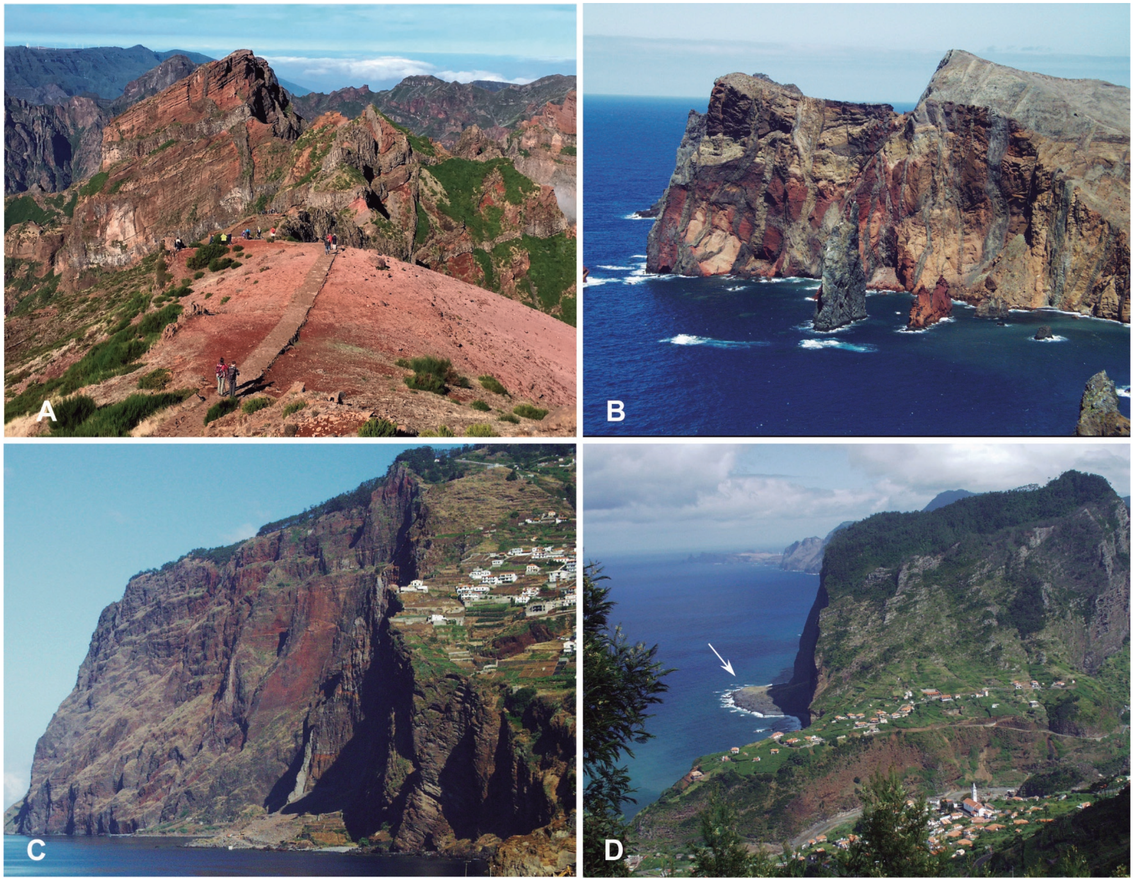

Fig. 11 (A) View of the area west of Pico do Areeiro, part of the volcanic massif that forms the central highlands of the island of Madeira. Predominant basaltic pyroclastic deposits and minor lava flows are profusely cut by dykes providing internal support that resists the erosion of the pyroclastic units (*image courtesy of Colin and Margaret Donaldson*). (B) Ponta de S. Lourenço, a narrow peninsula at the easternmost sector of the volcanic massif. The rapid erosion of formations of basaltic cinder and dykes reveals spectacular cliffs at the northern coast of the peninsula. (C) Cabo Girao (560 m asl), at the south coast. The majority of the coastline of the island of Madeira is abrupt, frequently presenting more than 250-m-high cliffs, especially in the western and northern coasts. D. View from Miradouro do Guindaste of the vertical, 250-m-high cliff north of Faial showing a slump at the base of the cliff ("Fajã" in Madeira). Small-scale slump deposits are frequent in Madeira, a common process favoring erosion and the regression of the coast. Similar features abound in the northern coast of La Palma (Fajanas).

Madeira share similarities with the younger Canary Islands of La Palma and El Hierro, with steep coastlines frequently presenting towering cliffs (Fig. 11C), particularly along the western and northern coasts.

The island of Porto Santo, 45 km northeast of Madeira, is an older ($\sim$14 Ma), and much smaller (42 km^2) independent island volcano (Geldmacher et al., 2000). Since its main growth episode, it has been considerably reduced in size because of the extensive period of exposure to erosion (from about 14 to 8 Ma), as shown by the –100 m bathymetric level (see Fig. 10). An extensive abrasion platform developed during the period when the sea level was $\sim$130 m below the present level (Ribeiro and Ramalho, 2010), a feature that is similar to the drowned ridge that connects Lanzarote and Fuerteventura in the Canaries (see Fig. 18).

The Canary Islands

Seven main islands form the Canary Archipelago. The largest and most populated are the central islands of Tenerife and Gran Canaria (Fig. 12 and Table 1). The two youngest and westernmost islands, El Hierro and La Palma, have a low population (11.000 and 85.000 inhabitants, respectively) and are at present in the fast-growing shield stage of development. The three central islands (La Gomera, Tenerife and Gran Canaria, 22,000, 950,000 and 865,000 inhabitants) are intermediate in age and have attained their maximum growth or even surpassed it (e.g., Tenerife, the highest island, located precisely at the center of the archipelago). The two easternmost islands, Fuerteventura and Lanzarote (120,000 and 150,000 inhabitants), are the oldest and lowest of the Canaries in altitude, and erosion is the primary ongoing geological process.

Although the islands of the Canary archipelago are in essence similar at their initial stages of development, showing predominantly basaltic volcanism, they change significantly as the islands mature and increase in altitude, progressively favoring the eruption of more evolved magmas. These are higher in silica and thus more viscous, and hence the construction of higher central felsic volcanoes (e.g., Teide Volcano on Tenerife) is favored by this magma composition.

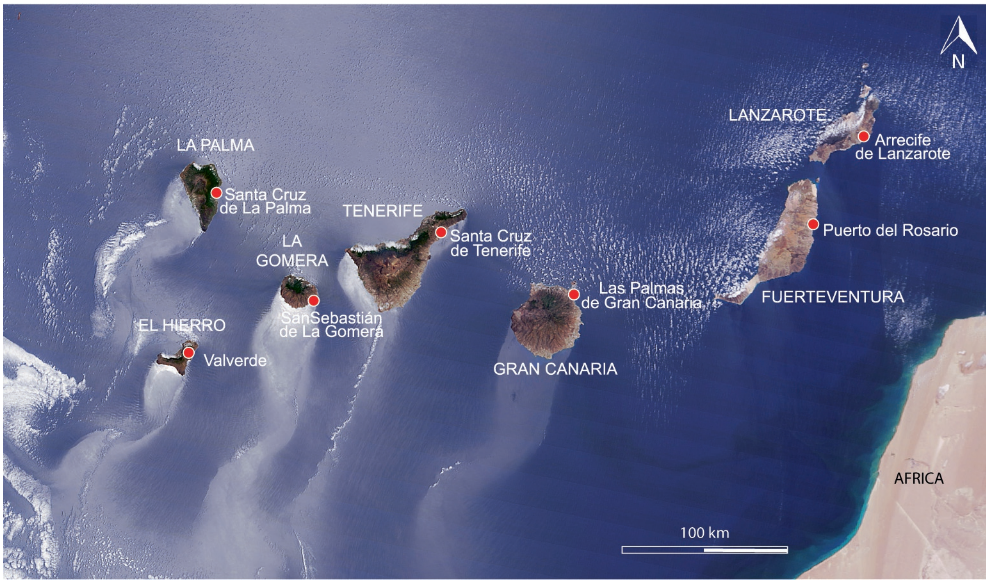

Fig. 12 The Canary Islands in satellite view. Image from NASA.

El Hierro

The characteristic shape of El Hierro, the youngest and smallest of the Canary Islands, derives from the prominent three-armed rift system that relates to several arcuate lateral collapse embayments (landslide scars) between the rift arms (Carracedo, 1994). Three overlapping Quaternary stages of primarily mafic alkaline volcanism—the Tiñor and El Golfo volcanoes, and the recent Rift eruptions—constitute El Hierro island (Guillou et al., 1996, see Fig. 4B).

Successive collapses on the north flank of the island comprise the Tiñor volcano (at about 0.8 Ma ago), and the El Golfo volcano (at about 130 ka ago) (Fig. 13A), which shaped the present El Golfo depression and its 1.500-m-high escarpment. The El Julan collapse, dated at about 158 ka, removed the SW flank of El Hierro and was later filled by eruptions from the NW rift. An aborted lateral collapse generated the San Andrés fault, visible along the main road at the NE side of the island, and is similar to examples on the Azores or Hawaii (e.g., the Ribeirinha fault on Faial or the Hilina fault on Hawaii), but is the only one of its kind in the Canaries (Carracedo and Troll, 2016).

The latest documented eruption on the island, from a vent on the NE rift (Mña. Chamuscada), was dated by ^{14}C at 2500 years ago (Carracedo et al., 2001). An intense seismic crisis, believed to be related to a submarine eruption, almost caused the evacuation of the island in 1793. In October 2011, another submarine eruption off the south coast, 2.5 km from the village of La Restinga (Fig. 13B), emitted a plume of stained waters and floating frothy lava bombs with a glassy, dark basanite crust enveloping light-colored, highly vesicular, pre-island sedimentary relicts ("xenopumice") that contained rounded quartz crystals and calcareous

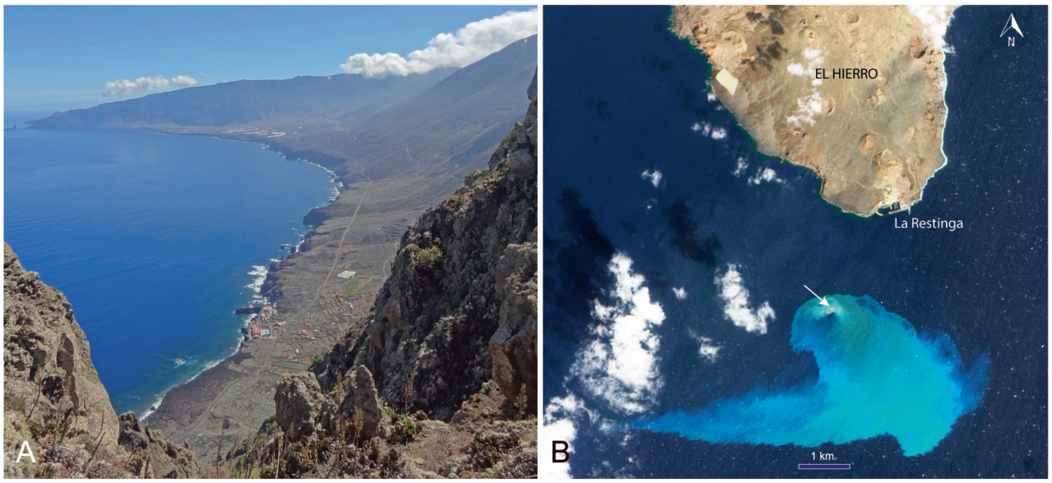

Fig. 13 (A) East to West view of El Golfo collapse embayment from Mirador de Bascos. (B) The October 2011 submarine eruption just south of El Hierro produced a plume of bright discolored seawater locally known as "La Mancha" (the stain) that was distributed for several kilometers to the south-west of the island before drifting off into the Atlantic. The arrow indicates the vent location. Satellite image by RapidEye.

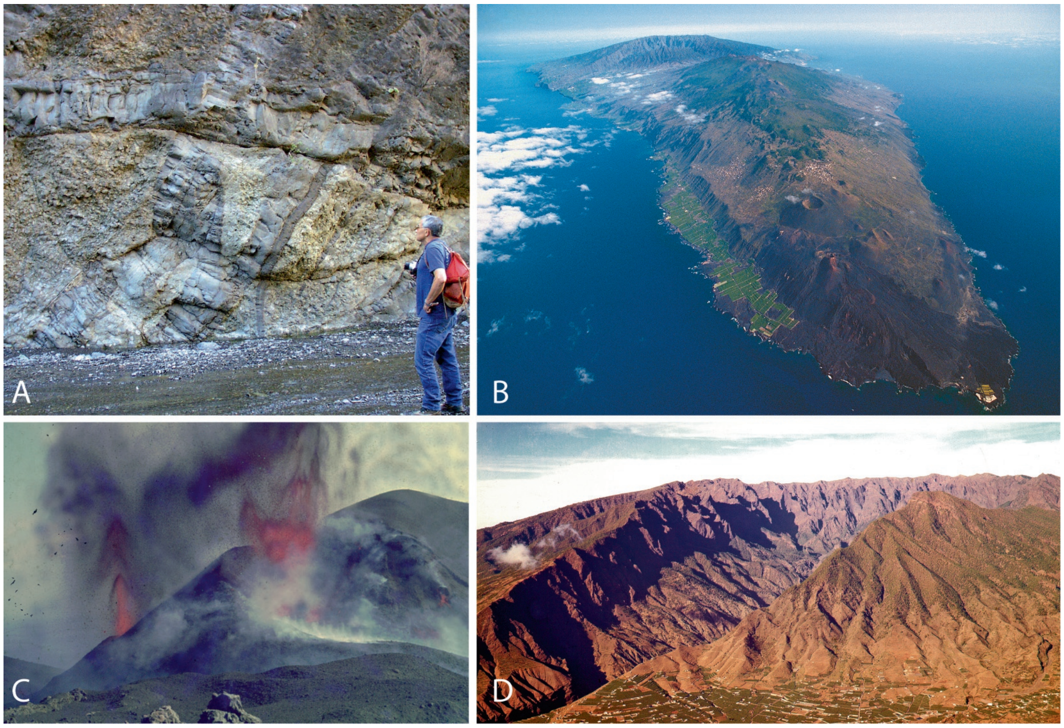

Fig. 14 (A) Dykes intruding pillow lavas and hyaloclastites in the Caldera de Taburiente, corresponding to the uplifted and tilted Pliocene seamount that is recording the initial stages of the emergence of La Palma. (B) Oblique aerial view of the Cumbre Vieja rift (*Photo courtesy of S. Socorro*). (C) Basaltic lapilli erupting from lateral vents of the 1971 Teneguía eruption of La Palma. (D) Caldera de Taburiente and the nested Bejenado edifice. The bottom of the caldera offers the extraordinary opportunity to observe the deep structure of the submerged stage of development of the island.

nannofossils (Troll et al., 2012; Zaczek et al., 2015). The nannofossils in the 2011 El Hierro xenopumice samples have been extremely useful to date the pre-island sedimentary strata (see Fig. 3B).

La Palma

La Palma has been the most volcanically active island of the Canaries in the Holocene. Three overlapping volcanoes formed the northern circular shield of La Palma, comprising the uplifted and tilted basaltic to trachytic pillow lavas and hyaloclastites of the Pliocene seamount complex (3–4 Ma), exposed on the floor and walls of the Caldera de Taburiente (Fig. 14A) (Staudigel and Schmincke, 1981, 1984), and the Garafía and Taburiente basaltic shield volcanoes (Carracedo et al., 2001; Carracedo and Troll, 2016). The coalescent north-south elongated Cumbre Nueva ridge later enlarged the island to the south (Walter and Troll 2003). At about 0.5 Ma ago, the lateral collapse of the Cumbre Nueva removed much of the south-western flank of the Taburiente volcano and the Cumbre Nueva ridge. The subsequent emplacement of the Bejenado volcano nested inside the collapse embayment forced the deep downcutting and retrogressive erosion that shaped the current Taburiente caldera (Fig. 14D).

The bottom of the Caldera de Taburiente offers the extraordinary opportunity to observe the deep structure of the submerged stage of development of the island. Here, the submarine volcano has been uplifted by intrusive growth to 1500 m above sea level, and tilted 50° to the southeast (towards the mouth of the caldera), implying that the route towards the interior of the caldera brings us deeper and deeper into the submarine volcanic edifice.

Continuing southward migration of volcanism ultimately resulted in the extinction of the northern shield ~0.4 Ma years ago and the formation of the Cumbre Vieja rift zone over the last 130 ka (Carracedo et al., 2001; Walter and Troll, 2003; Carracedo and Troll, 2016; Fig. 14B). The Cumbre Vieja is a 20-km-long, 1949-m-high ridge, composed predominantly of mafic alkaline lavas and minor phonolite intrusions. Half of the historical eruptions of the Canary Islands, typically Strombolian-type cinder cones and associated lava flows, occurred along the Cumbre Vieja rift zone (Fig. 4C). Eruptive activity in the last 150 ka occurred exclusively in the south of the island, forming the Cumbre Vieja ridge volcano, including the most recent onshore event in the archipelago, the Teneguía eruption in 1971 (e.g. Barker et al., 2015; Fig. 14C).

La Gomera

The island of La Gomera is composed of a central Miocene shield (~10–8 Ma old), that collapsed at ~8 Ma toward the north. Inside the 10–15 km-wide collapse scar of this landslide, post-collapse volcanic activity constructed a large felsic stratovolcano, termed the Vallehermoso Trachyphonolite Complex (Cendrero, 1971; Ancochea et al., 2003, 2006), which was possibly comparable to today's Teide Volcano on Tenerife. Both volcanoes formed "nested" inside collapse basins, became progressively more

Fig. 15 (A) Trachytic dykes of the Vallahermoso conical intrusion swarm (cone-sheets), with dykes in concentric arrangement around a central cone-sheet source, describing a ring some 10 km in diameter at sea level and with an estimated depth of focus at ~2100 m below the present-day sea level (see Ancochea et al., 2003, 2006). (B) The landscape of La Gomera is the result of a long period of erosion that exposed the core of felsic intrusions such as the Roque de Ojila (foreground), and the Roque de Agando (background). (C) The erosion of a trachytic dome, near Playa de Arguamul, removed half of the dome, thus exposing an internal structure of vertical, columnar joints know as Los Organos (the organ pipes), similar to the volcanic basalt columns of Fingal's Cave on the Isle of Staffa, Scotland or the Giant's Causeway in Northern Ireland. (D) View of La Caldera vent complex from the sea south of La Gomera. This 4.2 Ma volcanic cone is the only preserved recent volcanic feature on the island.

differentiated, and gave rise to terminal peripheral felsic domes. However, as the edifice of Vallehermoso volcano has been completely eroded, only the shallow roots of a conical dyke swarm, as well as breccias and domes remain (Fig. 15A).

La Gomera is moreover characterized by a large number of trachytic and phonolitic domes and coulées distributed over most of the island, although the highest concentration is in the island's center (Fig. 15B). The phonolitic dome of Punta de las Salinas that crops out in a cliff at the NW tip of the island has been partially removed by marine erosion, and its exposed interior shows spectacular rock columns, like pipes in a giant organ (Fig. 15C). Progressive loss of volume upon dome cooling caused these regular retraction fractures to form. La Gomera differs from the remaining Canary Islands because of its prolonged and continuing eruptive quiescence. La Gomera's last continuous phase of significant volcanic activity seems to have ceased ~2 million years ago (Paris et al., 2005, see Fig. 15D), and there are no signs of recurring volcanic activity on the island (Carracedo and Troll, 2016).

Tenerife

Three basaltic shield volcanoes form the base of the island of Tenerife: the Miocene Central and Teno shields (Fig. 16A), and the Pliocene Anaga volcano (Carracedo and Troll, 2016). After a long period of eruptive quiescence of the Central volcano (from ~8 Ma to ~3.5 Ma ago), eruptive activity resumed with the onset of the Las Cañadas volcano that developed a summit caldera complex that gave rise to sustained felsic and explosive volcanism. Up to 10 large explosive (Plinian) eruptions took place between 1.8 Ma and 0.17 Ma (Booth, 1973; Brown et al., 2003; Brown and Branney, 2004; Dávila-Harris, 2009), depositing thick mantles of trachytic to phonolitic air fall pumice and ignimbrites on the southern slopes of the island (Fig. 16B).

At about 180 ka ago, a lateral collapse destroyed the northern flank of Tenerife, creating the outline of the present-day Las Cañadas caldera (Fig. 16C) and facilitating the subsequent construction of the Teide volcanic system, which comprises the Teide and Pico Viejo volcanoes (Fig. 16D) and a cluster of peripheral phonolitic lava domes encircling these two stratocones (Carracedo and Troll, 2013). Voluminous pahoehoe lavas from a Pico Viejo eruption at ~27 ka ago (Carracedo and Troll, 2013, 2016) reached the northern 15-km-distant coast and favored the construction of spectacular lava tubes similar to those on the islands of Lanzarote, Fuerteventura and La Palma. Other additional important morphological features are the NW (Fig. 16E), NE and NS rift zones (locally "*dorsales*"), and the giant landslide depressions of La Orotava, Icod and Güímar. The majority of the basaltic Strombolian

Fig. 16 (A) The Los Gigantes cliff exposing a 600-m-thick sequence of basaltic lavas of the Miocene Teno shield volcano. (B) The Granadilla Plinian eruption (0.6 Ma) deposit, southern Tenerife, comprising an 8-m-thick layer of Plinian fall (pumice) and an overlying non-welded ignimbrite. (C) Satellite image (*courtesy of NASA*) of the 3718-m-high Teide Volcano, nested inside the Caldera de Las Cañadas (detailed geological map in Carracedo et al., 2001). (D) Closer (aerial) view of Teide and Pico Viejo stratovolcanoes. (E) Panoramic view of the NW Rift Zone of Tenerife from Pico Viejo volcano.

vents (Quaternary) is concentrated along this triple rift system (Fig. 4B), including all five historical (<500 years) eruptions of Tenerife (see Table 1).

Gran Canaria

The bulk of the island of Gran Canaria formed during the Miocene basaltic shield stage. The resulting island was circular and became incised with abundant radial barrancos. The summit of the basaltic shield has an extensive shallow magma chamber system in its central part, which collapsed vertically upon the eruption of a widespread (covering an area of more than 400 km^2), and voluminous (~45 km^3), ignimbrite ~14 Ma ago (McDougall and Schmincke, 1976; van den Bogaard and Schmincke, 1998; Guillou et al., 2004). The emptying of the chamber generated the massive elliptical Caldera de Tejeda (Troll et al., 2002), with associated evolved ignimbrites, lavas, and explosive fallout tephra of the Mogán and Fataga groups, totaling ~1400 km^3 of felsic eruptives (Schmincke, 1976; Schmincke and Sumita, 1998; Troll and Schmincke, 2002) (Fig. 17A). Alkali syenite intrusives and a spectacular trachytic-phonolitic cone sheet swarm of dykes (Fig. 17B), exposed by erosion in the central part of the island (Schmincke, 1967; Donoghue et al., 2010), provide evidence of Miocene felsic magmatic activity lasting to ~7 million years ago (van den Bogaard and Schmincke, 1998).

Volcanism recommenced around 5.6 million years ago, filling canyons in the deeply eroded Miocene volcanic edifice, and culminating with the construction of the Roque Nublo stratovolcano (~4.2–3.5 million years ago; Pérez-Torrado et al., 1995). The Roque Nublo stratocone is likely to have reached an elevation of more than 3000 m and thus may have been similar in height to the present-day Teide volcano on Tenerife (Carracedo and Troll, 2016). The Roque Nublo monolith (Fig. 17C) resisted the long period of erosion (Pérez-Torrado et al., 1995). The rejuvenated Pliocene and Quaternary eruptions (<3 million years ago), primarily basanitic and nephelinitic cinder cones, and lava flows that overlie an erosional unconformity, outcrop exclusively in the north-eastern half of the island. This includes the youngest dated volcanic eruption on Gran Canaria, the Bandama caldera and the associated Strombolian cone (Fig. 17D), dated at ~2000 years before present (Rodríguez González et al., 2009).

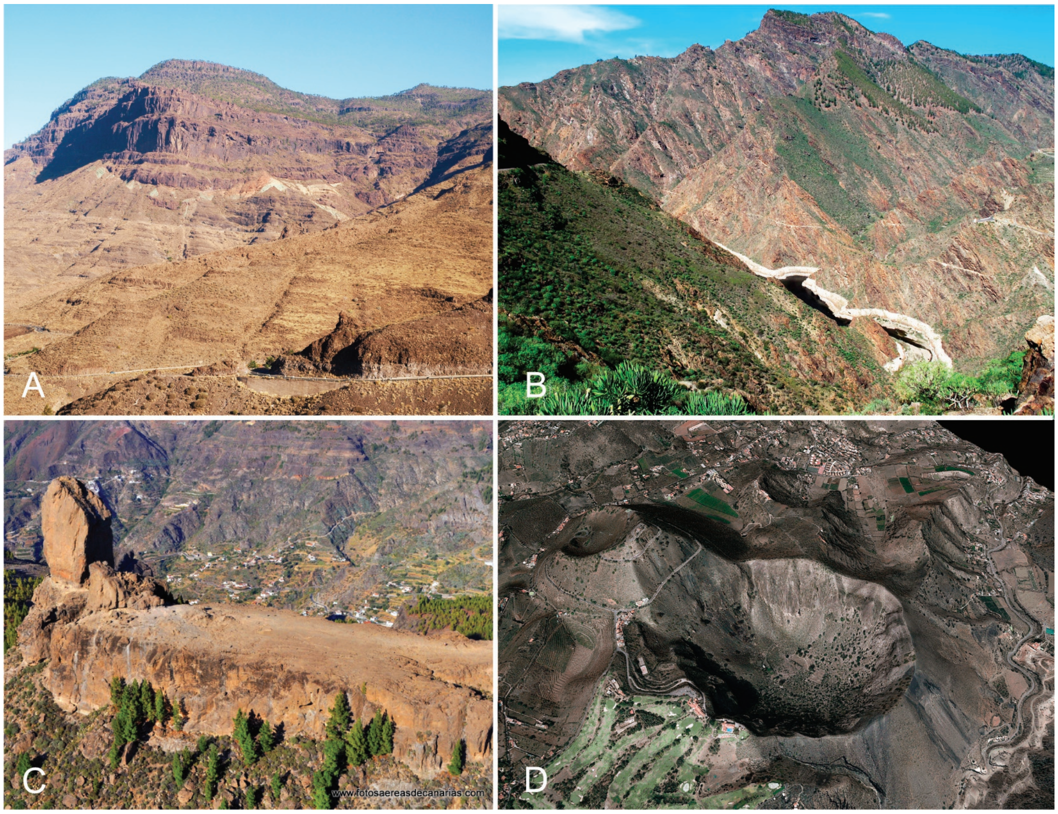

Fig. 17 (A) Caldera margin at Fuente de Los Azulejos showing the Miocene sequence of the shield stage basaltic lavas overlain by intracaldera ignimbrites. The bright-colored tuffs are characteristic of low-temperature hydrothermal alteration at the caldera margin. (B) View of the Miocene cone sheet swarm around the Presa del Parralillo. (C) Roque Nublo monolith, the remaining part of a thick slab of debris-avalanche deposits from the former Roque Nublo volcano. (D) Caldera de Bandama and Bandama Strombolian cone (*Image from Google Earth*), represents the youngest volcanic eruption on Gran Canaria (~2 ka).

Fuerteventura-Lanzarote

Fuerteventura and Lanzarote probably constitute a single elongated island edifice, as suggested by seafloor bathymetry (Fig. 18). They are separated by the strait of La Bocayna (<40 m deep) and were previously connected above sea-level during periods of sea-level low stands (e.g., during glaciations, see lower inset in Fig. 18). The Fuerteventura-Lanzarote volcanic ridge is composed of five Miocene shield volcanoes (see Fig. 18) and several late or rejuvenated Pliocene-Quaternary volcanic cones and vents (Carracedo and Troll, 2016).

The oldest rocks correspond to an Early Jurassic to Cretaceous sequence of tilted and intensely uplifted ocean floor sediments (Fig. 19A), which crop out on the western coast of Fuerteventura (Fúster et al., 1968; Robertson and Stillman, 1979). Overlying these deposits is a transition from submarine pillow lavas to transitional and finally subaerial volcanism documenting gradual growth and emergence on Fuerteventura (Gutiérrez et al., 2006; Carracedo and Troll, 2016). Exposed mafic to felsic plutonic intrusions (pyroxenite to syenite) at the central part of the island represent the magma reservoirs and conduits of the former (now eroded) Miocene volcanoes of Fuerteventura (see Fig. 18). Anatectic aureoles to these intrusions are locally accessible. The trachytic-syenitic ring dyke of Vega del Río Palmas, north of the village of Pájara, represents the magmatic roots of a felsic volcanic complex, probably similar to the Las Cañadas-Teide Complex on Tenerife, or the Vallehermoso Complex on La Gomera (Carracedo and Troll, 2016). The Miocene shields of Los Ajaches and Famara (Fig. 19C) form the bulk of the island of Lanzarote. Pliocene-Quaternary post-erosional basaltic activity resumed on this island after a period of general quiescence and erosion. Recent volcanism includes the Corona Volcano and lava tube (~21 ka), and the historical eruptions of 1730–36 (Fig. 19D) and 1824, the only Holocene volcanism of Lanzarote (Carracedo et al., 1992; Carracedo and Troll, 2016).

Cape Verde Islands

The Cape Verde Archipelago is a group of 10 larger and several smaller volcanic islands (~400 km^2), with 450,000 inhabitants (see Table 1). Situated 567 km off the western coast of Africa (Fig. 20), they take their name from the Cape Verde peninsula in Senegal.

As described for the Canary Islands, despite its proximity to the African continent, the Cape Verde Archipelago lies on old (120–140 Ma) oceanic crust. The Cape Verde Islands are widely considered to represent long-term oceanic intraplate volcanism

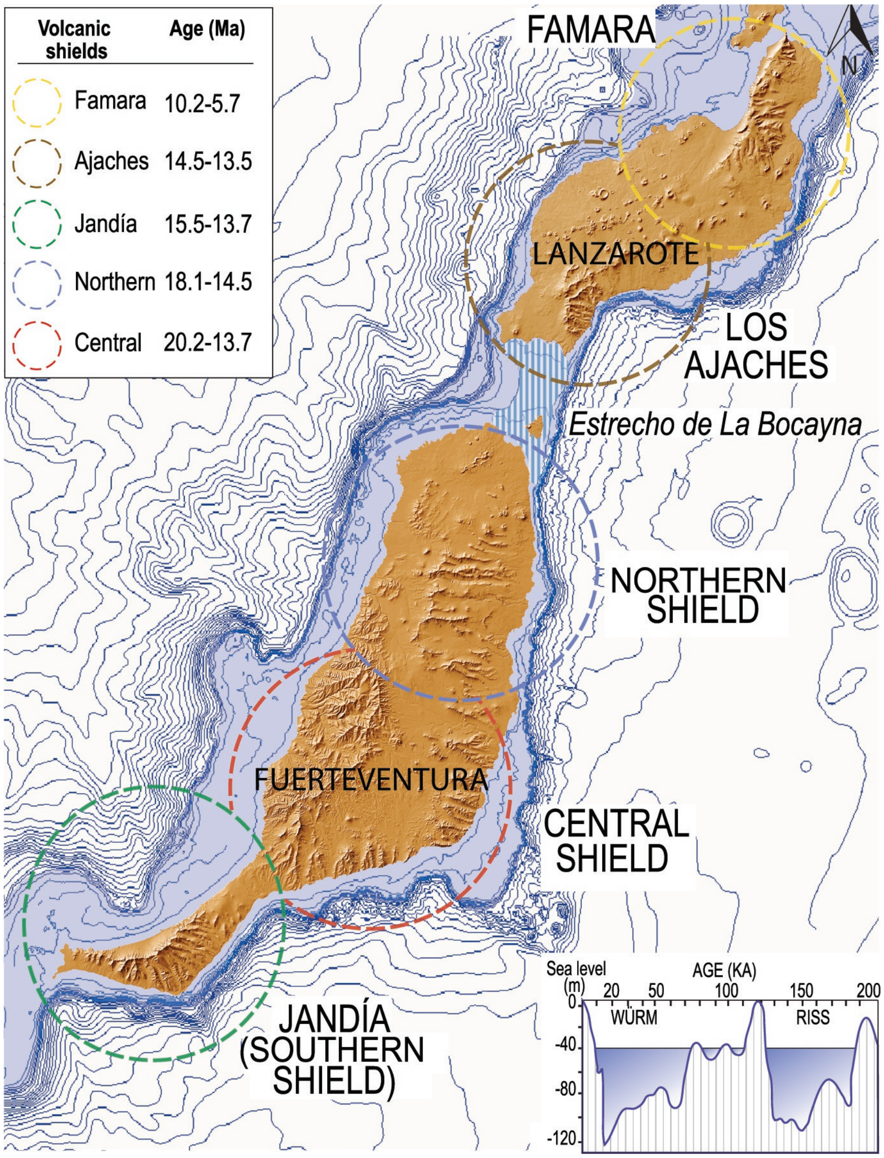

Fig. 18 Fuerteventura and Lanzarote, separated by a narrow (11 km) and shallow (≤40 m deep) strait (La Bocayna), formed a single island during periods of previous low sea-level stand. Lower inset: periods in which the Bocayna strait was emerged and both islands were connected (e.g., during glaciations).

associated with the Cape Verde plateau, which is generally assumed to be fed by a hotspot (Courtney and White, 1986; Holm et al., 2008; Ramalho et al., 2010). Situated close to the rotational pole of the slowly moving African plate, the islands are thus virtually stationary relative to the moving lithosphere. This setting explains why the Cape Verde islands appear more cluster-like relative to, e.g., the Canary Islands. Erupted lavas are predominantly mafic alkali basaltic rocks, and silica-saturated lithologies are rather rare.

The islands in the archipelago are arranged in a westward opening horseshoe-shaped geometry (Torres et al., 1997; Ramalho, 2011), comprising two alignments: The Northern (Windward) chain, where the islands formed approximately synchronous, and the Southern (Leeward) chain, where an age progression of the oldest exposed rocks seems present. Age progression is also reflected in the topography of the islands of the Southern (Leeward) Chain (Holm et al., 2008; Madeira et al., 2008, 2010; Fig. 20), where the island of Sal, at the NE edge of the island chain and the oldest in the archipelago, is deeply eroded and essentially flat (Fig. 21A and B), while the island edifices get progressively steeper in the islands of Santiago (Fig. 21C) and Fogo (Fig. 21D), towards the SW edge of the island chain. As on Fuerteventura, uplifted Jurassic ocean floor sedimentary and igneous rocks outcrop in the islands of Maio and Santiago (Stillman et al., 1982), and submarine lavas representing the transition to the Miocene subaerial volcanism also outcrop on several islands (see also, e.g., Fuerteventura and La Palma above). The volcanic activity in the Cape Verde region

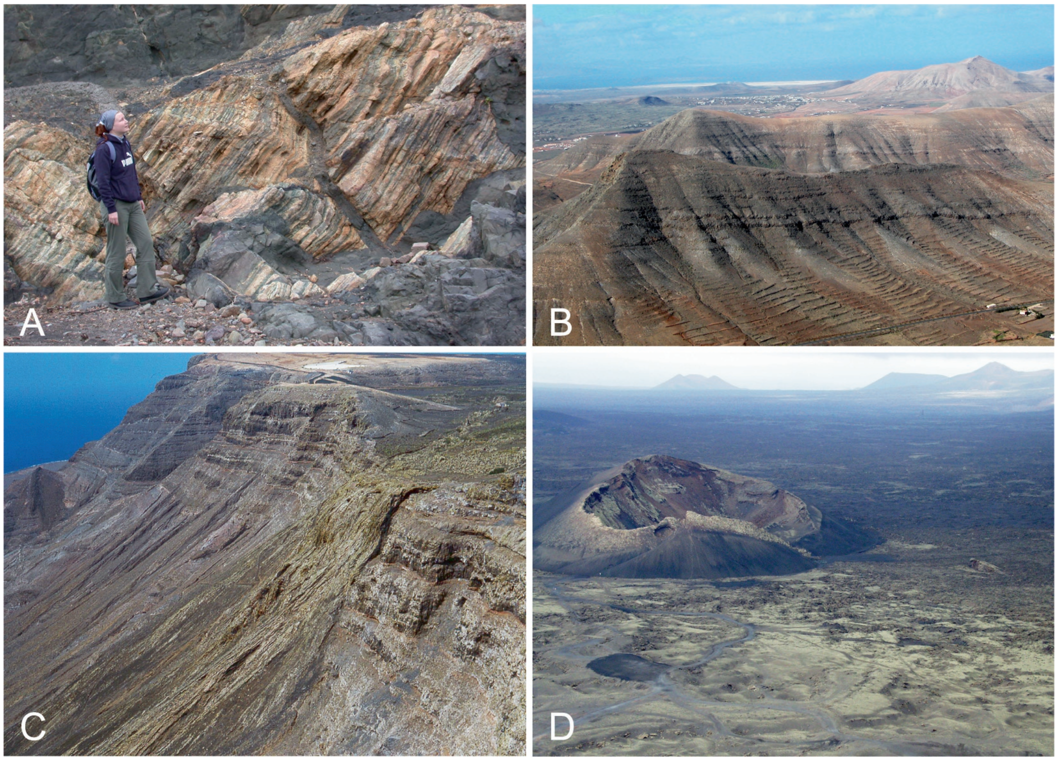

Fig. 19 (A) Sequence of overturned Mesozoic ocean floor sediments at the mouth of Barranco de Ajuy, Fuerteventura. (B) Deeply eroded basaltic lava sequences of the former Northern Miocene shield of Fuerteventura. (C) Lava flows of the 21 ka Corona Volcano that cascaded down the Famara Miocene shield. (D) Caldera de Los Cuervos, the initial vent of the AD 1730 to 1736 eruption on Lanzarote.

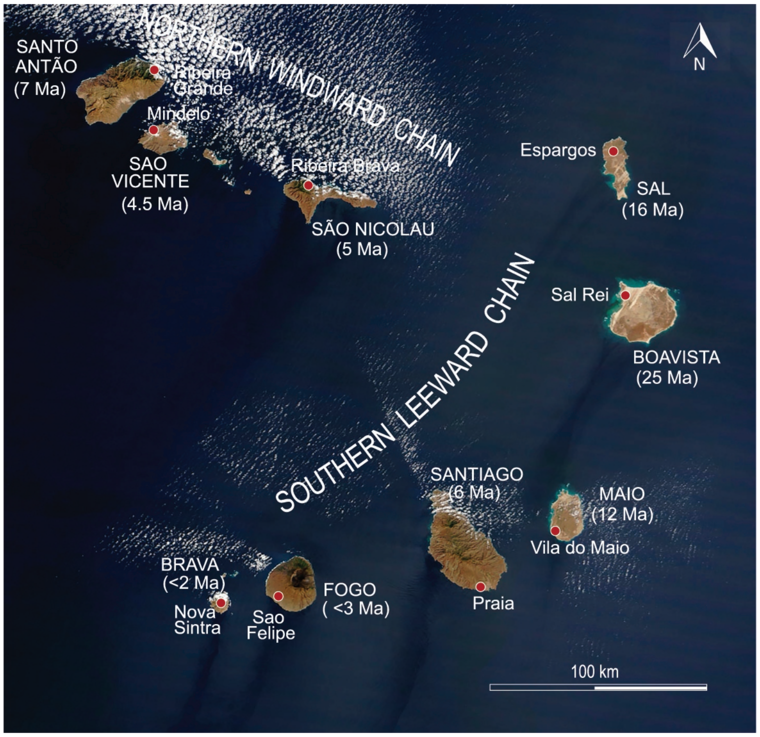

Fig. 20 The Cape Verde islands form two distinct lineations, the northern and the southern islands. Regional bathymetry also indicates that two submarine chains exist: the northern (Windward) chain, which runs NW to SE, and the curved southern (Leeward) chain, which runs broadly ENE to WSW, before curving northward. Age data shown are from Holm et al. (2008) and Madeira et al. (2008, 2010). Image source: Google Earth.

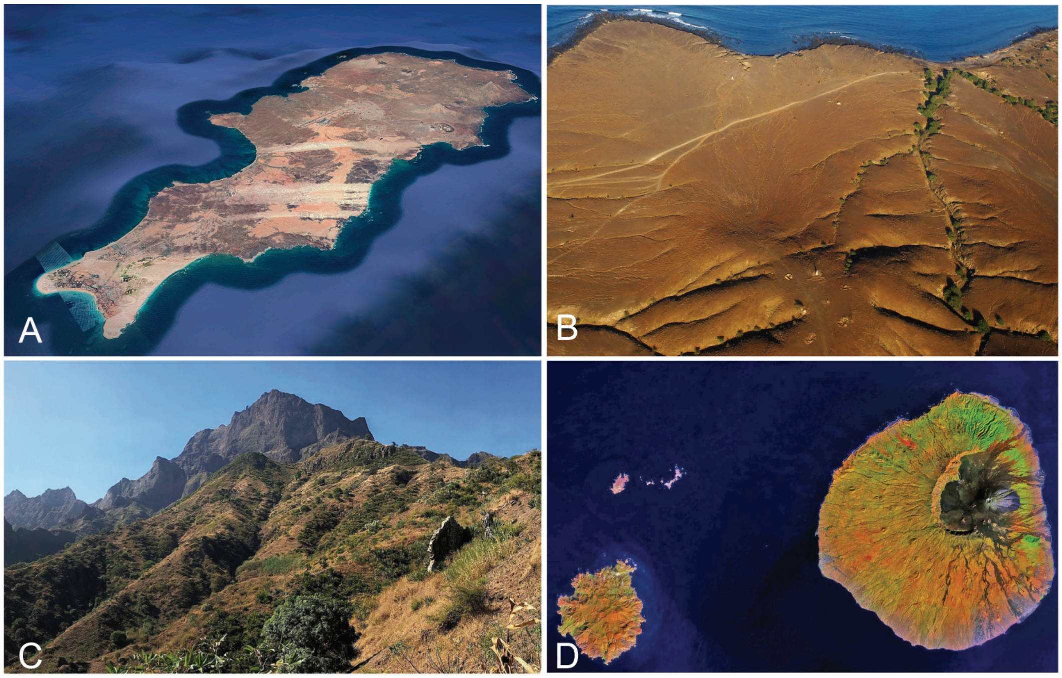

Fig. 21 (A) Satellite image (Google Earth) of the island of Sal, the oldest (~16 Ma) in the Cape Verde archipelago (see Table 1). The island is flat, and its highest point is Monte Grande (406 m asl). Note that eolian sand streaks cross the central part of the island *(Image: Google Earth)*. (B) Close up view of the northern region of Sal showing a deeply eroded, flat landscape, resembling the aspect of some old formations of Fuerteventura *(Image: Google Earth)*. (C) The Pico da Antónia (1394 m asl), the highest elevation of the island of Santiago (~6 Ma). A noticeable dyke is exposed by relief inversion, similar to the "taparuchas" of La Gomera, in the Canaries. (D) The young (<2 Ma) and steep island of Fogo (Mount Fogo, 2.829 m asl), at the NW edge of the Southern Cape Verde Chain *(Image after ESA Copernicus Sentinel data).*

probably started in the early Miocene and continued into the Holocene, but historical eruptions in Cape Verde (the archipelago was discovered in AD 1460) have been confined to one island exclusively, the island of Fogo (e.g., Carracedo et al., 2015).

The island of Fogo is architecturally remarkably similar to the Teide Volcanic Complex on Tenerife (Carracedo et al., 2015), where a lateral collapse scar, the Caldera de Las Cañadas, hosts the Teide stratovolcano (see Fig. 16C). On Fogo, the Cha das Caldeiras depression, a similar lateral collapse scar associated with the Monte Amarelo shield volcano, hosts the nested post-collapse Pico de Fogo stratovolcano (Fig. 22). Intracaldera lava flows from historical eruptions, the latest in 2014 (Carracedo et al., 2015; Mata et al., 2017), caused several recent evacuations of the Cha das Caldeiras villages of Portela (see Fig. 22) and Bangaeira. These historical lavas are dark, relatively thin (1–3 m) and of mafic composition, contrasting with lava flows inside the Las Cañadas caldera on Tenerife, which can be much thicker (up to 80 m thick), and are of light-colored phonolitic composition.

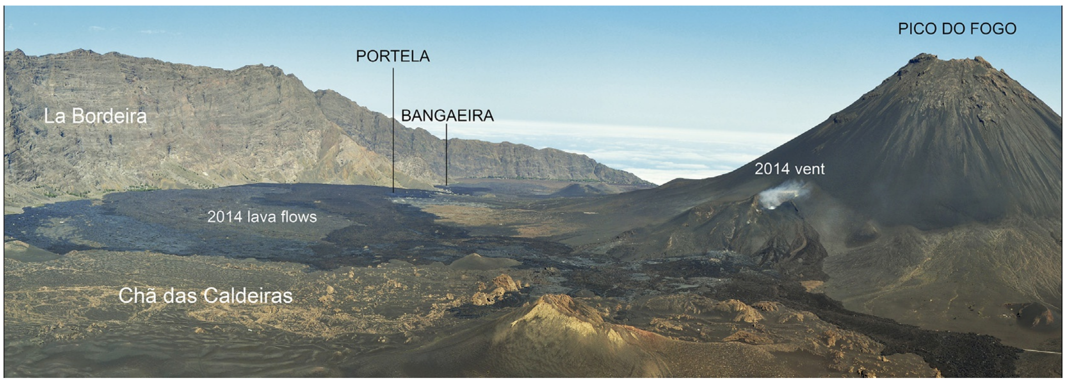

Fig. 22 (A) View of the Cha das Caldeiras depression, partly filled with nested volcanism that also constructed the 2829-m-high Pico do Fogo cone. Eight intracaldera eruptions, the latest in 2014, are recorded since colonization in 1460 (Table 1).

Conclusions

The Macaronesian archipelagos (the Azores, Madeira, the Canary and the Cape Verde Islands), the essential ocean-island magmatic systems of the Central-East Atlantic, show important similarities in the compositional ranges of their eruptive products, but significant diversities in their respective sizes, ages, and volcanic and seismic activity.

A relevant common feature of these intraplate islands is that they rest on oceanic crust, while their volcanic rocks belong to the "Ocean Island Basalt" Series (OIB), characterized by higher alkalinity at similar SiO_2 than standard tholeiitic Mid-ocean ridge type (MORB) basalts. A common OIB-type origin has been identified in all four archipelagos based on trace elements and especially radiogenic and stable isotope geochemistry. Basaltic volcanism is generally predominant in the early subaerial stages (shield stage) of island growth, while felsic (phonolite, trachyte, alkaline rhyolite) volcanism is usually associated with the more evolved phases of the islands.

In contrast, the most significant differences derive from their respective geodynamic settings. Whereas the Azores archipelago is located at the Mid-Atlantic ridge (an active plate margin), which reflects interaction between the Mid-Atlantic Ridge and a mantle plume, the Madeira, Canaries and Cape Verde islands are in the vicinity of the African coast, a passive continental margin, and their mantle plumes appear to be at considerable distance from the influence of active lithospheric fractures. A significant consequence is the lack of internal age progression for the construction of islands at the active plate margins, such as the fracture-related Azores archipelago. This contrasts with the passive margin archipelagos nearer to Africa that show an age progression consistent with hotspot tracks associated with deep upwelling mantle plumes that pierce through a moving lithosphere plate above. Active margin and passive margin Macaronesian archipelagos also show different island alignments and internal geometries, tightly clustered along active regional fractures in the former, but lacking preferred orientations in the latter.

Active and passive margin Macaronesian archipelagos also differ in the relevance of their respective eruptive and seismic activity, explaining the intense and strong seismicity and frequent historical eruptions in most of the Azores. In contrast, only moderate seismicity characterizes the passive margin Macaronesian archipelagos where historical volcanism also tends to focus on the younger islands.

An upwelling mantle plume intersecting a lithospheric fracture system therefore generates active volcanic islands with intense and strong seismicity throughout the archipelago, and islands presenting visibly elongated shapes alined with these underlying lithospheric fractures. In contrast, the three passive margin Macaronesian hotspot tracks require an average volcanic age progression of about 1.2 cm/year, which, for the Canary and Madeira islands, is consistent with the rotation of the African plate by $\sim 0.2^{\circ}$/Ma around a common Euler pole located at the southern tip of Greenland. A mantle plume source for all Macaronesian islands is also supported by finite-frequency tomographic images of S-wave velocities. This geophysical approach has recently corroborated the plume concept for the Macaronesian island groups, using whole-mantle imaging techniques. In these studies, the Macaronesian plumes appear as isolated anomalies extending down to >1000 km depth, but may originate from a common larger source at greater depth within the Earth's mantle.

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