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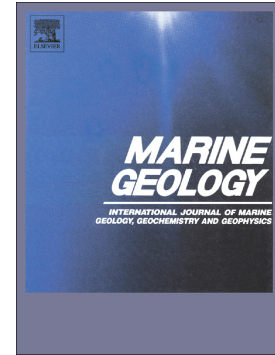


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First characterization of the volcanism in the southern Mozambique Channel: Geomorphological and structural analyses

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Abstract

The southern part of the Mozambique Channel is characterized by a cluster of isolated seamounts, including the Bassas da India atoll and Europa Island, ranging in latitude from 20°S to 22°S and from 38° to 40° in longitude, and located at the Rovuma-Lwandle plate boundary. Only Cenozoic carbonate platforms have previously been studied in this region, with very little work done on the volcanic history. We confirm here the volcanic nature of the basement of the Bassa da India/Europa complex by providing important constraints on the setting of this hitherto poorly understood volcanism.

Recent bathymetric surveys and dredging operations allowed us to map and date these seamounts, comprising, from west to east, the Hall Bank, the Jaguar Bank, Bassas da India, Ptolemee, and Europa. In addition, we discovered, to the south of Bassas da India, two large new polygenetic volcanic edifices, Pamela Seamount 1 (PS1) and Pamela Seamount 2 (PS2),

showing heights and diameters of up to 900 m and 13 km, respectively. Mapping and statistical analysis carried out revealed that the volcanic structures of the Bassas da India/Europa complex are organized along two main alignments with different stages of development: (i) a NE-SW volcanic alignment characterized by volcanic ridges up to 700 m in height, comprising small individual volcanic cones; and (ii) a NW-SE volcanic alignment in which many large and well-developed individual volcanic cones can be found. From this distribution of the volcanism, we suggest that the large volcanic edifices of the Bassas da India/Europa complex were fed by long-lived magma systems, repeatedly supplied from deep magma reservoirs through a significant network of dykes and faults, with lateral injections of magma guided by a dense network of faults allowing magma to reach the surface along rift-zones. $^{40}\text{Ar}/^{39}\text{Ar}$ dating confirms that the volcanism covers a period from the Oligo-Miocene to the Pleistocene, and probably extends to the present day. The two volcanic alignments are also consistent with the tectonic features already recognised for the region and are spatially superimposed by active seismicity. Magma ascent is strongly controlled by large pre-existing crustal structures.

Keywords: Mozambique channel, Bassas da India, Europa, volcanic ridge, volcanic cones, structural inheritance.

Highlights

- Bassas da India/Europa seafloor is characterized by seven large seamounts and more than 430 volcanic cones
- Miocene to Pleistocene volcanism is distributed along two main trends with different stages of maturation
- Magma ascent is strongly controlled by large pre-existing crustal structures
- Large edifices are fed by a well-developed magmatic system whereas volcanic ridges are supplied by episodic lateral magma migration through a network of faults.

1) Introduction

The most voluminous volcanic activity on Earth occurs in the deep sea environment (Crisp, 1984), but it is also the least known. Based on bathymetric surveys and satellite data, the number of estimated seamounts varies by several orders of magnitude, from 200,000 for large seamounts to 25 million including those with smaller features (Wessel, 2007; Wessel et al., 2010; Yesson et al., 2011). Despite the large number of volcanic seamounts, their eruptions are difficult to access, and they are rarely studied in sufficient detail to allow a good understanding of the eruption processes and magma emplacement in the submarine realm (Fornari et al., 1988; Rubin et al., 2012).

The Mozambique Channel is characterized by scattered young submarine volcanism. Over the past fifty years, much work has been done to understand the evolution of the Mozambique channel and its margins (e.g., Heirtzler & Puccinotti, 1971; Scrutton, 1978; Norton and Sclater, 1979; Segoufin and Patriat, 1980; Thompson et al., 1982; Martin and Hartnady, 1986; Mougenot et al., 1986; Coffin and Karabinowitz, 1987; Leclaire et al., 1989; Raillard, 1990; Cox, 1992; Hartnady et al., 1992; Ben Avraham et al., 1995; Tikku et al., 2002; Jokat et al., 2003; Bernard et al., 2005; König and Jokat, 2006; Eagles and König, 2008; König and Jokat, 2010; Leinweber and Jokat, 2012; Mahanjane, 2012; Leinweber et al., 2013; Reeves, 2014; Davis et al., 2016; Klimke et al., 2016; Mueller et al., 2016; Nguyen et al., 2016; Phethean et al., 2016; Reeves et al., 2016; Mueller and Jokat, 2017; Klimke et al., 2018; Reeves, 2018; Stamps et al., 2018; Turk Martin et al., 2018; Mueller and Jokat, 2019; Sinha et al., 2019; Thompson et al., 2019; Vormann et al., 2020; Stamps et al., 2021; Vormann and Jokat, 2021a). However, Cenozoic volcanism in the Mozambique Channel remains little studied.

Since the Cretaceous, volcanism has spread to many places in the Mozambique Channel, forming archipelagoes, isolated islands, atolls, seamounts and volcanic ridges. The morphology, nature and age of this volcanism, from the northernmost archipelagoes (i.e., Glorieuses and Comoros Islands, Fig. 1a) to the southernmost islands and seamounts (Europa and Bassas da India, Mt Bourcart, Almirante Leite, and Mozambique Ridge, Fig. 1b), is poorly known or incompletely understood, particularly with regard to the submarine part of these edifices. Several hypotheses coexist as to the source of this Cenozoic volcanism, suggesting a link with the East African Rift System (Kusky et al. 2010; Franke et al., 2015; Michon, 2016; Courgeon et al., 2018; Deville et al., 2018; O'Connor et al. 2019; Famin et al., 2020; Wiles et al. 2020; Vormann and Jokat, 2021b), involving lithospheric fractures and/or a combination of tectonic microplates (Upton, 1982; Nougier et al., 1986; Saria et al., 2014;

Franke et al., 2015; Michon, 2016; Deville et al., 2018; Courgeon et al., 2018; Stamps et al., 2018; Famin et al., 2020; Stamps et al., 2021; Tzevahirtzian et al., 2021), and/or the influence of plume-related thermal anomalies or a superplume mantle under East Africa (e.g., Emerick and Duncan, 1982; Hartnady, 1985; Späth et al., 1996; Class et al., 1998; O'Connor et al., 2019).

The northern entrance of the Mozambique channel is the site of a frequently active volcanism in the Comoros archipelago (Fig. 1a). Indeed, Karthala volcano (Grande Comore Island), which forms the highest point of the Comoros archipelago, is one of the largest active volcanoes in the world and the second most active volcano in the Indian Ocean (Bachèlery et al., 2016). In addition, volcanic products a few thousand years old have recently been identified on the island of Anjouan, southeast of Grande Comore (Quidelleur et al., 2022). Mayotte Island, the most easterly island of the archipelago is also affected by active volcanism with unprecedented offshore seismo-volcanic activity (Cesca et al., 2020; Lemoine et al., 2020; Berthod et al., 2021a; Feuillet et al., 2021). It is obvious that volcanism represents a major risk for the population living in the Comoros archipelago. Consequently, this active volcanism at the northern entrance of the Mozambique Channel is a focal point for study by the scientific community.

The southern part of the Mozambique Channel is also characterized by several scattered volcanic edifices, including Mt. Bourcart and an unnamed seamount identified as Mt. X (Breitzke et al., 2017), Almirante Leite (Hartnady, 1985; Wiles et al., 2014; O'Connor et al., 2019), and a cluster of volcanic landforms consisting of two uninhabited islands, the atoll of Bassas da India and the island of Europa (Fig. 1b, Jokat, 2006; Courgeon et al., 2016, 2017; Breitzke et al., 2017; Courgeon, 2017; Dorschel et al., 2018), where healthy and flourishing coral reefs can be observed (Bouchard and Crumplin, 2011; Jorry et al., 2016; Levin et al., 2018; McClanahan et al., 2021), as well as two drowned Neogene shallow-water carbonate platforms (Hall and Jaguar Banks, Fig. 1c), whose platform tops are currently located at a depth of hundreds of meters below sea level (Courgeon et al., 2016). These edifices are the most striking parts of a submarine volcanic complex extending over a length of 200 km. This complex, located between 21.5°S – 22.3° S and 39.5°E – 40.3° E, is poorly understood and is the target of our work.

Previous work by Courgeon et al., (2016), Courgeon (2017), and Counts et al. (2018) focused on the carbonate platforms and the associated superficial volcanic structures of this complex. The goal of this paper is to describe from a morphological perspective the volcanic

bedrock of these carbonate platforms, in order to better understand the origin of the Bassas da India/Europa complex and the related magmatic processes. For this purpose, we analyzed bathymetry DEMs and imaged the regional distribution and the morphology of the volcanic structures, using multibeam bathymetry and acoustic backscatter images extending around Bassas da India and Europa and the surrounding edifices, acquired during the PAMELA-MOZ01 (Olu, 2014) and PAMELA-MOZ04 (Jouet and Deville, 2015) cruises. We also carried out the first $^{40}\text{Ar}/^{39}\text{Ar}$ dating on dredged volcanic samples from this area. Our study confirms the volcanic nature of the Bassas da India/Europa complex, shows a clear tectonic control for the formation of the submarine seamounts, and highlights the relevance of considering Cenozoic volcanism in the geodynamic evolution of the Mozambique Channel.

2) Geological context

Gondwana break-up and inherited structures

The Mozambique Channel, in the SW Indian Ocean, between the East-African continental margin and the Madagascar continental fragment, is related to the break-up of Gondwana supercontinent and the relative drift of the African and “Antarctico-Indio-Madagascarian” continental blocks. The history of the opening of the Mozambique Channel has been well documented (Cox, 1992; Reeves, 2006; Jokat et al., 2003; König and Jokat, 2006; Eagles and König, 2008; Leinweber and Jokat, 2012; Mahanjane, 2012; Reeves 2014; Mueller and Jokat, 2017; Tuck-Martin et al., 2018; Mueller and Jokat, 2019; Thompson et al., 2019). The southward motion of Madagascar relative to Africa occurred from the Middle Jurassic to the Early Cretaceous (~165–120 Ma, Coffin and Rabinowitz, 1987; Leinweber and Jokat, 2012; Mahanjane, 2014; Mueller and Jokat, 2019; Thompson et al., 2019) through the activity of a major NNW-SSE transform fault known as “Davie Ridge” (Fig. 1a, Scrutton, 1978; Rabinowitz et al., 1983; Coffin and Rabinowitz, 1987; Leclaire et al., 1989; Bassias and Leclaire, 1990; Bassias, 1992; Mahanjane, 2014; Bassias and Bertagne, 2015; Courgeon et al., 2018; Vormann et al., 2020; Vormann and Jokat, 2021a).

To the south of this major tectonic structure, the Mozambique Basin is part of the Africa-Antarctica Corridor extending from the Mozambique coast in SE-Africa to the coast of East-Antarctica (Bernard et al., 2005; Mueller and Jokat, 2019). Since the northern part is characterized by east–west striking magnetic anomalies from about 20°S to 27°S (Fig. 1a), the Mozambique Basin was recognised to have been created by almost north–south oriented

spreading between Africa and Antarctica (Mueller and Jokat, 2019). Three major north–south oriented tectonic features, the Eric Simpson Fracture Zone (ESFZ), the Prince Edward Fracture Zone (PEFZ) and the the Andrew Bain Fracture Zone (Fig. 1a), have been identified and divide the Africa-Antarctica Corridor into three discrete spreading segments (Mueller and Jokat, 2019).

Cenozoic tectonic setting

The relative drift during the Jurassic was followed by volcano-tectonic stages associated with the separation of India and Antarctica from Madagascar during the Cretaceous period, and then with the development of the East African rift system (EARS) from the Oligocene up to the present (Chorowicz, 2005; Ebinger, 2012; MacGregor, 2015). The present-day EARS is a well-defined continental-scale rift, linked to volcanism and earthquakes, which extends southward along two main terrestrial branches (Chorowicz, 2005). These eastern and western branches separate the Nubian and Somalian plates, and between them lie two microplates, the northern Victoria and southern Rovuma microplates, which have developed in response to rift kinematics with a third microplate, the Lwandle microplate (Hartnady, 2002; Stamps et al., 2008; Saria et al., 2014; Stamps et al., 2021). The southern extension of the EARS is well-established north of the Mozambique Channel (Mougenot et al., 1986; Grimson and Chen, 1988; Calais et al. 2006; Stamps et al., 2008; Yang and Chen, 2010; Franke et al., 2015, Michon 2016). In addition, recent studies based largely on GPS measurements, seismology and structural analysis, proposed that the southern part of the Mozambique Channel is crossed, from NE to SW, by the Rovuma/Lwandle plate boundary, following the Quathlamba seismic axis, a linear cluster of seismicity between Madagascar and southern Mozambique (Hartnady, 1990; Hartnady et al. 1992; Stamps et al., 2008; Déprez et al., 2013; Saria et al., 2014; Stamps et al., 2019, 2021). Analysis of the spatial distribution of active faults in the area, performed by Deville et al. (2018), reveals the presence of a 200 km - wide system of faults, trending N45–80°, superimposed onto the Quathlamba seismic axis. An east-west orientated steep-flanked depression located in the southern part of the Mozambique Channel is also interpreted as the superficial expression of this regional extension, and associated with the present-day kinematics of the East African Rift System (Wiles et al., 2020). Furthermore, the structural study carried out by Deville et al. (2018) demonstrates that a second set of N160–180° trending faults, mostly observed north of 20°S, is probably associated with, and controlled by, the Davie Ridge structure.

Cenozoic volcanism

Since the Cretaceous, volcanic activity has been concentrated in several sectors along the Mozambique Channel. To the north, the origin of the Neogene Comoros volcanism is the subject of a long-lasting debate (Emerick and Duncan, 1982; Emerick, 1985; Class et al., 1998; Späth et al., 1996; Debeuf et al., 2003; Debeuf, 2009; Michon, 2016). Michon (2016) points out that the Comorian volcanism is superimposed onto seismic zones and graben structures (Nougier et al., 1986; Zinke et al., 2003; Debeuf, 2009; Pelleter et al., 2014). This has led the volcanism across the Comoros archipelago to be interpreted as being related to an E-W right-lateral shear zone or a wide trans-tensional boundary between the Lwandle and Somali plates, rather than simply the surface expression of a deep mantle plume (Michon, 2016; Famin et al., 2020; Feuillet et al., 2021; Tzevahirtzian et al., 2021). The Cretaceous Glorieuses volcanism to the north is older (ca. 69 Ma, Leroux et al., 2020), and has recently been explored and sampled (Berthod et al., 2021b).

To the south, Cenozoic volcanism has been recognized for the Sakalaves seamounts, the Bassas da India atoll, Europa Island, Hall and Jaguar Banks, Mt. Bourcart and an unnamed seamount identified as Mt. X which was discovered during the RV Sonne cruise SO-183 (Fig. 1b, Jokat, 2006). Young volcanic edifices are also present in the heart of the Natal Valley and on the Mozambique Ridge (Hartnady, 1986; Ben Avraham et al., 1995; Jokat, 2009, 2014; Castelino et al., 2016; O'Connor et al., 2019). The isotopic signature of these ~7 Ma basanites-alkaline basalts, coupled with recent tomographic models of the Afro-Arabian mantle (Hansen et al., 2012), suggests a link with an African Superplume beneath eastern Africa (O'Connor et al., 2019). Uplift of the South African Plateau during the Upper Cretaceous and Cenozoic has been documented (Ponte et al., 2019; Baby et al., 2020), interpreted as the African Plate passing over the African Superplume, and resulting in a partial rejuvenation of the topography in the Neogene (Baby et al., 2020).

Bassas da India/Europa region

The general features of the seafloor geomorphology of the Bassas da India/Europa region have been outlined by Breitzke et al. (2017), Dorschel et al. (2018), and Wiles et al. (2020). Volcanism appears to be diversely distributed in space, with an alignment of five edifices in two distinct directions (Figs 1 and 2). Hall and Jaguar Banks and Bassas da India atoll are roughly aligned along the N40° trend with the Mt. Bourcart and Almirente Leite seamounts, whereas in the southeast, Europa Island, Ptolemee seamount and Bassas da India atoll are aligned along a N150° trend. Furthermore, Europa Island and Mt. X are also aligned along the

N40° trend (Fig. 1b). Bassas da India atoll and Europa Island are topped by modern carbonate platforms (Fig. 1c). Hall and Jaguar Banks, SW of Bassas da India, which consist of drowned shallow-water carbonate platforms, now also lie at a depth of hundreds of meters (Courgeon et al. 2016). Sediment transfer on the slopes of Bassas da India, Europa and the carbonate platforms has been widely described by Counts et al. (2018). Volcanic rocks, identified as olivine basalts, pyroxene-phyric basalts and altered basalts, have been dredged from the flanks of the Jaguar seamount (Jokat, 2006). In addition, volcanic seamounts, such as Ptolemee seamount, southeast of Bassas da India (Fig. 1c; Jorry, 2014), were highlighted during recent oceanographic surveys (Jorry, 2014; Olu, 2014). In this region, the overall evolution of drowned flat-topped carbonate platforms is intimately linked with tectonics and rejuvenated volcanism (Courgeon et al., 2016, 2017; Courgeon, 2017). Previous studies mostly focus on shallow-water carbonate platforms and only give an indirect indication of the age and chronology of the recent volcanic activity. The Hall and Jaguar drowned carbonate platforms are locally overlain by volcanoclastic deposits and can have been cut by explosive volcanic features (e.g., craters – see Courgeon et al., 2017). These carbonate platforms and terraces are occasionally covered by submarine volcanic lava flows, indicating relatively recent (i.e., Late Cenozoic) volcanic activity, synchronous and/or postdating carbonate platform growth (Courgeon et al., 2017; Deville et al., 2018). These carbonate platforms have been dated at 16.3 to 5.4 Ma, giving a minimum age for the building of the volcanic edifice (Courgeon, 2017; Courgeon et al., 2017). Based on 2D seismic sections, Courgeon et al. (2017) proposed that volcanism began during Upper Oligocene times.

By describing the volcanic forms (cones, craters, calderas) and erosional-depositional features (landslide scars, channels, mass-wasting deposits) on their submarine flanks and neighboring slopes, our compilation of multibeam bathymetry data significantly improves our knowledge of the general seafloor geomorphology of the Bassas da India/Europa volcanic edifices (Breitzke et al., 2017; Dorschel et al., 2018; Wiles et al., 2020), and updates the various morphometric features published by Courgeon et al., (2016), Courgeon (2017), and Counts et al. (2018).

3) Material and methods

We performed a basic analysis of physical variables of all identified volcanic cones to describe the characteristics and distribution of the volcanic structures that form the Bassas da India/Europa complex. Our study was based on bathymetry and reflectivity data collected by Kongsberg EM122 and Kongsberg EM 710 multibeam echosounders (MBES), on board the R/V Atalante, during the PAMELA-MOZ01 (Olu, 2014) and PAMELA-MOZ04 (Jouet and Deville, 2015) cruises. For shallow water (0-1500 m), Kongsberg EM710 MBES was deployed with its 70 – 110 kHz frequency and 256 beams (400 in high-resolution mode). For deeper water, Kongsberg EM122 multibeam was used with its 12 kHz frequency and 288 beams (432 in high-resolution mode).

Geomatics

Acoustic data were processed by the Ifremer hydrography team with Caraibes software version 4.3 (©Ifremer): automatic and manual quality controls, tide and sound velocity corrections and gridding. We used the average of all the depths measured in each cell to grid the cleaned XYZ data. Cell size resolution of bathymetric and reflectivity rasters were chosen according to the spatial resolution of the echosounder, thus the sampling varies from 100 m to 10 m, accordingly. We used the datum WGS84 coordinate system with Mercator projection.

Individual seamounts were identified by visual inspection coupled with the bathymetry using ArcGIS™v10.3 software, based on bathymetry, associated slope and reflectivity data whose space grid resolutions range from 10 m to 30 m. The basal outlines of seamounts were then redigitized and combined in a shapefile in the WGS84 geographic coordinate system.

For the geometrical analysis, the perimeters, lengths and areas of seamounts were calculated with the *arcpy.AddGeometryAttributes_management* arcpy tool in a geodesic coordinate system. To define the direction of each seamount, we used the rotation values from the theoretic ellipses calculated for each seamount polygon in the Mercator projection system with the *Spatial Statistics Tools/Directional Distribution* ArcGis tool.

For the spatial analysis, in order to obtain comparable statistic results for each area studied, we used the bathymetric raster of 100 m cell size resolution which covers all seamounts homogeneously. Mean, maximum, minimum and the range of bathymetric values for each seamount were calculated with the *Spatial Analyst/Zonal statistics as table* ArcGis Tool. Maximum and mean slopes were calculated with the same ArcGis Tool directly from the 100 m slope raster, derived from the 100 m bathymetric raster.

$^{40}\text{Ar}/^{39}\text{Ar}$ dating

Dredges were performed on Hall and Jaguar Banks (DW05 and DR19, respectively, Fig. 1c, Tab. 1) and Bassas da India (DR08) during the PAMELA-MOZ01 (Olu, 2014) and PAMELA-MOZ04 (Jouet and Deville, 2015) cruises. Thin sections (Fig. S1 in supplementary material) helped select the freshest samples (Tab. 1): MOZ01-DW05-01 and MOZ01-DW05-13 (Hall Bank), MOZ01-DR19-04 (Jaguar Bank) and MOZ04-DR08-01 (Bassas da India). MOZ01-DW05-01 is a basanite made of olivine phenocrysts mostly iddingsitized in a fine-grained microcrystalline mesostasis (Fig. S1a in supplementary material). MOZ01-DW05-13 presents a more evolved composition with large euhedral feldspar phenocrysts in a groundmass composed of alkali feldspar, nepheline, clinopyroxene, biotite, titanite, amphibole and Fe-Ti oxides (Fig. S1b in supplementary material). MOZ01-DR19-04 and MOZ04-DR08-01 are ultramafic rocks and consist of sub-euhedral to euhedral olivine and zoned clinopyroxene phenocrysts embedded in an oxidized matrix (Fig. S1c,d in supplementary material). Using these petrological observations, we selected three millimetric (1 - 2 mm) whole rock grains (MOZ01-DW05-01, MOZ01-DR19-04 and MOZ04-DR08-01) and one biotite crystal (MOZ01-DW05-13). Selected fractions were analyzed by the $^{40}\text{Ar}/^{39}\text{Ar}$ method in step-heating using a CO_2 laser probe coupled with a MAP 215 mass spectrometer. The whole procedure is described in detail in Ruffet et al., (1991, 1995, 1997). These samples were irradiated in two batches, IR32 and IR34, in the 8C facility of the McMaster Nuclear Reactor (Hamilton, Ontario, Canada). Irradiation of biotite MOZ01-DW05-13 lasted 49.58 h with a global efficiency (J/h) of $8.201 \times 10^{-5} \text{ h}^{-1}$ whereas irradiation of whole-rock samples MOZ01-DW05-01, MOZ01-DR19-04 and MOZ04-DR08-01 lasted 50.00 h with a global efficiency (J/h) of $8.618 \times 10^{-5} \text{ h}^{-1}$. The irradiation standard was sanidine TCRs ($28.608 \pm 0.033 \text{ Ma}$, see Renne et al., 1998, 2010, 2011). Blanks were performed routinely each first or third/fourth run and are subtracted from the subsequent sample gas fractions. Apparent age errors are plotted at the 2σ level and do not include the errors on the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio, and age of the monitor and decay constant. Plateau ages were calculated if 70% or more of the $^{39}\text{Ar}_K$ was released in at least three or more contiguous steps that defined apparent ages in agreement, to within 2σ , with the integrated age of the plateau segment. The errors on the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio and age of the monitor and decay constant are included in the final calculation of the error margins on the plateau ages.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages are provided with 2σ errors. Analytical data and parameters used for calculations (e.g., isotopic ratios measured on pure K, Ca and Cl salts; mass discrimination; atmospheric argon ratios; J parameter; decay constants) and reference sources are available in the supplementary Table S1.

4) Results

Mapping and distribution of the volcanic edifices

A detailed analysis of the geomorphological features of each main edifice and of their submarine neighboring slopes, based on the multibeam backscatter and bathymetric data set, is provided in the following sections.

a. Hall Bank

Hall Bank is located in the western part of the area studied ($21^{\circ}52'$ S, $39^{\circ}04'$ E; Figs 1 and 2). Morphologically, Hall Bank constitutes a circular seamount with a diameter of 26 km that rises more than 2600 m from the surrounding seafloor (Fig. 3). The flat top of the seamount, 8 km in diameter and rising to within 500 m of sea level, corresponds to a drowned Cenozoic carbonate platform (Courgeon et al., 2016). Volcanic structures and material (Fig. 4a), including a clearly identifiable explosion crater (Fig. 5a), have been previously reported at the top of the platform indicating recent volcanic activity, postdating the carbonate platform development (Pliocene in age, Courgeon et al., 2017). Samples of volcanic rocks have been collected by dredging (MOZ01-DW05, see location on Figs 1c and 5a, b) from the top of the carbonate platform. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra yielded by analysis of a millimetric whole-rock fragment and biotite crystals from dredged samples MOZ01-DW05-01 and MOZ01-DW05-13, provided two perfectly concordant plateau ages at 20.5 ± 1.5 Ma and 20.2 ± 0.1 Ma (Fig. 6 and supplementary Table S1).

The carbonate platform and volcanic edifice are affected by several faults and numerous landslide scars (W, SW, NW, S and NE flanks, Figs 4b and 5a, b). The SW, W and NE flanks of the edifice are characterized by the presence of marked erosional channels and gullies that extend to the base of the seamount (Figs 2 and 5a, b). Volcanic cones can be identified on the north and southeast flanks of Hall Bank, as well as eastwards along a submarine structure toward Jaguar Bank. A cluster of volcanic cones is observed on the northern flank of Hall Bank (Fig. 5a, b). In this area, we also identified a surface morphology with irregular

contours, a constant slope and a high and homogenous sonar backscatter signal. Since high acoustic backscatter signals can be interpreted as volcanic units not covered by significant marine sedimentation, this surface morphology seems to reveal a lava flow that spreads more than 5 km northwards. The dimensions of this unit are up to 8 km in length, 50 – 100 m in height and more than 2 km in width (Fig. 5a, b). A similar acoustic signature and slope are observed in the southwestern portion of Hall Bank, where a thin lava flow might extend over an area of at least 4 km in length and 200 m in width (Fig. 5a, b). Alternatively, this high-backscatter trail can be interpreted as a recent coarse-grained volcanoclastic flow within a channel.

In other places, at a depth of more than 1200 m, the seafloor is characterized by a patchy backscatter pattern probably indicative of a coarse- to fine-grained sedimentary cover. In contrast, east of Hall Bank, a submarine high which is over 10 km long and 5 km wide, with high-backscatter and high topography, appears to extend the seamount with an average along-axis slope of 8 to 11° toward Jaguar Bank (Figs 3b, 5a, c). Interpreted as a volcanic ridge, the unit is marked by the presence of normal faults, cones, cone alignments and inferred lava flows.

b. Jaguar Bank

Jaguar Bank lies immediately to the east of Hall Bank (21°54' S, 39°26' E; Figs 1 and 2). This 2000 m-high seamount displays a triangular shape, extending over more than 40 km along its greatest axis, following NNW-SSE and WSW-ENE orientations (Fig. 2). The submarine relief is marked by a flat-topped morphology (Fig. 3a), which corresponds to a submerged Oligocene-Miocene shallow-water carbonate platform lying at about 300 – 500 m below sea level, previously described by Courgeon et al. 2017 (Fig. 5c, d). The carbonate platform top is characterized by a smooth surface and the presence of volcanic morphologies interpreted as being lava flows (Courgeon et al., 2017), and by a dense network of N70 – 75° oriented normal faults (Fig. 2) that lower the southern part of the platform surface (Courgeon et al., 2016; Miramontes et al., 2019). Following Courgeon et al. (2017), some of these faults are associated with volcanic activity. Similarly to Hall Bank, the edge of the carbonate platform is affected by multiple landslide scars that are associated with erosive channels and gullies affecting most of the edifice (Fig. 5c, d).

The slopes of the Jaguar edifice extend NNW with a 12 km-wide topographic high, trending N150° along a radial direction from the carbonate platform (Figs 2 and 5a, b). This

flank, with its uneven relief, and on which volcanic cones can be identified, can be considered a remnant of the volcanic bedrock. The acoustic backscatter pattern on this morphological high is not uniformly high, suggesting the presence, at least partially, of a sedimentary cover. The eastern part of this volcanic flank is cross-cut by a N60° normal fault that seems to be overlain by a large volcanic cone (labelled “Post-fault volcanic cone” on Fig. 5c, d).

North-east of Jaguar Bank, a volcanic ridge is clearly revealed by the bathymetry and the high-backscatter signal, contrasting with the lower backscatter of the surrounding seabed on either side of the ridge, indicative of a smooth, fine-grained sediment cover (Fig. 5c, d). This well-developed N65° volcanic ridge, with an average along-axis slope of 4°, rises locally to more than 1000 m above the surrounding seafloor (Fig. 2b). This ridge has a slightly convex along-axis profile, from the carbonate platform to the deep sea, with steeper slopes (up to 17°), before terminating in an extension composed of a series of pointy volcanic cones over 200 m high (Figs 5c, d and 7b). Numerous volcanic cones have been identified, their distribution providing insight into the preferential incision paths and extension of this volcanic ridge to more than 20 km from the carbonate platform. This volcanic relief, about 10 km wide, is parallel to a dense network of sub-kilometric N60 – 75° normal faults (Figs 2 and 5c, d) and spreads to Bassas da India atoll. Volcanic cones on both sides of this volcanic ridge seem also to be aligned along a N140° direction (Fig. 5c, d). A whole-rock fragment of the MOZ01-DR19-04 sample dredged on the northern flank of the ridge (see location on Figs 1c and 5c, d) yielded concordant plateau and isochron ages of 9.6 ± 0.2 Ma and 9.7 ± 0.3 Ma, respectively (Fig. 6 and supplementary Table S1).

It is likely that Jaguar Bank also extends in a SSE direction with the presence of several volcanic cones (see Fig. 2). The lack of bathymetric data in this area does not allow us to fully describe this submarine extension of the bank.

c. Bassas da India

Bassas da India atoll is located in the northeastern part of the volcanic complex (21°54' S, 39°26' E; Figs 1 and 2). The edifice constitutes a circular volcanic feature, 45 km in diameter, which rises more than 3000 m from the surrounding seafloor (Fig. 3a). On the northwestern to northeastern sides, submarine slopes are relatively steep, cut by slope failures and many erosive channels and gullies (Figs 2 and 7c, and *Figs 3b and 9b in Count et al., 2018*). Mass transport deposits have been recognized from interpretation of seismic data (Counts et al., 2018). The atoll itself is fringed by a drowned terrace, at a depth of about 400

m to 600 m, and mainly developed towards the south (Fig. 2). A major WSW-ENE normal fault is clearly discernible, separating this submarine terrace from the main platform, and affecting the flanks of the seamount (Figs 1 and 2 - see also Courgeon et al. 2016, Fig. 3a). Courgeon et al. (2017) recognized successive collapse structures along this southern flank related to normal faulting. Volcanic landforms have been identified along the southern edge of this submarine terrace (Fig. 4c and Courgeon et al., 2017), and volcanic rocks have been collected from there (MOZ04-DR08, Fig. 1c). A single whole rock fragment of sample MOZ04-DR08-01 yielded perfectly concordant plateau and isochron ages at 8.0 ± 0.2 Ma (Fig. 6 and supplementary Table S1).

The southern flank of Bassas da India shows high backscatter signals that are interpreted as areas of predominantly volcanic material (Figs 2, and 8a, b). The sector is characterized by N60° normal faults and many aligned volcanic cones, which is consistent with a preferential intrusion path. East of Bassas da India, the high-offset normal fault runs down the middle of a small volcanic ridge (average along-axis slope of 11°, about 10 km in length, 5 km in width, and 400 m in height at its maximum). To the southwest of Bassas da India, a volcanic promontory (10 km in width), associated with a dense fault network (Figs 2 and 7b), extends toward Jaguar Bank. This structure, which extends more than 15 km beyond the Bassas da India submarine terrace, with an along-axis average slope of 6° in its median section, seems to connect with the volcanic ridge northeast of Jaguar Bank described above, with a group of tall pointy volcanic cones marking the continuity between the two ridges (Figs 3b, 7b). In these areas, volcanism seems to be closely related to tectonics, with a dense networks of faults and volcanic cones. Although the faults frequently intersect the volcanic structures, at least some of the volcanic cones mask the fault zone, indicating later emplacement (Fig. 8a, b). This suggests that eruptive activity was coeval with tectonic activity, at least in this region.

d. Ptolemee seamount

Located between Bassas da India and Europa (22.00° S, 46.06° E, Figs 1 and 2), Ptolemee seamount was discovered in 2014 during the Ptolemee oceanographic expedition (Jorry, 2014). This circular edifice is about 20 km in diameter and up to 2000 m in height (Fig. 3a). The seamount rises to 770 m below sea level, and at least three distinct ridges extend south-southeast, north-northwest and east, from a very well-preserved caldera at its summit (Figs 7d and 8c, d). This caldera, about 5 km² in area, extending N70° – 75°, has a

horseshoe shape open to the east. Several volcanic cones are identifiable within and along the rim of the caldera. The main volcanic ridges are well defined by their high backscatter signal and numerous elongated and aligned volcanic cones (Fig. 8c, d). The north-northwest and south-southeast volcanic ridges share the same orientation (N155°). Together they are about 40 km in length and 3 – 6 km in width. The north-northwest volcanic ridge ends abruptly at the northern limit, whereas the south-southeast volcanic ridge extends to the south up to the Europa edifice with an average along-axis slope of 4° (Figs 3b, 7d, 8c, f). These volcanic ridges are dominated by the presence of numerous large volcanic cones. Another 3 km-wide volcanic ridge extends more than 18 km eastwards from the summit of Ptolemee seamount, with an along-axis average slope of 6°, and several large volcanic cones, mainly towards its eastern end (Figs 7d and 8c, d). To the west of the summit a topographic high and a cone alignment, with almost the same orientation as the eastern ridge, appears to exist. No mass transport deposits, erosive channels or superficial expression of faults were observed in this zone. Apart from the volcanic ridges and cones described above, the flanks of Ptolemee seamount are characterized by low acoustic backscatter, indicative of a smooth, fine-grained sedimentary cover.

e. **Pamela Seamounts 1 and 2**

The area between Bassas da India atoll and Ptolemee seamount comprises two domains characterized by massive and reflective edifices, and numerous volcanic features, suggesting the existence of two large volcanic edifices, previously unknown, hereafter called Pamela Seamount 1 (21.37° S, 39.56° E, Fig. 2) and Pamela Seamount 2 (21.80° S, 40.06° E). The existence of Pamela Seamount 1 (PS1) can be inferred from the 952 m-resolution 2014 GEBCO bathymetry but the new bathymetric map carried out during the PAMELA cruises provides greater accuracy, from 100 m to 30 m-resolution, of the morphology and characteristics of the northern and eastern flanks of this seamount. Its diameter and height were estimated at about 30 km and 1500 m, respectively (Fig. 7c, d). Numerous volcanic cones have been identified that lie along two main alignments oriented N70° and N115° (Figs 7d and 8a, b). These preferential orientations are also observed in the morphology of the elongated cones. As for Ptolemee seamount, 3 – 5 km-wide volcanic ridges radiating from the summit are identifiable to the east (average along-axis slope of 4°) and the south-southwest (with an along-axis average slope of 8°). They concentrate most of the identifiable volcanic cones of PS1. Extending the south-southeast volcanic ridge southwards, several large, isolated

pointy cones (over 400 m high) occur on the seafloor between PS1 and PS2 (Figs 3b and 7d). To the northwest of PS1, several faults can be identified, suggesting a NE-SW trending graben, a few hundred meters deep (Fig. 7c), between PS1 and Bassas da India. Volcanic cones are numerous in this region, and are distributed along a main NW-SE trend (Fig. 8a, b). This trend defines a topographic high between PS1 and Bassas da India, rising to about 700 m above the surrounding seabed, locally downcut by the NE-SW trending graben (Fig. 7a,c and 8a, b). On the eastern flank of PS1, a gully over 300 m wide and about 200 m deep is identifiable (Fig. 7a, c). It could be associated with a fault intersecting a volcanic cone (Fig. 8a, b).

Pamela seamount 2 (PS2) rises more than 900 m high from the seafloor to the north of Ptolemee (Fig. 7d). This seamount, also not previously reported in the literature, displays similar features to the Ptolemee seamount. The edifice is made of numerous volcanic cones and displays a roughly oval morphology (16 x 10 km in diameter) with an elongated base along a N50° axis, and no discernible volcanic ridges.

f. **Europa**

Europa Island, located in the southeastern part of the study area (22°21' S, 40°21' E; Figs 2 and 8e, f), rises more than 2500 m from the ocean floor (Fig. 3). The island, 6 km in diameter, with a maximum altitude of 6 m, is surrounded by a well-developed fringing reef (Jorry et al., 2016). Europa edifice exhibits a circular shape with a basal diameter of up to 40 km. The slopes are largely covered by a thin sedimentary cover, as evidence from seismic data and acoustic backscatter by Counts et al. (2018). Significant areas of erosion with many channels are identified all around the edifice (Fig. 8f). Some of them with higher backscatter values can be active. Irregular and undulating surfaces, located downslope of these channels, have been interpreted as downslope mass transport and gravity flow deposits (Counts et al., 2018). A normal fault has been identified in the northern part of Europa. The fault is oriented N40°, which is similar to the N40 – 80° system observed between Hall Bank and Bassas da India (Fig. 5). This fault seems to mark a transition zone between the well-defined channels running along the northern flank of Europa, and lobes of mass-wasting deposits (Fig. 8e, f). The presence of deposits at the base of the fault can be associated with a steep decrease in slope between the fault scarp and the plain. The absence of a change in slope and the regular decrease in slope along the channel confirm that its activity postdates the faulting, and indicates longterm channel activity (Fig. 8e). A few volcanic cones and volcanic outcrops,

even megablocks, with high-backscatter signatures, are visible around Europa (Figs 2 and 8e, f). Volcanic cones present no preferential distribution. Some of them seem to overlie mass transport deposits in the northern part of Europa, indicating a volcanic activity that could locally postdates sedimentation processes reaching the deep seafloor (see *Fig. 7a in Counts et al., 2018*).

Characteristics of the volcanic cones

Numerous volcanic cones and their alignments can be identified either on the flanks of the seven large edifices or along the volcanic ridges (Figs 2, 5 and 8). A total of 430 volcanic cones have been mapped with multibeam data used in this analysis and their morphology investigated. This number is certainly underestimated, as only about 45% of the Bassas da India/Europa region has been mapped by multibeam survey (Fig. 1c). The spatial distribution and shape of the cones are clearly non-random. Characteristics and distribution of the volcanic structures in this archipelago are given in Table 2 and described below.

Volcanic cones have mostly conical or conical-like forms with circular to elongate bases. A crater or a horseshoe-shaped crater have only been observed at the summit of less than 5% of the edifices (Figs 5 and 8). The basal area of individual volcanic cones ranges from 0.01 to 4.95 km² (Fig. 9a). The average basal area for volcanic cones around Ptolemee, PS1 and PS2 seamounts varies within a narrow range of between 0.92 and 1.2 km², whereas those in Hall and Jaguar Banks, Bassas da India and Europa region display smaller average values (0.24, 0.27, 0.49 and 0.44 km², respectively). Thus, the larger edifices are mainly located along the NW-SE volcanic alignment, from PS1 to Europa (Fig. 9a, 9d). Volcanic cone elevations range from 10 m to over 670 m (Fig. 9b) and almost 50% of cones are < 150 m in height. Only 2% of volcanic cones are > 500 m in relief and are mainly located on the northern part of Ptolemee seamount (Fig. 9b). In contrast, many small volcanic cones, with a height of < 100 m, are found on the volcanic ridge located between the eastern part of the Jaguar Bank and Bassas da India (Fig. 9b). The same tendency can be observed for average values. Average height is above 200 m for volcanic cones located around Ptolemee, PS1 and PS2 seamounts (230 m, 207 m and 280 m, respectively) whereas those around Hall and Jaguar Blanks, Bassas da India and Europa yield a smaller average height of 157 m, 124 m, 151 m and 158 m, respectively.

Aspect ratios (height/average base length) of the volcanic cones vary from 0.04 to 0.46 (Fig. 9c). Volcanic cones around Pamela Seamount 1 present the smaller average aspect ratio

of 0.18, whereas those located around Hall Bank display the highest (0.26 on average). With an average of 0.21, all of our results are in agreement with those obtained for scoria cones in many volcanic provinces such as the Comoros Archipelago (Tzevahirtzian et al. 2021), at Linosa (Romagnoli et al., 2020), Pico Island (Stretch et al., 2006; Mitchell et al., 2012), Terceira (Casalbore et al., 2015; Weiß et al., 2015), and higher than those in Canary (Mitchell et al., 2002) and Hawaii (Clague et al., 2000).

The mean slope distribution is presented in Figures 9d and 9e. 95% of mean slopes of the volcanic cones are $< 25^\circ$ (410/430), with 85% ranging from 10° to 25° (Fig. 9d). Less than 5% exceed 25° . Both small and large edifices can have mean slopes up to 20° (Fig. 9d). Moreover, small edifices with a basal area $< 1 \text{ km}^2$ tend to present a large range of mean slopes varying from 4° to 29° (Fig. 9d). On the contrary, large edifices with a basal area of up to 2 km^2 are characterized by elevated mean slopes that are up to 15° . The distribution of the mean slopes is fairly unimodal, centered on $15 - 20^\circ$ for Pamela Seamount 1 and Pamela Seamount 2 and on $20 - 25^\circ$ for Bassas da India, Ptolemy and Europa, and Hall Bank (Fig. 9e). Jaguar Bank presents a larger range of distribution, with mean slopes between 10° and 25° . As for the mean slopes, the distribution of maximum slope is fairly unimodal with the most frequent slope being between 25° and 35° (Fig. 9f). Volcanic cones of Hall Bank, Ptolemy and Bassas da India display the most elevated maximum slopes, with angles of $30 - 35^\circ$. There appears to be a correlation between maximum slope and volcanic cone elevation. In fact, we observe a logarithmic increase of the maximum slope with height (Fig. 9g). Maximum slopes are found on high edifices, but we note that values rarely exceed 40° (Fig. 9g).

Directions of elongation have been obtained for each volcanic cone and plotted in Figure 9h. The distribution of directions of elongation is more or less bimodal. The most frequent direction ranges from 160 to 200° , while a second subset lies between 080 and 100° .

5) Discussion

a. Volcanic morphologies

The complex morphologies of volcanic edifices result from a long-term equilibrium between cyclic stages of growth and destruction (e.g., Mitchell et al., 2002). The landforms depicted on the submarine areas of the volcanic islands and seamounts are usually classified into two groups: landforms of volcanic origin and those derived from erosive-depositional

processes (Casalbore, 2018). Volcanic landforms primarily consist of volcanic cones, lava flows, calderas and craters, and areas of undifferentiated volcanic bedrock. Erosive-depositional landforms mainly result from channel erosion, gravity-driven instability and wave erosion.

In the Bassas da India/Europa complex, we describe several types of morphologies including large volcanic edifices topped by an atoll or a carbonate platform, volcanic seamounts, and volcanic ridges.

Large volcanic edifices with emerged or drowned carbonate platforms

The Bassas da India atoll and Europa island are the tops of volcanic edifices characterized by well-developed erosion systems, mainly consisting of numerous gullies and large channels, both active and inactive, some of which terminate in a lobe of deposits (Fig. 8e, f, and *Figs 3b and 9b in Count et al., 2018*). Only a few outcrops of the volcanic basement form relief that emerges from the sedimentary cover. Some are relatively well-developed, such as south of Bassas da India and northwest of Europa (Fig. 8e and f). Few individual volcanic cones were mapped on these edifices (Figs 5 and 8). The predominance of erosive-depositional processes for Bassas da India and Europa edifices results in smooth slopes that tend to become gentler towards the base, giving a slightly concave shape (Fig. 3a). This is particularly noticeable for Europa, which has the most concave slopes (Fig. 3a), reflecting significant spreading of sediments on the lower slopes and the nearby seafloor, controlled by gravity-driven instability (Counts et al., 2018).

Landslide scars are frequently visible around the submarine volcanoes of the Bassas da India/Europa complex (Jorry et al., 2016; Counts et al., 2018). They frequently originate at the edge of the carbonate platforms that exhibit scalloped margins (see Courgeon et al., 2016) and extend down to the volcanic slope of the seamounts, resulting in steep upper slope gradients where little sedimentation occurs. These scars participate to the destabilization and the progressive erosion of the volcanic slopes (Fig. 5). At Bassas da India, the presence of a large scar has induced an important asymmetry of the top of the volcanic edifice, which explains why the modern reef ring exhibits a scalloped margin along the northeastern part of the atoll. This process that creates scalloped margins may result in erosional deep-water carbonate basins and, potentially, the demise and disintegration of carbonate platforms on the long term, according to Mullins and Hine (1989).

Hall and Jaguar Banks also have many well-developed narrow gullies, canyons and channels mostly originating from steep landslide scars. Even if they are partly covered by a fine-grained sedimentation, characterised by low backscatter, the submarine slopes of these two seamounts have slightly more uneven relief compared to those of Bassas da India and Europa, with more frequent volcanic bedrock outcrops and volcanic cones, especially along the well-developed volcanic ridges. This difference in morphology (Fig. 3a) can be related to a greater contribution of sediment supply from coastal hydrodynamic processes (wind- or tide-generated water movement, shallow currents, or density cascading) for the emergent Bassas da India atoll and Europa Island, due to wave erosion, whereas Hall and Jaguar Banks lie at a depth of several hundred meters.

A potential difference in age of volcanism should also be considered. In the Comoros archipelago, Mayotte and Moheli display smooth slopes shaped by erosion-depositional processes, many small slope failures and channels and well-developed insular shelf and terraces. On the contrary, Grande Comore and Anjouan are characterized by submarine flanks shaped mainly by volcanism, with very narrow shelves and no submarine terraces. Based on these morphologies, Tzevahirtzian et al. (2021) suggested that Mayotte and Moheli are older than Grande Comore and Anjouan. Accordingly, we suggest that the existence of better-preserved volcanic morphologies on the flanks of the Hall and Jaguar Banks could reflect more recent volcanic activity than for Bassas da India and Europa. A structural component cannot, of course, be totally excluded as tectonics and rejuvenated volcanism are linked in the evolution of islands and drowned platforms (Courgeon et al, 2016).

Volcanic seamounts without carbonate platforms

The three volcanic seamounts not topped by a carbonate platform, namely Ptolemee, Pamela Seamount 1 (PS1) and Pamela Seamount 2 (PS2), exhibit remarkably well-preserved primary volcanic morphologies both at their tops and along the volcanic ridges (Figs 7 and 8). Unfortunately, the available data do not cover the summit of PS1. Despite this, we can clearly identify numerous volcanic cones and cone alignments on these three edifices. Ptolemee seamount is probably the most exceptional, with an impressive caldera and numerous volcanic cones, sometimes with a summit crater, within and around the caldera, and sharp volcanic ridges that develop radially from the caldera, extending south-southeastward toward Europa, north-northwestward, and eastward. The first two define a N155° alignment. Their morphologies allows us to compare them to rift zones like those described, for example, at

Lō‘ihi seamount, Hawaii (Fornari et al., 1988; Clague et al., 2019). These very well-preserved morphologies, with few signs of gravitational instability, and their higher backscatter compared to the surrounding sediment-covered seabed, are indicative of a relatively recent age for this volcanism.

Volcanic ridges

As noted for Ptolemee, the distribution of the volcanic cones does not appear to be random. Volcanic cones are located on the flanks of the main volcanic edifices (Bassas da India, Europa, Hall and Jaguar banks, Ptolemee and Pamela Seamounts 1 and 2), but mostly along volcanic ridges. Volcanic ridges have been identified E of Hall Bank, NE of Jaguar Bank, SSW and E of Bassas da India atoll, SSE, E and W of Ptolemee seamount, and SSE and E Pamela Seamount 1 (Figs 2, 5, 7, and 8). Furthermore, Jaguar Bank has a clearly elongated shape along a SE-NW orientation, with its northwest and southeast flanks characterized by a high acoustic backscatter and numerous elongated volcanic cones (Figs 2 and 5). This elongated shape could also reflect the existence of a volcanic ridge with a N150° orientation.

The volcanic ridges constitute elongated topographic highs with numerous volcanic cones and areas of high backscatter signal that can indicate extensive lava flows not covered by significant marine sedimentation. As noted above, the volcanic ridges have average along-axis slopes of between 11° (E of Hall Bank, E of Bassas da India) and 4° (NE of Jaguar Bank, SSE of Ptolemee seamount, E of Pamela Seamount 1). They often show a higher slope at shallower water depths, close to the atoll or carbonate bank or top of the seamount, except for the NE ridge of Jaguar Bank which has a slightly convex profile (Figs 3b and 7b). We also noted that the volcanic ridges of the Hall Bank, Jaguar Bank and Bassas da India often coincide with fault networks running along the ridge axis. They are also more evenly shaped and rise more prominently from the surrounding seafloor than those of Ptolemee seamount and Pamela Seamount 1 (Fig. 3b).

The elongation and width of the volcanic ridges, the regularly plunging along-strike slope from the top of the main volcanic center (Figs 3, 5, 7 and 8), and the high concentration of volcanic cones and faults, leads us to compare them to the rift zones described for shield volcanoes (MacDonald, 1972). Volcanic rift zones are preferential pathways for intrusive/extrusive activity, resulting in narrow elongated ridges. The morphology of the rift zones of shield volcanoes is a valuable indicator of the processes that can be responsible for their construction (e.g., Harpp et al., 2003). The length and width of a rift zone, as well as

along-axis slope, is directly controlled by the capability of magma to migrate laterally under magmatic driving pressure (Dieterich, 1988; Fialko and Rubin, 1999). The changes in slope along the rift axis and the regularity of the slope make it possible to assess the continuity of the intrusive dyke system and the constancy of magma supply (Angevine et al., 1984; Harpp et al., 2003). The slope values of the identified volcanic ridges (Table 3) are similar to those obtained for the offshore section of the rift-zones of Hawaiian volcanoes (Mark and Moore, 1987; Fornari et al., 1988; Lonsdale, 1989; Clague et al., 2019), Canary Islands (Gee et al., 2001; Mitchell et al., 2002; Acosta et al., 2003b), Galapagos Islands (Harpp et al., 2003; Geist et al., 2006, 2008), and Grande Comore Island (Tzevahirtzian et al., 2021).

However, there are significant differences to typical Hawaiian rift zones such as Puna Ridge (Smith et al., 2002) or Hilo Ridge (Lipman and Calvert, 2011). Rift zones in the Bassas da India-Europa complex are less long (less than 30 km) than those of the Hawaiian volcanoes, and their morphology is more discontinuous. Such differences have already been reported for some rift zones in the Canary Islands (Acosta et al., 2003b) and the Galapagos Islands (Harpp et al., 2003). In the Bassas da India/Europa complex, most of the volcanic ridges have uneven relief with significant slope reversals due to the presence of large volcanic cones. At or near the end of volcanic ridges, large volcanic cones frequently dominate the landforms, and can even occur in isolation on the seafloor within the axis of the ridge, as noted for example for the SSE ridge of P. Olemee seamount.

Such differences can be related to magmatic driving pressure and magma supply rate. For Acosta et al. (2003b), the magma supply rate on La Palma and El Hierro is too low to smooth out the topographic irregularities along the rift zone axis, explaining the morphological differences to Hawaiian rift zones. According to Harpp et al. (2003), short rift zones with uneven relief suggest that magma input into the rift is sporadic and reflects low magmatic driving pressure that decreases progressively with distance as magma migrates laterally from a shallow magma chamber.

A low magma supply rate from a shallow magma chamber fits well with the morphologies of the proximal rift zone sections of the volcanoes of the Bassas da India-Europa complex. However, this does not appear to be consistent with the presence of numerous large volcanic cones in the distal sector of these rift zones. The presence of large volcanic cones in these areas suggests that they were fed by a poorly degassed magma from a deep reservoir, similarly to the current eruption offshore Mayotte (Berthod et al., 2021a; Feuillet et al., 2021). It therefore seems necessary to consider the coexistence of two different

scenarios to explain the feeding of the eruptions that built the volcanic rifts (Fig. 10): (i) Lateral injection of magma from a shallow magma chamber located under the main volcanic center mainly feeding eruptions in the proximal section of the rift zones, and (ii) direct magma injections from a deeper storage zone feeding the large volcanic cones in the distal section of the rift zones, or, occasionally, at higher altitude. In both cases, magma injections follow the same weakness zones, at least near-surface, determining the rift zone's orientation.

Volcanic cones

Four hundred and thirty volcanic cones have been identified on the flanks of the seven major volcanic edifices and along the volcanic ridges (Figs 2, 5 and 8). Each individual volcanic cone, showing a relatively simple shape, is inferred to be the result of a unique eruption. They are interpreted as monogenetic volcanic edifices formed by pyroclastic rock fragments and/or low effusion rate lava flows (pillow lava). Some of them have an elongated shape or form alignments of cones that represent the trace of a dyke intrusion and a linear eruptive fissure. Physical and chemical properties such as effusive rate, cooling rate, magma composition, viscosity or volatiles content, and the pre-eruptive topography and the water depth also control the shape of volcanic cones in the submarine realm (Bonatti and Harrison, 1988; Fink and Griffiths, 1990; Rappaport et al., 1997 ; Gregg and Fink, 2000). Our mapping does not allow us to establish the role of each of these parameters. Nevertheless, we note that volcanic cones of the Bassas da India/Europa complex are characterized by high aspect ratios (0.21 in average, Fig. 9c) and high slope values, which can reach 40° (Fig. 9f). These morphological characteristics are steeper than those found for worldwide seamounts (Mukhopadhyay and Khadger, 1990; Mukhopadhyay and Batiza, 1994; Rappaport et al., 1997; Clague and Dixon, 2000; Clague et al., 2000; Rowden et al., 2005; Stretch et al., 2006; Mitchell et al., 2012, 2002; Casalbore et al., 2015; Weiß et al., 2015; Romagnoli et al., 2020; Tzevahirtzian et al., 2021). This may be due to low effusion rates favoring in-situ accumulation of pillow lavas and pyroclasts, rather than large sheet flows (Rubin et al., 2012), or higher magma viscosity. It is generally accepted that increasing silica content leads to an increase in viscosity of melts (Liebske et al., 2003; Bouhifd et al., 2004; Stabile et al., 2016). Volcanic rocks of the Bassas da India/Europa complex are composed of alkali mafic lavas with low silica content (olivine basalts to nephelinites; Courgeon et al., 2017). Some authors suggest that alkali basalts are slightly more viscous than tholeiites (Acosta et al., 2003b; Chevrel et al., 2014), which could be consistent with the observed high slope values.

b. Chronology

Previously, little was known about magmatic activity in the southern Mozambique Channel and only a few indirect ages have been obtained for Bassas da India, Hall Bank and Jaguar Bank (Courgeon et al., 2016, 2017). These authors showed that the oldest shallow-water carbonate of Hall Bank is Burdigalian in age (i.e., 16.3 ± 0.1 Ma) suggesting that the underlying volcanic units are older than the Late Oligocene to Early Miocene. As we obtained $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 20.5 ± 1.5 and 20.2 ± 0.1 Ma (Early Miocene) on MOZ01-DW05-01 and MOZ01-DW05-13 volcanic samples, respectively (Fig. 5), our geochronological data suggest that the dated samples may indeed belong to the Hall Bank volcanic basement. However, these samples correspond to loose volcanic fragments that were collected by dredging at the top of the youngest carbonate platform of Hall Bank (Fig. 1c). Courgeon et al. (2017) showed that the carbonate platform was affected by several late explosive and effusive eruptions, as evidenced by the presence of volcanic craters and lava flows on the top of the platform. The volcanoclastic deposits dredged from the top of Hall Bank and the very well-preserved crater morphology imply a plinian magmatic eruption affecting the Hall Bank carbonate platform during the Pleistocene (Courgeon et al., 2017). Therefore, we can deduce that our rocks, dated at about 20 Ma, could correspond to fragments of the deep volcanic basement, brought up by this recent explosive eruption.

The lava sample collected from the northeast volcanic ridge of Jaguar provided an $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 9.6 ± 0.2 Ma. This age is close to previous ages obtained for a packstone sample collected along the southern flank of the Jaguar Bank carbonate platform (11.45 ± 0.37 Ma, strontium isotopic stratigraphy, after Courgeon et al., 2017). This indicates that the volcanism contributing to the building of this submarine ridge occurred synchronously with, or shortly after, the growth of the carbonate platform. Similarly, the volcanic rock dated for Bassas da India comes from the submarine ridge extending southwest of the atoll. The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau and isochron ages of 8.0 ± 0.2 Ma obtained for this sample (Fig. 6) is also very close to that obtained for the drowned carbonate terraces south of Bassas da India (8.48 ± 0.49 Ma - strontium isotopic stratigraphy on a packstone) by Courgeon et al. (2016, 2017). These data all show that, while the major phase of building of the volcanic edifices occurred up to the Early Miocene, volcanism resumed and continued during and after carbonate platform growth, during Late Miocene to Pliocene times, and probably until the Pleistocene.

Though we do not have a direct age for the seamounts located between Bassas da India and Europa (Ptolemee seamount, Pamela Seamounts 1 and 2), their very well-preserved morphology, with perfectly identifiable volcanic structures, argues for a relatively recent activity, probably of Pliocene-Pleistocene age.

Thus, from our $^{40}\text{Ar}/^{39}\text{Ar}$ data, and following Courgeon et al. (2016, 2017), we can state that, while the main building phases of the seamounts of the Bassas da India/Europa complex are Oligocene to Early Miocene in age (> 20 Ma), volcanism resumed and continued during and after the growth of the carbonate platforms, until the Late Miocene (8 – 10 Ma) and probably more recently (until the Pleistocene - see Courgeon et al, 2017), along the volcanic ridges and on drowned carbonate platforms.

The volcanism on the Bassas da India/Europa complex is similar in age to the Miocene Rungwe Volcanic Province located in the southern part of the Western branch of the East African Rift, in Tanzania (Fig. 1a, Mesko et al., 2014), and the Neogene Comoros volcanism in the northern entrance of the Mozambique Channel (Debeuf, 2009; Pelleter et al., 2014; Michon et al., 2016; Quidelleur et al. 2022). These results, together with the ages (6 - 7 Ma) obtained by O'Connor et al. (2019) for the young Mozambique Ridge volcanism, are in line with what would be expected for the southward migration of the East African Rift System and related magmatism. Petrological and geochemical studies are still needed to support and confirm this relationship.

c. Relationship between tectonics and volcanism

Linear volcanic ridges, elongated volcanic cones and alignments of cones are often used as tectonic markers of the near-field stress, or can be seen as the result of magma emplacement into a pre-existing damaged lithosphere (Tibaldi, 1995 ; Michon et al., 2007; Navarro et al., 2009). Previous structural studies in the southern Mozambique Channel, by Courgeon et al. (2016; 2017) and Deville et al. (2018), described a dense network of faults with a dominant N45 – 80° orientation in the areas of Hall Bank, Jaguar Bank and Bassas da India atoll (Figs 2, 5 and 10) and further south-west, whereas faults with a N160 – 180° orientation are predominant north of Bassas da India and in the Davie Ridge area. Drowned carbonate platforms and the recent volcanic units of Hall and Jaguar Banks are clearly affected by N45 – 80° normal faults (Fig. 5b, d), indicating that some of them are probably active and contemporaneous with the most recent volcanic events (Courgeon et al., 2017). Based on the interpretation of seismic profiles, Deville et al. (2018) deduce that the period of

faulting lasted from late Miocene to the present-day, pointing out that the most recent faults affect the entire sedimentary cover and are clearly expressed in the topography of the seafloor. They deduce that faults were active during the Quaternary and were probably contemporaneous with the most recent volcanism.

Our own observations confirm that $N45 - 80^\circ$ faults are widespread in the area from Bassas da India to Hall Bank, whereas very few faults are observed between Pamela Seamount 1 and Europa Island (Figs 2 and 8). These faults vary in length and can reach up to several kilometers. In many places the faults crosscut the seamounts and volcanic deposits (Figs 4b-d and 8a, b). But locally they can be masked by volcanic deposits, in particular by some of the volcanic cones (Figs 4, 5, and 8a, b), thus supporting the contemporaneity of volcanism and tectonics. If we consider the overall pattern of the main volcanic edifices and ridges, there are two clear alignments (Fig. 11). Between Hall Bank and Bassas da India, the volcanic features are organized according to an overall NE-SW orientation (hereafter called the NE-SW trend), whereas the volcanic features between Bassas da India and Europa are mainly aligned according to a global NW-SE orientation (the NW-SE trend).

The NE-SW trend is characterized by two flat-topped seamounts (Hall and Jaguar Banks) with a carbonate platform currently at a depth of several hundred meters, and a large volcanic edifice now topped by an atoll (Bassas da India). Volcanic ridges that we interpret as rift zones dominate the submarine morphology of all these volcanic edifices. They develop mainly along the overall NE-SW orientation of the trend, but Jaguar bank also shows a $\sim N150^\circ$ elongation, similar to the orientation of the NW-SE trend. Statistical analysis of the volcanic cones along this NE-SW trend show that they have small basal areas, and are low in elevation (Fig. 11a, b). More than 60% are < 150 m high and 95% have a surface ranging from 0.02 to 1 km^2 (Fig. 11c, d).

Along the NW-SE trend, between Bassas da India and Europa, three large seamounts have been discovered, including Ptolemee seamount, the two largest having well-developed rift zones with an orientation parallel to the NW-SE trend, and shorter rift zones following an ENE-WSW orientation. Numerous isolated volcanic cones, mainly located along the extension of the southern rift zones, characterize the area between the edifices. (Figs 2, 8 and 10). These volcanic cones are, on average, larger and higher than those located in the NE-SW trend (Fig. 11). Indeed, 81.8% of the $> 2 \text{ km}^2$ volcanic cones are located on this trend (Fig. 11c) and 58.7 % of the volcanic cones are > 150 m in height (Fig. 11d).

In summary, several observations can be made:

(1) The NE-SW trend is characterized by large volcanic edifices topped by carbonate platforms with well-developed polygenetic rift zones making up long, wide and high landforms associated with numerous small volcanic cones

(2) The NW-SE trend includes seamounts with volcanic ridges that are lower in relief but have larger volcanic cones.

(3) The orientation of the rift zones, or volcanic ridges, close to the dominant NE-SW and NW-SE orientations, indicates that their development was influenced by the general regional tectonic stress field or by inherited structures in the lithosphere.

This difference in morphology, controlled by the magmatic activity, suggests a higher magma supply rate along the NE-SW trend, through a better expressed network of faults, leading to the growth of well-developed volcanic ridges.

d. Magma supply, and magma feeding system.

The long-term magma supply rate for the Bassas da India/Europa volcanism can be approximated from the area occupied by volcanic formations on the seafloor. Assuming a uniform crustal thickness of 6 km (Leinweber et al., 2013), the total volume of all volcanic edifices represents 4% of the total crustal volume over the 27,900 km² study area. The seamount and volcanic cone basal areas cover 5,905 km², which represents a minimum of 21% of the seafloor. Comparable values have been obtained from the Canary archipelago volcanism, at 7,273 km² (Acosta et al., 2003b), whereas it represents 56 % of the area for the island of Hawaii (10,458 km², Acosta et al., 2003a). This difference in the area covered by volcanic products of these archipelagoes is interpreted as being due to a weaker magma supply for Canary and Bassas da India/Europa archipelagos than for Hawaii, leading to a low effusive rate and sporadic eruptions, in good agreement with the alkaline nature of the volcanism.

It is challenging to obtain information on the geometry of magma supply and storage systems from the morphology of the volcanic edifices and the spatial distribution of the magma vents alone (Tibaldi, 2015). The magma feeding system is often complex, including multiple levels of magma storage from which magma can be drained into rift zones. The depth and geometry of the magma reservoir(s) beneath a volcano is likely to be a result of the combined effects of the stress field, the magma supply rate which determines thermal conditions, and the density structure beneath and within the volcanic edifice. The Bassas da

India/Europa complex comprises both central, or shield, volcanoes and diverging elongated volcanic ridges. Hall Bank, Jaguar Bank, Bassas da India and Europa are large central volcanoes rising more than 2000 m from the surrounding seafloor (Fig. 3a). The two newly discovered seamounts (PS1 and PS2) and Ptolemee seamount, between Bassas da India and Europa, are smaller, but rise 900 m, 1500 m and 2000 m above the surrounding seabed, respectively. The volcanic ridges originating from these central volcanoes form reliefs several hundred meters high, regularly plunging along-strike from the main volcanic center (Fig. 3b). The volcanic cones around these seven volcanic edifices are most likely monogenetic cones, ranging in height from > 10 to 665 m (Fig. 9a, b). They have been mapped mainly along the ridges, but also off-ridge, on the flanks of the seamounts. Such geomorphological patterns are not unique to the Bassas da India/Europa complex. They are strongly reminiscent of the morphology of other oceanic volcanoes, such as Lō'ihi Hawaiian Islands (Fornari et al., 1988; Clague et al., 2019), Canary Islands (Acosta et al., 2013a; Llanes et al., 2009), Comoros Islands (Tzevahirtzian et al., 2021), Galapagos Islands (Harpp et al., 2003; Geist et al., 2006; Glass et al., 2007) and the Azores (Romer et al., 2018). The similarities in volcanic morphology between these islands and seamounts suggest similar modes of formation, involving long-term building of central volcanoes and magma injections into rift zones from shallow magma reservoir.

We show that volcanic products of the Bassas da India/Europa complex are associated with faults contemporaneous with volcanism, which probably favor magma ascent. The largest volcanic edifices appear to be located at the intersection of fault zones affecting the oceanic lithosphere (Figs 7, 8c, d and 8c, d). This fracturing in the lithosphere has probably played an important role in the construction and the dimension of volcanic edifices, facilitating the ascent and storage of magma, and thus the construction of polygenetic edifices that can last several million years. In the northern part of the Mozambique basin, investigation of seismic refraction data along profiles across the Mozambican margin (20140010 profile, Mueller and Jokat, 2017) located the crust-mantle boundary at a depth of about 15 km. Therefore, it seems reasonable to suggest that deep magma reservoirs might be located at this crust-mantle boundary (Fig. 10), as magmatic underplating beneath the oceanic crust is commonly associated with intraplate volcanism (e.g., Charvis et al., 1999; Fulla et al., 2015; Merz et al., 2019). After initial eruptions of basic magmas and increasing edifice load, magma would be stored in shallower reservoirs. Moderate to shallow depth magma chambers can have existed within the crust when the magma supply rate was high enough to provide

suitable thermal conditions. The morphology of the rift zones is an indicator of the existence of such high-level magma storage, at least during the main period of growth of Bassas da India and Jaguar Bank, allowing magma to be emplaced laterally from a shallow magma chamber into the rift zones. In contrast, the largest volcanic cones probably result from subvertical magma ascent from the mantle through the crust, bypassing the shallower storage zones.

We suggest that the well-developed NE-SW trends (Bassas da India - Jaguar Bank - Hall Bank, Figs 1c and 11) might result from long-lasting magmatic activity or high magma transfer rate, with volcanic shields being able to build rift zones fed by lateral transfer of magma from a storage system situated beneath the main shield. In contrast, the NW-SE trend (between Bassas da India and Europa Island, Figs 2 and 11), with seamounts and volcanic ridges whose morphology reveals the presence of many large monogenetic volcanic cones, might represent less mature stage of growth, with more frequent deep magma injections and rapid magma ascent.

e. Integration in the geodynamic evolution of the Mozambique Channel

Our study demonstrates that magma ascent is strongly controlled by large pre-existing crustal structures as shown, at different scales, by the NE-SW and NW-SE alignment of the main volcanic edifices (Figs 2, 10 and 11), the orientation of the volcanic ridges and faults, the alignment of the volcanic cones and the shape of the elongated cones. We suggest that these large pre-existing crustal structures controlling magma ascent correspond to the fault zones affecting the oceanic lithosphere of the Mozambique Basin, active since at least the Late Miocene, described by Deville et al. (2018). The NE-SW fault trend, parallel to the magnetic anomalies of the oceanic crust (Fig. 1a, König and Jokat, 2010; Leinweber and Jokat, 2012; Mueller and Jokat, 2017), corresponds to the still active Quathlamba seismic axis (Hartnady, 1990), related to southward movement of the Lwandle block relative to the Rovuma block (Saria et al., 2014). The NW-SE volcanic alignments in our study area show orientations close to the N160-180° fractures predominant to the north of Bassa da India (Deville et al., 2018), and probably controlled by the Davie Ridge system and the transform fracture zones affecting the Mozambique Basin (König and Jokat, 2010; Leinweber & Jokat, 2012).

Many authors consider the structures currently active in the Mozambique Channel as related to the progressive southward extension of the East African Rift System since the Oligocene (e.g. Mougenot et al., 1986; Kusky et al. 2010; Franke et al., 2015; MacGregor, 2015; Michon, 2016; Courgeon et al., 2018; Deville et al., 2018; O'Connor et al. 2019; Famin et al., 2020; Wiles et al., 2020; Vormann and Jokat, 2021b). The correlation between fault systems and earthquake epicenters is used by Deville et al. (2018) to suggest that the tectonically active zones in the Mozambique Channel, including the Davie Ridge, are directly connected to the eastern branch of the East African Rift System.

The Cenozoic volcanic systems within and around the Mozambique Channel (including Madagascar and the Mozambique Ridge) raise the question of their possible link with a southward extension of the East African Rift System (Breitzke et al., 2017; Dorschel et al., 2018; Deville et al., 2018; Courgeon et al., 2018; Wiles et al., 2020). For the Bassas da India/Europa complex, the coexistence of active fault systems and Oligo-Miocene to Pleistocene age volcanism argues for such a relationship. Such a context, where Neogene eruptive episodes are contemporaneous with tectonic activity, is reminiscent of others EARS-related settings such as the Comoros archipelago (Feuillet et al., 2021; Tzevahirtzian et al., 2021) or the Miocene Rungwe Volcanic Province in the southern part of the Western Rift in Tanzania (Fig. 1a, Mesko et al., 2014). Geochemical and petrological data on the dredged rocks collected during the PAMELA-MOZ01 (Olu, 2014) and PAMELA-MOZ04 (Jouet and Deville, 2015) cruises will provide more information on the origin of the magma, and the potential connection of this volcanism with the East African Rift System (Berthod et al. in preparation) and the superplume mantle tracked isotopically along Africa from the Red Sea to the Indian Ocean (O'Connor et al., 2019).

6) Conclusion

New bathymetric mapping in the Bassas da India/Europa region in the Mozambique Channel, acquired during the 2014 PAMELA-MOZ1 and the 2015 PAMELA-MOZ04 cruises, provide new constraints on the Cenozoic volcanism emplaced on the surrounding seafloor. Our comprehensive geomorphological survey of the Bassas da India/Europa complex has enabled us to describe the underwater volcanic morphology of Bassas da India and Europa, and the Hall Bank, Jaguar Bank and Ptolemee seamounts. In addition, we discovered and described two new large edifices located immediately to the south of Bassas

da India and rising more than 900 m and 1500 m respectively, named here Pamela Seamount 1 and Pamela seamount 2. $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained for a number of dredged samples from lava flows together with data from the literature confirm that this volcanism covers a period from the Oligo-Miocene to the Pleistocene, and probably extends to the present day. The main building phases of the seamounts of the Bassas da India/Europa complex are Oligocene to Early Miocene in age (> 20 Ma). But volcanism continued during and after the growth of carbonate platforms on top of the main volcanic edifices, until the Late Miocene (8 – 10 Ma) and probably more recently, along the volcanic ridges and on drowned carbonate platforms as well.

Bathymetry and acoustic backscatter images clearly show that these volcanoes have volcanic ridges forming landforms whose orientations appear to be strongly controlled by regional tectonics. The morphology of these ridges and the presence of volcanic cones and faults indicate that they are volcanic rift zones, typical of many oceanic shield volcanoes. However, the presence of large volcanic cones along these volcanic ridges leads us to deduce the involvement of at least two levels of magma storage feeding these structures. The morphology of the rift zones is consistent with the existence of shallow magma storage zones, allowing magma to intrude laterally into the rift zones to feed fissure eruptions and building small volcanic cones and lava flows. In contrast, we suggest that the large volcanic cones are more likely to be the result of sporadic subvertical ascent of magma from a deep reservoir located in the mantle or at the base of the crust, bypassing more superficial storage areas.

The distribution and features of the main volcanoes, the orientation and differences in morphology of the volcanic ridges, and the morphological properties of the 430 volcanic cones identified, allowed us to characterize the two main trends, NE-SW and NW-SE, which are linked to structural features in the region. The NE-SW trend, with volcanic edifices topped by carbonate platforms and well-developed polygenetic rift zones, might result from long-term magmatic activity or a high magma transfer rate. The NW-SE trend that includes seamounts with less-developed volcanic ridges but larger volcanic cones, might represent a less mature stage of growth, with more frequent deep magma injections and rapid magma ascent. For both trends, the orientation of the rift zones, or volcanic ridges, close to the dominant NE-SW and NW-SE orientations, indicates that their development was influenced by the overall regional tectonic stress field or by inherited structures in the lithosphere.

Indeed, the Bassas da India/Europa complex is located on the Quathlamba seismic axis and on the Rovuma-Lwandle boundary characterized by the two main strikes of lithospheric

faults of N45 – 80° and N160 – 180°. Thus, all of these results converge toward a model in which magma ascent is strongly controlled by large pre-existing crustal structures associated with the opening of the Mozambique Basin and the movement of the Davie ridge, formed as a consequence of the breakup of Gondwana, and of the ongoing southward propagation of the East African Rift System. This potential link to the present-day kinematics of the East African Rift System and a possible superplume beneath southern Africa needs to be confirmed with geochemical and petrological data of the dredged rocks.

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References

- Acosta, J., Uchupi, E., Muñoz, A., Herranz, P., Palomo, C., Ballesteros, M., Group, Z.E.E.W., 2003a. Geologic evolution of the Canarian Islands of Lanzarote, Fuerteventura, Gran Canaria and La Gomera and comparison of landslides at these islands with those at Tenerife, La Palma and El Hierro. *Geophys. Canar. Islands* 1–40.
<https://doi.org/10.1007/s11001-004-1513-3>
- Acosta, J., Uchupi, E., Smith, D., Muñoz, A., Herranz, P., Palomo, C., Llanes, P., Ballesteros, M., Group, Z.E.E.W. 2003b. Comparison of volcanic rifts on La Palma and El Hierro, Canary Islands and the island of Hawaii. *Geophys. Canar. Islands* 59–90.
<https://doi.org/10.1007/s11001-004-1162-6>.
- Angevine, C.L., Turcotte, D.L., Ockendon, J.R., 1984. Geometrical form of aseismic ridges, volcanoes, and seamounts. *J. Geophys. Res. Solid Earth* 89, 11287–11292.
<https://doi.org/10.1029/JB089iB13p11287>
- Baby, G., Guillocheau, F., Braun, J., Robin, C., Dall'Asta, M., 2020. Solid sedimentation rates history of the Southern African continental margins: Implications for the uplift history of the South African Plateau. *Terra Nova*, 32(1), 53–65.
- Bachèlery, P., Morin, J., Villeneuve, N., Soulé, H., Nassor, H., Ali, A.R., 2016. Structure and eruptive history of Karthala volcano, in: *Active Volcanoes of the Southwest Indian*

- Ocean. Springer, pp. 345–366.
- Bassias, Y., 1992. Petrological and geochemical investigation of rocks from the Davie Fracture Zone (Mozambique Channel) and some tectonic implications. *J. African Earth Sci. (and Middle East)* 15, 321–339. [https://doi.org/10.1016/0899-5362\(92\)90018-8](https://doi.org/10.1016/0899-5362(92)90018-8)
- Bassias, Y., & Bertagne, R., 2015. Study updates uplift-erosion correlation, Davie fracture zone. *Oil & Gas Journal*, 113(9), 64-75.
- Bassias, Y., & Leclaire, L., 1990. The Davie Ridge in the Mozambique Channel: Crystalline basement and intraplate magmatism. *Neues Jahrbuch für Geologie und Paläontologie-Monatshefte*, 67-90.
- Ben Avraham, Z., Hartnady, C.J.H., Le Roex, A.P., 1995. Neotectonic activity on continental fragments on the Southwest Indian Ocean: Agulhas Plateau and Mozambique Ridge. *J. Geophys. Res.* 100, 6199–6211. <https://doi.org/10.1029/94JB02881>
- Bernard, A., Munsch, M., Rotstein, Y., & Sauter, D., 2005. Refined spreading history at the Southwest Indian Ridge for the last 96 Ma, with the aid of satellite gravity data. *Geophysical Journal International*, 162(3), 765–778.
- Berthod C, Médard E, Bachèlery P, Gurio H, Le Muro A, Peltier A, Komorowski J, Benbakkar M, Devidal J, Langlade J, Tesson P, Boudon G, Rose-Koga E, Deplus C, Le Friant A, Bickert M, Nowak S, Thirion I, Burckel P, Hidalgo S, Jorry S, Fouquet Y, Feuillet N (2021) The 2018-ongoing Mayotte submarine eruption: magma migration imaged by petrological monitoring. *Earth Planet Sci Lett* 571:117085. <https://doi.org/10.1016/j.epsl.2021.117085>
- Berthod, C., Zaragosi, S., Famin, V., 2021b. SCRATCH cruise : Sampling in the Comoros Region: Anthropization, Tectonics, volcanism, and Climate Hypotheses, NV Marion Dufresne II. <https://doi.org/10.17600/18002274>
- Bonatti, E., Harrison, C.G.A., 1988. Eruption styles of basalt in oceanic spreading ridges and seamounts: Effect of magma temperature and viscosity. *J. Geophys. Res. Solid Earth* 93, 2967–2980. <https://doi.org/10.1029/JB093iB04p02967>
- Bouchard, C., Crumplin, W., 2011. Two faces of France: ‘France of the Indian Ocean’/‘France in the Indian Ocean.’ *J. Indian Ocean Reg.* 7, 161–182. <https://doi.org/10.1080/19480881.2011.637423>
- Bouhifd, M.A., Richet, P., Besson, P., Roskosz, M., Ingrin, J., 2004. Redox state, microstructure and viscosity of a partially crystallized basalt melt. *Earth Planet. Sci. Lett.* 218, 31–44. [https://doi.org/10.1016/S0012-821X\(03\)00641-1](https://doi.org/10.1016/S0012-821X(03)00641-1)

- Breitzke, M., Wiles, E., Krockner, R., Watkeys, M.K., Jokat, W., 2017. Seafloor morphology in the Mozambique Channel: evidence for long-term persistent bottom-current flow and deep-reaching eddy activity. *Mar. Geophys. Res.* 38, 241–269.
<https://doi.org/10.1007/s11001-017-9322-7>
- Calais, E., Hartnady, C., Ebinger, C., Nocquet, J.M., 2006. Kinematics of the East African Rift from GPS and earthquake slip vector data. In: Yirgu, G., Ebinger, C.J., Maguire, P.K.H. (Eds.), *Structure and Evolution of the Rift Systems Within the Afar Volcanic Province, Northeast Africa*. In: *Geol. Soc. (Lond.) Spec. Publ.*, vol. 259, pp. 9–22.
- Casalbore, D., 2018. Volcanic islands and seamounts, in: *Submarine Geomorphology*. Springer, pp. 333–347. https://doi.org/10.1007/978-3-319-57852-1_17
- Casalbore, D., Romagnoli, C., Pimentel, A., Quartau, R., Casas, D., Ercilla, G., Hipólito, A., Sposato, A., Chiocci, F.L., 2015. Volcanic, tectonic and mass-wasting processes offshore Terceira Island (Azores) revealed by high-resolution seafloor mapping. *Bull. Volcanol.* 77, 24. <https://doi.org/10.1007/s00445-015-0905-3>
- Castelino, J. A., Eagles, G., Jokat, W., 2016. Anomalous bathymetry and palaeobathymetric models of the Mozambique Basin and Nansen-Larsen Sea. *Earth and Planetary Science Letters*, 455, 25–37. <https://doi.org/10.1016/j.epsl.2016.09.018>
- Cesca, S., Letort, J., Razafindrakoto, H.N.T., Heimann, S., Rivalta, E., Isken, M.P., Nikkhoo, M., Passarelli, L., Petersen, G.M., Cotton, F., Dahm, T., 2020. Drainage of a deep magma reservoir near Mayotte inferred from seismicity and deformation. *Nat. Geosci.* 13, 87–93. <https://doi.org/10.1038/s41561-019-0505-5>
- Charvis, P., Laesanpura, A., Chert, J., A., H., Lépine, J.-C., de Voogd, B., Minshull, T., Hello, Y., Pontolillo, P., 1999. Spatial distribution of hotspot material added to the lithosphere under La Reunion, from wide-angle seismic data. *J. Geophys. Res.* 104, 2875–2893. <https://doi.org/10.1029/98JB02841>
- Chevrel, M.O., Baratoux, D., Hess, K.-U., Dingwell, D.B., 2014. Viscous flow behavior of tholeiitic and alkaline Fe-rich martian basalts. *Geochim. Cosmochim. Acta* 124, 348–365. <https://doi.org/10.1016/j.gca.2013.08.026>
- Chorowicz, J., 2005. The east African rift system. *J. African Earth Sci.* 43, 379–410.
<https://doi.org/10.1016/j.jafrearsci.2005.07.019>
- Clague, D.A., Paduan, J.B., Caress, D.W., Moyer, C.L., Glazer, B.T., Yoerger, D.R., 2019. Structure of Lō ‘ihi Seamount, Hawai‘i and Lava Flow Morphology From High-Resolution Mapping. *Front. Earth Sci.* 7, 58. <https://doi.org/10.3389/feart.2019.00058>

- Clague, D.A., Dixon, J.E., 2000. Extrinsic controls on the evolution of Hawaiian ocean island volcanoes. *Geochemistry, Geophys. Geosystems* 1.
<https://doi.org/10.1029/1999GC000023>
- Class, C., Goldstein, S.L., Altherr, R., Bachèlery, P., 1998. The process of plume–lithosphere interactions in the ocean basins—the case of Grande Comore. *J. Petrol.* 39, 881–903.
<https://doi.org/doi.org/10.1093/petroj/39.5.881>
- Coffin, M.F., Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: evidence from the Davie fracture zone and western Somali basin. *J. Geophys. Res. Solid Earth* 92, 9385–9406. <https://doi.org/10.1029/JB092iB09p09385>
- Counts, J.W., Jorry, S.J., Leroux, E., Miramontes, E., Jouet, G., 2018. Sedimentation adjacent to atolls and volcano-cored carbonate platforms in the Mozambique Channel (SW Indian Ocean). *Mar. Geol.* 404, 41–59. <https://doi.org/10.1016/j.margeo.2018.07.003>
- Courgeon, S., 2017. Cenozoic evolution of isolated carbonate platforms from the Mozambique Channel (SW Indian Ocean): development and controls in active geodynamic settings. Aix-Marseille.
- Courgeon, S., Bachèlery, P., Jouet, G., Jorry, S.J., Bou, E., BouDagher-Fadel, M.K., Révillon, S., Camoin, G., Poli, E., 2018. The onshore east African rift system: new insights from the Sakalaves seamounts (Davie Ridge, SW Indian Ocean). *Terra Nov.* 30, 380–388.
<https://doi.org/10.1111/ter.12353>
- Courgeon, S., Jorry, S.J., Jouet, G., Camoin, G., BouDagher-Fadel, M.K., Bachèlery, P., Caline, B., Boichard, R., Révillon, S., Thomas, Y., 2017. Impact of tectonic and volcanism on the Neogene evolution of isolated carbonate platforms (SW Indian Ocean). *Sediment. Geol.* 355, 114–131. <https://doi.org/10.1016/j.sedgeo.2017.04.008>
- Courgeon, S., Jorry, S.J., Camoin, G.F., BouDagher-Fadel, M.K., Jouet, G., Révillon, S., Bachèlery, P., Pelleter, E., Borgomano, J., Poli, E., 2016. Growth and demise of Cenozoic isolated carbonate platforms: New insights from the Mozambique Channel seamounts (SW Indian Ocean). *Mar. Geol.* 380, 90–105.
<https://doi.org/10.1016/j.margeo.2016.07.006>
- Cox, K.G., 1992. Karoo igneous activity, and the early stages of the break-up of Gondwanaland. *Geol. Soc. London, Spec. Publ.* 68, 137–148.
<https://doi.org/10.1144/GSL.SP.1992.068.01.09>
- Crisp JA 1984 Rates of magma emplacement and volcanic output. *J Volcanol Geotherm Res* 20:177–211. [https://doi.org/10.1016/0377-0273\(84\)90039-8](https://doi.org/10.1016/0377-0273(84)90039-8)

- Davis, J.K., Lawver, L.A., Norton, I.O., Gahagan, L.M., 2016. New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean. *Gondwana Res.* 34, 16–28. <https://doi.org/10.1016/j.gr.2016.02.010>.
- Debeuf, D., 2009. Étude de l'évolution volcano-structurale et magmatique de Mayotte, Archipel des Comores, océan Indien: approches structurale, pétrographique, géochimique et géochronologique.
- Debeuf, D., Bachèlery, P., Sigmarsson, O., 2003. Two contemporaneous magma series on Mayotte Island, Comores Archipelago, Indian Ocean, in: EGS-AGU-EUG Joint Assembly, p. 9625.
- Déprez, A., Doubre, C., Masson, F., Ulrich, P., 2013. Seismic and aseismic deformation along the East African Rift System from a reanalysis of the GPS velocity field of Africa. *Geophys. J. Int.* 193, 1353–1369.
- Deville, E., Marsset, T., Courgeon, S., Jatiault, R., Poite, J.-P., Thereau, E., Jouet, G., Jorry, S.J., Droz, L., 2018. Active fault system across the oceanic lithosphere of the Mozambique Channel: Implications for the Nubia–Somalia southern plate boundary. *Earth Planet. Sci. Lett.* 502, 210–220. <https://doi.org/10.1093/gji/ggt085>
- Dieterich, J., 1988. Growth and Persistence of Hawaiian Volcanic Rift Zones. *J. Geophys. Res.* 93, 4258–4270. <https://doi.org/10.1029/JB093iB05p04258>
- Dorschel, B., Jensen, L., Arndt, J.E., Frummer, G., De Haas, H., Fielies, A., Franke, D., Jokat, W., Krocker, R., Krohn, D., 2018. The Southwest Indian Ocean Bathymetric Compilation (swIOBC). *Geochemistry, Geophys. Geosystems* 19, 968–976. <https://doi.org/10.1002/2017GC007274>
- Eagles, G., König, M., 2008. A model of plate kinematics in Gondwana breakup. *Geophys. J. Int.* 173, 703–717. <https://doi.org/10.1111/j.1365-246X.2008.03753.x>
- Ebinger, C., 2012. Evolution of the Cenozoic East African Rift System: cratons, plumes and continental breakup, in: *Regional Geology and Tectonics: Phanerozoic Rift Systems and Sedimentary Basins*. Elsevier Boston, pp. 132–162.
- Emerick, C.M., 1985. Geochronology and geochemistry of lavas from the Comores Islands and northern Madagascar [Ph. D. dissert.]. Oregon State Univ., Corvallis.
- Emerick, C.M., Duncan, R.A., 1982. Age progressive volcanism in the Comores Archipelago, western Indian Ocean and implications for Somali plate tectonics. *Earth Planet. Sci. Lett.* 60, 415–428. [https://doi.org/10.1016/0012-821X\(82\)90077-2](https://doi.org/10.1016/0012-821X(82)90077-2)
- Famin, V., Michon, L., Bourhane, A., 2020. The Comoros archipelago: a right-lateral

- transform boundary between the Somalia and Lwandle plates. *Tectonophysics* 789, 228539. <https://doi.org/10.1016/j.tecto.2020.228539>
- Feuillet, N., Jorry, S., Crawford, W.C. et al. 2021. Birth of a large volcanic edifice offshore Mayotte via lithosphere-scale dyke intrusion. *Nat. Geosci.* 14, 787–795. <https://doi.org/10.1038/s41561-021-00809-x>
- Fialko, Y.A., Rubin, A.M., 1999. What controls the along-strike slopes of volcanic rift zones? *J. Geophys. Res. Solid Earth* 104, 20007–20020. <https://doi.org/10.1029/1999JB900143>
- Fink, J.H., Griffiths, R.W., 1990. Radial spreading of viscous-gravity currents with solidifying crust. *J. Fluid Mech.* 221, 485–509.
- Fornari, D.J., Perfit, M.R., Allan, J.F., Batiza, R., Haymon, R., Parone, A., Ryan, W.B.F., Smith, T., Simkin, T., Luckman, M.A., 1988. Geochemical and structural studies of the Lamont seamounts: seamounts as indicators of mantle processes. *Earth Planet. Sci. Lett.* 89, 63–83. [https://doi.org/10.1016/0012-821X\(85\)90053-7](https://doi.org/10.1016/0012-821X(85)90053-7)
- Franke, D., Jokat, W., Ladage, S., Stollhofen, H., Klinker, J., Lutz, R., Mahanjane, E.S., Ehrhardt, A., Schreckenberger, B., 2015. The offshore East African Rift System: Structural framework at the toe of a juvenile rift. *Tectonics* 34, 2086–2104. <https://doi.org/10.1002/2015TC003921>
- Fullea, J., Camacho, A.G., Negredo, A.M., Fernández, J., 2015. The Canary Islands hot spot: New insights from 3D coupled geophysical–petrological modelling of the lithosphere and uppermost mantle. *Earth Planet. Sci. Lett.* 409, 71–88. <https://doi.org/10.1016/j.epsl.2014.10.038>
- Gee, M.J.R., Masson, D.G., Watts, A.B., Mitchell, N.C., 2001. Offshore continuation of volcanic rift zones: El Hierro, Canary Islands. *J. Volcanol. Geotherm. Res.* 105, 107–119. [https://doi.org/10.1016/S0377-0273\(00\)00241-9](https://doi.org/10.1016/S0377-0273(00)00241-9)
- Geist, D., Diefenbach, B.A., Fornari, D.J., Kurz, M.D., Harpp, K., Blusztajn, J., 2008. Construction of the Galápagos platform by large submarine volcanic terraces. *Geochemistry, Geophys. Geosystems* 9. <https://doi.org/10.1029/2007GC001795>
- Geist, D.J., Fornari, D.J., Kurz, M.D., Harpp, K.S., Adam Soule, S., Perfit, M.R., Koleszar, A.M., 2006. Submarine Fernandina: Magmatism at the leading edge of the Galápagos hot spot. *Geochemistry, Geophys. Geosystems* 7. <https://doi.org/10.1029/2006GC001290>
- Gregg, T.K.P., Fink, J.H., 2000. A laboratory investigation into the effects of slope on lava flow morphology. *J. Volcanol. Geotherm. Res.* 96, 145–159. [https://doi.org/10.1016/S0377-0273\(99\)00148-1](https://doi.org/10.1016/S0377-0273(99)00148-1)

- Grimison, N.L., Chen, W.P., 1988. Earthquakes in Davie Ridge–Madagascar region and the southern Nubian–Somalian plate boundary. *J. Geophys. Res.* 93, 10,439–10,450.
- Hansen, S.E., Nyblade, A.A., Benoit, M.H., 2012. Mantle structure beneath Africa and Arabia from adaptively parameterized P-wave tomography: Implications for the origin of Cenozoic Afro-Arabian tectonism. *Earth Planet. Sci. Lett.* 319, 23–34.
<https://doi.org/10.1016/j.epsl.2011.12.023>
- Harpp, K.S., Fornari, D.J., Geist, D.J., Kurz, M.D., 2003. Genovesa Submarine Ridge: A manifestation of plume-ridge interaction in the northern Galápagos Islands. *Geochemistry, Geophys. Geosystems* 4. <https://doi.org/10.1029/2003GC000531>
- Hartnady, C. J. H., 1985. Uplift, faulting, seismicity, thermal spring and possible incipient volcanic activity in the Lesotho-Natal Region, SE Africa: The Quathlamba Hotspot Hypothesis. *Tectonics*, 4(4), 371-377.
- Hartnady, C.J.H., 1990. Seismicity and plate boundary evolution in southeastern Africa. *South African J. Geol.* 93, 473–484.
- Hartnady, CJH, Ben-Avraham, Z., Rogers, J., 1992. Deep-ocean basins and submarine rises off the continental margin of south-eastern Africa: new geological research. *S. Afr. J. Sci.* 88 (11-12), 534–539.
- Heirtzler, J. R., & Burroughs, R. H., 1971. Madagascar's paleoposition: new data from the Mozambique Channel. *Science*, 174(4008), 488-490.
- Jokat, W., 2014. The expedition of the research vessel ‘Sonne’ to the Mozambique Basin in 2014 (SO-230). Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, 125. <http://epic.awi.de>.
- Jokat, W., 2009. The expedition of the research vessel Pelagia to the natal basin and the Mozambique ridge in 2009 (Project AISTEK III). Alfred-Wegener-Institut für Polar- und Meeresforschung, 67, <http://epic.awi.de>.
- Jokat, W, 2006. Southeastern Atlantic and southwestern Indian Ocean: reconstruction of the sedimentary and tectonic development since the Cretaceous AISTEK-II: Mozambique Ridge and Mozambique Basin. *Berichte zur Polarforsch.* 521.
- Jokat, W., Boebel, T., König, M., Meyer, U., 2003. Timing and geometry of early Gondwana breakup. *J. Geophys. Res. Solid Earth* 108. <https://doi.org/10.1029/2002JB001802>
- Jorry, S., 2014. PTOLEMEE cruise, RV L’Atalante.
- Jorry, S.J., Camoin, G.F., Jouet, G., Le Roy, P., Vella, C., Courgeon, S., Prat, S., Fontanier, C., Paumard, V., Boulle, J., 2016. Modern sediments and Pleistocene reefs from isolated

- carbonate platforms (Iles Eparses, SW Indian Ocean): a preliminary study. *Acta Oecologica* 72, 129–143. <https://doi.org/10.1016/j.actao.2015.10.014>
- Jouet, G., Deville, E., 2015. PAMELA-MOZ04 cruise. Pourquoi pas ? <https://doi.org/https://doi.org/10.17600/15000700>
- Klimke, J., Franke, D., Mahanjane, E.S. & Leitchenkov, G., 2018. Tie points for Gondwana reconstructions from a structural interpretation of the Mozambique Basin, East Africa and the Riiser-Larsen Sea, Antarctica, *Solid Earth*, 9, 25–37. <https://doi.org/10.5194/se-9-25-2018>
- Klimke, J., Franke, D., Gaedicke, C., Schreckenberger, B., Schnabel, M., Stollhofen, H., Rose, J., Chaheire, M., 2016. How to identify oceanic crust — Evidence for a complex break-up in the Mozambique Channel, off East Africa. *Tectonophysics*, 693, 436–452. <https://doi.org/10.1016/j.tecto.2015.10.012>
- König, M., Jokat, W., 2006. The mesozoic breakup of the weddell sea. *Journal of Geophysical Research: Solid Earth*, 111(B12). <https://doi.org/10.1029/2005JB004035>
- König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data. *Geophys. J. Int.* 180, 158–180. <https://doi.org/10.1111/j.1365-246X.2009.04433.x>
- Kusky, T.M., Toraman, E., Raharimahefa, T., Rasoazanamparany, C., 2010. Active tectonics of the Alaotra–Ankay Graben System, Madagascar: possible extension of Somalian–African diffusive plate boundary. *Gondwana Res* 18:274–294
- Leclaire, L., Bassias, Y., Clochiatti, M., Segoufin, J., 1989. La Ride de Davie dans le Canal de Mozambique: approche stratigraphique et géodynamique. *CR Acad. Sci.(Paris, série 2)* 308, 1077–1082.
- Leinweber, V.T., Jokat, W., 2012. The Jurassic history of the Africa–Antarctica corridor—new constraints from magnetic data on the conjugate continental margins. *Tectonophysics* 530, 87–101. <https://doi.org/10.1016/j.tecto.2011.11.008>
- Leinweber, V.T., Klingelhoefer, F., Neben, S., Reichert, C., Aslanian, D., Matias, L., Heyde, I., Schreckenberger, B., Jokat, W., 2013. The crustal structure of the Central Mozambique continental margin—Wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa. *Tectonophysics* 599, 170–196. <https://doi.org/10.1016/j.tecto.2013.04.015>
- Lemoine, A., Briole, P., Bertil, D., Roullé, A., Foumel, M., THINON, I., Raucoules, D., Michele, M. de, Valté, P., 2020. The 2018-2019 seismo-volcanic crisis east of Mayotte,

- Comoros islands: seismicity and ground deformation markers of an exceptional submarine eruption. <https://doi.org/10.31223/osf.io/d46xj>
- Leroux, E., Counts, J., Jorry, S., Jouet, G., Révillon, S., Boudagher-Fadel, M.K., Courgeon, S., Berthod, C., Ruffet, G., Bachèlery, P., 2020. Evolution of the glorieuses seamount in the sw indian ocean and surrounding deep somali basin since the cretaceous. *Mar. Geol.* <https://doi.org/10.1016/j.margeo.2020.106202>
- Levin, N., Beger, M., Maina, J., McClanahan, T., Kark, S., 2018. Evaluating the potential for transboundary management of marine biodiversity in the Western Indian Ocean. *Australas. J. Environ. Manag.* 25, 62–85. <https://doi.org/10.1080/14486563.2017.1417167>
- Liebske, C., Behrens, H., Holtz, F., Lange, R.A., 2003. The influence of pressure and composition on the viscosity of andesitic melts. *Geochim. Cosmochim. Acta* 67, 473–485. [https://doi.org/10.1016/S0016-7037\(02\)01139-7](https://doi.org/10.1016/S0016-7037(02)01139-7)
- Lipman, P.W., Calvert, A.T., 2011. Early growth of Kilauea volcano and formation of long Hawaiian rift zones. *Geology* 39, 659–662. <http://doi.org/10.1130/G31929.1>
- Llanes, P., Herrera, R., Gómez, M., Muñoz, A., Acosta, J., Uchupi, E., Smith, D., 2009. Geological evolution of the volcanic island of La Gomera, Canary Islands, from analysis of its geomorphology. *Mar. Geol.* 264, 123–139. <https://doi.org/10.1016/j.margeo.2009.05.001>
- Lonsdale, P., 1989. A geomorphological reconnaissance of the submarine part of the East Rift Zone of Kilauea Volcano, Hawaii. *Bull. Volcanol.* 51, 123–144. <https://doi.org/10.1007/BF01081981>
- MacDonald, G.A., 1972. *Volcanoes*, Prentice H. ed. New Jersey.
- Macgregor, D., 2015. History of the development of the East African Rift System: a series of interpreted maps through time. *J. African Earth Sci.* 101, 232–252. <https://doi.org/10.1016/j.jafrearsci.2014.09.016>
- Mahanjane, E. S., 2014. The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – A new insights for the hydrocarbon potential. *Marine and Petroleum Geology*, 57, 561–571. <https://doi.org/10.1016/j.marpetgeo.2014.06.015>
- Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High – A contribution for the understanding of its development. *Mar. Pet. Geol.* 36, 1–12. <https://doi.org/10.1016/j.marpetgeo.2012.05.007>
- Mark, R.K., Moore, J.G., 1987. Slopes of the Hawaiian ridge. *US Geol. Surv. Prof. Pap* 1350,

101–107.

- Martin, A.K., Hartnady, C.J.H., 1986. Plate tectonic development of the South West Indian Ocean: a revised reconstruction of East Antarctica and Africa. *J. Geophys. Res.* 91, 4767–4786. <https://doi.org/10.1029/JB091iB05p04767>.
- McClanahan, T.R., Friedlander, A.M., Graham, N.A.J., Chabanet, P., Bruggemann, J.H., 2021. Variability in coral reef fish baseline and benchmark biomass in the central and western Indian Ocean provinces. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 31, 28–42. <https://doi.org/10.1002/aqc.3448>
- Merz, D.K., Caplan-Auerbach, J., Thurber, C.H., 2019. Seismicity and Velocity Structure of Lōʻihi Submarine Volcano and Southeastern Hawaiʻi. *J. Geophys. Res. Solid Earth* 124, 11380–11393. <https://doi.org/10.1029/2019JB018168>
- Mesko, G.T., Class, C., Maqway, M.D., Boniface, N., Munye, S., Hemming, S.R., 2014. The timing of early magmatism and extension in the Southern East African rift: tracking geochemical source variability with $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology at the Rungwe Volcanic Province, SW Tanzania, in: AGU Fall Meeting Abstracts. pp. V51A-4730.
- Michon, L., 2016. The volcanism of the Comoros archipelago integrated at a regional scale, in: *Active Volcanoes of the Southwest Indian Ocean*. Springer, pp. 333–344. https://doi.org/10.1007/978-3-642-21395-0_21
- Michon, L., Saint-Ange, F., Bachelery, F., Villeneuve, N., Staudacher, T., 2007. Role of the structural inheritance of the oceanic lithosphere in the magmato-tectonic evolution of Piton de la Fournaise volcano (La Réunion Island). *J. Geophys. Res. Solid Earth* 112, 1–21. <https://doi.org/10.1029/2006JB004598>
- Miramontes, E., Penvier, P., Hierens, R., Droz, L., Toucanne, S., Jorry, S.J., Jouet, G., Pastor, L., Jacinto, R.S., Gaillet, A., 2019. The influence of bottom currents on the Zambezi Valley morphology (Mozambique Channel, SW Indian Ocean): In situ current observations and hydrodynamic modelling. *Mar. Geol.* 410, 42–55. <https://doi.org/10.1016/j.margeo.2019.01.002>
- Mitchell, N.C., Masson, D.G., Watts, A.B., Gee, M.J.R., Urgeles, R., 2002. The morphology of the submarine flanks of volcanic ocean islands: a comparative study of the Canary and Hawaiian hotspot islands. *J. Volcanol. Geotherm. Res.* 115, 83–107. [https://doi.org/10.1016/S0377-0273\(01\)00310-9](https://doi.org/10.1016/S0377-0273(01)00310-9)
- Mitchell, N.C., Stretch, R., Oppenheimer, C., Kay, D., Beier, C., 2012. Cone morphologies associated with shallow marine eruptions: east Pico Island, Azores. *Bull. Volcanol.* 74,

- 2289–2301. <https://doi.org/10.1007/s00445-012-0662-5>
- Mougenot, D., Recq, M., Virlogeux, P., Lepvrier, C., 1986. Seaward extension of the East African rift. *Nature* 321, 599. <https://doi.org/10.1038/321599a0>
- Mueller, C.O., Jokat, W., 2019. The initial Gondwana break-up: a synthesis based on new potential field data of the Africa-Antarctica Corridor. *Tectonophysics* 750, 301–328. <https://doi.org/10.1016/j.tecto.2018.11.008>
- Mueller, C.O., Jokat, W., 2017. Geophysical evidence for the crustal variation and distribution of magmatism along the central coast of Mozambique. *Tectonophysics* 712, 684–703. <https://doi.org/10.1016/j.tecto.2017.06.007>
- Mueller, C.O., Jokat, W., Schreckenberger, B., 2016. The crustal structure of Beira High, central Mozambique—combined investigation of wide-angle seismic and potential field data. *Tectonophysics* 683, 233–254. <https://doi.org/10.1016/j.tecto.2016.06.028>
- Mukhopadhyay, R., Batiza, R., 1994. Basinal seamounts and seamount chains of the central Indian Ocean: Probable near-axis origin from a fast-spreading ridge. *Mar. Geophys. Res.* 16, 303–314. <https://doi.org/10.1007/BF01247477>
- Mukhopadhyay, R., Khadge, N.H., 1990. Seamounts in the Central Indian Ocean Basin: indicators of the Indian plate movement. *Proc. Indian Acad. Sci. Planet. Sci.* 99, 357–365.
- Mullins HT and Hine AC (1989) Scallop bank margins: Beginning of the end for carbonate platforms? *Geology* 17 (1) 30-33
- Navarro, a., Lourenço, N., Chrońiewicz, J., Miranda, J.M., Catalão, J., 2009. Analysis of geometry of volcanoes and faults in Terceira Island (Azores): Evidence for reactivation tectonics at the EUR/AFR plate boundary in the Azores triple junction. *Tectonophysics* 465, 98–113. <https://doi.org/10.1016/j.tecto.2008.10.020>
- Nguyen, L.C., Hall, S.A., Bird, D.E., Ball, P.J., 2016. Reconstruction of the East Africa and Antarctica continental margins. *J. Geophys. Res. Solid Earth* 121, 4156–4179. <https://doi.org/10.1002/2015JB012776>
- Norton, I.O., Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. *J. Geophys. Res.* 84, 6803–6830. <https://doi.org/10.1029/JB084iB12p06803>
- Nougier, J., Cantagrel, J.M., Karche, J.P., 1986. The Comores archipelago in the western Indian Ocean: volcanology, geochronology and geodynamic setting. *J. African Earth Sci.* 5, 135–144. [https://doi.org/10.1016/0899-5362\(86\)90003-5](https://doi.org/10.1016/0899-5362(86)90003-5)

- O'Connor, J.M., Jokat, W., Regelous, M., Kuiper, K.F., Miggins, D.P., Koppers, A.A.P., 2019. Superplume mantle tracked isotopically the length of Africa from the Indian Ocean to the Red Sea. *Nat. Commun.* 10, 1–13. <https://doi.org/10.1038/s41467-019-13181-7>
- Olu, K., 2014. PAMELA-MOZ01 cruise, RV L'Atalante. <https://doi.org/10.17600/14001000>
- Pelleter, A.-A., Caroff, M., Cordier, C., Bachèlery, P., Nehlig, P., Debeuf, D., Arnaud, N., 2014. Melilite-bearing lavas in Mayotte (France): An insight into the mantle source below the Comores. *Lithos* 208, 281–297. <https://doi.org/10.1016/j.lithos.2014.09.012>
- Phethean, J.J.J., Kalnins, L.M., van Hunen, J., Biffi, P.G., Davies, R.J., McCaffrey, K.J.W., 2016. Madagascar's escape from Africa: a high-resolution plate reconstruction for the Western Somali Basin and implications for supercontinent dispersal. *Geochem. Geophys. Geosyst.* 17, 2825–2834. <https://doi.org/10.1002/2016GC006624>
- Ponte, J. P., Robin, C., Guillocheau, F., Popescu, S., Suc, J. P., Dall'Asta, M., Melinte-Dobrinescu, M.C., Bubik, M., Dupont, G., Gaillois, J., 2019. The Zambezi delta (Mozambique Channel, East Africa): High resolution dating combining bio-orbital and seismic stratigraphies to determine climate (paleoprecipitation) and tectonic controls on a passive margin. *Marine and Petroleum Geology*, 105, 293-312. <https://doi.org/10.1016/j.marpetgeo.2018.07.017>
- Quidelleur, X., Michon, L., Famin, V., Ceffray, M. C., Danišík, M., Gardiner, N., Rusquet, A., Zakaria, M. G., 2022. Holocene volcanic activity in Anjouan Island (Comoros archipelago) revealed by new Cassinot-Gillot groundmass K–Ar and ¹⁴C ages. *Quaternary Geochronology*, 57, 101236. <https://doi.org/10.1016/j.quageo.2021.101236>
- Rabinowitz, P.D., Coffin, M.F., Falvey, D., 1983. The separation of Madagascar and Africa. *Science (80-.)*. 220, 57–69.
- Raillard, S., 1990. Les Marges de l'Afrique de l'Est et les Zones de Fracture Associées: Chaîne Davie et Ride du Mozambique (PhD Thesis). Université Pierre et Marie Curie Paris VI.
- Rappaport, Y., Naar, D.F., Barton, C.C., Liu, Z.J., Hey, R.N., 1997. Morphology and distribution of seamounts surrounding Easter Island. *J. Geophys. Res. Solid Earth* 102, 24713–24728. <https://doi.org/10.1029/97JB01634>
- Reeves, C.V., 2018. The development of the East African margin during Jurassic and Lower Cretaceous times: a perspective from global tectonics. *Pet. Geosci.* 24, 41–56. <https://doi.org/10.1144/petgeo2017-021>
- Reeves, C.V., Teasdale, J.P., Mahanjane, E.S., 2016. Insight into the Eastern Margin of Africa

- from a new tectonic model of the Indian Ocean. *Geol. Soc. Lond. Spec. Publ.* 431, 1–24. <https://doi.org/10.1144/SP431.12>.
- Reeves, C., 2014. The position of Madagascar within Gondwana and its movements during Gondwana dispersal. *J. African Earth Sci.* 94, 45–57. <https://doi.org/10.1016/j.jafrearsci.2013.07.011>
- Reeves, C., De Wit, M., 2000. Making ends meet in Gondwana: retracing the transforms of the Indian Ocean and reconnecting continental shear zones. *Terra Nov.* 12, 272–280. <https://doi.org/10.1046/j.1365-3121.2000.00309.x>
- Renne, P.R., Balco, G., Ludwig, K.R., Mundil, R., Min, K., 2011. Response to the comment by WH Schwarz et al. on “Joint determination of 40K decay constants and 40Ar*/40K for the Fish Canyon sanidine standard, and improved accuracy for 40Ar/39Ar geochronology” by PR Renne et al.(2010). *Geochim. Cosmochim. Acta* 75, 5097–5100.
- Renne, P.R., Mundil, R., Balco, G., Min, K., Ludwig, K.R., 2010. Joint determination of 40K decay constants and 40Ar*/40K for the Fish Canyon sanidine standard, and improved accuracy for 40Ar/39Ar geochronology. *Geochim. Cosmochim. Acta* 74, 5349–5367. <https://doi.org/10.1016/j.gca.2010.06.017>
- Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., DePaolo, D.J., 1998. Intercalibration of standards, absolute ages and uncertainties in 40Ar/39Ar dating. *Chem. Geol.* 145, 117–152. [https://doi.org/10.1016/S0009-2541\(97\)00159-9](https://doi.org/10.1016/S0009-2541(97)00159-9)
- Romagnoli, C., Belvisi, V., Innangi, S., Di Martino, G., Tonielli, R. 2020. New insights on the evolution of the Linosa volcano (Sicily Channel) from the study of its submarine portions, *Marine Geology*, 2020, 419, pp. 1 – 12. [10.1016/j.margeo.2019.106060](https://doi.org/10.1016/j.margeo.2019.106060)
- Romer, R.H.W., Beier, C., Paase, K.M., Hübscher, C., 2018. Correlated changes between volcanic structures and magma composition in the Faial volcanic system, Azores. *Front. Earth Sci.* 6, 78. <https://doi.org/10.3389/feart.2018.00078>
- Rowden, A.A., Clark, M.R., Wright, I.C., 2005. Physical characterisation and a biologically focused classification of “seamounts” in the New Zealand region. *New Zeal. J. Mar. Freshw. Res.* 39, 1039–1059. <https://doi.org/10.1080/00288330.2005.9517374>
- Rubin, K.H., Soule, S.A., Chadwick, W.W., Fornari, D.J., Clague, D.A., Embley, R.W., Baker, E.T., Perfit, M.R., Caress, D.W., Dziak, R.P., 2012. Volcanic eruptions in the deep sea. *Oceanography* 25, 142–157.
- Ruffet, G., Gruau, G., Ballèvre, M., Féraud, G., Philippot, P., 1997. Rb/Sr and 40Ar/39Ar laser probe dating of high-pressure phengites from the Sesia zone (Western Alps):

- underscoring of excess argon and new age constraints on the high-pressure metamorphism. *Chem. Geol.* 141, 1–18. [https://doi.org/10.1016/S0009-2541\(97\)00052-1](https://doi.org/10.1016/S0009-2541(97)00052-1)
- Ruffet, G., Féraud, G., Balèvre, M., Kiénast, J.-R., 1995. Plateau ages and excess argon in phengites: an $^{40}\text{Ar}/^{39}\text{Ar}$ laser probe study of Alpine micas (Sesia Zone, Western Alps, northern Italy). *Chem. Geol.* 121, 327–343. [https://doi.org/10.1016/0009-2541\(94\)00132-R](https://doi.org/10.1016/0009-2541(94)00132-R)
- Ruffet, G., Féraud, G., Amouric, M., 1991. Comparison of $^{40}\text{Ar}/^{39}\text{Ar}$ conventional and laser dating of biotites from the North Trégor Batholith. *Geochim. Cosmochim. Acta* 55, 1675–1688. [https://doi.org/10.1016/0016-7037\(91\)90138-U](https://doi.org/10.1016/0016-7037(91)90138-U)
- Saria, E., Calais, E., Stamps, D.S., Delvaux, D., Hartnady, C.J.H., 2014. Present-day kinematics of the East African Rift. *J. Geophys. Res. Solid Earth* 119, 3584–3600. <https://doi.org/10.1002/2013JB010901>
- Scrutton, R.a., 1978. Davie fracture zone and the movement of Madagascar, *Earth planet. Sci. Lett.*, 39, 84–88.
- Segoufin, J., Patriat, P., 1980. Existences d'anoréites mésozoïques dans le bassin de Somalie: implications pour les relations Afrique-Antarctique-Madagascar. *C.R. Acad. Sci.* 291 (1980), 85–88.
- Sinha, S.T., Saha, S., Longacre, M., Basu, S., Jha, R. & Mondal, T., 2019. Crustal Architecture and nature of continental breakup along a transform margin: new insights from Tanzania–Mozambique Margin, *Tectonics*, 2018TC005221. <https://doi.org/10.1029/2018TC005221>
- Smith, D.K., Kong, L.S.L., Johnson, K.T.M., Reynolds, J.R., 2002. Volcanic morphology of the submarine Puu Ridge, Kilauea volcano. *Geophys. Monogr. Geophys. UNION* 128, 125–142.
- Späth, A., Roex, A.P. Le, Duncan, R.A., 1996. The geochemistry of lavas from the Comores Archipelago, Western Indian Ocean: petrogenesis and mantle source region characteristics. *J. Petrol.* 37, 961–991. <https://doi.org/10.1093/petrology/37.4.961>
- Stabile, P., Webb, S., Knipping, J.L., Behrens, H., Paris, E., Giuli, G., 2016. Viscosity of pantelleritic and alkali-silicate melts: Effect of Fe redox state and $\text{Na}/(\text{Na} + \text{K})$ ratio. *Chem. Geol.* 442, 73–82. <https://doi.org/10.1016/j.chemgeo.2016.09.003>
- Stamps, D.S., Calais, E., Saria, E., Hartnady, C., Nocquet, J., Ebinger, C.J., Fernandes, R.M., 2008. A kinematic model for the East African Rift. *Geophys. Res. Lett.* 35. <https://doi.org/10.1029/2007GL032781>

- Stamps, D.S., Saria, E., Kreemer, C., 2018. A Geodetic Strain Rate Model for the East African Rift System. *Sci. Rep.* 8, 732. <https://doi.org/10.1038/s41598-017-19097-w>
- Stamps, D.S., Kreemer, C., Fernandes, R., Rajaonarison, T.A., Rambolamanana, G., 2021. Redefining East African Rift System kinematics. *Geology*. <https://doi.org/10.1130/G47985.1>
- Stretch, R.C., Mitchell, N.C., Portaro, R.A., 2006. A morphometric analysis of the submarine volcanic ridge south-east of Pico Island, Azores. *J. Volcanol. Geotherm. Res.* 156, 35–54. <https://doi.org/10.1016/j.jvolgeores.2006.03.009>
- Thompson, G., Bryan, W. B., Frey, F. A., Dickey, J. S., & Davies, H., 1982. Petrology, geochemistry and original tectonic setting of basalts from the Mozambique Basin and Ridge (DSDP sites 248, 249 and 250), and from the Southwest Indian Ridge (DSDP site 251). *Marine Geology*, 48(3-4), 175-195.
- Thompson, J.O., Moulin, M., Aslanian, D., De Clarers, F., Guillocheau, F., 2019. New starting point for the Indian Ocean: Second phase of breakup for Gondwana. *Earth-Science Rev.* 191, 26–56. <https://doi.org/10.1016/j.earscirev.2019.01.018>
- Tibaldi, A., 1995. Morphology of pyroclastic cones and tectonics. *J. Geophys. Res.* 100, 24,521-24,535. <https://doi.org/10.1029/95JB02250>
- Tuck-Martin, A., Adam, J. & Eagles, G., 2018. New plate kinematic model and tectono-stratigraphic history of the East African and West Madagascar Margins, *Basin Res.*, 30, 1118–1140.
- Tibaldi, A., 2015. Structure of volcano plumbing systems : A review of multi-parametric effects. *J. Volcanol. Geotherm. Res.* 298, 85–135. <https://doi.org/10.1016/j.jvolgeores.2015.03.023>
- Tzevahirtzian, A., Zaragosi, S., Bachèlery, P., Biscara, L., Marchès, E., 2021. Submarine morphology of the Comoros volcanic archipelago. *Mar. Geol.* 432. <https://doi.org/10.1016/j.margeo.2020.106383>
- Upton, B.G.J., 1982. Oceanic Islands. In: Nairn, P., Stehli, F. (Eds.), *Ocean Basins and their Margins, Indian Ocean*, 6(13). Plenum Press, New York, pp. 585–648.
- Vormann, M., Franke, D. & Jokat, W., 2020. The crustal structure of the southern Davie Ridge offshore northern Mozambique—a wide- angle seismic and potential field study, *Tectonophysics*, 778, 228370. <https://doi.org/10.1016/j.tecto.2020.228370>.
- Vormann, M., Jokat, W., 2021a. Crustal variability along the rifted/sheared East African margin: a review. *Geo-Marine Letters*, 41(2), 1-9. <https://doi.org/10.1007/s00367-021->

00690-y

- Vormann, M., Jokat, W., 2021b. The crustal structure of the Kerimbass Basin across the offshore branch of the East African Rift System. *Geophys. J. Int.* 226, 2073–2102. <https://doi.org/10.1093/gji/ggab194>
- Weiß, B.J., Hübscher, C., Lüdmann, T., 2015. The tectonic evolution of the southeastern Terceira Rift/São Miguel region (Azores). *Tectonophysics* 654, 75–95. <https://doi.org/10.1016/j.tecto.2015.04.018>
- Wessel P (2007) Seamount characteristics. *Seamounts Ecol Fish Conserv* 3–25
- Wessel P, Sandwell DT, Kim S-S (2010) The global seamount census. *Oceanography* 23:24–33
- Wiles, E., Green, A., Watkeys, M., Jokat, W., & Krocker, P., 2014. Anomalous seafloor mounds in the northern Natal Valley, southwest Indian Ocean: implications for the East African Rift System. *Tectonophysics*, 630, 300–312. <https://doi.org/10.1016/j.tecto.2014.05.030>
- Wiles, E., Watkeys, M., Jokat, W., 2020. Surface expression of microplate boundary kinematics: An isolated abyssal hill in the Mozambique Channel. *J. African Earth Sci.* 168, 103830. <https://doi.org/10.1016/j.jafrearsci.2020.103830>
- Yang, Z., Chen, W.-P., 2010. Earthquakes along the East African Rift System: a multi-scale, system-wide perspective. *J. Geophys. Res.* 115, B12309. <https://doi.org/10.1029/2009JB006779>.
- Yesson C, Clark MR, Taylor ML, Rogers AD (2011) The global distribution of seamounts based on 30 arc seconds bathymetry data. *Deep Sea Res Part I Oceanogr Res Pap* 58:442–453
- York, D., 1968. Least squares fitting of a straight line with correlated errors. *Earth Planet. Sci. Lett.* 5, 320–324.
- York, D., Evensen, N.M., Martinez, M.L., De Basabe Delgado, J., 2004. Unified equations for the slope, intercept, and standard errors of the best straight line. *Am. J. Phys.* 72, 367–375. <https://doi.org/10.1119/1.1632486>
- Zinke, J., Reijmer, J.J.G., Thomassin, B.A., Dullo, W.-C., Grootes, P.M., Erlenkeuser, H., 2003. Postglacial flooding history of Mayotte lagoon (Comoro archipelago, southwest Indian Ocean). *Mar. Geol.* 194, 181–196. [https://doi.org/10.1016/S0025-3227\(02\)00705-3](https://doi.org/10.1016/S0025-3227(02)00705-3)

Figure captions

Figure 1: a) Geological context showing the study area (red box) located on the Quathlamba seismic axis (after Courgeon, 2017 and Deville et al., 2018), GEBCO 30 arc-second global grid of elevation 2014, about 930 m-resolution. White hatched lines : proposed plate boundaries, b) Bathymetric map of the seamounts located in the southern part of the Mozambique Channel, c) Morphological map of the region showing profiles across edifice summit (A-B) and volcanic ridge (X-Y), and dredge locations (in red) for samples used in $^{40}\text{Ar}/^{39}\text{Ar}$ dating. G : Glorieuses, ABFZ : Andrew Bain Fracture Zone, EPFZ : Prince Edward Fracture Zone, ESFZ : Eric Simpson Fracture Zone, MOZ: Mozambique Ridge

Figure 2: Interpretative map of the Bassas da India/Europa complex showing main geomorphologic features. Boxes indicate areas shown in more detail in Figures 5 and 8.

Figure 3: Bathymetric elevation of a) major volcanic edifices in the southern part of the Mozambique channel and b) identified volcanic ridges. All sections are marked on Fig. 1c.

Figure 4: Submarine pictures from the Hall Bank to the volcanic ridge located in the southwest part of Bassas da India. a) Volcanic rocks on carbonate substrate on the top of Hall Bank. b) Breccia in a faulted zone on the top of Hall Bank. c) Lava outcrops on a drowned terrace on the southern edge of Bassas da India. d) Recent fracture affecting sediments and volcanic rocks in the southeast of Bassas da India. Picture locations are marked on Fig. 2.

Figure 5: Details of delineated geomorphologic features interpreted from multibeam backscatter and bathymetry. a-b) Hall Bank and the west part of Jaguar Bank and c-d) Jaguar Bank. Dark shades indicate regions of greater acoustic backscatter and are interpreted as volcanic or carbonated units not covered by significant marine sedimentation. Volcanic features located on the carbonate platform have been identified by Courgeon et al., 2016.

Figure 6: $^{39}\text{Ar}/^{40}\text{Ar}$ age spectra and $^{37}\text{ArCa}/^{39}\text{ArK}$ spectra of samples MOZ01-DW05-01 and MOZ01-DW05-13 samples collected on Hall Bank, and samples MOZ01-DR19-04 and MOZ04-DR08-01 collected near Jaguar Bank and Bassas da India, respectively. Apparent age error bars are at the 2σ level; errors in the J-parameter are not included. Plateau age is given

with 2σ uncertainties including errors in the J-parameter. Inverse isochron (correlation) diagram with $^{36}\text{Ar}/^{40}\text{Ar}$ vs. $^{39}\text{Ar}/^{40}\text{Ar}$. White ellipses are excluded from isochron regression (York, 1968; York et al., 2004), MSWD stands for Mean Squares of Weighted Deviates. Dredge locations are marked on Fig. 1c.

Figure 7: 3D images, with x5 vertical exaggeration, showing the main structures recognized in the Bassas da India-Europa complex. a) General view of the three seamounts discovered between Bassas da India and Europa. b) Volcanic ridges between Jaguar Bank and Bassas da India. c) Northeast side of Pamela Seamount 1 (PS1) seamount and Bassas da India atoll. d) View of PS1, Pamela Seamount 2 (PS2) and Ptolemee north of Europa.

Figure 8: Details of delineated geomorphologic features deduced from multibeam backscatter and bathymetry. a-b) PS1 located on the south flank of Bassas da India, c-d) Ptolemee seamount, and e-f) Northern flank of Europa. Dark shades indicate regions of greater acoustic backscatter.

Figure 9: Morphological characteristics of volcanic cones identified. a) Basal area of volcanic cones versus height, b) Frequency of volcanic cones height, c) Average base length versus height of volcanic cones, dashed lines indicate values of aspect ratio (height/average base length). Linoas, Hawaii, Canary, Azores and Comoros data are from Romagnoli et al. 2021; Clague et al. 2000, Mitchell et al., 2002; Stretch et al., 2006; Mitchell et al., 2012; Casalbore et al., 2015; Weiß et al. 2015 and Tzevahirtzian et al., 2021, respectively, d) Mean slope versus basal area of volcanic cones, e) Frequency of mean slope of volcanic cones, f) Frequency of maximum slope of volcanic cones, g) Maximum slope versus height of volcanic cones, h) Frequency of direction of elongation of volcanic cones.

Figure 10: 3D diagram illustrating the magma emplacement in Bassas da India/Europa complex. The eruptions of the proximal section of the rift zones are fed by lateral injections of magma from a shallow magma chamber located under the main volcanic center, whereas direct magma injections from a deeper storage zone feed the large volcanic cones in the distal section of the rift zones, or, occasionally, at higher altitude. Large edifices are supplied by deep and shallow depth magma chambers. The lithosphere structuration has been inferred by Mueller and Jokat (2017) from synthetic amplitude modelling along the two seismic

refraction profiles (including the 20140010 seismic profile which is located to the north-west of the Bassas da India/Europa complex) coupled with two magnetic models.

Figure 11: Map of seamounts' basal area (a) and height (b). Statistical analysis of seamounts' basal area (c) and height (d) for NE-SW and SE-NW trends, in pink and in green, respectively. e) stereographic projections of fault strikes (Deville et al., 2018) and elongated seamount orientations.

Table captions

Table 1: Location of dredges performed during PAMELA-MOZ01 (DW5 and DR19) and PAMELA-MOZ04 (DR08) oceanographic cruises.

Dredge	Oceanographic campaign	Location	DOI	Latitude	Longitude	Depth	Latitude	Longitude	Depth
MOZ01-DW05	PAMELA-MOZ01	Hall Bank	<u>10.17600/14001000</u>	S 21° 51,340 9'	E 39° 6,1521 7'	51 2	S 21° 51,8027 4'	E 39° 6,3816 8'	50 7
MOZ01-DR19	PAMELA-MOZ01	Jaguar Bank	<u>10.17600/14001000</u>	S 21°44, 190'	E 39°32, 295'	94 1	S 21°44,1 01'	E 39°32,3 02'	99 1
MOZ04-DR08	PAMELA-MOZ04	Bassas da India	<u>10.17600/15000700</u>	21°34' 14.9" S	39°40' 34.7" E	52 1	21°34' 4.4" S	39°40' 35.3" E	51 0

Table 2: Physical variables of all identified volcanic structures that form the Bassas da India/Europa complex.

Site	Name	Latitude (DD)	Longitude (DD)	Diameter (m)	Area (Km ²)	Elevation (m)	Profile MEAN (m)	Pentagon MEAN (°)	Pentagon MAX (°)	Pentagon MEAN (°)	ORIENTATION	Aspect ratio
Hall Bank	S 1	39.0446	-21.8019	241	0.04	47	-1718	15.00	24.07	20.30	162	0.20
Hall Bank	S 2	39.0457	-21.7931	1456	0.9180	353	-1715	4.78	32.05	21.15	123	0.24
Hall Bank	S 3	39.0515	-21.8028	335	0.91	63	-1629	2.55	20.65	11.95	172	0.19
Hall	S	39.0519	-21.8028	519	0.91	140	-1629	2.18	29.7	20.14	167	0.19

Bank	M-	108	21.9		19		1374		3			27
	4	3	190		07							
	S	39.	-		0.							
Hall	M-	121	21.9		17		-	15.4	32.1			0.
Bank	5	0	222	524	91	243	1565	8	2	25.09	117	46
	S	39.	-		0.							
Hall	M-	133	21.8		04		-	20.2	29.0			0.
Bank	6	9	542	253	56	54	1009	2	6	24.99	90	21
	S	39.	-		0.							
Hall	M-	135	21.9		22		-		33.3			0.
Bank	7	2	265	553	69	179	1851	6.88	5	23.06	135	32
	S	39.	-		0.							
Hall	M-	150	21.8		14		-	10.2	31.0			0.
Bank	8	1	496	477	71	151	1378	8	1	21.97	97	32
	S	39.	-		0.							
Hall	M-	150	21.8		24		-		31.1			0.
Bank	9	9	318	605	82	183	1819	1.61	6	23.43	124	30
	S	39.	-		0.							
Hall	M-	151	21.8		06		-	14.0	25.6			0.
Bank	10	6	727	289	12	63	1404	8	1	19.33	90	22
	S	39.	-		0.							
Hall	M-	155	21.8		22		-		24.5			0.
Bank	11	7	825	654	87	126	1648	4.33	5	15.42	99	19
	S	39.	-		0.							
Hall	M-	156	21.8		31		-		34.3			0.
Bank	12	9	709	660	15	217	1499	5.25	2	21.85	144	33
	S	39.	-		0.							
Hall	M-	158	21.9		33		-		32.1			0.
Bank	13	6	191	711	43	157	2130	1.14	6	19.71	139	22
	S	39.	-		0.							
Hall	M-	163	21.8		29		-		32.7			0.
Bank	14	0	761	703	90	233	1682	8.98	3	23.58	172	33
	S	39.	-		0.							
Hall	M-	172	21.8		36		-		28.2			0.
Bank	15	4	915	745	76	193	2117	3.05	1	16.63	163	26
	S	39.	-		0.							
Hall	M-	204	21.8		13		-		26.7			0.
Bank	16	0	451	428	14	104	2228	7.74	3	18.71	45	24
	S	39.	-		0.							
Jaguar	M-	230	21.8	111	78		-		34.6			0.
Bank	17	9	888	6	06	237	2347	9.36	2	22.03	10	21
	S	39.	-		0.							
Jaguar	M-	232	21.7		20		-		23.6			0.
Bank	18	8	858	536	99	104	2638	1.78	0	12.96	0	19
	S	39.	-		0.							
Jaguar	M-	251	21.8	103	47		-		31.6			0.
Bank	19	1	648	2	85	202	2217	5.64	9	20.18	15	20
	S	39.	-		0.							
Jaguar	M-	254	21.8		56		-	10.3	28.2			0.
Bank	20	0	262	932	09	273	2269	1	0	20.81	21	29

	S	39.	-		0.							
Jaguar	M-	258	21.9		30		-		29.8			0.
Bank	21	8	034	777	61	171	2224	5.39	3	19.82	169	22
	S	39.	-		0.							
Jaguar	M-	262	21.9		10		-		18.3			0.
Bank	22	5	080	409	29	65	2259	1.38	0	11.65	31	16
	S	39.	-		0.							
Jaguar	M-	263	21.8		71		-		32.6			0.
Bank	23	6	611	985	09	309	2083	4.22	3	26.10	172	31
	S	39.	-		0.							
Jaguar	M-	270	21.8		39		-		31.3			0.
Bank	24	3	402	737	42	195	2027	7.74	0	19.41	131	26
	S	39.	-		0.							
Jaguar	M-	279	21.7		32		-		28.0			0.
Bank	25	2	861	683	35	234	1660	3.78	6	20.59	177	34
	S	39.	-		0.							
Jaguar	M-	285	21.7		14		-		27.8			0.
Bank	26	8	800	482	14	136	1483	8.07	6	19.92	25	28
	S	39.	-		0.							
Jaguar	M-	291	21.7		30		-		29.0			0.
Bank	27	9	385	637	73	139	1932	5.65	7	17.99	33	22
	S	39.	-		0.							
Jaguar	M-	296	21.7		10		-		25.8			0.
Bank	28	6	665	417	54	5	1452	6.08	1	16.72	15	12
	S	39.	-		0.							
Jaguar	M-	296	21.8		34		-		34.4			0.
Bank	29	8	663	728	22	250	1638	4.77	2	25.02	168	34
	S	39.	-		0.							
Jaguar	M-	297	21.7		10		-		25.9			0.
Bank	30	5	955	396	48	128	-970	6.76	8	18.85	0	32
	S	39.	-		0.							
Jaguar	M-	298	21.7		07		-	14.9	30.0			0.
Bank	31	6	909	332	95	123	1022	5	8	24.81	20	37
	S	39.	-		0.							
Jaguar	M-	299	21.7		09		-		30.7			0.
Bank	32	0	825	359	41	125	1220	1.39	7	23.34	0	35
	S	39.	-		0.							
Jaguar	M-	299	21.9		25		-		29.6			0.
Bank	33	3	145	684	65	173	1871	3.68	9	22.52	157	25
	S	39.	-		0.							
Jaguar	M-	302	21.7		63		-		32.9			0.
Bank	34	7	559	969	39	332	1813	5.26	6	23.03	136	34
	S	39.	-		0.							
Jaguar	M-	303	21.7		08		-	12.3	19.5			0.
Bank	35	9	649	372	39	96	1491	3	9	15.45	130	26
	S	39.	-		0.							
Jaguar	M-	305	21.7		07		-		22.7			0.
Bank	36	1	909	314	28	89	-884	6.55	8	17.72	160	28
Jaguar	S	39.	-		0.		-		27.9			0.
Bank	M-	305	21.7	779	44	240	1296	4.33	2	20.02	174	31

	37	8	746		42							
	S	39.	-		1.							
Jaguar	M-	307	21.9	179	70		-		35.5			0.
Bank	38	4	244	7	00	390	1837	4.17	5	20.85	21	22
	S	39.	-		0.							
Jaguar	M-	308	21.7		13		-		26.7			0.
Bank	39	1	700	517	62	74	1339	4.31	7	14.06	141	14
	S	39.	-		0.							
Jaguar	M-	312	21.7		01		-	13.1	13.2			0.
Bank	40	5	753	153	58	28	1294	8	1	13.19	90	19
	S	39.	-		0.							
Jaguar	M-	316	21.7		05		-	19.8	28.1			0.
Bank	41	7	809	276	49	77	1115	0	0	24.47	135	28
	S	39.	-		0.							
Jaguar	M-	317	21.7		01		-	19.7	20.1			0.
Bank	42	8	771	164	80	43	1274	8	0	19.69	0	26
	S	39.	-		1.							
Jaguar	M-	319	21.7	177	56		-		34.1			0.
Bank	43	0	562	5	76	523	1816	2.68	2	22.29	123	29
	S	39.	-		0.							
Jaguar	M-	339	21.8		03		-	16.5	28.5			0.
Bank	44	1	930	214	24	59	-919	3	5	22.79	90	28
	S	39.	-		0.							
Jaguar	M-	340	21.7	105	78		-		31.4			0.
Bank	45	6	390	4	25	209	1979	1.10	5	17.84	146	20
	S	39.	-		0.							
Jaguar	M-	348	21.7		17		-		27.4			0.
Bank	46	0	427	479	01	114	2103	0.85	8	14.95	90	24
	S	39.	-		0.							
Jaguar	M-	348	21.7		35		-	12.4	31.7			0.
Bank	47	3	497	703	55	225	1949	2	9	26.53	173	32
	S	39.	-		0.							
Jaguar	M-	349	21.9		02		-	13.6	19.3			0.
Bank	48	0	054	205	84	34	-944	5	9	16.88	90	17
	S	39.	-		0.							
Jaguar	M-	365	21.9		05		-	13.0	27.1			0.
Bank	49	2	045	280	60	34	-721	1	7	19.88	0	12
	S	39.	-		0.							
Jaguar	M-	367	21.9		04		-	21.4	30.3			0.
Bank	50	8	013	271	83	90	-587	5	9	25.55	143	33
	S	39.	-		0.							
Jaguar	M-	402	21.9		05		-		24.0			0.
Bank	51	7	910	285	80	58	-957	9.85	3	17.27	0	20
	S	39.	-		0.							
Jaguar	M-	440	21.7		45		-		21.8			0.
Bank	52	7	020	880	70	120	2422	2.39	9	12.97	122	14
	S	39.	-		0.							
Jaguar	M-	452	21.7	107	88		-		28.1			0.
Bank	53	8	106	8	05	333	2175	6.87	9	21.65	2	31

	S	39.	-		0.							
Jaguar	M-	468	21.8		18				27.4			0.
Bank	54	6	135	496	20	156	-628	6.89	9	22.01	17	31
	S	39.	-		1.							
Jaguar	M-	471	21.7	151	50		-		36.3			0.
Bank	55	1	241	9	59	464	1828	2.97	8	25.75	178	31
	S	39.	-		0.							
Jaguar	M-	472	21.8		06				22.1			0.
Bank	56	0	051	308	91	54	-774	4.77	1	13.74	90	17
	S	39.	-		0.							
Jaguar	M-	474	21.8		09				24.9			0.
Bank	57	6	017	359	32	50	-754	6.85	6	14.61	12	14
	S	39.	-		0.							
Jaguar	M-	474	21.8		03			14.2	18.6			0.
Bank	58	8	062	230	79	42	-841	7	5	17.36	90	18
	S	39.	-		0.							
Jaguar	M-	476	21.8		02			9.8	22.2			0.
Bank	59	9	172	183	42	44	-678	9	8	21.08	90	24
	S	39.	-		0.							
Jaguar	M-	478	21.8		27				25.3			0.
Bank	60	6	408	673	87	186	-741	2.47	1	19.57	8	28
	S	39.	-		0.							
Jaguar	M-	478	21.7		09				24.7			0.
Bank	61	7	999	364	50	5	-810	1.25	9	12.05	165	14
	S	39.	-		0.							
Jaguar	M-	480	21.8		09							0.
Bank	62	4	312	105	72	10	-576	5.24	6.17	5.71	90	09
	S	39.	-		0.							
Jaguar	M-	481	21.8		05				17.6			0.
Bank	63	5	295	235	90	30	-572	1.48	4	9.55	90	10
	S	39.	-		0.							
Jaguar	M-	483	21.8		02			10.6	21.1			0.
Bank	64	1	319	187	56	32	-616	9	3	15.91	0	17
	S	39.	-		0.							
Jaguar	M-	483	21.7		29				33.7			0.
Bank	65	2	930	637	85	190	-862	9.63	5	22.13	45	30
	S	39.	-		0.							
Jaguar	M-	483	21.8		12				29.4			0.
Bank	66	3	350	448	22	150	-641	1.85	5	19.55	163	33
	S	39.	-		0.							
Jaguar	M-	485	21.8		41				30.4			0.
Bank	67	4	120	771	55	183	-881	4.39	6	19.97	76	24
	S	39.	-		0.							
Jaguar	M-	485	21.7		43		-	12.2	48.8			0.
Bank	68	5	406	769	62	347	1400	2	6	28.62	12	45
	S	39.	-		0.							
Jaguar	M-	485	21.7		08				15.5			0.
Bank	69	8	824	342	34	27	-825	3.30	1	10.81	27	08
Jaguar	S	39.	-		0.				25.4			0.
Bank	M-	487	21.8	299	06	73	-699	6.74	2	19.22	0	25

		70	6	285		51						
		S	39.	-		0.						
Jaguar	M-	487	21.7		16			11.5	26.6			0.
Bank	71	9	866	474	62	145	-938	2	5	20.68	15	31
	S	39.	-		0.							
Jaguar	M-	489	21.8		09				23.9			0.
Bank	72	8	316	361	28	68	-777	4.05	7	15.10	63	19
	S	39.	-		0.							
Jaguar	M-	491	21.8		04			12.4	23.0			0.
Bank	73	0	282	246	47	31	-795	0	7	18.01	0	12
	S	39.	-		0.							
Jaguar	M-	491	21.7		06				12.9			0.
Bank	74	8	756	321	92	19	-781	3.31	5	7.23	0	06
	S	39.	-		0.							
Jaguar	M-	494	21.7		06				17.4			0.
Bank	75	2	810	294	08	58	-874	1.25	9	10.76	0	20
	S	39.	-		0.							
Jaguar	M-	494	21.7		03				11.1			0.
Bank	76	4	708	224	47	8	-741	4.31	4	7.28	0	03
	S	39.	-		0.							
Jaguar	M-	497	21.7		08				24.2			0.
Bank	77	2	606	357	48	53	-742	0.70	4	13.82	13	15
	S	39.	-		0.							
Jaguar	M-	497	21.7		16				24.0			0.
Bank	78	7	764	484	90	55	-792	9.99	9	17.91	42	18
	S	39.	-		0.							
Jaguar	M-	498	21.7		05				18.8			0.
Bank	79	2	692	301	57	54	-761	2.44	3	11.27	45	18
	S	39.	-		0.							
Jaguar	M-	502	21.7		06				13.8			0.
Bank	80	2	658	295	36	25	-738	2.66	0	9.47	173	08
	S	39.	-		0.							
Jaguar	M-	505	21.7		03			11.0	15.8			0.
Bank	81	4	564	226	54	13	-817	1	5	13.21	0	06
	S	39.	-		0.							
Jaguar	M-	506	21.7	111	45				26.5			0.
Bank	82	0	812	3	28	371	-984	7.70	2	17.26	78	33
	S	39.	-		0.							
Jaguar	M-	511	21.7		06				20.3			0.
Bank	83	5	749	303	54	53	-810	7.18	7	13.60	0	17
	S	39.	-		0.							
Jaguar	M-	511	21.8	114	83		-		32.3			0.
Bank	84	8	014	3	77	271	1242	6.21	3	22.89	81	24
	S	39.	-		0.							
Jaguar	M-	515	21.7		10				19.9			0.
Bank	85	5	709	382	47	44	-847	1.47	8	12.01	165	12
	S	39.	-		0.							
Jaguar	M-	517	21.7		04			11.5	17.2			0.
Bank	86	8	577	238	04	30	-840	7	5	14.95	162	13

	S	39.	-		0.							
Jaguar	M-	518	21.7		04				14.6			0.
Bank	87	7	632	246	29	26	-847	6.04	8	10.65	18	10
	S	39.	-		0.							
Jaguar	M-	519	21.7		04				13.2			0.
Bank	88	5	537	240	02	37	-910	5.03	1	7.73	90	15
	S	39.	-		0.							
Jaguar	M-	521	21.7		06				14.6			0.
Bank	89	6	568	318	73	47	-908	1.53	2	9.62	0	15
	S	39.	-		0.							
Jaguar	M-	521	21.7		13				21.3			0.
Bank	90	7	448	430	43	81	-965	0.58	9	14.97	180	19
	S	39.	-		0.							
Jaguar	M-	522	21.6		57		-		29.5			0.
Bank	91	3	697	895	32	163	2354	2.86	6	19.02	46	18
	S	39.	-		0.							
Jaguar	M-	522	21.7		02			11.0	15.0			0.
Bank	92	7	525	199	80	40	-946	6	6	13.06	90	20
	S	39.	-		0.							
Jaguar	M-	523	21.7		03				13.4			0.
Bank	93	2	602	230	55	21	-911	4.83	7	10.37	0	09
	S	39.	-		0.							
Jaguar	M-	524	21.8		29		-		27.0			0.
Bank	94	3	153	705	32	142	1579	3.18	9	18.36	44	20
	S	39.	-		0.							
Jaguar	M-	525	21.7		12		-		22.7			0.
Bank	95	9	851	431	78	32	1201	1.39	5	11.00	99	07
	S	39.	-		0.							
Jaguar	M-	526	21.7		04				10.8			0.
Bank	96	2	581	248	30	44	-943	2.98	6	7.89	72	18
	S	39.	-		0.							
Jaguar	M-	526	21.7		06				11.5			0.
Bank	97	9	538	336	84	37	-964	1.84	8	5.14	8	11
	S	39.	-		0.							
Jaguar	M-	529	21.7		14				21.6			0.
Bank	98	7	482	450	98	96	-902	4.15	8	14.84	28	21
	S	39.	-		0.							
Jaguar	M-	530	21.7		03				13.5			0.
Bank	99	8	566	219	29	21	-954	6.63	7	9.99	0	10
	S	39.	-		0.							
Jaguar	M-	533	21.7		25				26.0			0.
Bank	0	4	535	598	99	143	-915	9.39	6	21.07	177	24
	S	39.	-		0.							
Jaguar	M-	534	21.7		17				22.9			0.
Bank	1	7	461	491	92	79	-962	3.91	6	14.13	6	16
	S	39.	-		1.							
Jaguar	M-	534	21.7	133	33		-		27.8			0.
Bank	10	7	983	9	38	280	1453	1.64	1	18.49	19	21

	2											
	S											
	M-	39.	-		0.							
Jaguar	10	535	21.6		12		-	12.4	27.6			0.
Bank	3	1	967	425	48	149	2041	7	7	21.92	159	35
	S											
	M-	39.	-		1.							
Jaguar	10	537	21.8	154	78		-		33.5			0.
Bank	4	5	256	1	49	399	1750	3.31	9	22.78	15	26
	S											
	M-	39.	-		0.							
Jaguar	10	540	21.7		20		-		24.1			0.
Bank	5	6	007	586	62	81	1891	5.65	5	14.97	165	14
	S											
	M-	39.	-		0.							
Jaguar	10	541	21.7		04		-		19.0			0.
Bank	6	3	501	255	49	56	1024	1.24	9	12.47	135	22
	S											
	M-	39.	-		0.							
Jaguar	10	542	21.7		15		-		30.3			0.
Bank	7	8	327	478	43	171	1018	6.09	3	23.20	70	36
	S											
	M-	39.	-		0.							
Jaguar	10	542	21.7		29		-		19.0			0.
Bank	8	9	444	880	02	124	1016	4.68	0	12.94	120	14
	S											
	M-	39.	-		0.							
Jaguar	10	543	21.6		21		-		18.0			0.
Bank	9	3	610	59	22	79	2370	3.52	8	11.27	25	13
	S											
	M-	39.	-		0.							
Jaguar	11	544	21.7		33		-		28.6			0.
Bank	0	6	048	725	26	155	1809	2.96	6	18.26	9	21
	S											
	M-	39.	-		0.							
Jaguar	11	545	21.7		02		-					0.
Bank	1	2	384	200	83	22	1060	4.61	4.85	4.73	135	11
	S											
	M-	39.	-		0.							
Jaguar	11	545	21.7		07		-		17.0			0.
Bank	2	4	561	326	34	50	1128	2.88	3	9.34	20	15
	S											
	M-	39.	-		0.							
Jaguar	11	545	21.7		03		-		10.4			0.
Bank	3	9	412	211	03	19	1024	2.65	4	6.88	0	09
	S											
	M-	39.	-		0.							
Jaguar	11	547	21.7		05		-		14.2			0.
Bank	4	9	368	279	39	37	1044	5.92	9	10.65	90	13

	S											
	M-	39.	-		0.							
Jaguar	11	548	21.7		05		-		17.5			0.
Bank	5	2	582	277	33	58	1161	2.97	7	11.82	45	21
	S											
	M-	39.	-		0.							
Jaguar	11	548	21.6		42		-		27.9			0.
Bank	6	6	867	751	34	218	2155	2.52	9	22.26	171	29
	S											
	M-	39.	-		0.							
Jaguar	11	549	21.7		04		-		11.5			0.
Bank	7	8	512	263	72	35	1134	5.04	0	8.29	90	13
	S											
	M-	39.	-		0.							
Jaguar	11	550	21.7		17		-		31.0			0.
Bank	8	9	633	488	25	132	1303	3.30	4	22.65	0	27
	S											
	M-	39.	-		0.							
Jaguar	11	552	21.7		05		-		16.4			0.
Bank	9	4	394	270	01	31	1143	5.11	2	11.09	90	11
	S											
	M-	39.	-		0.							
Jaguar	12	553	21.8		35		-		24.5			0.
Bank	0	1	327	702	89	127	1968	7.53	5	16.41	6	18
	S											
	M-	39.	-		0.							
Jaguar	12	558	21.7		10		-		25.0			0.
Bank	1	2	322	384	77	64	1102	3.28	1	16.66	0	17
	S											
	M-	39.	-		0.							
Jaguar	12	564	21.7		51		-		30.2			0.
Bank	2	0	352	825	51	216	1186	2.37	4	20.30	8	26
	S											
	M-	39.	-		0.							
Jaguar	12	564	21.7		18		-		26.0			0.
Bank	3	2	684	512	64	100	1727	5.09	7	16.51	164	20
	S											
	M-	39.	-		0.							
Jaguar	12	567	21.7		37		-		30.6			0.
Bank	4	0	048	774	65	232	1748	4.52	4	22.91	59	30
	S											
	M-	39.	-		0.							
Jaguar	12	567	21.7		05		-		24.4			0.
Bank	5	9	302	281	63	57	1313	5.63	5	14.91	30	20
	S											
	M-	39.	-		1.							
Jaguar	12	572	21.8	207	49		-		27.9			0.
Bank	6	5	070	3	61	275	2051	2.12	0	15.40	127	13
Jaguar	S	39.	-		0.		-	10.6	32.2			0.
Bank	M-	572	21.6	747	30	209	1880	5	2	22.72	169	28

	12	6	992		58							
	7											
	S											
	M-	39.	-		0.							
Jaguar	12	573	21.7		16		-		28.3			0.
Bank	8	7	747	478	76	71	1982	3.27	7	15.20	0	15
	S											
	M-	39.	-		0.							
Jaguar	12	590	21.7		22		-		24.6			0.
Bank	9	8	633	559	51	81	2091	4.67	7	16.40	163	14
	S											
	M-	40.	-		0.							
	13	473	22.4		37		-	13.2	33.0			0.
Europa	0	1	855	722	36	158	2563	1	0	21.33	61	22
	S											
	M-	40.	-		0.							
	13	579	22.4		45		-		31.8			0.
Europa	1	8	634	778	15	196	3153	5.98	4	23.28	60	25
	S											
	M-	40.	-		1.							
	13	437	22.4	129	00		-		30.9			0.
Europa	2	5	616	8	31	365	2049	7.14	5	22.65	99	28
	S											
	M-	40.	-		0.							
	13	481	22.4		19		-		34.6			0.
Europa	3	5	445	523	53	141	2467	4.79	2	24.49	3	27
	S											
	M-	40.	-		0.							
	13	485	22.4		18		-	11.6	32.0			0.
Europa	4	1	334	508	48	143	2463	3	4	24.85	13	28
	S											
	M-	40.	-		0.							
	13	442	22.4		28		-		30.5			0.
Europa	5	8	258	639	94	169	1853	5.72	0	22.02	161	26
	S											
	M-	40.	-		0.							
	13	502	22.4	101	60		-		32.6			0.
Europa	6	5	203	2	64	192	2619	6.03	5	22.05	163	19
	S											
	M-	40.	-		0.							
	13	561	22.4		43		-		30.7			0.
Europa	7	9	180	779	55	146	3075	6.66	8	20.99	157	19
	S											
	M-	40.	-		0.							
	13	281	22.4		23		-		36.9			0.
Europa	8	3	174	594	47	218	1936	5.25	6	25.30	25	37
	S											
	M-	40.	-		0.							
	13	198	22.4	103	69		-		36.5			0.
Europa	9	1	142	8	25	275	2836	5.74	8	22.99	100	26

	S											
	M-	40.	-		0.							
	14	579	22.4	106	81		-		25.4			0.
Europa	0	0	078	5	93	164	3143	2.48	1	12.50	131	15
	S											
	M-	40.	-		0.							
	14	203	22.4		30		-		26.5			0.
Europa	1	0	064	791	47	127	2812	2.86	9	16.54	178	16
	S											
	M-	40.	-		0.							
	14	555	22.3	118	86		-		30.0			0.
Europa	2	6	998	2	30	208	2995	2.65	9	18.02	177	18
	S											
	M-	40.	-		0.							
	14	239	22.3	103	54		-		27.7			0.
Europa	3	1	877	1	20	226	2410	7.92	9	20.11	27	22
	S											
	M-	40.	-		0.							
	14	175	22.3		07		-		12.0			0.
Europa	4	5	767	334	96	47	3047	1.07	1	8.89	160	14
	S											
	M-	40.	-		1.							
	14	216	22.3	160	85		-		33.4			0.
Europa	5	6	683	6	82	445	2614	0.16	6	23.81	97	28
	S											
	M-	40.	-		0.							
	14	197	22.3		11		-		27.9			0.
Europa	6	8	475	797	19	199	2916	3.89	6	15.92	179	25
	S											
	M-	40.	-		0.							
	14	202	22.3		12		-		16.9			0.
Europa	7	5	177	49	51	69	2993	4.13	2	12.00	90	16
	S											
	M-	40.	-		1.							
	14	187	22.3	138	23		-		32.1			0.
Europa	8	0	091	5	86	255	3013	2.50	5	19.05	161	18
	S											
	M-	40.	-		0.							
	14	187	22.2		07		-		25.5			0.
Europa	9	4	971	318	05	84	3021	6.19	9	17.76	0	26
	S											
	M-	40.	-		0.							
	15	182	22.2		13		-		24.0			0.
Europa	0	6	946	430	31	91	3036	5.95	3	18.00	0	21
	S											
	M-	40.	-		0.							
	15	292	22.2		07		-	16.9	23.1			0.
Europa	1	8	922	325	13	102	2308	7	2	20.39	135	31
	S	40.	-	114	0.		-		32.2			0.
Europa	M-	226	22.2	6	80	226	2956	1.87	4	21.42	166	20

	15	1	685		34							
	2											
	S											
	M-	40.	-		0.							
	15	212	22.2		10		-		11.3			0.
Europa	3	1	658	436	61	40	3081	4.77	3	6.66	157	09
	S											
	M-	40.	-		0.							
	15	321	22.2		24		-		27.0			0.
Europa	4	9	652	598	92	141	2380	3.85	9	19.86	97	24
	S											
	M-	40.	-		0.							
	15	229	22.2		50		-		27.3			0.
Europa	5	6	604	912	09	166	2966	0.45	9	17.76	144	18
	S											
	M-	40.	-		0.							
	15	193	22.2		48		-		26.8			0.
Europa	6	5	601	804	36	143	3048	5.00	9	17.18	169	18
	S											
	M-	40.	-		0.							
	15	312	22.2		30		-		26.4			0.
Europa	7	6	587	642	05	184	2509	7.70	1	20.80	145	29
	S											
	M-	40.	-		0.							
	15	222	22.2		06		-	13.3	19.9			0.
Europa	8	6	586	310	54	66	3071	9	2	16.74	90	21
	S											
	M-	40.	-		0.							
	15	222	22.2		09		-		16.9			0.
Europa	9	7	525	371	85	79	3069	6.42	4	11.31	90	21
	S											
	M-	40.	-		0.							
	16	430	22.2		31		-		27.7			0.
Europa	0	2	521	654	27	144	2696	3.02	9	17.33	136	22
	S											
	M-	40.	-		0.							
	16	397	22.2		41		-		29.7			0.
Europa	1	4	488	747	24	208	2538	9.20	4	20.50	163	28
	S											
	M-	40.	-		0.							
	16	256	22.2		54		-		32.2			0.
Europa	2	2	472	869	43	206	2907	1.91	3	20.72	165	24
	S											
	M-	40.	-		0.							
	16	208	22.2		08		-		13.5			0.
Europa	3	7	467	338	15	55	3086	7.44	9	11.33	165	16
	S											
	M-	40.	-		0.							
	16	209	22.2		04		-		18.4			0.
Europa	4	2	421	260	71	40	3058	2.33	3	11.81	18	16

Europa	S											
	M-16	40.205	-22.2		0.52				26.7			0.
Europa	S	5	8	384	846	86	128	3048	1.25	2	13.01	37
	M-16	40.424	-22.2	142	51					31.9		0.
Europa	S	6	9	381	9	59	334	2704	6.35	0	21.46	174
	M-16	40.245	-22.2		0.07					15.2		0.
Europa	S	7	6	378	334	85	54	3026	7.59	1	10.50	20
	M-16	40.340	-22.2		0.16					25.5		0.
Europa	S	8	5	322	478	41	120	2634	8.61	4	18.74	165
	M-16	40.376	-22.2		0.37					29.3		0.
Europa	S	9	2	258	722	22	135	2696	4.92	6	18.33	107
	M-17	40.277	-22.2		0.21					22.9		0.
Europa	S	0	9	252	642	01	120	2969	1.87	3	13.83	125
	M-17	40.224	-22.2		0.08					12.0		0.
Europa	S	1	3	228	341	57	49	3081	3.92	7	7.41	90
	M-17	40.243	-22.2	135	10					29.7		0.
Europa	S	2	1	172		24	271	2997	6.01	8	19.90	55
	M-17	40.272	-22.2		0.07							0.
Europa	S	3	6	151	331	69	34	3017	1.79	7.81	5.58	63
	M-17	40.257	-22.2	233	06					32.8		0.
Ptoleme	S	4	9	133	8	05	256	2979	1.95	6	18.29	140
	M-17	40.414	-22.2		0.30				10.5	30.9		0.
Ptoleme	S	5	1	119	646	42	160	2876	2	8	22.32	23
	M-17	40.237	-22.2		0.07					18.1		0.
Ptoleme	S	6	8	097	334	88	63	3054	8.46	7	13.84	45
	M-17	40.240	-22.1	683	34	130	130	3009	5.39	7	18.98	80
Ptoleme	S	40.	-		0.					24.9		0.
	M-17	40.	-		0.							19

	17 7 S	9	999		53							
Ptoleme	M-17 8 S	40. 259 6	- 22.1 992		0. 41 85		- 171 2978		30.2 5	23.42	26	0. 23
Ptoleme	M-17 9 S	40. 253 7	- 22.1 985		0. 12 48		- 90 3036		19.9 6	14.26	173	0. 21
Ptoleme	M-18 0 S	40. 226 6	- 22.1 984	180 4	2. 04 22		- 353 2911		33.6 4	23.90	132	0. 20
Ptoleme	M-18 1 S	40. 204 4	- 22.1 939		0. 16 59		- 85 3037		18.1 3	13.76	0	0. 18
Ptoleme	M-18 2 S	40. 255 1	- 22.1 934		0. 01 21		- 10 304		4.33	4.54	4.44	0. 07
Ptoleme	M-18 3 S	40. 250 4	- 22.1 922		0. 37 72		- 206 2990		29.2 9	21.84	71	0. 28
Ptoleme	M-18 4 S	40. 255 5	- 22.1 904		0. 06 18		- 95 3060		24.9 5	17.20	18	0. 29
Ptoleme	M-18 5 S	40. 218 3	- 22.1 898		0. 43 98		- 211 2929		28.1 7	21.52	26	0. 27
Ptoleme	M-18 6 S	40. 323 3	- 22.1 895		0. 20 22		- 70 3036		22.4 4	13.77	51	0. 13
Ptoleme	M-18 7 S	40. 246 0	- 22.1 881		0. 27 56		- 186 2990		25.1 1	16.58	58	0. 30
Ptoleme	M-18 8 S	40. 256 5	- 22.1 869		0. 11 07		- 54 3013		16.4 9	11.87	81	0. 13
Ptoleme	M-18 9	40. 320 1	- 22.1 857		0. 22 27		- 87 3065		21.3 4	12.55	51	0. 12

Ptoleme	S	M-	40.	-	0.								
	19	0	281	22.1	09	39	-	3038	3.93	16.0	9.68	15	0.
Ptoleme	S	M-	40.	-	0.								
	19	1	214	22.1	83	285	-	2848	7.61	31.8	24.41	53	0.
Ptoleme	S	M-	40.	-	0.								
	19	2	277	22.1	17	81	-	3013	6.24	23.1	14.86	137	0.
Ptoleme	S	M-	40.	-	0.								
	19	3	270	22.1	35	149	-	2947	6.49	29.3	22.01	112	0.
Ptoleme	S	M-	40.	-	0.								
	19	4	315	22.1	12	58	-	3072	7.04	18.3	12.14	90	0.
Ptoleme	S	M-	40.	-	0.								
	19	5	254	22.1	53	163	-	2933	4.29	25.8	19.03	168	0.
Ptoleme	S	M-	40.	-	0.								
	19	6	291	22.1	68	29	-	3056	2.78	11.8	6.79	0	0.
Ptoleme	S	M-	40.	-	3.								
	19	7	202	22.1	28	387	-	2586	1.49	31.4	22.07	130	0.
Ptoleme	S	M-	40.	-	1.								
	19	8	252	22.1	66	304	-	2888	6.27	33.1	20.84	149	0.
Ptoleme	S	M-	40.	-	1.								
	19	9	276	22.1	94	280	-	2921	0.35	34.9	16.72	6	0.
Ptoleme	S	M-	40.	-	1.								
	20	0	224	22.1	37	289	-	2671	4.47	31.6	21.60	5	0.
Ptoleme	S	M-	40.	-	0.								
	20	1	341	22.1	48	154	-	3061	5.00	29.2	19.36	11	0.
Ptoleme	S	M-	40.	-	0.								
e	M-	20	225	22.1	31	144	-	2615	9.25	32.2	23.18	119	0.

	20 2 S	6	418		70							
Ptoleme e	M- 20 3 S	40. 278 9	- 22.1 411		0. 08 54	17	- 3050	2.98	8.58	5.56	6	0. 05
Ptoleme e	M- 20 4 S	40. 178 4	- 22.1 408	232 7	4. 10 64	627	- 2337	5.94	37.8 5	22.94	83	0. 27
Ptoleme e	M- 20 5 S	40. 200 3	- 22.1 408	200 3	1. 92 76	281	- 2398	0.99	22.9 6	15.13	86	0. 14
Ptoleme e	M- 20 6 S	40. 239 0	- 22.1 387	140 3	1. 39 23	335	- 2727	2.69	31.2 7	22.33	162	0. 24
Ptoleme e	M- 20 7 S	40. 336 8	- 22.1 379	408	0. 10 89	34	- 3008	2.26	11.7 8	7.67	37	0. 08
Ptoleme e	M- 20 8 S	40. 204 0	- 22.1 169	191 9	2. 67 44	435	- 2349	6.29	27.8 8	19.93	21	0. 23
Ptoleme e	M- 20 9 S	40. 234 3	- 22.1 156	922 40	0. 13 40	195	- 2660	7.00	26.9 1	18.62	10	0. 21
Ptoleme e	M- 21 0 S	40. 150 3	- 22.1 125	292 4	4. 05 54	574	- 2261	5.06	35.0 8	24.92	112	0. 20
Ptoleme e	M- 21 1 S	40. 449 1	- 22.1 125	296	0. 06 17	48	- 3143	2.46	7.55	4.84	0	0. 16
Ptoleme e	M- 21 2 S	40. 025 1	- 22.1 121	428	0. 12 22	58	- 2742	11.2 7	19.8 4	15.00	70	0. 13
Ptoleme e	M- 21 3 S	40. 461 7	- 22.1 062	615	0. 22 32	86	- 3099	3.80	21.9 6	13.14	10	0. 14
Ptoleme e	M- 21 4	40. 454 0	- 22.1 061	197	0. 02 36	18	- 3132	4.45	4.94	4.69	90	0. 09

	S											
	M-	40.	-		0.							
Ptoleme	21	195	22.0	109	89		-		32.3			0.
e	5	4	956	8	92	301	2366	4.53	9	23.90	21	27
	S											
	M-	40.	-		1.							
Ptoleme	21	011	22.0	130	01		-		27.9			0.
e	6	8	955	1	20	181	2689	3.16	9	17.75	92	14
	S											
	M-	40.	-		2.							
Ptoleme	21	182	22.0	169	17		-		39.2			0.
e	7	5	944	5	14	429	2207	2.26	1	23.27	168	25
	S											
	M-	40.	-		4.							
Ptoleme	21	133	22.0	315	43		-		32.9			0.
e	8	2	843	3	34	643	2122	4.02	2	21.49	78	20
	S											
	M-	40.	-		0.							
Ptoleme	21	186	22.0		61		-		26.4			0.
e	9	6	820	934	83	252	2406	8.70	0	19.76	9	27
	S											
	M-	40.	-		0.							
Ptoleme	22	170	22.0		14		-		15.1			0.
e	0	5	793	449	58	40	2378	4.32	0	10.52	90	11
	S											
	M-	40.	-		4.							
Ptoleme	22	158	22.0	330	95		-		34.1			0.
e	1	3	724	7	01	582	2152	1.70	8	21.30	97	18
	S											
	M-	40.	-		1.							
Ptoleme	22	028	22.0	163	69		-		33.6			0.
e	2	7	724	0	17	271	2476	1.71	0	22.51	81	17
	S											
	M-	40.	-		1.							
Ptoleme	22	127	22.0	144	42		-		31.8			0.
e	3	8	651	7	94	409	1859	4.37	0	24.88	171	28
	S											
	M-	40.	-		1.							
Ptoleme	22	137	22.0	136	20		-		31.4			0.
e	4	7	425	1	87	381	1939	1.78	4	22.91	138	28
	S											
	M-	40.	-		0.							
Ptoleme	22	115	22.0	114	94		-		32.0			0.
e	5	2	402	7	72	329	1823	3.38	8	21.84	23	29
	S											
	M-	40.	-		0.							
Ptoleme	22	133	22.0		40		-		30.6			0.
e	6	5	322	820	24	246	1761	1.03	7	20.92	134	30
Ptoleme	S	40.	-	116	1.		-		34.3			0.
e	M-	118	22.0	1	02	293	1535	5.06	6	23.96	10	25

	22 7 S	8	289		30							
Ptoleme	M- 22 8 S	40. 061 2	- 22.0 235		0. 37 14		- 1722	4.88	29.6 0	21.76	170	0. 23
Ptoleme	M- 22 9 S	40. 049 7	- 22.0 115	102 4	0. 75 90		- 1655	2.09	29.8 9	22.50	36	0. 20
Ptoleme	M- 23 0 S	40. 117 5	- 22.0 036	219 6	3. 10 86		- 1235	5.44	31.6 3	22.28	43	0. 30
Ptoleme	M- 23 1 S	40. 079 0	- 22.0 033	985	0. 70 86		- 1245	4.57	34.9 1	21.02	4	0. 26
Ptoleme	M- 23 2 S	40. 134 4	- 21.9 988	480	0. 16 95		- 1641	4.96	29.0 8	16.82	0	0. 20
Ptoleme	M- 23 3 S	40. 142 4	- 21.9 974	929	0. 48 68		- 1775	7.48	31.5 5	23.89	32	0. 30
Ptoleme	M- 23 4 S	40. 152 9	- 21.9 937	434	0. 11 81		- 1999	2.52	21.4 5	11.89	12	0. 16
Ptoleme	M- 23 5 S	40. 108 1	- 21.9 903	163 2	1. 78 19		- 1043	4.43	28.0 8	20.61	11	0. 24
Ptoleme	M- 23 6 S	40. 029 3	- 21.9 871	484	0. 16 22		- 1957	3.50	25.7 9	16.72	9	0. 26
Ptoleme	M- 23 7 S	40. 090 3	- 21.9 858	210 2	2. 06 07		- 939	2.81	36.6 5	17.74	31	0. 14
Ptoleme	M- 23 8 S	40. 012 0	- 21.9 852	977	0. 70 85		- 1899	7.95	34.2 8	26.39	136	0. 31
Ptoleme	M- 23 9	40. 255 2	- 21.9 842	535	0. 20 69		- 2797	7.46	24.4 0	15.58	18	0. 19

Ptoleme	S	M-	40.	-	0.							
	24	187	21.9		19		-		31.3			0.
e	0	5	826	535	19	154	2280	9.02	9	20.95	2	29
Ptoleme	S	M-	40.	-	0.							
	24	031	21.9		03		-		17.1			0.
e	1	6	812	207	04	40	1978	7.87	8	12.66	0	19
Ptoleme	S	M-	40.	-	0.							
	24	215	21.9		56		-		28.9			0.
e	2	7	796	882	04	194	2542	3.57	6	15.53	14	22
Ptoleme	S	M-	40.	-	0.							
	24	030	21.9		03		-		14.2			0.
e	3	0	793	228	59	59	2030	6.33	5	9.95	162	26
Ptoleme	S	M-	40.	-	1.							
	24	040	21.9	127	21		-		31.5			0.
e	4	9	790	9	92	404	1854	8.17	7	24.71	177	32
Ptoleme	S	M-	40.	-	0.							
	24	197	21.9		48		-		36.3			0.
e	5	8	784	898	30	307	2364	9.22	7	26.97	174	34
Ptoleme	S	M-	40.	-	0.							
	24	032	21.9		02		-		10.4			0.
e	6	8	780	192	37	31	2038	4.45	5	6.98	0	16
Ptoleme	S	M-	40.	-	0.							
	24	032	21.9		04		-	11.3	16.5			0.
e	7	4	759	212	66	60	2066	8	7	13.89	162	24
Ptoleme	S	M-	40.	-	0.							
	24	264	21.9		44		-		28.3			0.
e	8	1	757	829	60	130	2837	2.68	5	16.91	25	16
Ptoleme	S	M-	40.	-	0.							
	24	080	21.9		11		-	10.6	28.2			0.
e	9	2	746	404	78	141	1271	1	0	21.01	70	35
Ptoleme	S	M-	40.	-	3.							
	25	018	21.9	280	81		-		33.5			0.
e	0	1	736	5	61	511	1887	3.63	6	21.69	125	18
Ptoleme	S	M-	40.	-	0.							
	25	174	21.9		40		-		34.2			0.
e	1	9	735	748	09	255	2218	7.23	7	22.68	24	34
Ptoleme	S	M-	40.	-	0.							
	25	094	21.9	441	13	83	1030	8.73	9	15.97	114	19

	25 2 S	5	723		94							
Ptoleme	M- 25 3 S	40. 186 6	- 21.9 723	128 4	1. 23 63	398	- 2204	8.27	32.8 9	25.91	8	0. 31
Ptoleme	M- 25 4 S	40. 049 0	- 21.9 716	100 4	0. 62 14	410	- 1812	1.47	32.1 0	22.36	155	0. 41
Ptoleme	M- 25 5 S	40. 031 2	- 21.9 704	482	0. 14 04	114	- 2120	4.12	27.5 0	16.97	161	0. 24
Ptoleme	M- 25 6 S	40. 242 3	- 21.9 697	278 1	3. 03 43	391	- 2600	2.36	38.8 3	21.46	12	0. 14
Ptoleme	M- 25 7 S	40. 078 0	- 21.9 691	557	0. 22 18	177	- 1338	5.52	40.8 3	20.73	86	0. 32
Ptoleme	M- 25 8 S	40. 067 3	- 21.9 687	218 5	2. 41 45	637	- 1388	4.47	33.6 0	23.69	87	0. 29
Ptoleme	M- 25 9 S	40. 220 6	- 21.9 685	120 1	0. 25 69	247	- 2439	1.11	29.6 5	18.73	23	0. 21
Ptoleme	M- 26 0 S	40. 204 0	- 21.9 683	181 8	2. 22 60	440	- 2175	3.48	31.7 2	24.21	5	0. 24
Ptoleme	M- 26 1 S	40. 097 4	- 21.9 660	547	0. 21 57	177	- 1179	9.01	29.3 9	23.89	135	0. 32
Ptoleme	M- 26 2 S	40. 091 0	- 21.9 656	589	0. 25 17	157	- 1256	2.91	35.9 2	21.75	90	0. 27
Ptoleme	M- 26 3 S	40. 106 8	- 21.9 635	260	0. 04 53	77	- 1415	14.9 8	20.7 8	18.81	90	0. 30
Ptoleme	M- 26 4	40. 212 7	- 21.9 582	126 2	1. 17 62	498	- 2286	3.43	32.0 1	26.41	171	0. 39

Ptoleme	S M- 26 5	40. 094 1	- 21.9 566	129 9	1. 09 59	371	- 1449	2.41	33.2 4	23.14	46	0. 29
Ptoleme	S M- 26 6	40. 056 0	- 21.9 548	906	0. 58 49	334	- 1742	7.49	33.2 9	25.63	172	0. 37
Ptoleme	S M- 26 7	39. 914 7	- 21.9 543	135 6	1. 22 43	289	- 2758	7.18	37.3 6	21.42	70	0. 21
Ptoleme	S M- 26 8	40. 116 1	- 21.9 503	517	0. 18 99	164	- 1775	1.48	31.9 4	19.76	83	0. 32
Ptoleme	S M- 26 9	40. 188 4	- 21.9 448	675	0. 32 79	184	- 2445	11.9 3	31.8 9	23.15	3	0. 27
Ptoleme	S M- 27 0	40. 580 1	- 21.9 394	510	0. 19 13	105	- 3044	3.36	21.4 6	14.64	47	0. 21
Ptoleme	S M- 27 1	40. 167 6	- 21.9 392	159 8	1. 03 65	418	- 2371	8.46	37.0 4	24.79	41	0. 26
Ptoleme	S M- 27 2	40. 210 8	- 21.9 357	114 4	1. 70 52	167	- 2572	5.82	31.3 7	20.16	65	0. 15
Ptoleme	S M- 27 3	40. 116 8	- 21.9 345	174 0	2. 20 83	448	- 1884	6.21	30.3 9	23.37	1	0. 26
Ptoleme	S M- 27 4	40. 171 8	- 21.9 297	441	0. 13 06	92	- 2510	4.43	20.8 0	13.23	172	0. 21
Ptoleme	S M- 27 5	40. 141 0	- 21.9 293	200 3	2. 80 48	574	- 2140	7.49	34.9 2	24.97	23	0. 29
Ptoleme	S M- 27 6	40. 034 5	- 21.9 251	307 1	4. 42 73	515	- 2308	1.32	33.1 0	20.37	167	0. 17
Ptoleme	S M- 27 7	40. 130 1	- 21.9 1	126 1	0. 86	304	- 2318	3.36	28.7 9	19.30	86	0. 24

	27	7	159		33							
	7											
	S											
	M-	40.	-		1.							
Ptoleme	27	068	21.9	131	28		-		30.7			0.
e	8	2	133	8	34	367	2290	5.60	0	22.57	147	28
	S											
	M-	40.	-		0.							
Ptoleme	27	058	21.9		51		-		23.6			0.
e	9	1	101	844	21	156	2394	3.75	8	14.80	168	19
	S											
	M-	40.	-		0.							
Ptoleme	28	021	21.9		44		-		31.8			0.
e	0	1	011	801	18	215	2452	5.40	2	22.92	176	27
	S											
	M-	40.	-		0.							
Ptoleme	28	053	21.8		12		-		26.7			0.
e	1	5	978	412	43	127	2595	7.54	2	20.19	15	31
	S											
	M-	40.	-		0.							
Ptoleme	28	041	21.8		38		-	14.9	30.3			0.
e	2	9	952	812	22	198	2502	6	6	22.87	167	24
	S											
	M-	40.	-		0.							
Ptoleme	28	032	21.8		46		-		27.0			0.
e	3	3	912	795	17	170	2489	5.12	4	17.00	3	21
	S											
	M-	40.	-		0.							
Ptoleme	28	122	21.8		14		-		22.6			0.
e	4	7	867	456	48	68	2610	0.77	6	14.53	97	15
	S											
	M-	40.	-		0.							
Ptoleme	28	075	21.8		48		-		29.3			0.
e	5	8	808	815	01	235	2643	5.62	2	22.45	177	29
	S											
	M-	40.	-		0.							
Ptoleme	28	115	21.8		30		-		25.0			0.
e	6	9	829	657	36	109	2600	7.97	1	17.31	39	17
	S											
	M-	40.	-		0.							
Ptoleme	28	009	21.8	107	82		-		34.2			0.
e	7	5	780	4	07	274	2653	2.10	5	20.32	1	25
	S											
	M-	40.	-		0.							
Ptoleme	28	075	21.8		29		-		24.5			0.
e	8	0	749	667	36	128	2698	3.22	4	16.47	30	19
	S											
	M-	40.	-		0.							
Ptoleme	28	020	21.8		53		-		30.8			0.
e	9	9	690	993	88	269	2684	4.01	0	19.82	81	27

	S													
Ptoleme	M-	40.	-		0.									
e	29	132	21.8		22		-		22.4					0.
	0	4	679	605	98	117	2687	3.39	8	15.42	113			19
	S													
Ptoleme	M-	40.	-		0.									
e	29	009	21.8		07		-		19.2					0.
	1	2	600	348	32	64	2824	2.90	1	13.44	135			18
Pammel	S													
a	M-	40.	-		1.									
Seamou	29	121	21.8	196	35		-		33.6					0.
nt 2	2	4	506	7	73	383	2380	3.12	5	21.32	131			19
Pammel	S													
a	M-	40.	-		2.									
Seamou	29	056	21.8	190	31		-		27.2					0.
nt 2	3	5	420	7	59	479	2609	5.28	0	23.08	180			25
Pammel	S													
a	M-	40.	-		0.									
Seamou	29	168	21.8	118	98		-		25.1					0.
nt 2	4	7	226	2	44	175	2508	1.39	8	16.56	169			15
Pammel	S													
a	M-	40.	-		1.									
Seamou	29	096	21.8	158	89		-		30.3					0.
nt 2	5	1	183	8	65	401	2112	2.94	4	20.89	176			25
Pammel	S													
a	M-	40.	-		2.									
Seamou	29	045	21.8	168	62		-	10.1	35.1					0.
nt 2	6	1	087	3	05	557	2618	4	1	26.72	161			33
Pammel	S													
a	M-	40.	-		0.									
Seamou	29	177	21.8	40			-		29.8					0.
nt 2	7	0	028	7	i	56	151	2595	3.33	9	18.69	147		20
Pammel	S													
a	M-	40.	-		0.									
Seamou	29	032	21.7	105	55		-		28.1					0.
nt 2	8	2	917	9	34	228	2752	2.29	8	19.11	168			22
Pammel	S													
a	M-	40.	-		1.									
Seamou	29	050	21.7	127	14		-		31.2					0.
nt 2	9	2	934	8	12	374	2504	4.21	6	24.53	177			29
Pammel	S													
a	M-	40.	-		0.									
Seamou	30	149	21.7	46			-		27.0					0.
nt 2	0	3	929	815	17	123	2210	0.66	1	15.60	51			15
Pammel	S													
a	M-	40.	-		0.									
Seamou	30	131	21.7	32			-		27.9					0.
nt 2	1	2	924	696	83	112	1970	1.43	0	13.88	179			16
Pammel	S	40.	-	137	1.		-		29.5					0.
a	M-	079	21.7	0	11	319	2413	4.19	0	16.72	174			23

Seamou nt 2	30 2	3	880		96							
Pammel a	S M-											
Seamou nt 2	30 3	40. 0	- 841		0. 19	10 47	- 2053	17.3 7.02				0. 12
Pammel a	S M-											
Seamou nt 2	30 4	019 9	21.7 835	186 5	54 14	482	- 2619	36.2 0.53				0. 26
Pammel a	S M-											
Seamou nt 2	30 5	030 5	21.7 726	189 2	63 72	510	- 2591	32.7 6.77				0. 27
Pammel a	S M-											
Seamou nt 2	30 6	071 9	21.7 667	102 8	73 02	178	- 2586	26.1 2.74				0. 17
Pammel a	S M-											
Seamou nt 2	30 7	164 3	21.7 659	133 4	93 39	211	- 2514	34.2 3.98				0. 16
Pammel a	S M-											
Seamou nt 2	30 8	099 4	21.7 556		10 26	89	- 2671	22.2 3.06				0. 23
Pammel a	S M-											
Seamou nt 2	30 9	018 4	21.7 509	251 1	90 37	519	- 2711	34.5 2.51				0. 21
Pammel a	S M-											
Seamou nt 2	31 0	109 7	21.7 229		12 71	79	- 2885	15.5 3.58				0. 19
Pammel a	S M-											
Seamou nt 2	31 1	003 5	21.7 221	115 2	93 67	369	- 2525	33.2 5.39				0. 32
Pammel a	S M-											
Seamou nt 2	31 2	023 3	21.7 293	103 2	59 17	116	- 2831	23.1 3.33				0. 11
Pammel a	S M-											
Seamou nt 1	31 3	188 0	21.7 820	225 6	46 75	375	- 2803	32.5 1.18				0. 17
Pammel a	S M-											
Seamou nt 1	31 4	981 6	21.7 420		15 73	80	- 2828	19.8 6.13				0. 17

Pammel	S											
a	M-	39.	-		1.							
Seamou	31	987	21.7	127	17		-		31.2			0.
nt 1	5	1	248	8	88	443	2433	3.46	4	25.15	60	35
Pammel	S											
a	M-	40.	-		0.							
Seamou	31	027	21.6		45		-		25.3			0.
nt 1	6	0	916	794	58	167	2608	2.32	7	18.53	125	21
Pammel	S											
a	M-	40.	-		0.							
Seamou	31	106	21.6		24		-		26.9			0.
nt 1	7	6	756	578	30	118	2891	3.62	7	15.68	125	20
Pammel	S											
a	M-	40.	-		3.							
Seamou	31	113	21.6	243	84		-		39.1			0.
nt 1	8	6	952	6	88	335	2841	0.65	2	15.13	21	14
Pammel	S											
a	M-	40.	-		4.							
Seamou	31	067	21.6	302	09		-		30.8			0.
nt 1	9	9	638	7	61	318	2680	0.43	3	16.74	178	10
Pammel	S											
a	M-	39.	-		0.							
Seamou	32	977	21.6		42		-		29.6			0.
nt 1	0	1	634	759	28	217	1744	2.64	6	20.00	4	29
Pammel	S											
a	M-	39.	-		0.							
Seamou	32	971	21.6		53		-		29.9			0.
nt 1	1	8	549	870	85	191	1512	5.31	6	20.82	120	22
Pammel	S											
a	M-	39.	-		0.							
Seamou	32	963	21.6		28		-		31.1			0.
nt 1	2	6	524	630	52	140	1395	4.44	1	17.81	31	22
Pammel	S											
a	M-	40.	-		0.							
Seamou	32	058	21.6		16		-		16.7			0.
nt 1	3	7	498	569	72	57	2665	6.04	5	11.36	177	10
Pammel	S											
a	M-	40.	-		1.							
Seamou	32	034	21.6	176	08		-		28.1			0.
nt 1	4	9	470	3	53	177	2497	3.71	2	14.82	90	10
Pammel	S											
a	M-	40.	-		0.							
Seamou	32	055	21.6	114	72		-		26.5			0.
nt 1	5	2	437	9	11	149	2631	1.05	9	14.16	30	13
Pammel	S											
a	M-	40.	-		0.							
Seamou	32	063	21.6		55		-		23.4			0.
nt 1	6	9	368	874	64	149	2650	3.39	9	15.17	3	17
Pammel	S											
a	M-	40.	-	123	1.		-		32.4			0.
		040	21.6	0	13	290	2524	1.26	9	22.09	14	24

Seamou nt 1	32 7	4	300		98							
Pammel a	S M-	40.	-		2.							
Seamou nt 1	32 8	071 9	21.6 257	303 8	52 32	- 301	2567	2.89	36.8 5	18.30	161	0. 10
Pammel a	S M-	40.	-		0.							
Seamou nt 1	32 9	094 0	21.6 229	139 8	49 11	- 87	2633	1.28	27.2 7	13.53	103	0. 06
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 0	107 9	21.6 212		24 36	- 84	2763	3.83	23.1 6	15.34	137	0. 14
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 1	173 4	21.6 196	115 5	97 16	- 221	3043	1.99	34.7 9	16.89	35	0. 19
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 2	119 7	21.6 063	427	12 57	- 59	2744	7.87	19.5 4	14.03	171	0. 14
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 3	142 7	21.6 037	809	47 78	- 214	2981	5.04	27.8 0	19.37	173	0. 26
Pammel a	S M-	39.	-		1.							
Seamou nt 1	33 4	890 8	21.4 601	125 8	21 09	- 263	2700	1.46	35.7 0	17.34	179	0. 20
Pammel a	S M-	39.	-		0.							
Seamou nt 1	33 5	938 9	21.4 577	911	47 92	- 115	3013	3.54	26.9 4	15.84	51	0. 13
Pammel a	S M-	39.	-		0.							
Seamou nt 1	33 6	945 3	21.4 471	110 1	92 04	- 264	3007	2.68	33.1 7	21.66	0	0. 24
Pammel a	S M-	39.	-		0.							
Seamou nt 1	33 7	942 1	21.4 391	889	34 73	- 136	3049	7.27	24.4 1	16.01	43	0. 15
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 8	078 4	21.5 942	548	21 50	- 148	2746	1.92	31.5 8	23.03	3	0. 27
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 9	143 5	21.5 896	750	39 79	- 103	3026	6.57	22.7 3	14.76	133	0. 14

Pammel	S											
a	M-	39.	-		0.							
Seamou	34	914	21.5		49		-		27.3			0.
nt 1	0	5	839	812	96	186	1794	1.83	7	18.36	1	23
Pammel	S											
a	M-	39.	-		0.							
Seamou	34	920	21.5		12		-		21.6			0.
nt 1	1	8	765	443	57	71	1969	4.55	4	15.51	7	16
Pammel	S											
a	M-	39.	-		0.							
Seamou	34	924	21.5	116	94		-		32.6			0.
nt 1	2	0	696	0	58	281	2046	0.59	8	21.99	178	24
Pammel	S											
a	M-	40.	-		0.							
Seamou	34	151	21.6		63		-		13.3			0.
nt 1	3	0	259	914	45	75	2985	2.48	7	9.08	21	08
Pammel	S											
a	M-	39.	-		4.							
Seamou	34	629	21.6	421	05		-		33.4			0.
nt 1	4	5	182	9	05	666	1535	1.44	5	21.92	64	16
Pammel	S											
a	M-	39.	-		1.							
Seamou	34	859	21.5	138	31		-		46.2			0.
nt 1	5	3	794	1	22	292	1799	2.87	7	21.99	9	21
Pammel	S											
a	M-	39.	-		1.							
Seamou	34	815	21.5	129	25		-		28.9			0.
nt 1	6	3	787	9	85	275	1882	5.98	1	19.32	176	21
Pammel	S											
a	M-	39.	-		0.							
Seamou	34	872	21.5	113	94		-		27.8			0.
nt 1	7	1	725	0	33	199	1908	0.42	3	12.61	176	17
Pammel	S											
a	M-	39.	-		0.							
Seamou	34	841	21.5	114	65		-		25.9			0.
nt 1	8	6	712	3	06	160	1974	2.23	8	17.44	120	14
Pammel	S											
a	M-	39.	-		1.							
Seamou	34	801	21.5	125	15		-		27.7			0.
nt 1	9	7	683	7	43	264	1737	0.66	0	17.97	173	21
Pammel	S											
a	M-	39.	-		0.							
Seamou	35	836	21.5		34		-		27.3			0.
nt 1	0	1	586	983	33	138	2034	1.71	1	17.66	153	14
Pammel	S											
a	M-	39.	-		0.							
Seamou	35	907	21.5		11		-		19.1			0.
nt 1	1	9	569	415	82	70	2195	5.97	2	12.80	148	17
Pammel	S											
a	M-	39.	-	231	2.		-		33.1			0.
		804	21.5	6	19	511	1612	3.44	9	22.36	140	22

Seamou nt 1	35 2	3	539		34								
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 3	824 0	21.5 533	971	55 80	230	- 1892		31.0 5	22.36	156	0. 24	
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 4	887 0	21.5 510	103 7	74 95	197	- 2184		35.2 8	22.09	32	0. 19	
Pammel a	S M-		39.	-	1.								
Seamou nt 1	35 5	850 7	21.5 437	143 2	37 76	291	- 2017		34.5 7	23.08	138	0. 20	
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 6	818 6	21.5 437	980	51 21	196	- 1812		31.8 4	20.91	30	0. 20	
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 7	876 6	21.5 408	346	07 99	45	- 2305		19.5 0	13.44	135	0. 13	
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 8	835 1	21.5 405	121 1	71 48	222	- 1959		30.0 4	18.41	90	0. 18	
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 9	800 1	21.5 391	419	11 05	59	- 1628		20.6 8	14.81	58	0. 14	
Pammel a	S M-		39.	-	1.								
Seamou nt 1	36 0	946 7	21.5 311	145 7	14 97	223	- 2657		26.4 7	15.34	33	0. 15	
Pammel a	S M-		39.	-	2.								
Seamou nt 1	36 1	862 2	21.5 253	167 9	09 63	309	- 2067		24.0 2	16.92	169	0. 18	
	S M-		39.	-	0.								
Bassas da India	36 2	609 1	21.7 808	714	37 51	123	- 2199		25.3 8	15.09	166	0. 17	
	S M-		39.	-	1.								
Bassas da India	36 3	611 4	21.7 542	159 9	42 47	319	- 2159		29.8 0	20.08	2	0. 20	
	S M-		39.	-	0.								
Bassas da India	36 4	577 3	21.7 479	821	48 94	332	- 1518		36.2 0	28.56	159	0. 40	

	S											
	M-	39.	-		0.							
Bassas	36	585	21.7		42		-		35.6			0.
da India	5	4	318	766	20	212	1559	5.46	0	25.51	157	28
	S											
	M-	39.	-		1.							
Bassas	36	626	21.7	140	26		-		33.5			0.
da India	6	9	275	3	88	353	1993	9.91	9	22.94	23	25
	S											
	M-	39.	-		0.							
Bassas	36	586	21.7		11		-		18.0			0.
da India	7	4	274	402	08	35	1596	0.96	5	9.42	164	09
	S											
	M-	39.	-		0.							
Bassas	36	613	21.7		09		-		23.8			0.
da India	8	4	237	360	33	50	1899	5.98	8	14.53	135	14
	S											
	M-	39.	-		0.							
Bassas	36	590	21.7		26		-		24.5			0.
da India	9	8	231	627	56	106	1651	2.97	4	15.68	157	17
	S											
	M-	39.	-		0.							
Bassas	37	601	21.7		31		-		28.0			0.
da India	0	2	208	667	00	130	1563	6.78	1	21.41	53	20
	S											
	M-	39.	-		0.							
Bassas	37	581	21.7		09		-		21.2			0.
da India	1	5	202	395	42	36	1564	4.70	0	13.47	52	09
	S											
	M-	39.	-		0.							
Bassas	37	596	21.7		34		-		28.3			0.
da India	2	7	156	713	08	231	1536	7.30	8	21.49	21	32
	S											
	M-	39.	-		0.							
Bassas	37	647	21.7		37		-		26.4			0.
da India	3	2	150	713	33	148	2344	1.29	3	18.44	4	21
	S											
	M-	39.	-		0.							
Bassas	37	604	21.7		23		-		25.9			0.
da India	4	7	963	564	40	88	2099	9.71	0	18.31	17	16
	S											
	M-	39.	-		0.							
Bassas	37	667	21.7	106	84		-		26.5			0.
da India	5	9	132	3	32	206	2460	5.49	1	19.01	14	19
	S											
	M-	39.	-		0.							
Bassas	37	599	21.7		54		-		30.2			0.
da India	6	9	097	879	75	218	1512	0.97	4	21.47	116	25
Bassas	S	39.	-		0.		-					0.
da India	M-	992	21.7	373	09	26	2341	0.55	7.40	3.79	15	07

	37	4	085		54							
	7											
	S											
	M-	39.	-		0.							
Bassas	37	575	21.7		08		-		13.9			0.
da India	8	7	071	358	86	42	1878	1.25	6	8.89	165	12
	S											
	M-	39.	-		1.							
Bassas	37	614	21.7	121	06		-		31.0			0.
da India	9	6	039	3	03	297	1798	4.52	8	21.46	154	24
	S											
	M-	39.	-		0.							
Bassas	38	651	21.7		25		-		27.4			0.
da India	0	0	012	618	43	114	2364	6.14	2	17.14	74	19
	S											
	M-	40.	-		0.							
Bassas	38	094	21.6		12		-		13.0			0.
da India	1	6	963	459	54	45	2903	2.38	8	8.25	115	10
	S											
	M-	39.	-		0.							
Bassas	38	584	21.6		19		-		21.7			0.
da India	2	7	905	563	14	84	2012	0.84	5	12.74	75	15
	S											
	M-	39.	-		0.							
Bassas	38	601	21.6		09		-		25.7			0.
da India	3	5	893	368	58	46	1739	7.80	9	16.74	131	13
	S											
	M-	39.	-		0.							
Bassas	38	581	21.6		15		-		23.7			0.
da India	4	1	880	599	20	48	2049	4.73	7	11.58	64	08
	S											
	M-	39.	-		2.							
Bassas	38	598	21.6	198	99		-		32.6			0.
da India	5	5	705	5	29	469	1747	2.77	3	23.96	165	24
	S											
	M-	39.	-		0.							
Bassas	38	612	21.6		13		-		20.9			0.
da India	6	2	734	431	47	51	1926	3.64	5	11.98	90	12
	S											
	M-	39.	-		0.							
Bassas	38	618	21.6		38		-		23.9			0.
da India	7	4	716	753	99	107	2017	3.18	5	14.29	122	14
	S											
	M-	39.	-		0.							
Bassas	38	611	21.6		06		-		10.3			0.
da India	8	5	680	300	38	38	1940	2.71	9	7.78	0	13
	S											
	M-	39.	-		0.							
Bassas	38	587	21.6		31		-		30.6			0.
da India	9	3	653	666	55	152	1974	8.37	3	21.59	176	23

	S											
	M-	39.	-		0.							
Bassas	39	613	21.6		05		-		22.0			0.
da India	0	6	634	293	87	24	1846	7.96	6	14.41	72	08
	S											
	M-	39.	-		0.							
Bassas	39	609	21.6		44		-		26.1			0.
da India	1	6	585	771	41	171	1723	8.33	8	20.81	152	22
	S											
	M-	39.	-		1.							
Bassas	39	638	21.6	166	74		-		32.0			0.
da India	2	2	565	5	86	348	1959	2.13	4	22.21	37	21
	S											
	M-	39.	-		0.							
Bassas	39	584	21.6	138	91		-		31.3			0.
da India	3	2	557	4	38	321	2136	3.32	0	19.36	103	23
	S											
	M-	39.	-		0.							
Bassas	39	594	21.6		09		-		11.8			0.
da India	4	2	552	358	38	49	2135	3.94	2	7.59	75	14
	S											
	M-	39.	-		0.							
Bassas	39	626	21.6		27		-		22.5			0.
da India	5	5	546	816	93	7	2004	1.58	9	11.35	58	10
	S											
	M-	39.	-		0.							
Bassas	39	616	21.6		25		-		25.5			0.
da India	6	6	529	590	62	108	1808	3.03	2	14.21	157	18
	S											
	M-	39.	-		0.							
Bassas	39	696	21.6		26		-		26.5			0.
da India	7	0	524	618	25	126	2431	7.28	9	19.48	153	18
	S											
	M-	39.	-		0.							
Bassas	39	647	21.6		37		-		29.0			0.
da India	8	0	483	824	21	259	2055	4.39	0	21.91	5	31
	S											
	M-	39.	-		3.							
Bassas	39	676	21.6	252	33		-		33.5			0.
da India	9	0	462	5	84	463	2236	3.48	9	21.19	98	18
	S											
	M-	39.	-		2.							
Bassas	40	595	21.6	181	47		-		32.1			0.
da India	0	1	437	1	66	407	2064	2.75	0	20.62	32	22
	S											
	M-	40.	-		1.							
Bassas	40	027	21.6	135	12		-		30.0			0.
da India	1	9	147	9	02	208	2520	1.62	9	15.31	99	15
Bassas	S	39.	-	148	1.		-		32.1			0.
da India	M-	624	21.6	2	33	477	1563	3.38	0	23.42	46	32

	40	6	081		42							
	2											
	S											
	M-	39.	-		0.							
Bassas	40	646	21.6		18		-	10.0	26.5			0.
da India	3	9	014	516	01	83	1347	5	3	19.16	147	16
	S											
	M-	39.	-		0.							
Bassas	40	703	21.6		23		-		29.9			0.
da India	4	4	007	567	15	134	1699	5.37	9	21.59	110	24
	S											
	M-	39.	-		1.							
Bassas	40	614	21.6	128	04		-		31.2			0.
da India	5	8	006	6	30	325	1704	4.87	2	23.90	86	25
	S											
	M-	39.	-		0.							
Bassas	40	626	21.5	121	70		-		31.5			0.
da India	6	0	859	1	49	269	1535	3.27	5	22.83	79	22
	S											
	M-	39.	-		0.							
Bassas	40	855	21.5		04		-		11.9			0.
da India	7	2	721	253	05	22	208	1.92	6	6.68	0	09
	S											
	M-	39.	-		0.							
Bassas	40	635	21.5		17		-		30.0			0.
da India	8	0	716	492	72	150	1089	8.40	5	20.96	31	30
	S											
	M-	39.	-		0.							
Bassas	40	851	21.5		06		-		11.3			0.
da India	9	7	707	293	11	44	2040	3.80	3	9.09	0	15
	S											
	M-	39.	-		0.							
Bassas	41	886	21.5	116	95		-		28.5			0.
da India	0	3	600	6	07	182	2011	2.29	7	16.24	1	16
	S											
	M-	39.	-		0.							
Bassas	41	857	21.5		08		-		14.1			0.
da India	1	5	645	351	25	44	2081	5.89	0	9.14	84	12
	S											
	M-	39.	-		0.							
Bassas	41	801	21.5		06		-		17.5			0.
da India	2	1	612	303	64	55	1691	5.39	0	11.78	0	18
	S											
	M-	39.	-		0.							
Bassas	41	860	21.5		04		-		17.9			0.
da India	3	3	606	252	37	56	2124	2.97	2	11.23	90	22
	S											
	M-	39.	-		0.							
Bassas	41	622	21.5		01		-	13.8	13.9			0.
da India	4	7	586	132	24	31	1064	8	4	13.91	0	24

	S											
	M-	39.	-		0.							
Bassas	41	625	21.5		07				21.5			0.
da India	5	9	581	357	36	82	-967	7.26	4	16.93	163	23
	S											
	M-	39.	-		0.							
Bassas	41	917	21.5		13		-		28.6			0.
da India	6	6	550	432	60	134	2232	3.29	6	19.06	18	31
	S											
	M-	39.	-		0.							
Bassas	41	861	21.5		19		-	12.7	33.3			0.
da India	7	0	545	522	73	153	2067	3	1	23.20	165	29
	S											
	M-	39.	-		0.							
Bassas	41	609	21.5		04		-	12.8	21.9			0.
da India	8	0	504	234	04	55	1233	1	8	17.87	0	23
	S											
	M-	39.	-		0.							
Bassas	41	766	21.5		04		-		15.2			0.
da India	9	5	499	261	89	30	1396	4.83	8	9.98	162	12
	S											
	M-	39.	-		0.							
Bassas	42	761	21.5		06		-		22.4			0.
da India	0	9	494	305	56	40	1305	5.13	0	13.40	150	16
	S											
	M-	39.	-		0.							
Bassas	42	607	21.5		03		-	13.6	21.6			0.
da India	1	9	482	205	03	48	1225	4	2	17.28	90	24
	S											
	M-	39.	-		0.							
Bassas	42	772	21.5		07		-		18.5			0.
da India	2	8	456	302	22	52	1422	2.96	9	10.83	160	17
	S											
	M-	39.	-		0.							
Bassas	42	777	21.5	120	55		-		30.9			0.
da India	3	8	420	0	35	241	1398	2.20	9	20.71	165	20
	S											
	M-	39.	-		0.							
Bassas	42	803	21.5	101	42		-		30.4			0.
da India	4	5	300	4	78	174	1617	3.29	8	19.48	42	17
	S											
	M-	39.	-		1.							
Bassas	42	818	21.5	144	16		-		30.0			0.
da India	5	7	240	3	85	278	1649	5.16	1	17.01	159	19
	S											
	M-	39.	-		0.							
Bassas	42	625	21.5		27				27.0			0.
da India	6	5	228	608	47	155	-412	9.06	0	22.38	0	25
Bassas	S	39.	-		0.				21.3			0.
da India	M-	606	21.5	330	07	76	-993	2.97	6	13.70	27	23

	42	5	169		26							
	7											
	S											
	M-	39.	-		0.							
Bassas	42	622	21.5		08			24.2				0.
da India	8	5	149	342	34	88	-555	6.83	0	19.52	17	26
	S											
	M-	39.	-		0.							
Bassas	42	825	21.2	114	70		-		15.4			0.
da India	9	1	995	0	52	77	3066	1.37	5	9.20	39	07

Table 3: Comparison of the offshore section of the volcanic ridges of Bassas da India/Europa complex, Hawaiian volcanoes (Mark and Moore, 1987; Fornari et al., 1988; Lonsdale, 1989; Clague et al., 2019), Canary Islands (Gee et al., 2001; Mitchell et al., 2002; Acosta et al., 2003b), Grande Comore Island (Tzevahirtzian et al., 2021), and Galapagos and Fernandina Islands (Harpp et al., 2003; Geist et al., 2006, 2008).

	Average long axis slope	Length	Width (max)
Bassas da India/Europa complex			
Hall Bank (east)	8-11°	10 km	5 km
Jaguar Bank (east)	4°	20 km	10 km
Bassas da India (east)	11°	10 km	5 km
Bassas da India (south)	6°	15 km	10 km
Ptolemee (south)	4°	40 km	3-6 km
Ptolemee (east)	6°	18 km	3 km
PS1 (east)	4°	30 km	3-5 km
PS1 (south)	8°	15 km	3-5 km
Canary Islands			
Cumbre Vieja Ridge	11-17°	38 km	27 km
El Hierro Northeast Ridge	22°	15 km	26 km
El Hierro Northwest Ridge	11-17°	16 km	26 km
Hawaii Islands			
Puna ridge	2-4°	70 km	> 40 km
Hilo Ridge	4°	40 km	20 km
Loihi	6-10°	11-19 km	20 km
Comoros archipelago			
Southeast Karthala	4°	13 km	15 km
Galapagos			
Genovesa	2-3°	50 km	20 km

Fernandina			
Fernandina NW Rift	9°	13 km	8 km

Figure 1

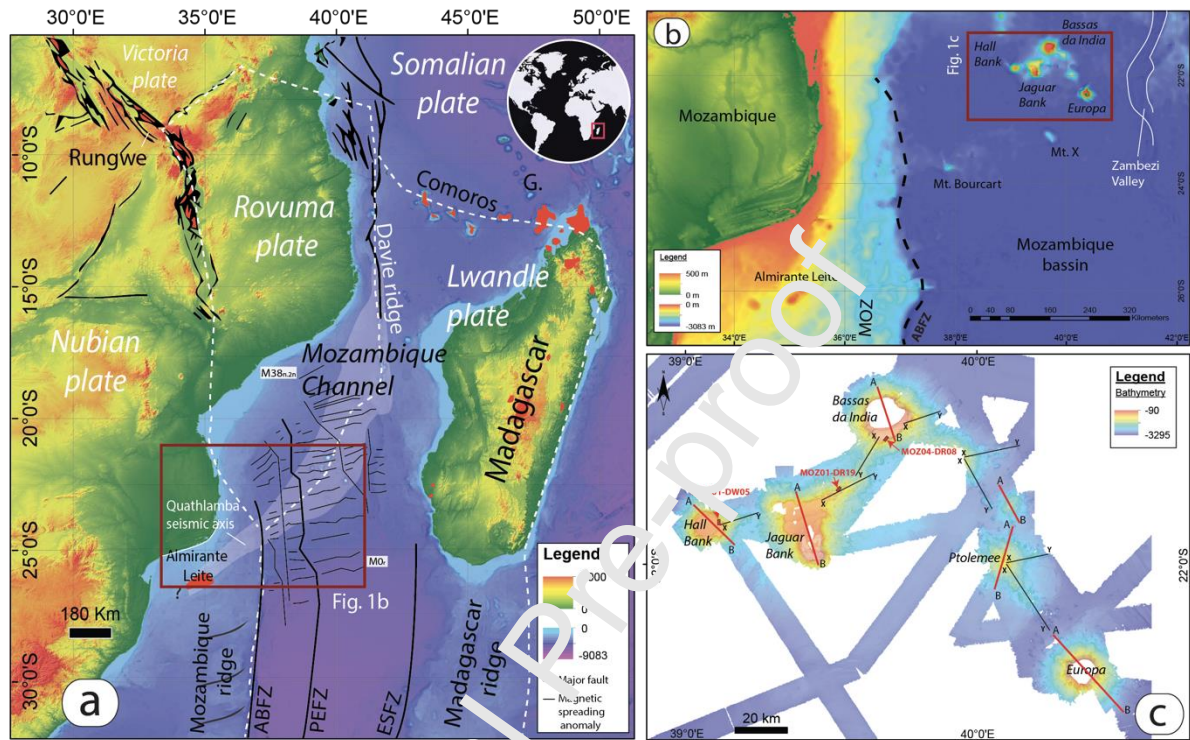


Figure 2

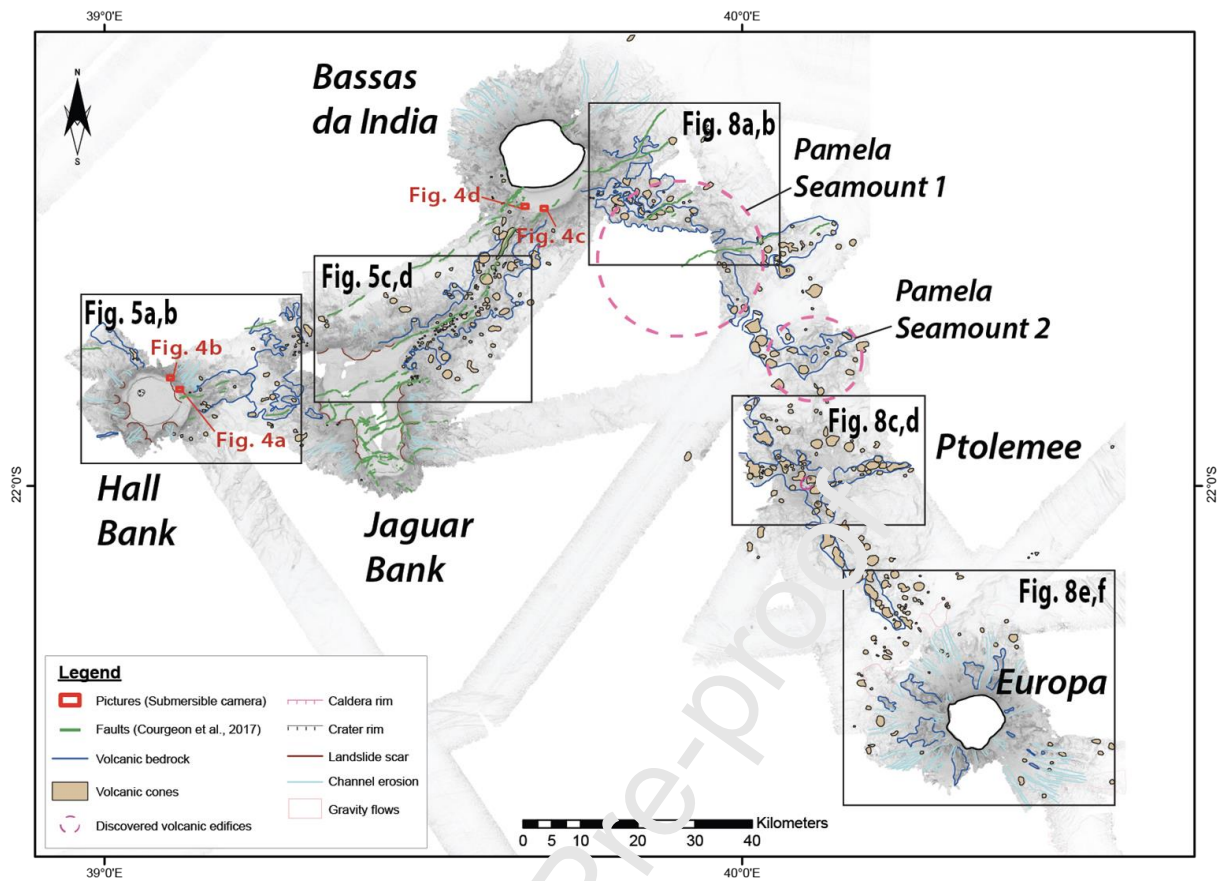


Figure 3

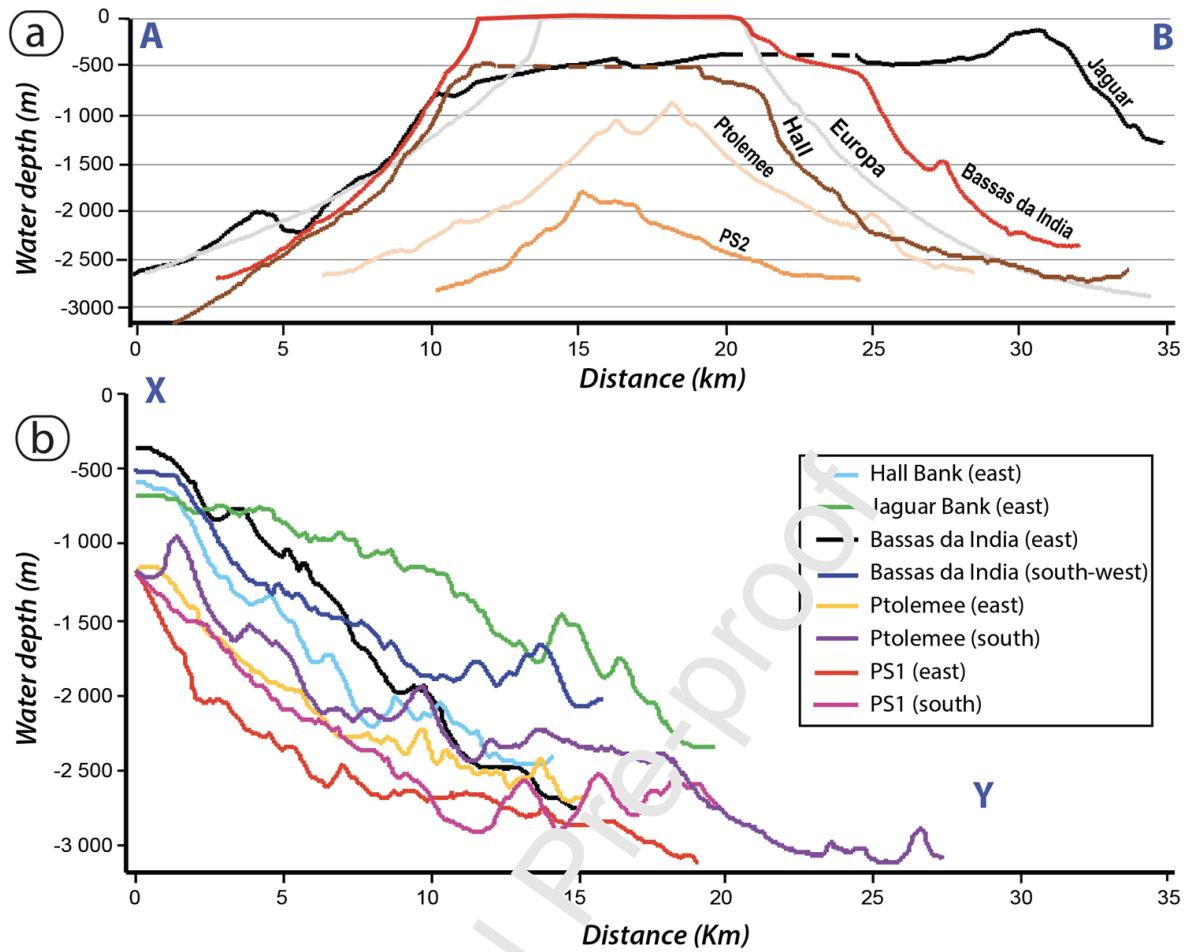
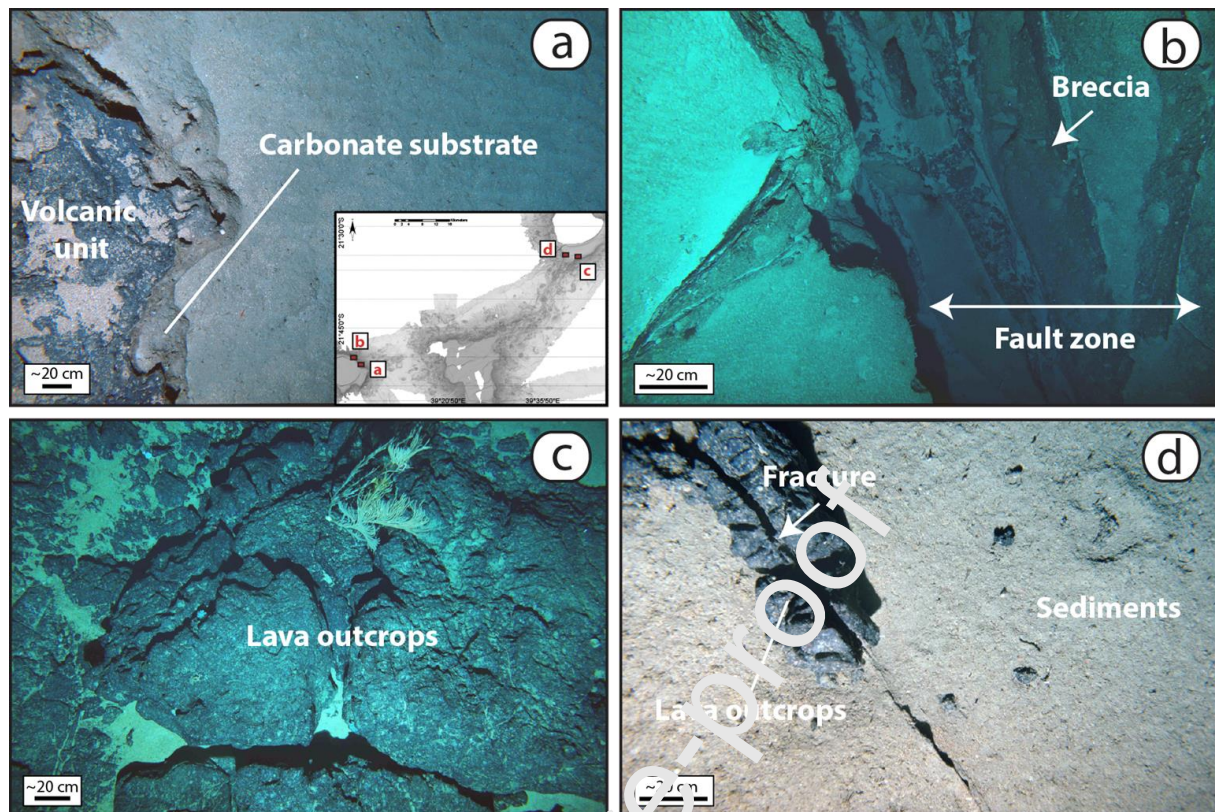
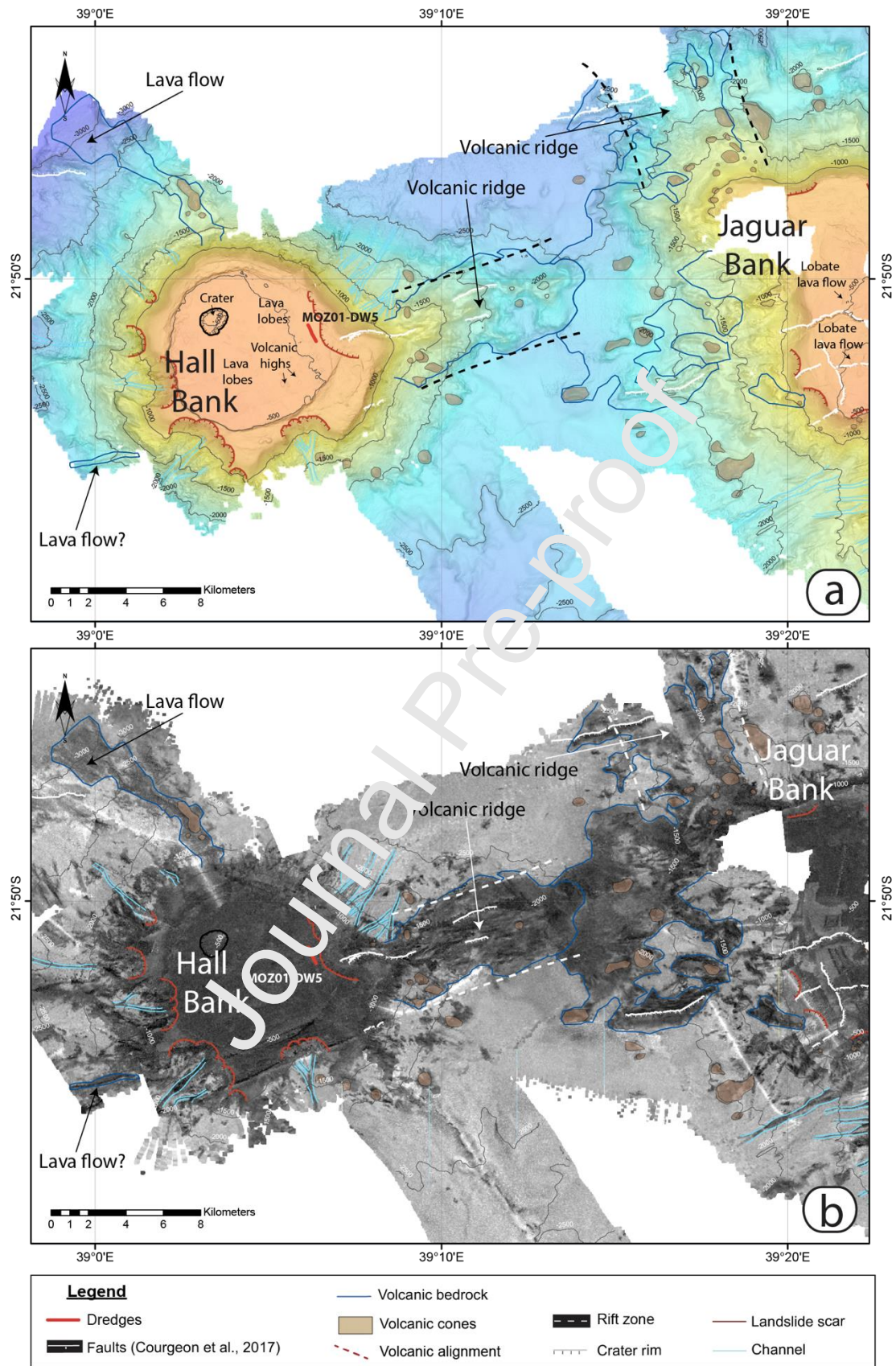


Figure 4

**Figure 5**



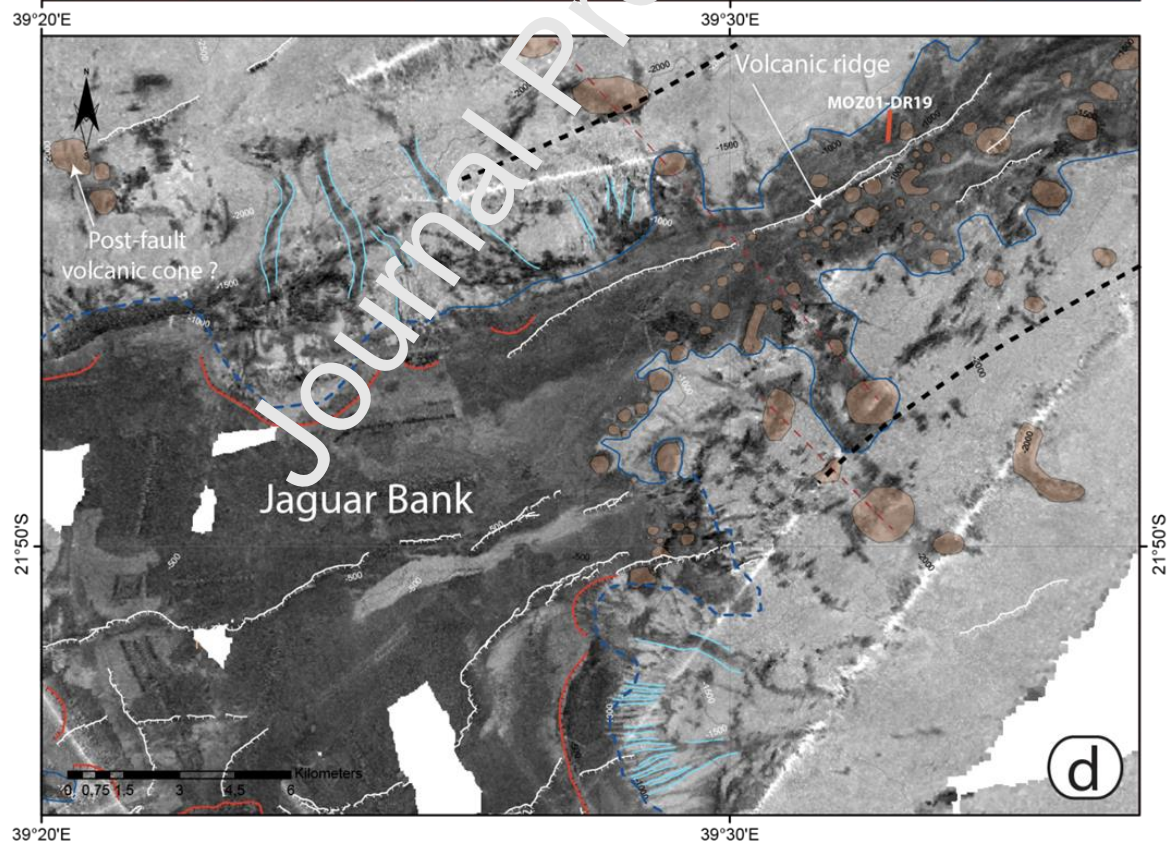
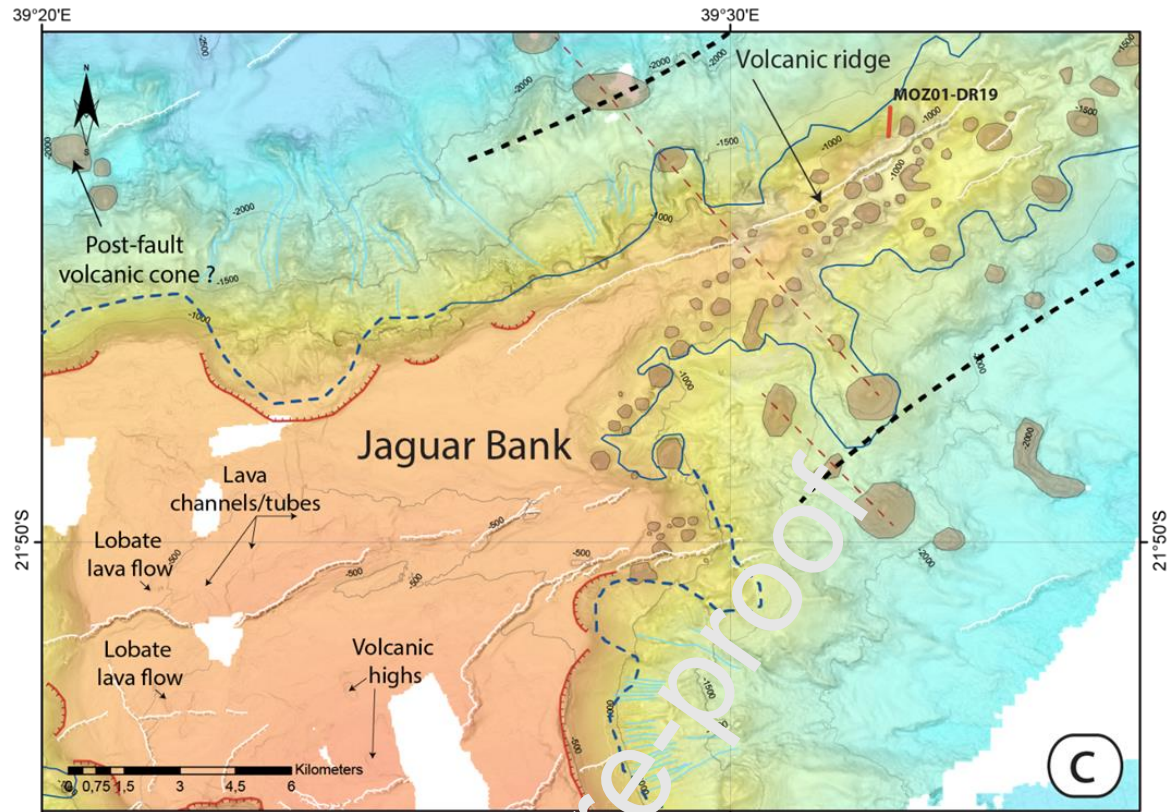


Figure 6

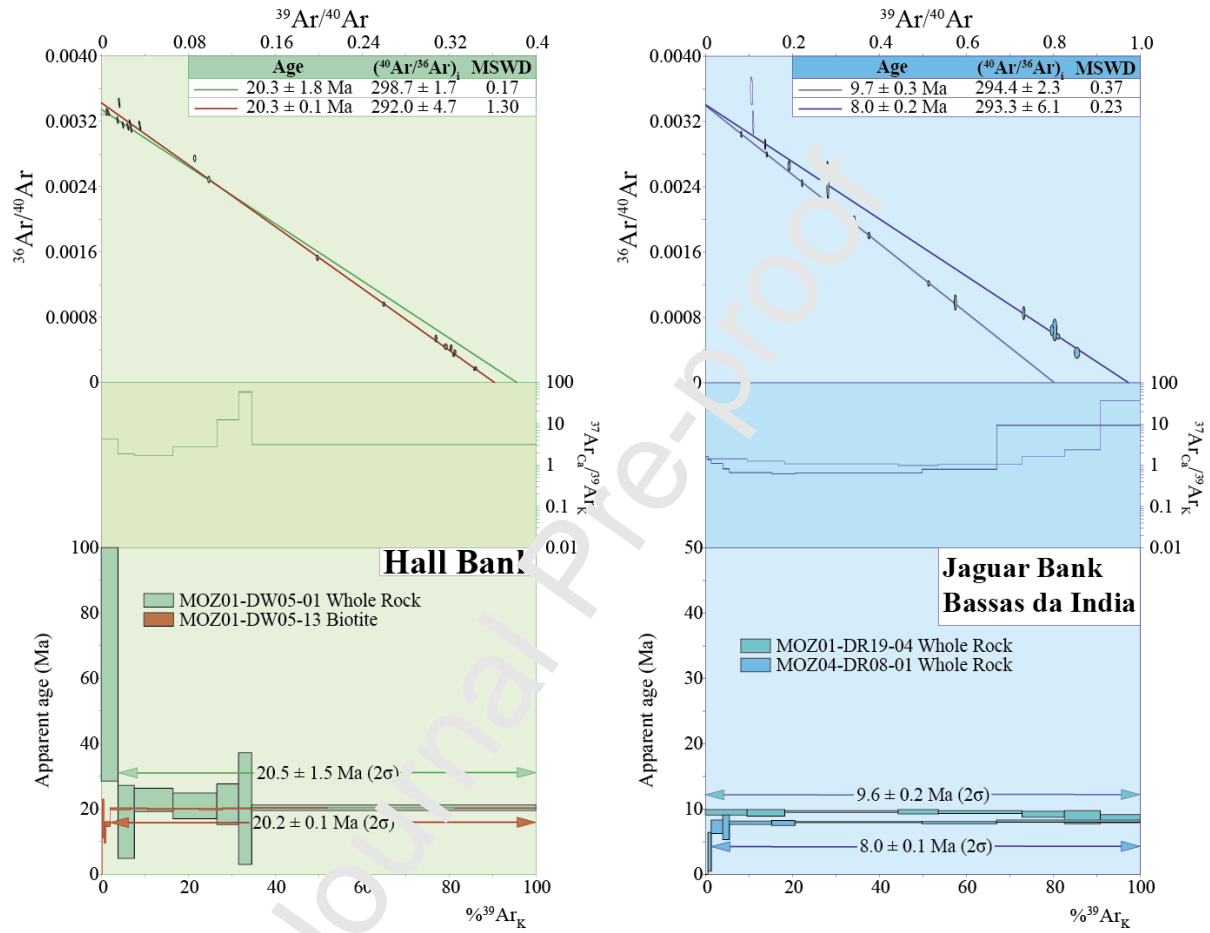


Figure 7

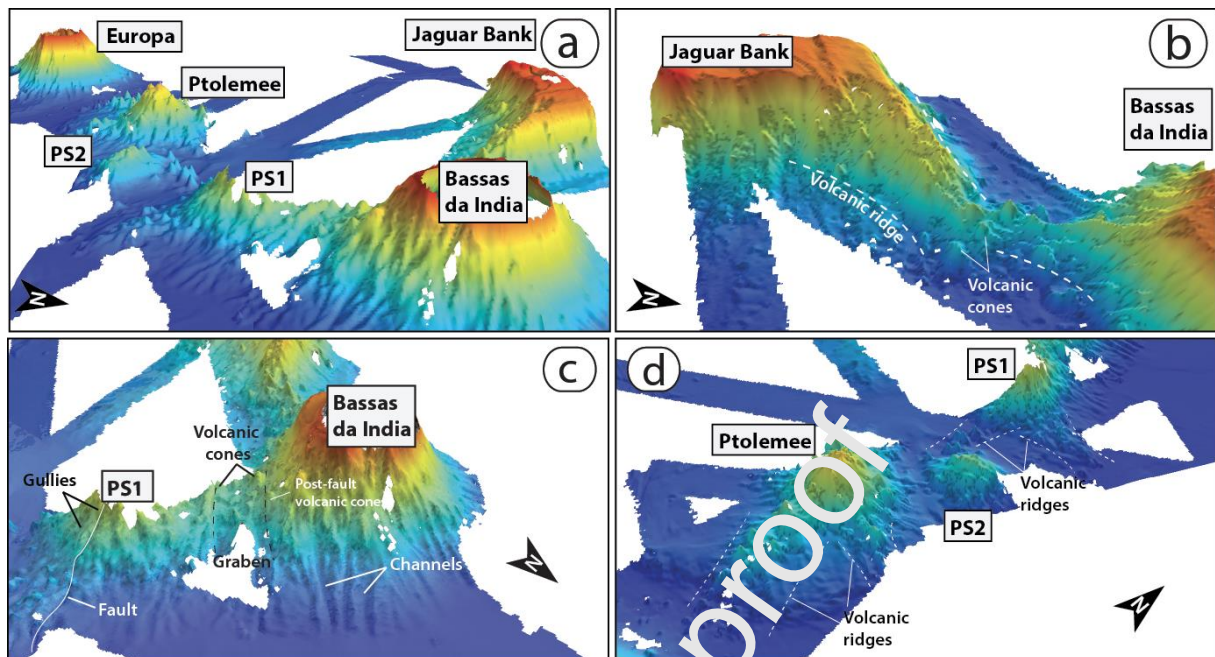
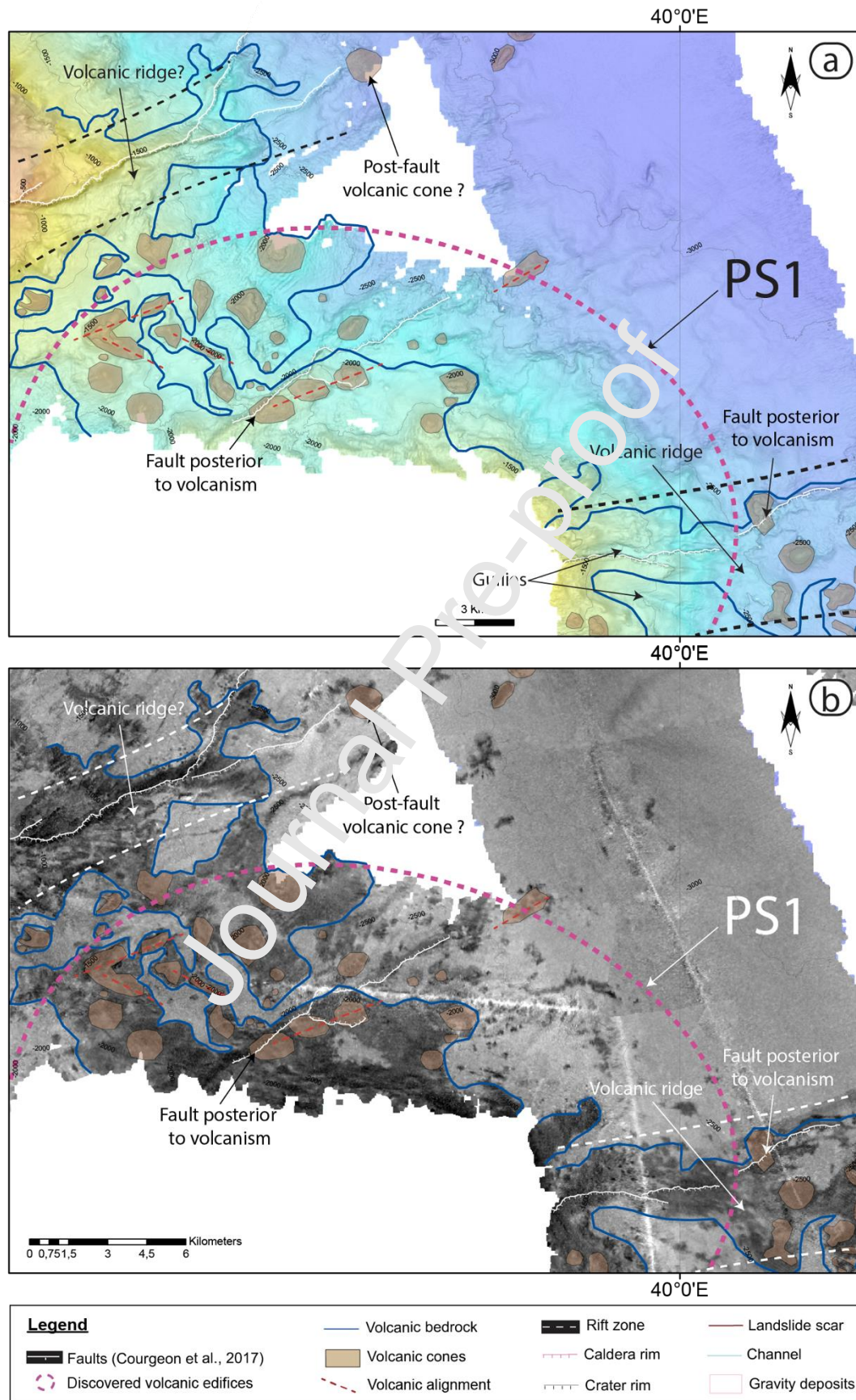
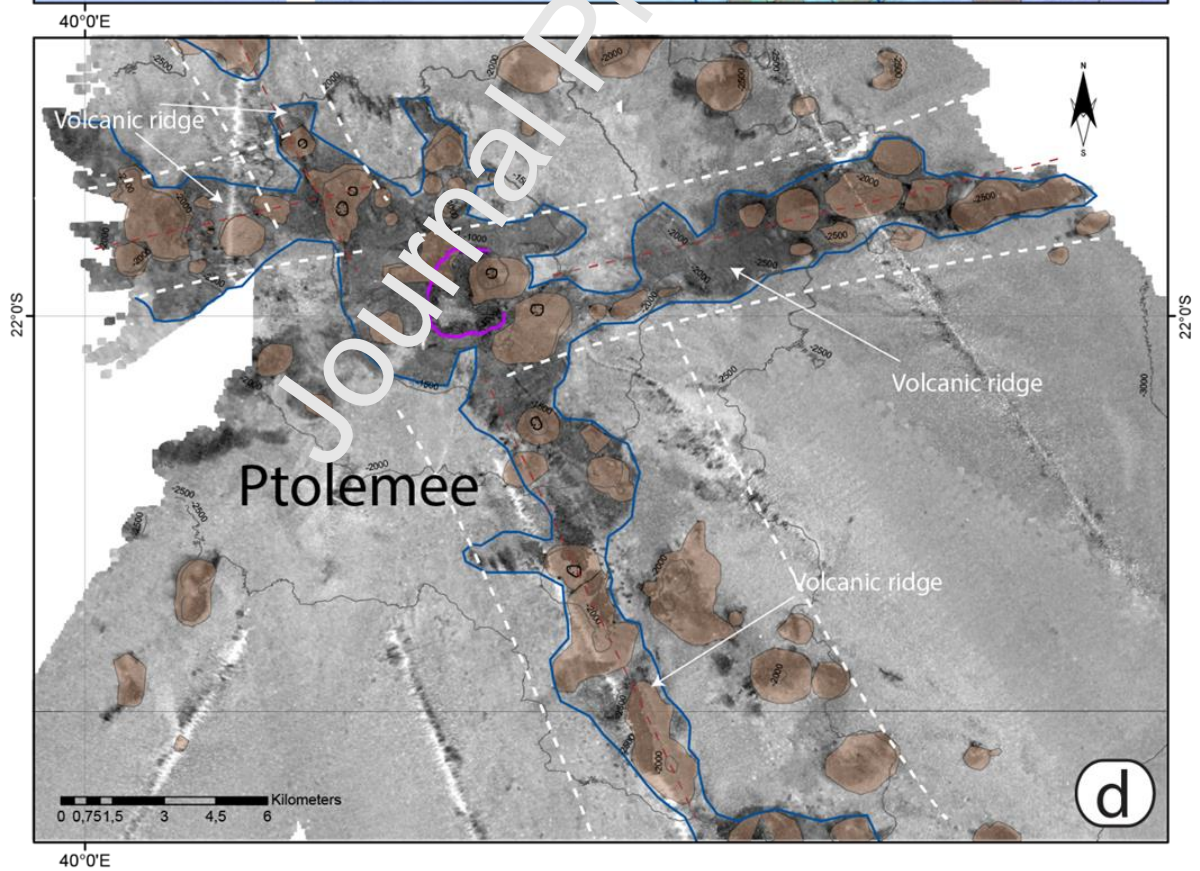
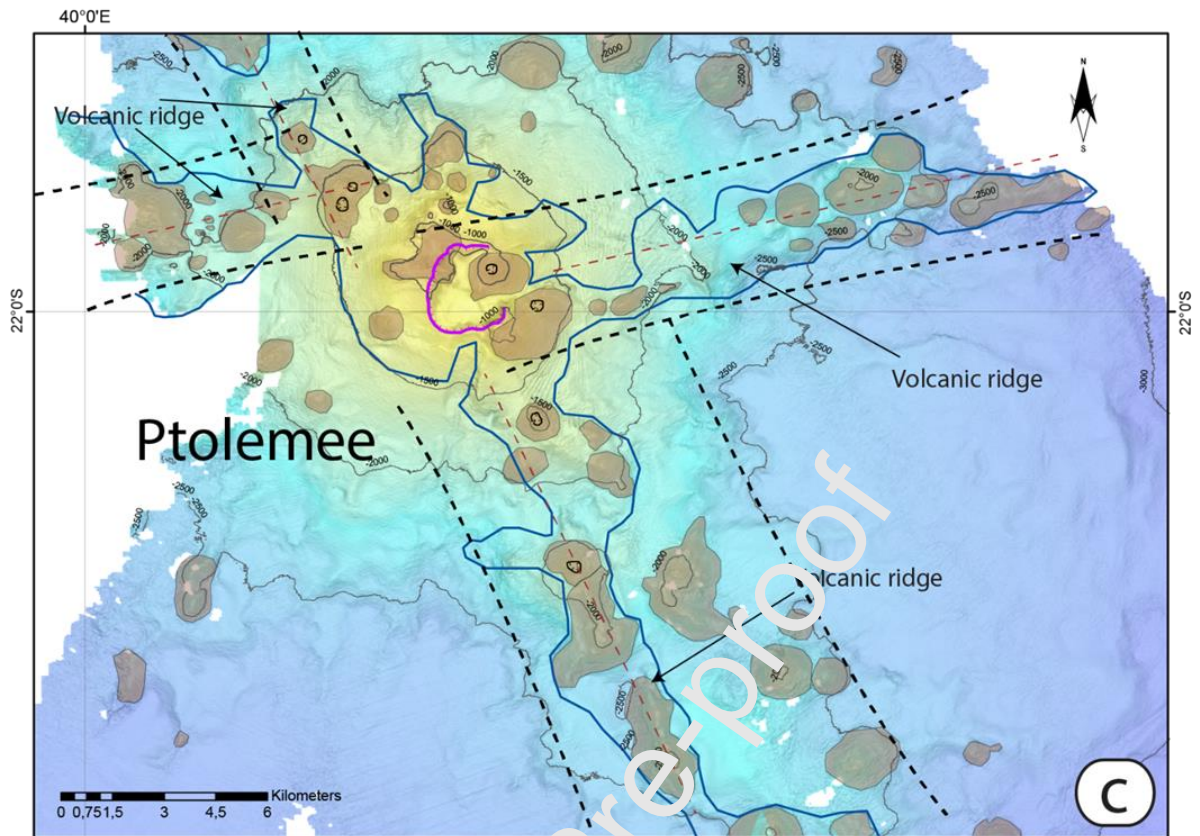


Figure 8





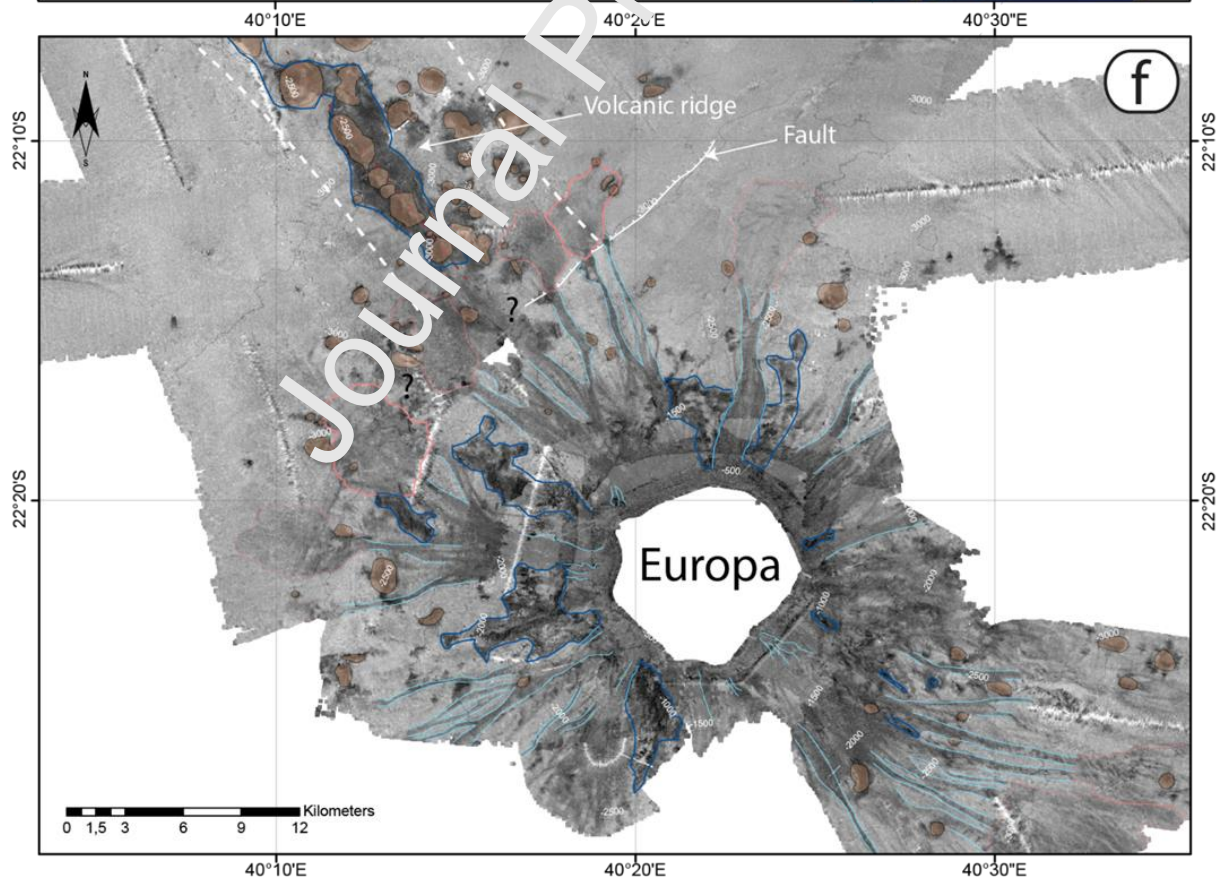
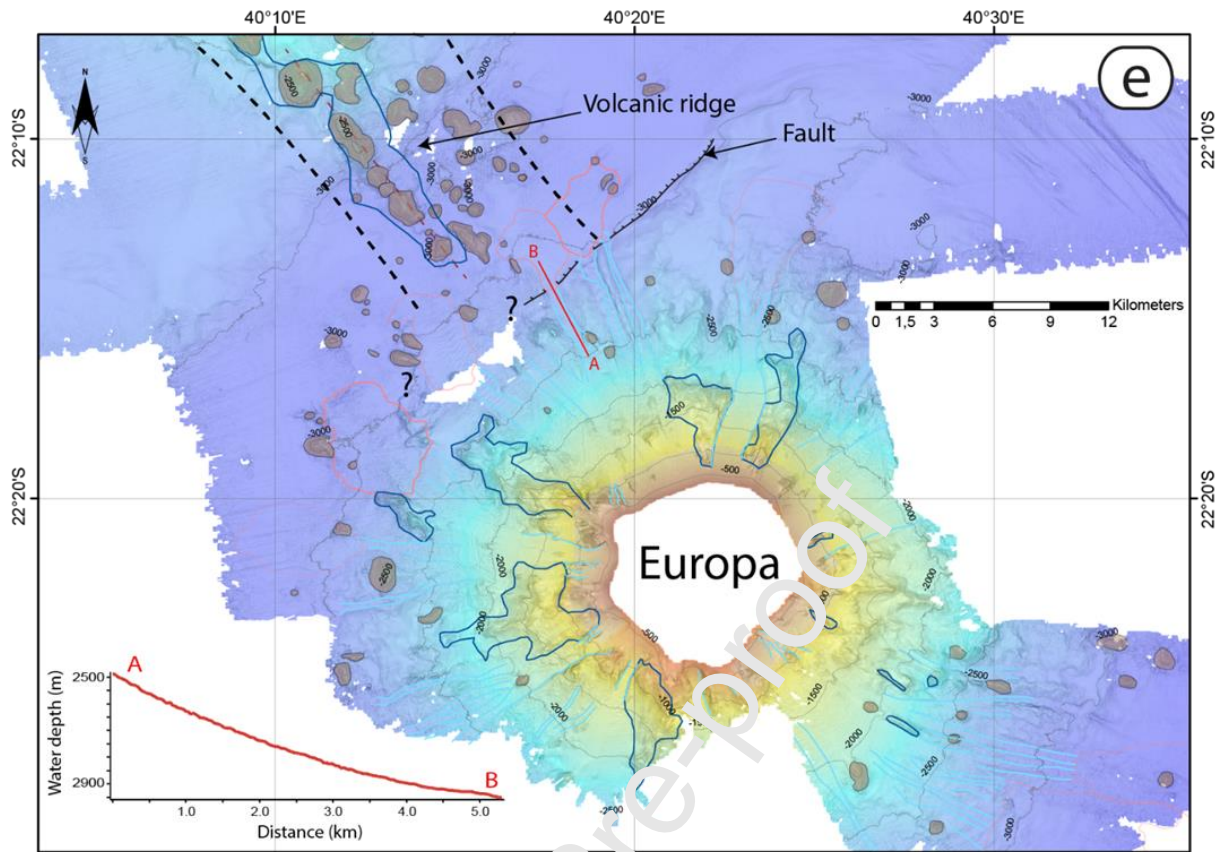


Figure 9

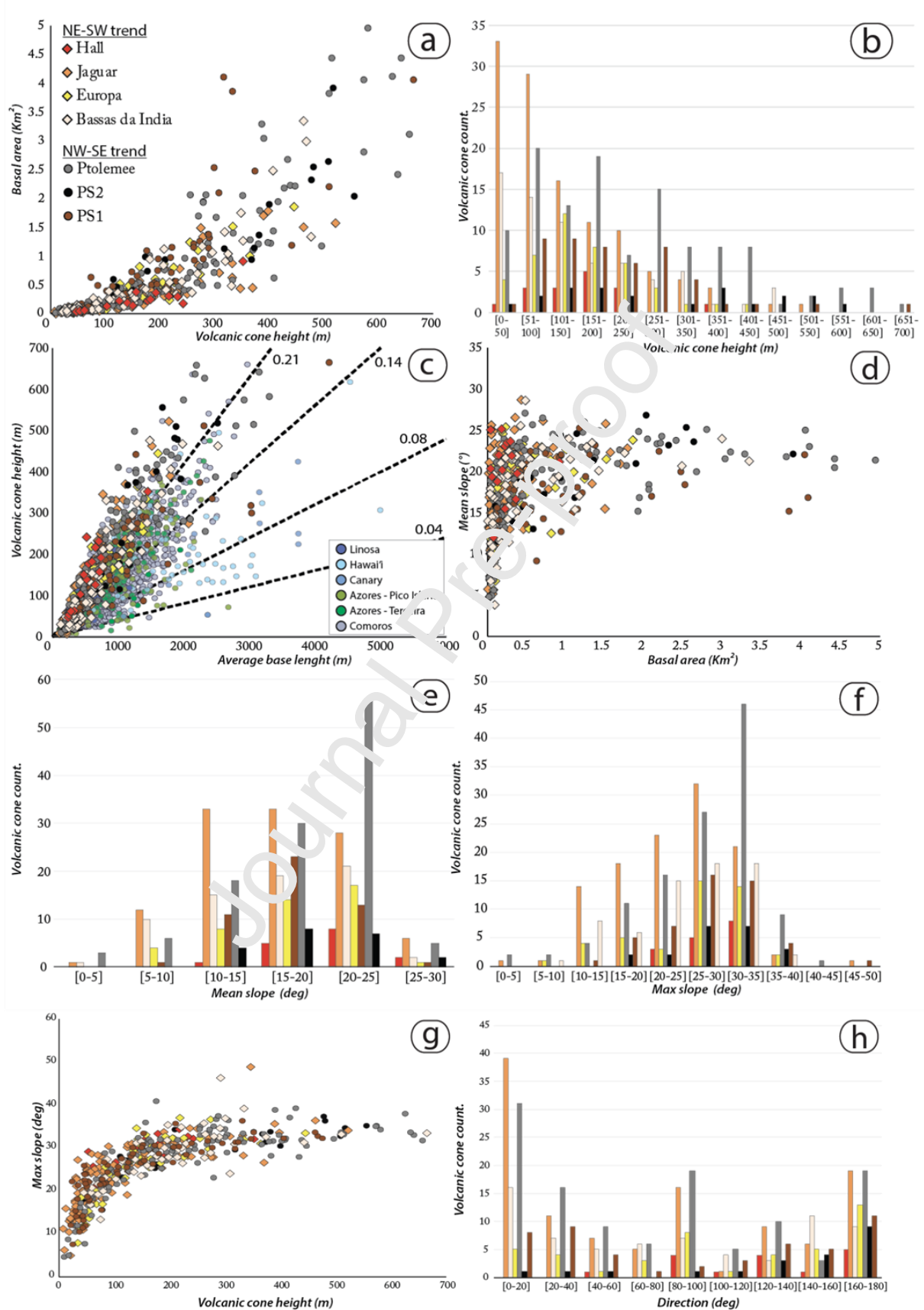


Figure 10

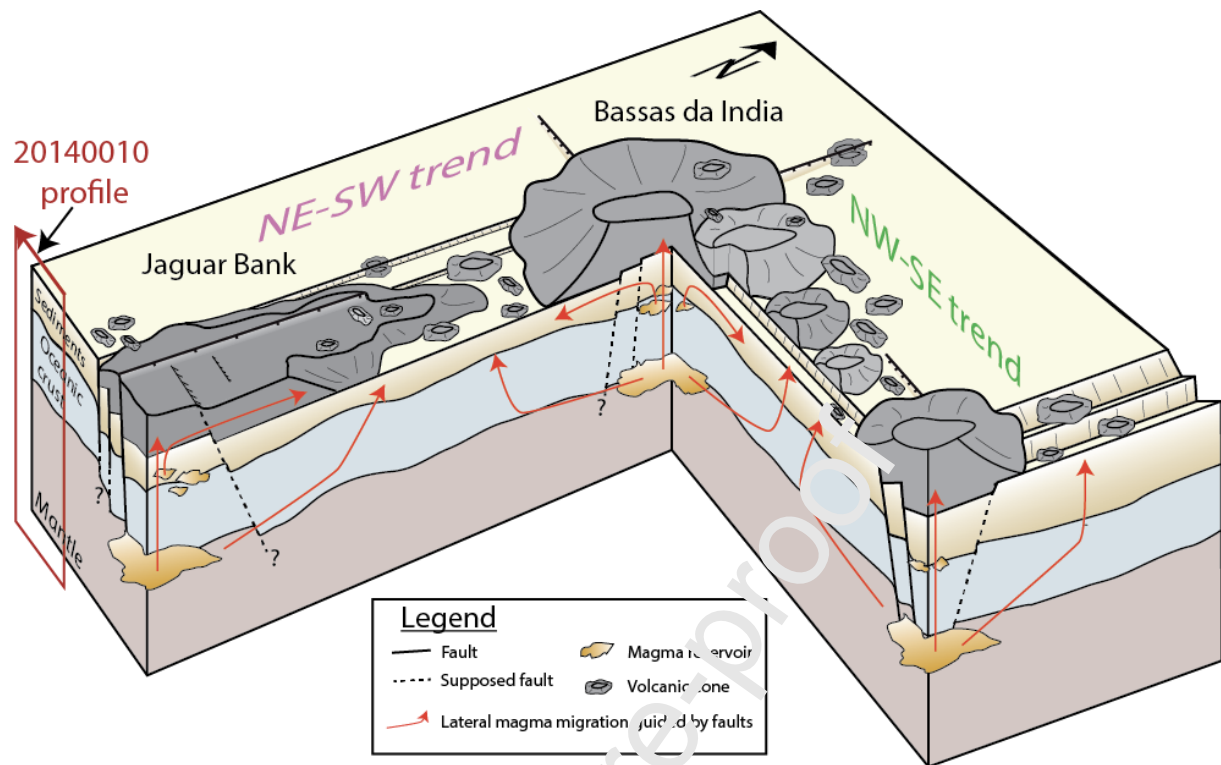
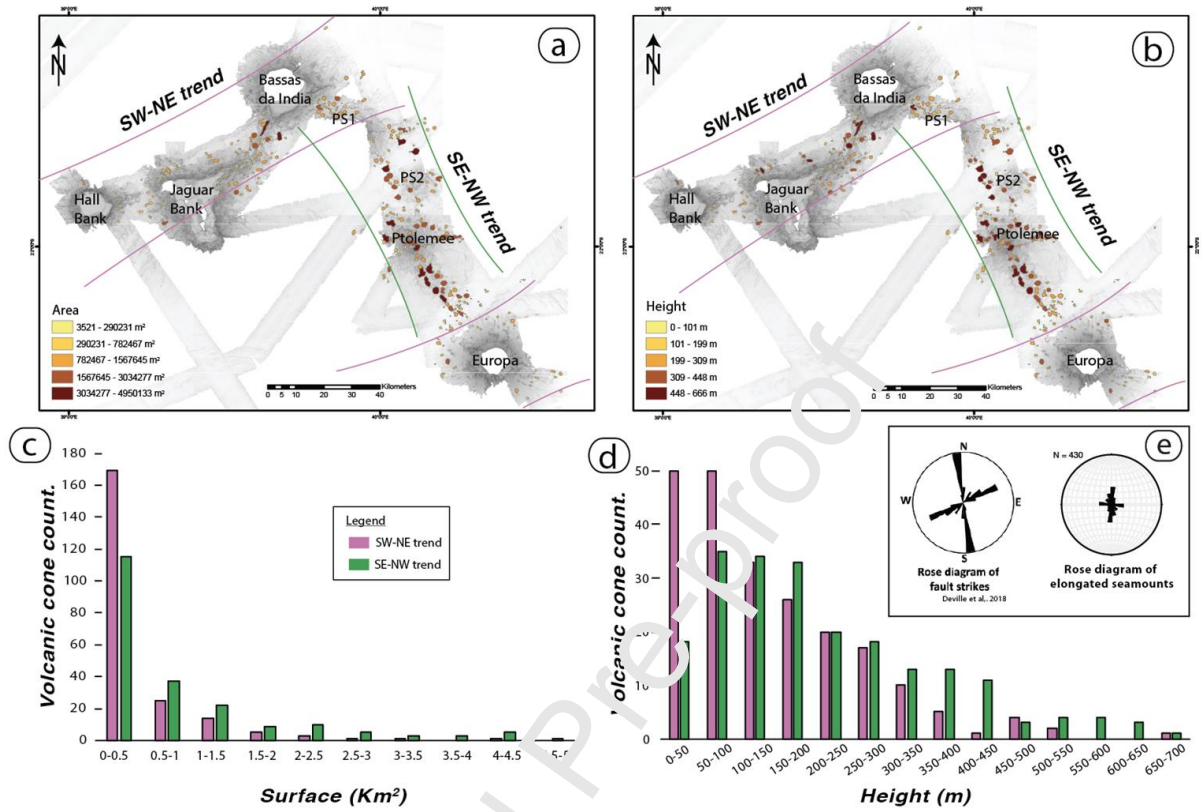


Figure 11



Supplementary material

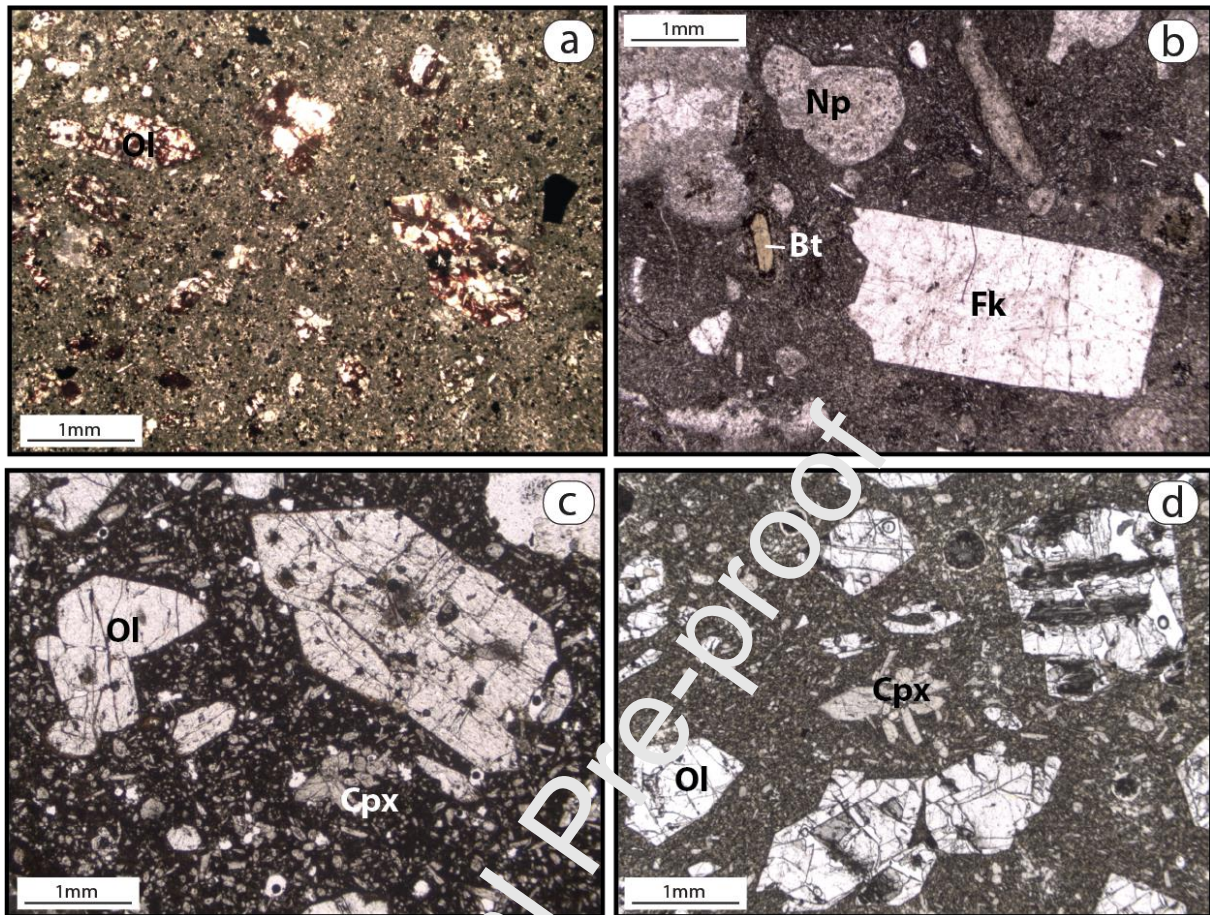


Figure S1: Petrological characteristics of the dated samples. a) MOZ01-DW05-01 collected on the Hall Bank is characterized by a porphyritic texture made of olivine phenocrysts, mostly iddingsitized, set in a fine-grained microcrystalline mesostasis. b) MOZ01-DW05-13 sample also collected on the Hall Bank has a moderately porphyritic texture, with phenocrysts set in a fine-grained microcrystalline mesostasis. The mineral assemblage includes alkali feldspar, nepheline, clinopyroxene, biotite, titanite, amphibole and Fe-Ti oxides; Feldspar is the dominant phenocryst phase and occurs as large euhedral to sub-euhedral crystals (0.5 mm – 4 cm). Samples MOZ01-DR19-04 (c) and MOZ04-DR08-01 (d), collected on the east volcanic ridge of the Jaguar Bank and on Bassas da India, respectively, display similar textures and paragenesis. Porphyritic ultramafic rocks are composed of sub-euhedral to euhedral olivine and zoned clinopyroxene phenocrysts (< 1 cm) embedded in an oxidized matrix with clinopyroxene microcrysts (< 500 μm).

Table S1: $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating experiments on our dredged samples.

MOZ01-DW5-13 biotite															
J parameter			error J			Mass Discrimination (1 σ)			Err Discrimination						
4.08E-03			1.39E-05			1.009908			1.33E-03						
step	40Ar	Error 40Ar	39Ar	Error 39Ar	38Ar	Error 38Ar	37Ar	Error 37Ar	36Ar	Error 36Ar	40Ar*/39Ar K	Error 40Ar*/39ArK	Apparent age (My)	Error Age (My)	Delay to irradiation (day)
1	385.411568	0.428596	6.509944	0.029067	0.000001	0.010199	0.510051	0.010898	1.382542	0.019291	0	0.920563	0	6.834839	196.974306
2	252.941334	0.247867	6.915365	0.015432	0.000001	0.008902	0.217861	0.018183	0.829109	0.018706	2.330799	0.806391	17.12405	5.896907	196.994444
3	314.274656	0.396079	11.230689	0.020672	0.009476	0.008083	0.695231	0.026279	1.038852	0.015839	1.735863	0.434794	12.768531	3.187405	197.013889
4	267.636822	0.192829	23.27455	0.065593	0.000001	0.009252	1.737723	0.027669	0.792768	0.008842	2.087948	0.123054	15.347407	0.902946	197.034028
5	542.244428	0.262818	109.030433	0.108392	0.000001	0.009583	4.301922	0.032841	0.930493	0.016375	2.730719	0.04652	20.045978	0.349722	197.074306
6	359.92882	0.28556	94.490864	0.179321	0.001153	0.009968	2.318811	0.03904	0.39568	0.006336	2.744075	0.022581	20.143474	0.184964	197.094444
7	480.464993	0.433517	149.38211	0.227387	0.000001	0.00797	2.163108	0.028907	0.304297	0.015778	2.721693	0.0317	19.980079	0.245936	197.674306
8	400.936632	0.390937	131.589392	0.205723	0.000001	0.009027	0.065927	0.010832	0.154752	0.008569	2.732862	0.020319	20.061617	0.170245	197.694444
9	393.060208	0.379621	127.636468	0.139604	0.000001	0.009619	0.086873	0.010653	0.17396	0.009828	2.712551	0.023405	19.913339	0.189938	197.713889
10	480.437759	0.519898	153.474684	0.263251	0.000001	0.00787	0.08443	0.010797	0.220714	0.012953	2.741474	0.025797	20.124485	0.206128	197.734028
11	1272.68246	1.253008	416.4303	0.341594	0.000001	0.014453	0.236125	0.015162	0.451383	0.018299	2.769214	0.01433	20.32698	0.134565	197.774306
12	1987.91084	0.78428	688.467334	0.569702	0.000001	0.014311	0.184131	0.016143	0.336427	0.015797	2.769914	0.008437	20.332091	0.1047	197.794444
Fusion	1288.90899	1.389094	447.999198	0.46926	0.000001	0.013076	0.106165	0.009742	0.232223	0.016558	2.750672	0.012378	20.191633	0.123435	197.824306

MOZ01-DR19-04 Whole Rock															
J parameter			error J			Mass Discrimination (1 σ)			Err Discrimination						
4.32E-03			1.47E-05			1.006618			1.31E-03						
step	40Ar	Error 40Ar	39Ar	Error 39Ar	38Ar	Error 38Ar	37Ar	Error 37Ar	36Ar	Error 36Ar	40Ar*/39Ar K	Error 40Ar*/39ArK	Apparent age (My)	Error Age (My)	Delay to irradiation (day)
1	752.219412	0.558791	168.775152	0.247464	0.007708	0.026546	45.356493	0.138616	1.964096	0.028882	1.216715	0.053667	9.478394	0.148855	85.135417
2	434.073944	0.770252	149.564211	0.190932	0.000001	0.022149	35.32527	0.086195	0.935121	0.033183	1.211245	0.066061	9.435891	0.514796	85.154861
3	885.841882	0.616075	458.186266	0.321156	0.013175	0.018783	92.624707	0.207301	1.264601	0.023816	1.240643	0.016246	9.664298	0.132502	85.175
4	277.496028	0.236155	160.677318	0.235519	0.031058	0.035546	29.917103	0.075644	0.330806	0.024992	1.23001	0.04581	9.581694	0.35815	85.204861
5	890.507637	0.673696	337.104247	0.295343	0.012218	0.032726	66.131921	0.13799	1.76228	0.029541	1.228294	0.027351	9.568362	0.216221	85.225
6	1195.85101	2.255198	170.164897	0.553717	0.005016	0.017899	51.449434	0.194476	3.517098	0.077798	1.180244	0.061275	9.195005	0.477771	85.815278
7	1732.53458	6.604745	144.266204	0.622706	0.000001	0.027761	63.589164	0.278817	5.516084	0.085	1.12539	0.129336	8.768684	1.005975	85.835417
Fusion	827.38112	2.307547	164.636052	0.584807	0.000001	0.034934	1099.10002	4.162705	4.191983	0.041	1.096235	0.083524	8.542055	0.650279	85.854861

MOZ01-DW5-01 Whole Rock															
J parameter			error J			Mass Discrimination (1 σ)			Err Discrimination						
4.31E-03			1.46E-05			1.006618			1.31E-03						
step	40Ar	Error 40Ar	39Ar	Error 39Ar	38Ar	Error 38Ar	37Ar	Error 37Ar	36Ar	Error 36Ar	40Ar*/39Ar K	Error 40Ar*/39ArK	Apparent age (My)	Error Age (My)	Delay to irradiation (day)
1	3912.15731	12.641408	8.862702	0.029537	0.04684	0.036467	59.764598	0.104782	13.32176	0.19667	8.586164	4.942875	65.685929	37.136345	92.045139
2	1223.89152	2.696425	8.174462	0.038631	0.003056	0.036381	25.1137	0.16177	4.2138	0.02198	2.06305	1.45087	16.001938	11.204139	92.065278
3	981.836203	1.964471	19.811315	0.066767	0.016114	0.035836	54.81991	0.162053	2.789	0.05327	2.944215	0.467239	22.79372	3.595847	92.085417
4	898.178117	1.131746	22.53953	0.041194	0.014325	0.036841	101.092521	0.153263	0.88006	0.035005	2.696969	0.510734	20.890593	3.934313	92.104861
5	724.032838	2.209216	11.951379	0.037835	0.000001	0.032872	222.932076	0.652743	7.7405	0.025988	2.770315	0.810394	21.45537	6.239835	92.145139
6	1311.47625	2.002547	9.650924	0.056109	0.000001	0.031795	636.290765	1.8213	5.74	0.042583	2.585703	2.21952	20.03349	17.10166	92.165278
Fusion	1440.58644	1.843377	146.687293	0.29507	0.000001	0.034705	733.712539	2.11135	1.4158	0.04157	2.625534	0.098287	20.340363	0.761901	92.185417

MOZ04-DR08-01 Whole Rock															
J parameter			error J			Mass Discrimination (1 σ)			Err Discrimination						
4.33E-03			1.47E-05			1.006618			1.31E-03						
step	40Ar	Error 40Ar	39Ar	Error 39Ar	38Ar	Error 38Ar	37Ar	Error 37Ar	36Ar	Error 36Ar	40Ar*/39Ar K	Error 40Ar*/39ArK	Apparent age (My)	Error Age (My)	Delay to irradiation (day)
250	155.054117	0.48814	16.574689	0.086119	0.008541	0.029195	4.39717	0.07387	0.578154	0.026283	0	0.468309	0	3.67728	92.825
2	175.08921	0.333479	19.429654	0.072289	0.000001	0.019195	4.22413	0.07135	0.581273	0.024799	0.442332	0.376942	3.460338	2.946016	92.845139
3	476.071677	0.504718	66.005708	0.201061	0.000001	0.030458	11.023	0.074813	1.450318	0.028216	0.933555	0.130037	7.295409	1.014602	92.865278
4	129.112283	0.220541	36.528654	0.099535	0.000001	0.02141	23.842	0.05035	0.337984	0.029999	0.926878	0.240956	7.243337	1.879491	92.885417
5	336.964462	0.40802	248.328634	0.330411	0.000001	0.030983	26.6745	0.072977	0.349696	0.025152	1.016045	0.029901	7.938628	0.235455	92.915278
6	172.117981	0.654262	139.003518	0.379131	0.000001	0.027684	3.9653	0.077275	0.142801	0.022079	1.004061	0.046887	7.845195	0.367021	92.935417
7	913.641183	1.517056	744.708571	1.507084	0.000001	0.027294	77.590259	0.429754	0.689724	0.027833	1.024483	0.011613	8.004407	0.096501	92.965278
8	541.566323	0.898145	434.617078	0.563821	0.000001	0.027416	56.133091	0.238338	0.469281	0.031435	1.013925	0.02149	7.9221	0.17077	92.975
Fusion	981.594324	1.969666	845.241982	2.424601	0.073196	0.042349	1261.731225	2.872931	2.939812	0.058694	1.047889	0.021177	8.186866	0.168578	92.995139

Parameters															
	(36Ar/37Ar)Ca	0.000322	3 %												
	(39Ar/37Ar)Ca	0.000788	4 %												
	(38Ar/37Ar)Ca	0.000026	100 %												
	(40Ar/37Ar)Ca	0.0006	100 %												
	(40Ar/39Ar)K	0.00085	4 %												
	(38Ar/39Ar)K	0.011	91 %												
[3]	(36Cl/38Cl)	316	5 %												
[1] and [1']	(40Ar/36Ar)At	298.56	0.104 %												
[1] and [1']	(38Ar/36Ar)At	0.1885	0.159 %												
[2]	Lambda 40	5.53E-10	1.35E-12 y-1												
	Lambda 39	2.58E-03	y-1												
	Lambda 37	1.98E-02	d-1												
	Lambda 36Cl	2.26E-06	y-1												

References:

[1] Lee, J.Y., Marti, K., Severinghaus, J.P., Kawamura, K., Yano, K., Sato, J., et al., (2006). A redetermination of the isotopic abundances of atmospheric Ar. *Geochimica Cosmochimica Acta*, 70, 4507-4512.

[1'] Mark, D.F., Stuart, F.M., De Podesta, M (2011). New high-precision measurements of the isotopic composition of atmospheric argon. *Geochimica Cosmochimica Acta*, 75, 7494-7501.

Renne, P.R., Balco, G., Ludwig, R.L., Mundil, R., Min, K., et al., (2011). Response to the comment by W.H. Schwarz et al. on "Joint determination of (40)K decay constants and (40)Ar*/(40)K for the Fish Canyon sanidine standard, and improved accuracy for (40)Ar/(39)Ar geochronology" by P.R. Renne et al. *Geochimica Cosmochimica Acta*, 75, 5097-5100.

[2] York, D., Personal Communication - McMaster University.

[3] York, D. (1969). Least-squares fitting of a straight line with correlated errors. *Earth Planet. Sci. Lett.* 5, 320-4.

Renne, P.R., Balco, G., Ludwig, Mundil, R., Min, K., et al., (2011). Response to the comment by W.H. Schwarz et al. on "Joint determination of (40)K decay constants and (40)Ar*/(40)K for the Fish Canyon sanidine standard, and improved accuracy for (40)Ar/(39)Ar geochronology" by P.R. Renne et al. *Geochimica Cosmochimica Acta*, 75, 5097-5100.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Bassas da India/Europa seafloor is characterized by seven large seamounts and more than 430 volcanic cones
- Miocene to Pleistocene volcanism is distributed along two main trends with different stages of maturation
- Magma ascent is strongly controlled by large pre-existing crustal structures
- Large edifices are fed by a well-developed magmatic system whereas volcanic ridges are supplied by episodic lateral magma migration through a network of faults.