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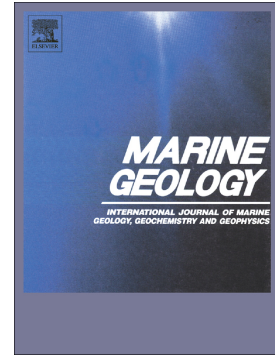
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# First characterization of the volcanism in the southern Mozambique Channel: Geomorphological and structural analyses

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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; Mougnot et al., 1986; Coffin and Kaminowitz, 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 (~155-120 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; Grimison 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, 1985; 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 Caribes 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  $\text{CO}_2$  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  $2\sigma$  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  $2\sigma$ , 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  $2\sigma$  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  $20.5 \pm 1.5$  Ma and  $20.2 \pm 0.1$  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 volcaniclastic 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 multi-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  $9.6 \pm 0.2$  Ma and  $9.7 \pm 0.3$  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  $8.0 \pm 0.2$  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  $N60^\circ$  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  $11^\circ$ , 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  $6^\circ$  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 ( $22.00^\circ$  S,  $46.06^\circ$  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  $5 \text{ km}^2$  in area, extending  $N70^\circ - 75^\circ$ , 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 km<sup>2</sup> (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 km<sup>2</sup>, 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 km<sup>2</sup>, respectively). Thus, the larger edifices are mainly located along the NW-SF 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  $10^\circ$  to  $25^\circ$  (Fig. 9d). Less than 5% exceed  $25^\circ$ . Both small and large edifices can have mean slopes up to  $20^\circ$  (Fig. 9d). Moreover, small edifices with a basal area  $< 1 \text{ km}^2$  tend to present a large range of mean slopes varying from  $4^\circ$  to  $29^\circ$  (Fig. 9d). On the contrary, large edifices with a basal area of up to  $2 \text{ km}^2$  are characterized by elevated mean slopes that are up to  $15^\circ$ . 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  $10^\circ$  and  $25^\circ$ . As for the mean slopes, the distribution of maximum slope is fairly unimodal with the most frequent slope being between  $25^\circ$  and  $35^\circ$  (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  $40^\circ$  (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  $200^\circ$ , while a second subset lies between  $080$  and  $100^\circ$ .

## 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 to 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 Ptolemy, 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, Ptolemy 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 Ptolemy 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 Ptolemy 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 Ptolemy 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 Polemee 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 Khadge, 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.,  $16.3 \pm 0.1$  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  $20.5 \pm 1.5$  and  $20.2 \pm 0.1$  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  $9.6 \pm 0.2$  Ma. This age is close to previous ages obtained for a packstone sample collected along the southern flank of the Jaguar Bank carbonate platform ( $11.45 \pm 0.37$  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  $8.0 \pm 0.2$  Ma obtained for this sample (Fig. 6) is also very close to that obtained for the drowned carbonate terraces south of Bassas da India ( $8.48 \pm 0.49$  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  $1 \text{ km}^2$  (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 km<sup>2</sup> study area. The seamount and volcanic cone basal areas cover 5,905 km<sup>2</sup>, which represents a minimum of 21% of the seafloor. Comparable values have been obtained from the Canary archipelago volcanism, at 7,273 km<sup>2</sup> (Acosta et al., 2003b), whereas it represents 56 % of the area for the island of Hawaii (10,458 km<sup>2</sup>, 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 Hawaii Islands (Fornari et al., 1988; Clague et al., 2019), Canary Islands (Acosta et al., 2003a; Llanes et al., 2009), Comoros Islands (Tzevahirtzian et al., 2021), Galapagos Islands (Marpp 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 7c, 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. Mougénot 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 other 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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## 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  $2\sigma$  level; errors in the J-parameter are not included. Plateau age is given

with  $2\sigma$  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.

<i>Dredge</i>	<i>Oceanographic campaign</i>	<i>Location</i>	<i>DOI</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Depth</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Depth</i>
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.

<i>Site</i>	<i>Name</i>	<i>Latitude (DD)</i>	<i>Longitude (DD)</i>	<i>Diameter (m)</i>	<i>Area (Km<sup>2</sup>)</i>	<i>Elevation (m)</i>	<i>Prof_ME AN (m)</i>	<i>Pent_e_M IN (°)</i>	<i>Pent_e_M AX (°)</i>	<i>Pent_e_M AN (°)</i>	<i>ORIENTATION</i>	<i>Aspect ratio</i>
Hall Bank	S M-1	39.044	-21.8019	241	0.0404	47	1718	15.0	24.0	20.30	162	0.20
Hall Bank	S M-2	39.045	-21.7931	145	0.09180	353	1715	4.78	32.0	21.15	123	0.24
Hall Bank	S M-3	39.051	-21.8028	335	0.091	63	1629	2.55	20.6	11.95	172	0.19
Hall	S	39.0519	-21.8028	519	0.091	140	-	2.18	29.7	20.14	167	0.0

Bank	M-4	108	21.9		19		1374		3			27
	S	39.	-		0.							
Hall Bank	M-5	121	21.9		17		-	15.4	32.1			0.
	S	39.	-	524	91	243	1565	8	2	25.09	117	46
Hall Bank	M-6	133	21.8		04		-	20.2	29.0			0.
	S	39.	-	253	56	54	1009	2	6	24.99	90	21
Hall Bank	M-7	135	21.9		22		-		33.3			0.
	S	39.	-	553	69	179	1851	6.88	5	23.06	135	32
Hall Bank	M-8	150	21.8		14		-	10.2	31.0			0.
	S	39.	-	477	71	151	1378	8	1	21.97	97	32
Hall Bank	M-9	150	21.8		24		-		31.1			0.
	S	39.	-	605	82	183	1819	6.61	6	23.43	124	30
Hall Bank	M-10	151	21.8		06		-	14.0	25.6			0.
	S	39.	-	289	12	63	1404	8	1	19.33	90	22
Hall Bank	M-11	155	21.8		22		-		24.5			0.
	S	39.	-	654	87	126	1648	4.33	5	15.42	99	19
Hall Bank	M-12	156	21.8		31		-		34.3			0.
	S	39.	-	660	15	217	1499	5.25	2	21.85	144	33
Hall Bank	M-13	158	21.9		33		-		32.1			0.
	S	39.	-	711	43	157	2130	1.14	6	19.71	139	22
Hall Bank	M-14	163	21.8		29		-		32.7			0.
	S	39.	-	703	90	233	1682	8.98	3	23.58	172	33
Hall Bank	M-15	172	21.8		36		-		28.2			0.
	S	39.	-	745	76	193	2117	3.05	1	16.63	163	26
Hall Bank	M-16	204	21.8		13		-		26.7			0.
	S	39.	-	428	14	104	2228	7.74	3	18.71	45	24
Jaguar Bank	M-17	230	21.8	111	78		-		34.6			0.
	S	39.	-	6	06	237	2347	9.36	2	22.03	10	21
Jaguar Bank	M-18	232	21.7		20		-		23.6			0.
	S	39.	-	536	99	104	2638	1.78	0	12.96	0	19
Jaguar Bank	M-19	251	21.8	103	47		-		31.6			0.
	S	39.	-	2	85	202	2217	5.64	9	20.18	15	20
Jaguar Bank	M-20	254	21.8		56		-	10.3	28.2			0.
	S	39.	-	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 Bank	M-38	307	21.9	179	70		-		35.5			0.
	S	39.	-		0.	390	1837	4.17	5	20.85	21	22
Jaguar Bank	M-39	308	21.7		13		-		26.7			0.
	S	39.	-		0.	74	1339	4.31	7	14.06	141	14
Jaguar Bank	M-40	312	21.7		01		-	13.1	13.2			0.
	S	39.	-		0.	28	1294	8	1	13.19	90	19
Jaguar Bank	M-41	316	21.7		05		-	19.8	28.1			0.
	S	39.	-		0.	77	1115	0	0	24.47	135	28
Jaguar Bank	M-42	317	21.7		01		-	19.7	20.1			0.
	S	39.	-		1.	43	1274	8	0	19.69	0	26
Jaguar Bank	M-43	319	21.7	177	56		-		34.1			0.
	S	39.	-		0.	523	1816	2.68	2	22.29	123	29
Jaguar Bank	M-44	339	21.8		03		-	16.5	28.5			0.
	S	39.	-		0.	59	919	3	5	22.79	90	28
Jaguar Bank	M-45	340	21.7	105	78		-		31.4			0.
	S	39.	-		0.	209	1979	1.10	5	17.84	146	20
Jaguar Bank	M-46	348	21.7		17		-		27.4			0.
	S	39.	-		0.	114	2103	0.85	8	14.95	90	24
Jaguar Bank	M-47	348	21.7		35		-	12.4	31.7			0.
	S	39.	-		0.	225	1949	2	9	26.53	173	32
Jaguar Bank	M-48	349	21.9		02		-	13.6	19.3			0.
	S	39.	-		0.	34	-944	5	9	16.88	90	17
Jaguar Bank	M-49	365	21.9		05		-	13.0	27.1			0.
	S	39.	-		0.	34	-721	1	7	19.88	0	12
Jaguar Bank	M-50	367	21.9		04		-	21.4	30.3			0.
	S	39.	-		0.	90	-587	5	9	25.55	143	33
Jaguar Bank	M-51	402	21.9		05		-		24.0			0.
	S	39.	-		0.	58	-957	9.85	3	17.27	0	20
Jaguar Bank	M-52	440	21.7		45		-		21.8			0.
	S	39.	-		0.	120	2422	2.39	9	12.97	122	14
Jaguar Bank	M-53	452	21.7	107	88		-		28.1			0.
	S	39.	-		0.	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	79	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
	S	39.	-		0.				25.4			0.
Jaguar	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	-772	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	65	-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	558	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	10	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											
Jaguar Bank	M-11	39.548	-	21.7	0.05	-	17.5					0.
	S	2	582	277	33	58	1161	2.97	7	11.82	45	21
Jaguar Bank	M-11	39.548	-	21.6	0.42	-	27.9					0.
	S	6	867	751	34	218	2155	2.52	9	22.26	171	29
Jaguar Bank	M-11	39.549	-	21.7	0.04	-	11.5					0.
	S	7	512	263	72	35	1134	5.04	0	8.29	90	13
Jaguar Bank	M-11	39.550	-	21.7	0.17	-	31.0					0.
	S	8	633	488	25	132	1303	3.30	4	22.65	0	27
Jaguar Bank	M-11	39.552	-	21.7	0.05	-	16.4					0.
	S	9	394	270	01	31	1143	5.11	2	11.09	90	11
Jaguar Bank	M-12	39.553	-	21.8	0.35	-	24.5					0.
	S	0	327	702	89	127	1968	7.53	5	16.41	6	18
Jaguar Bank	M-12	39.558	-	21.7	0.19	-	25.0					0.
	S	1	322	384	77	64	1102	3.28	1	16.66	0	17
Jaguar Bank	M-12	39.564	-	21.7	0.51	-	30.2					0.
	S	2	352	835	51	216	1186	2.37	4	20.30	8	26
Jaguar Bank	M-12	39.564	-	21.7	0.18	-	26.0					0.
	S	3	684	512	64	100	1727	5.09	7	16.51	164	20
Jaguar Bank	M-12	39.567	-	21.7	0.37	-	30.6					0.
	S	4	048	774	65	232	1748	4.52	4	22.91	59	30
Jaguar Bank	M-12	39.567	-	21.7	0.05	-	24.4					0.
	S	5	302	281	63	57	1313	5.63	5	14.91	30	20
Jaguar Bank	M-12	39.572	-	21.8	1.49	-	27.9					0.
	S	6	070	3	61	275	2051	2.12	0	15.40	127	13
Jaguar Bank	M-12	39.572	-	21.6	0.30	-	32.2					0.
	S	572	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.							
Europa	13	473	22.4		37		-	13.2	33.0			0.
	0	1	855	722	36	158	2563	1	0	21.33	61	22
	S											
	M-	40.	-		0.							
Europa	13	579	22.4		45		-		31.8			0.
	1	8	634	778	15	196	3153	5.98	4	23.28	60	25
	S											
	M-	40.	-		1.							
Europa	13	437	22.4	129	00		-		30.9			0.
	2	5	616	8	31	365	2049	7.14	5	22.65	99	28
	S											
	M-	40.	-		0.							
Europa	13	481	22.4		19		-		34.6			0.
	3	5	445	523	53	141	2467	4.79	2	24.49	3	27
	S											
	M-	40.	-		0.							
Europa	13	485	22.4		18		-	11.6	32.0			0.
	4	1	334	508	48	143	2463	3	4	24.85	13	28
	S											
	M-	40.	-		0.							
Europa	13	442	22.4		28		-		30.5			0.
	5	8	258	639	94	169	1853	5.72	0	22.02	161	26
	S											
	M-	40.	-		0.							
Europa	13	502	22.4	101	60		-		32.6			0.
	6	5	203	2	64	192	2619	6.03	5	22.05	163	19
	S											
	M-	40.	-		0.							
Europa	13	561	22.4		43		-		30.7			0.
	7	9	180	779	55	146	3075	6.66	8	20.99	157	19
	S											
	M-	40.	-		0.							
Europa	13	281	22.4		23		-		36.9			0.
	8	3	174	594	47	218	1936	5.25	6	25.30	25	37
	S											
	M-	40.	-		0.							
Europa	13	198	22.4	103	69		-		36.5			0.
	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	377	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

	S											
	M-	40.	-		0.							
	16	205	22.2		52		-		26.7			0.
Europa	5	8	384	846	86	128	3048	1.25	2	13.01	37	15
	S											
	M-	40.	-		1.							
	16	424	22.2	142	51		-		31.9			0.
Europa	6	9	381	9	59	334	2704	6.35	0	21.46	174	23
	S											
	M-	40.	-		0.							
	16	245	22.2		07		-		15.2			0.
Europa	7	6	378	334	85	54	3026	7.59	1	10.50	20	16
	S											
	M-	40.	-		0.							
	16	340	22.2		16		-		25.5			0.
Europa	8	5	322	478	41	120	2634	8.61	4	18.74	165	25
	S											
	M-	40.	-		0.							
	16	376	22.2		37		-		29.3			0.
Europa	9	2	258	722	22	135	2696	4.92	6	18.33	107	19
	S											
	M-	40.	-		0.							
	17	277	22.2		21		-		22.9			0.
Europa	0	9	252	642	01	120	2969	1.87	3	13.83	125	19
	S											
	M-	40.	-		0.							
	17	224	22.2		08		-		12.0			0.
Europa	1	3	228	341	57	49	3081	3.92	7	7.41	90	14
	S											
	M-	40.	-		1.							
	17	243	22.2	136	10		-		29.7			0.
Europa	2	1	172		24	271	2997	6.01	8	19.90	55	20
	S											
	M-	40.	-		0.							
	17	272	22.2		07		-					0.
Europa	3	6	151	331	69	34	3017	1.79	7.81	5.58	63	10
	S											
	M-	40.	-		2.							
	17	257	22.2	233	06		-		32.8			0.
Ptoleme	4	9	133	8	05	256	2979	1.95	6	18.29	140	11
	S											
	M-	40.	-		0.							
	17	414	22.2		30		-	10.5	30.9			0.
Ptoleme	5	1	119	646	42	160	2876	2	8	22.32	23	25
	S											
	M-	40.	-		0.							
	17	237	22.2		07		-		18.1			0.
Ptoleme	6	8	097	334	88	63	3054	8.46	7	13.84	45	19
	S											
	M-	40.	-		0.				24.9			0.
Ptoleme	7	240	22.1	683	34	130	3009	5.39	7	18.98	80	19



	17	9	999		53								
	7												
	S												
	M-	40.	-		0.								
Ptoleme	17	259	22.1		41		-		30.2				0.
e	8	6	992	749	85	171	2978	8.58	5	23.42	26		23
	S												
	M-	40.	-		0.								
Ptoleme	17	253	22.1		12		-		19.9				0.
e	9	7	985	425	48	90	3036	6.37	6	14.26	173		21
	S												
	M-	40.	-		2.								
Ptoleme	18	226	22.1	180	04		-		33.6				0.
e	0	6	984	4	22	353	2911	5.36	4	23.90	132		20
	S												
	M-	40.	-		0.								
Ptoleme	18	204	22.1		16		-		18.1				0.
e	1	4	939	473	59	85	3037	7.26	3	13.76	0		18
	S												
	M-	40.	-		0.								
Ptoleme	18	255	22.1		01		-						0.
e	2	1	934	141	21	10	3004	4.33	4.54	4.44	90		07
	S												
	M-	40.	-		0.								
Ptoleme	18	250	22.1		37		-		29.2				0.
e	3	4	922	745	72	206	2990	7.13	9	21.84	71		28
	S												
	M-	40.	-		0.								
Ptoleme	18	255	22.1		06		-		24.9				0.
e	4	5	904	323	18	95	3060	6.95	5	17.20	18		29
	S												
	M-	40.	-		0.								
Ptoleme	18	218	22.1		43		-		28.1				0.
e	5	3	858	790	98	211	2929	8.15	7	21.52	26		27
	S												
	M-	40.	-		0.								
Ptoleme	18	323	22.1		20		-		22.4				0.
e	6	3	895	534	22	70	3036	6.18	4	13.77	51		13
	S												
	M-	40.	-		0.								
Ptoleme	18	246	22.1		27		-		25.1				0.
e	7	0	881	624	56	186	2990	6.36	1	16.58	58		30
	S												
	M-	40.	-		0.								
Ptoleme	18	256	22.1		11		-		16.4				0.
e	8	5	869	425	07	54	3013	7.22	9	11.87	81		13
	S												
	M-	40.	-		0.								
Ptoleme	18	320	22.1		22		-		21.3				0.
e	9	1	857	700	27	87	3065	2.64	4	12.55	51		12

Ptoleme	S	40.	-	0.								
	M-19	281	22.1	09					16.0			0.
Ptoleme	S	40.	-	0.								
	M-19	214	22.1	110	83				31.8			0.
Ptoleme	S	40.	-	0.								
	M-19	277	22.1	17					23.1			0.
Ptoleme	S	40.	-	0.								
	M-19	270	22.1	35					29.3			0.
Ptoleme	S	40.	-	0.								
	M-19	315	22.1	12					18.3			0.
Ptoleme	S	40.	-	0.								
	M-19	254	22.1	53					25.8			0.
Ptoleme	S	40.	-	0.								
	M-19	291	22.1	68					11.8			0.
Ptoleme	S	40.	-	0.								
	M-19	202	22.1	24	28				31.4			0.
Ptoleme	S	40.	-	0.								
	M-19	252	22.1	182	66				33.1			0.
Ptoleme	S	40.	-	0.								
	M-19	276	22.1	160	94				34.9			0.
Ptoleme	S	40.	-	0.								
	M-19	224	22.1	157	37				31.6			0.
Ptoleme	S	40.	-	0.								
	M-19	341	22.1	48					29.2			0.
Ptoleme	S	40.	-	0.								
	M-19	225	22.1	664	31	144	2615	9.25	9	23.18	119	22

	20	6	418		70								
	2												
	S												
	M-	40.	-		0.								
Ptoleme	20	278	22.1		08		-						0.
e	3	9	411	344	54	17	3050	2.98	8.58	5.56	6		05
	S												
	M-	40.	-		4.								
Ptoleme	20	178	22.1	232	10		-		37.8				0.
e	4	4	408	7	64	627	2337	5.94	5	22.94	83		27
	S												
	M-	40.	-		1.								
Ptoleme	20	200	22.1	200	92		-		22.9				0.
e	5	3	408	3	76	281	2398	0.99	6	15.13	86		14
	S												
	M-	40.	-		1.								
Ptoleme	20	239	22.1	140	39		-		31.2				0.
e	6	0	387	3	23	335	2727	2.69	7	22.33	162		24
	S												
	M-	40.	-		0.								
Ptoleme	20	336	22.1		10		-		11.7				0.
e	7	8	379	408	89	34	5078	2.26	8	7.67	37		08
	S												
	M-	40.	-		2.								
Ptoleme	20	204	22.1	191	67		-		27.8				0.
e	8	0	169	9	41	435	2349	6.29	8	19.93	21		23
	S												
	M-	40.	-		0.								
Ptoleme	20	234	22.1		13		-		26.9				0.
e	9	3	156	522	40	195	2660	7.00	1	18.62	10		21
	S												
	M-	40.	-		4.								
Ptoleme	21	150	22.1	292	05		-		35.0				0.
e	0	3	125	4	54	574	2261	5.06	8	24.92	112		20
	S												
	M-	40.	-		0.								
Ptoleme	21	449	22.1		06		-						0.
e	1	1	125	296	17	48	3143	2.46	7.55	4.84	0		16
	S												
	M-	40.	-		0.								
Ptoleme	21	025	22.1		12		-	11.2	19.8				0.
e	2	1	121	428	22	58	2742	7	4	15.00	70		13
	S												
	M-	40.	-		0.								
Ptoleme	21	461	22.1		22		-		21.9				0.
e	3	7	062	615	32	86	3099	3.80	6	13.14	10		14
	S												
	M-	40.	-		0.								
Ptoleme	21	454	22.1		02		-						0.
e	4	0	061	197	36	18	3132	4.45	4.94	4.69	90		09

	S											
Ptoleme	M-	40.	-	0.								
e	21	195	22.0	109	89		-		32.3			0.
	5	4	956	8	92	301	2366	4.53	9	23.90	21	27
	S											
Ptoleme	M-	40.	-	1.								
e	21	011	22.0	130	01		-		27.9			0.
	6	8	955	1	20	181	2689	3.16	9	17.75	92	14
	S											
Ptoleme	M-	40.	-	2.								
e	21	182	22.0	169	17		-		39.2			0.
	7	5	944	5	14	429	2207	2.26	1	23.27	168	25
	S											
Ptoleme	M-	40.	-	4.								
e	21	133	22.0	315	43		-		32.9			0.
	8	2	843	3	34	643	2122	4.02	2	21.49	78	20
	S											
Ptoleme	M-	40.	-	0.								
e	21	186	22.0		61		-		26.4			0.
	9	6	820	934	83	252	2406	8.70	0	19.76	9	27
	S											
Ptoleme	M-	40.	-	0.								
e	22	170	22.0		14		-		15.1			0.
	0	5	793	449	58	4	2378	4.32	0	10.52	90	11
	S											
Ptoleme	M-	40.	-	4.								
e	22	158	22.0	330	95		-		34.1			0.
	1	3	724	7	01	582	2152	1.70	8	21.30	97	18
	S											
Ptoleme	M-	40.	-	1.								
e	22	028	22.0	163	69		-		33.6			0.
	2	7	724	0	17	271	2476	1.71	0	22.51	81	17
	S											
Ptoleme	M-	40.	-	1.								
e	22	127	22.0	144	42		-		31.8			0.
	3	8	651	7	94	409	1859	4.37	0	24.88	171	28
	S											
Ptoleme	M-	40.	-	1.								
e	22	137	22.0	136	20		-		31.4			0.
	4	7	425	1	87	381	1939	1.78	4	22.91	138	28
	S											
Ptoleme	M-	40.	-	0.								
e	22	115	22.0	114	94		-		32.0			0.
	5	2	402	7	72	329	1823	3.38	8	21.84	23	29
	S											
Ptoleme	M-	40.	-	0.								
e	22	133	22.0		40		-		30.6			0.
	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	8	289		30							
	7											
	S											
Ptoleme	M-	40.	-		0.							
e	22	061	22.0		37		-		29.6			0.
	8	2	235	712	14	163	1722	4.88	0	21.76	170	23
	S											
Ptoleme	M-	40.	-		0.							
e	22	049	22.0	102	75		-		29.8			0.
	9	7	115	4	90	210	1655	2.09	9	22.50	36	20
	S											
Ptoleme	M-	40.	-		3.							
e	23	117	22.0	219	10		-		31.6			0.
	0	5	036	6	86	658	1235	5.44	3	22.28	43	30
	S											
Ptoleme	M-	40.	-		0.							
e	23	079	22.0		70		-		34.9			0.
	1	0	033	985	86	257	1245	4.57	1	21.02	4	26
	S											
Ptoleme	M-	40.	-		0.							
e	23	134	21.9		16		-		29.0			0.
	2	4	988	480	95	97	1601	4.96	8	16.82	0	20
	S											
Ptoleme	M-	40.	-		0.							
e	23	142	21.9		48		-		31.5			0.
	3	4	974	929	68	279	1775	7.48	5	23.89	32	30
	S											
Ptoleme	M-	40.	-		0.							
e	23	152	21.9		11		-		21.4			0.
	4	9	937	434	81	76	1999	2.52	5	11.89	12	16
	S											
Ptoleme	M-	40.	-		1.							
e	23	108	21.9	163	78		-		28.0			0.
	5	1	903	2	19	384	1043	4.43	8	20.61	11	24
	S											
Ptoleme	M-	40.	-		0.							
e	23	029	21.9		16		-		25.7			0.
	6	3	871	484	22	125	1957	3.50	9	16.72	9	26
	S											
Ptoleme	M-	40.	-		2.							
e	23	090	21.9	210	06		-		36.6			0.
	7	3	858	2	07	286	-939	2.81	5	17.74	31	14
	S											
Ptoleme	M-	40.	-		0.							
e	23	012	21.9		70		-		34.2			0.
	8	0	852	977	85	301	1899	7.95	8	26.39	136	31
	S											
Ptoleme	M-	40.	-		0.							
e	23	255	21.9		20		-		24.4			0.
	9	2	842	535	69	101	2797	7.46	0	15.58	18	19

	S											
Ptoleme	M-24	40.187	-	0.19					31.3			0.29
e	05	826	535	19	154	2280	9.02	9	20.95	2		
	S											
Ptoleme	M-24	40.031	-	0.03					17.1			0.19
e	16	812	207	04	40	1978	7.87	8	12.66	0		
	S											
Ptoleme	M-24	40.215	-	0.56					28.9			0.22
e	27	796	882	04	194	2542	3.57	6	15.53	14		
	S											
Ptoleme	M-24	40.030	-	0.03					14.2			0.26
e	30	793	228	59	59	2030	6.33	5	9.95	162		
	S											
Ptoleme	M-24	40.040	-	1.21					31.5			0.32
e	49	790	1279	2192	404	1854	8.17	7	24.71	177		
	S											
Ptoleme	M-24	40.197	-	0.48					36.3			0.34
e	58	784	898	30	307	2364	9.22	7	26.97	174		
	S											
Ptoleme	M-24	40.032	-	0.02					10.4			0.16
e	68	780	192	37	31	2038	4.45	5	6.98	0		
	S											
Ptoleme	M-24	40.032	-	0.04					11.3			0.24
e	74	759	222	66	60	2066	8	7	13.89	162		
	S											
Ptoleme	M-24	40.264	-	0.44					28.3			0.16
e	81	757	829	60	130	2837	2.68	5	16.91	25		
	S											
Ptoleme	M-24	40.080	-	0.11					10.6			0.35
e	92	746	404	78	141	1271	1	0	21.01	70		
	S											
Ptoleme	M-25	40.018	-	3.81					33.5			0.18
e	01	736	2805	61	511	1887	3.63	6	21.69	125		
	S											
Ptoleme	M-25	40.174	-	0.40					34.2			0.34
e	19	735	748	09	255	2218	7.23	7	22.68	24		
Ptoleme	S	40.094	-	0.13					28.6			0.19
e	M-	21.9	441	13	83	1030	8.73	9	15.97	114		

	25	5	723		94							
	2											
	S											
	M-	40.	-		1.							
Ptole	25	186	21.9	128	23		-		32.8			0.
e	3	6	723	4	63	398	2204	8.27	9	25.91	8	31
	S											
	M-	40.	-		0.							
Ptole	25	049	21.9	100	62		-		32.1			0.
e	4	0	716	4	14	410	1812	1.47	0	22.36	155	41
	S											
	M-	40.	-		0.							
Ptole	25	031	21.9		14		-		27.5			0.
e	5	2	704	482	04	114	2120	4.12	0	16.97	161	24
	S											
	M-	40.	-		3.							
Ptole	25	242	21.9	278	03		-		38.8			0.
e	6	3	697	1	43	391	2600	2.36	3	21.46	12	14
	S											
	M-	40.	-		0.							
Ptole	25	078	21.9		22		-		40.8			0.
e	7	0	691	557	18	177	1338	5.52	3	20.73	86	32
	S											
	M-	40.	-		2.							
Ptole	25	067	21.9	218	41		-		33.6			0.
e	8	3	687	5	45	637	1388	4.47	0	23.69	87	29
	S											
	M-	40.	-		0.							
Ptole	25	220	21.9	120	25		-		29.6			0.
e	9	6	685	1	69	247	2439	1.11	5	18.73	23	21
	S											
	M-	40.	-		2.							
Ptole	26	204	21.9	181	22		-		31.7			0.
e	0	0	623	8	60	440	2175	3.48	2	24.21	5	24
	S											
	M-	40.	-		0.							
Ptole	26	097	21.9		21		-		29.3			0.
e	1	4	660	547	57	177	1179	9.01	9	23.89	135	32
	S											
	M-	40.	-		0.							
Ptole	26	091	21.9		25		-		35.9			0.
e	2	0	656	589	17	157	1256	2.91	2	21.75	90	27
	S											
	M-	40.	-		0.							
Ptole	26	106	21.9		04		-	14.9	20.7			0.
e	3	8	635	260	53	77	1415	8	8	18.81	90	30
	S											
	M-	40.	-		1.							
Ptole	26	212	21.9	126	17		-		32.0			0.
e	4	7	582	2	62	498	2286	3.43	1	26.41	171	39

Ptoleme	S M- 26	40. 094	- 21.9	129	1. 09		-		33.2			0.
e	S 5	1	566	9	59	371	1449	2.41	4	23.14	46	29
Ptoleme	S M- 26	40. 056	- 21.9		0. 58		-		33.2			0.
e	S 6	0	548	906	49	334	1742	7.49	9	25.63	172	37
Ptoleme	S M- 26	39. 914	- 21.9	135	1. 22		-		37.3			0.
e	S 7	7	543	6	43	289	2758	7.18	6	21.42	70	21
Ptoleme	S M- 26	40. 116	- 21.9		0. 18		-		31.9			0.
e	S 8	1	503	517	99	164	1775	1.48	4	19.76	83	32
Ptoleme	S M- 26	40. 188	- 21.9		0. 32		-	11.9	31.8			0.
e	S 9	4	448	675	79	184	2449	3	9	23.15	3	27
Ptoleme	S M- 27	40. 580	- 21.9		0. 19		-		21.4			0.
e	S 0	1	394	510	13	105	3044	3.36	6	14.64	47	21
Ptoleme	S M- 27	40. 167	- 21.9	159	1. 03		-		37.0			0.
e	S 1	6	392	8	65	418	2371	8.46	4	24.79	41	26
Ptoleme	S M- 27	40. 210	- 21.9	114	0. 70		-		31.3			0.
e	S 2	8	357	4	52	167	2572	5.82	7	20.16	65	15
Ptoleme	S M- 27	40. 116	- 21.9	174	2. 20		-		30.3			0.
e	S 3	8	545	0	83	448	1884	6.21	9	23.37	1	26
Ptoleme	S M- 27	40. 171	- 21.9		0. 13		-		20.8			0.
e	S 4	8	297	441	06	92	2510	4.43	0	13.23	172	21
Ptoleme	S M- 27	40. 141	- 21.9	200	2. 80		-		34.9			0.
e	S 5	0	293	3	48	574	2140	7.49	2	24.97	23	29
Ptoleme	S M- 27	40. 034	- 21.9	307	4. 42		-		33.1			0.
e	S 6	5	251	1	73	515	2308	1.32	0	20.37	167	17
Ptoleme	S M- 27	40. 130	- 21.9	126	0. 86		-		28.7			0.
e	S 1	1	130	1	86	304	2318	3.36	9	19.30	86	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	838	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

Ptoleme	S	40.	-	0.								
e	M-	29	132	21.8	22				22.4			0.
	0	4	679	605	98	117	2687	3.39	8	15.42	113	19
Ptoleme	S	40.	-	0.								
e	M-	29	009	21.8	07				19.2			0.
	1	2	600	348	32	64	2824	2.90	1	13.44	135	18
Pammel	S	40.	-	1.								
a	M-	29	121	21.8	196	35			33.6			0.
Seamou	2	4	506	7	73	383	2380	3.12	5	21.32	131	19
Pammel	S	40.	-	2.								
a	M-	29	056	21.8	190	31			27.2			0.
Seamou	3	5	420	7	59	479	2609	5.28	0	23.08	180	25
Pammel	S	40.	-	0.								
a	M-	29	168	21.8	118	98			25.1			0.
Seamou	4	7	226	2	44	175	2508	1.39	8	16.56	169	15
Pammel	S	40.	-	1.								
a	M-	29	096	21.8	158	89			30.3			0.
Seamou	5	1	183	8	65	401	2112	2.94	4	20.89	176	25
Pammel	S	40.	-	2.								
a	M-	29	045	21.8	168	62			10.1	35.1		0.
Seamou	6	1	087	3	05	557	2618	4	1	26.72	161	33
Pammel	S	40.	-	0.								
a	M-	29	177	21.8	40				29.8			0.
Seamou	7	0	028	7	56	151	2595	3.33	9	18.69	147	20
Pammel	S	40.	-	0.								
a	M-	29	032	21.7	105	55			28.1			0.
Seamou	8	2	977	9	34	228	2752	2.29	8	19.11	168	22
Pammel	S	40.	-	1.								
a	M-	29	050	21.7	127	14			31.2			0.
Seamou	9	2	934	8	12	374	2504	4.21	6	24.53	177	29
Pammel	S	40.	-	0.								
a	M-	30	149	21.7	46				27.0			0.
Seamou	0	3	929	815	17	123	2210	0.66	1	15.60	51	15
Pammel	S	40.	-	0.								
a	M-	30	131	21.7	32				27.9			0.
Seamou	1	2	924	696	83	112	1970	1.43	0	13.88	179	16
Pammel	S	40.	-	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-		40.	-	0.								
Seamou nt 2	30 3	134 0	21.7 841		10 379		- 47		17.3 2053				0. 12
Pammel a	S M-		40.	-	2.								
Seamou nt 2	30 4	019 9	21.7 835	186 5	54 14		- 482		36.2 2619				0. 26
Pammel a	S M-		40.	-	2.								
Seamou nt 2	30 5	030 5	21.7 726	189 2	63 72		- 510		32.7 2591				0. 27
Pammel a	S M-		40.	-	0.								
Seamou nt 2	30 6	071 9	21.7 667	102 8	73 02		- 178		26.1 2586				0. 17
Pammel a	S M-		40.	-	0.								
Seamou nt 2	30 7	164 3	21.7 659	133 4	93 39		- 211		34.2 2504				0. 16
Pammel a	S M-		40.	-	0.								
Seamou nt 2	30 8	099 4	21.7 556		10 382		- 89		22.2 2671				0. 23
Pammel a	S M-		40.	-	3.								
Seamou nt 2	30 9	018 4	21.7 509	250 1	90 37		- 519		34.5 2711				0. 21
Pammel a	S M-		40.	-	0.								
Seamou nt 2	31 0	109 7	21.7 229		12 417		- 79		15.5 2885				0. 19
Pammel a	S M-		40.	-	0.								
Seamou nt 2	31 1	003 5	21.7 221	115 2	93 67		- 369		33.2 2525				0. 32
Pammel a	S M-		40.	-	0.								
Seamou nt 2	31 2	023 3	21.7 293	103 2	59 17		- 116		23.1 2831				0. 11
Pammel a	S M-		40.	-	2.								
Seamou nt 1	31 3	188 0	21.7 820	225 6	46 75		- 375		32.5 2803				0. 17
Pammel a	S M-		39.	-	0.								
Seamou nt 1	31 4	981 6	21.7 420		15 465		- 80		19.8 2828				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	600	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		36.8 2567			0. 10
Pammel a	S M-	40.	-		0.							
Seamou nt 1	32 9	094 0	21.6 229	139 8	49 11		- 87		27.2 2633			0. 06
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 0	107 9	21.6 212	599 36	24 84		- 2763		23.1 3.83			0. 14
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 1	173 4	21.6 196	115 5	97 16		- 221		34.7 3043			0. 19
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 2	119 7	21.6 063	427 57	12 59		- 2764		19.5 7.87			0. 14
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 3	142 7	21.6 037	809 78	47 78		- 214		27.8 2981			0. 26
Pammel a	S M-	39.	-		1.							
Seamou nt 1	33 4	890 8	21.4 601	125 8	21 09		- 263		35.7 2700			0. 20
Pammel a	S M-	39.	-		0.							
Seamou nt 1	33 5	938 9	21.4 577	911 92	47 115		- 3013		26.9 3.54			0. 13
Pammel a	S M-	39.	-		0.							
Seamou nt 1	33 6	945 3	21.4 471	110 1	92 04		- 264		33.1 3007			0. 24
Pammel a	S M-	39.	-		0.							
Seamou nt 1	33 7	942 1	21.4 391	889 73	34 136		- 3049		24.4 7.27			0. 15
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 8	078 4	21.5 942	548 50	21 148		- 2746		31.5 1.92			0. 27
Pammel a	S M-	40.	-		0.							
Seamou nt 1	33 9	143 5	21.5 896	750 79	39 103		- 3026		22.7 6.57			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	6.90	31.0 5	22.36	156	24	0.
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 4	887 0	21.5 510	103 7	74 95	197	- 2184	4.88	35.2 8	22.09	32	19	0.
Pammel a	S M-		39.	-	1.								
Seamou nt 1	35 5	850 7	21.5 437	143 2	37 76	291	- 2017	5.41	34.5 7	23.08	138	20	0.
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 6	818 6	21.5 437	980	51 21	196	- 1812	8.09	31.8 4	20.91	30	20	0.
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 7	876 6	21.5 408	346	07 99	45	- 2305	6.54	19.5 0	13.44	135	13	0.
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 8	835 1	21.5 405	121 1	71 48	222	- 1959	3.42	30.0 4	18.41	90	18	0.
Pammel a	S M-		39.	-	0.								
Seamou nt 1	35 9	800 1	21.5 391	419	11 05	59	- 1628	5.85	20.6 8	14.81	58	14	0.
Pammel a	S M-		39.	-	1.								
Seamou nt 1	36 0	946 7	21.5 311	145 7	14 97	223	- 2657	0.92	26.4 7	15.34	33	15	0.
Pammel a	S M-		39.	-	2.								
Seamou nt 1	36 1	862 2	21.5 253	167 9	09 63	309	- 2067	3.83	24.0 2	16.92	169	18	0.
	S												
Bassas da India	36 2	609 1	39. 21.7	- 808	0. 714	37 51	- 123	2.89	25.3 8	15.09	166	17	0.
	S												
Bassas da India	36 3	611 4	39. 21.7	- 542	1. 159	42 47	- 319	0.32	29.8 0	20.08	2	20	0.
	S												
Bassas da India	36 4	577 3	39. 21.7	- 479	0. 821	48 94	- 332	6.44	36.2 0	28.56	159	40	0.

	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	73	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											
Bassas	M-	39.	-		0.							
da India	37	575	21.7		08		-		13.9			0.
	8	7	071	358	86	42	1878	1.25	6	8.89	165	12
	S											
Bassas	M-	39.	-		1.							
da India	37	614	21.7	121	06		-		31.0			0.
	9	6	039	3	03	297	1798	4.52	8	21.46	154	24
	S											
Bassas	M-	39.	-		0.							
da India	38	651	21.7		25		-		27.4			0.
	0	0	012	618	43	114	2364	6.14	2	17.14	74	19
	S											
Bassas	M-	40.	-		0.							
da India	38	094	21.6		12		-		13.0			0.
	1	6	963	459	54	45	2903	2.38	8	8.25	115	10
	S											
Bassas	M-	39.	-		0.							
da India	38	584	21.6		19		-		21.7			0.
	2	7	905	563	14	84	2012	0.84	5	12.74	75	15
	S											
Bassas	M-	39.	-		0.							
da India	38	601	21.6		09		-		25.7			0.
	3	5	893	368	58	46	1739	7.80	9	16.74	131	13
	S											
Bassas	M-	39.	-		0.							
da India	38	581	21.6		15		-		23.7			0.
	4	1	880	599	20	48	2049	4.73	7	11.58	64	08
	S											
Bassas	M-	39.	-		2.							
da India	38	598	21.6	198	99		-		32.6			0.
	5	5	765	5	29	469	1747	2.77	3	23.96	165	24
	S											
Bassas	M-	39.	-		0.							
da India	38	612	21.6		13		-		20.9			0.
	6	2	734	431	47	51	1926	3.64	5	11.98	90	12
	S											
Bassas	M-	39.	-		0.							
da India	38	618	21.6		38		-		23.9			0.
	7	4	716	753	99	107	2017	3.18	5	14.29	122	14
	S											
Bassas	M-	39.	-		0.							
da India	38	611	21.6		06		-		10.3			0.
	8	5	680	300	38	38	1940	2.71	9	7.78	0	13
	S											
Bassas	M-	39.	-		0.							
da India	38	587	21.6		31		-		30.6			0.
	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	2139	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	638	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	41	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	322	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

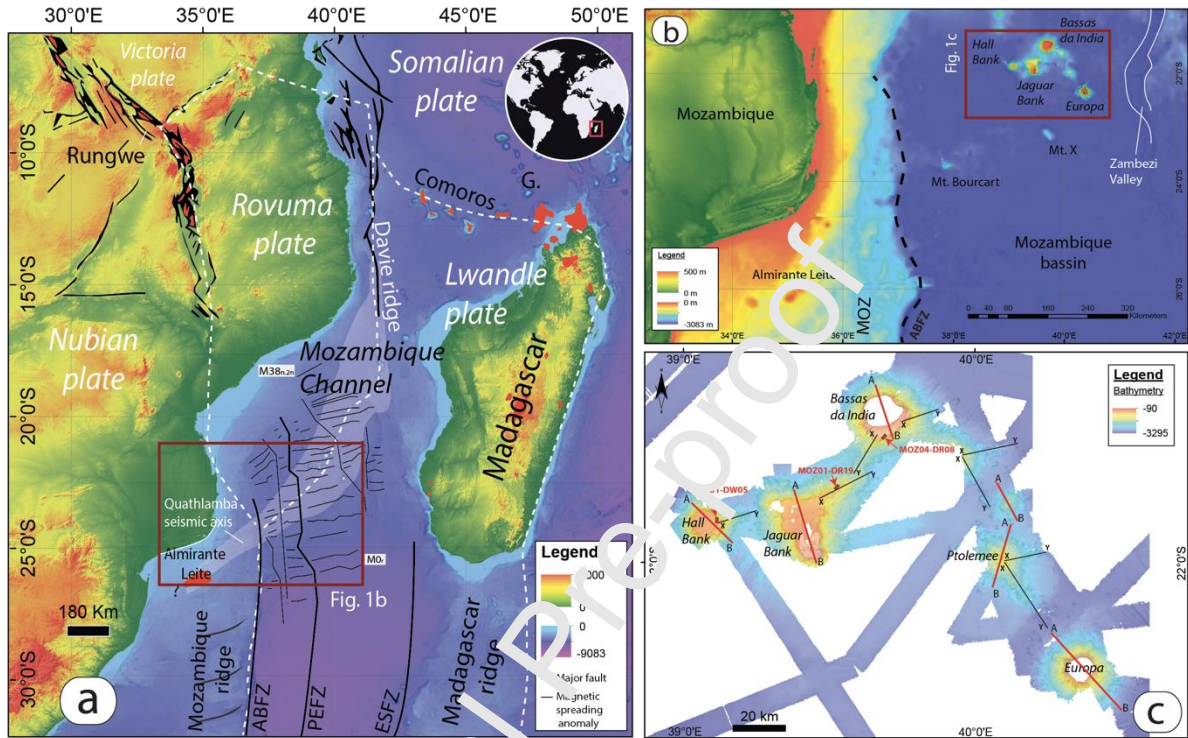
**Table 3:** Comparison of the offshore section of the volcanic ridges of Bassas da India/Europa complex, Hawaiian volcanoes (Mark and Moore, 1987; Fornari et al., 1988; Lonsdale, 1989; Clague et al., 2019), Canary Islands (Gee et al., 2001; Mitchell et al., 2002; Acosta et al., 2003b), Grande Comore 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)
<b>Bassas da India/Europa complex</b>			
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
<b>Canary Islands</b>			
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
<b>Hawaii Islands</b>			
Puna ridge	2-4°	70 km	> 40 km
Hilo Ridge	4°	40 km	20 km
Loihi	6-10°	11-19 km	20 km
<b>Comoros archipelago</b>			
Southeast Karthala	4°	13 km	15 km
<b>Galapagos</b>			
Genovesa	2-3°	50 km	20 km

**Fernandina**

Fernandina NW Rift	9°	13 km	8 km
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**Figure 1**



**Figure 2**

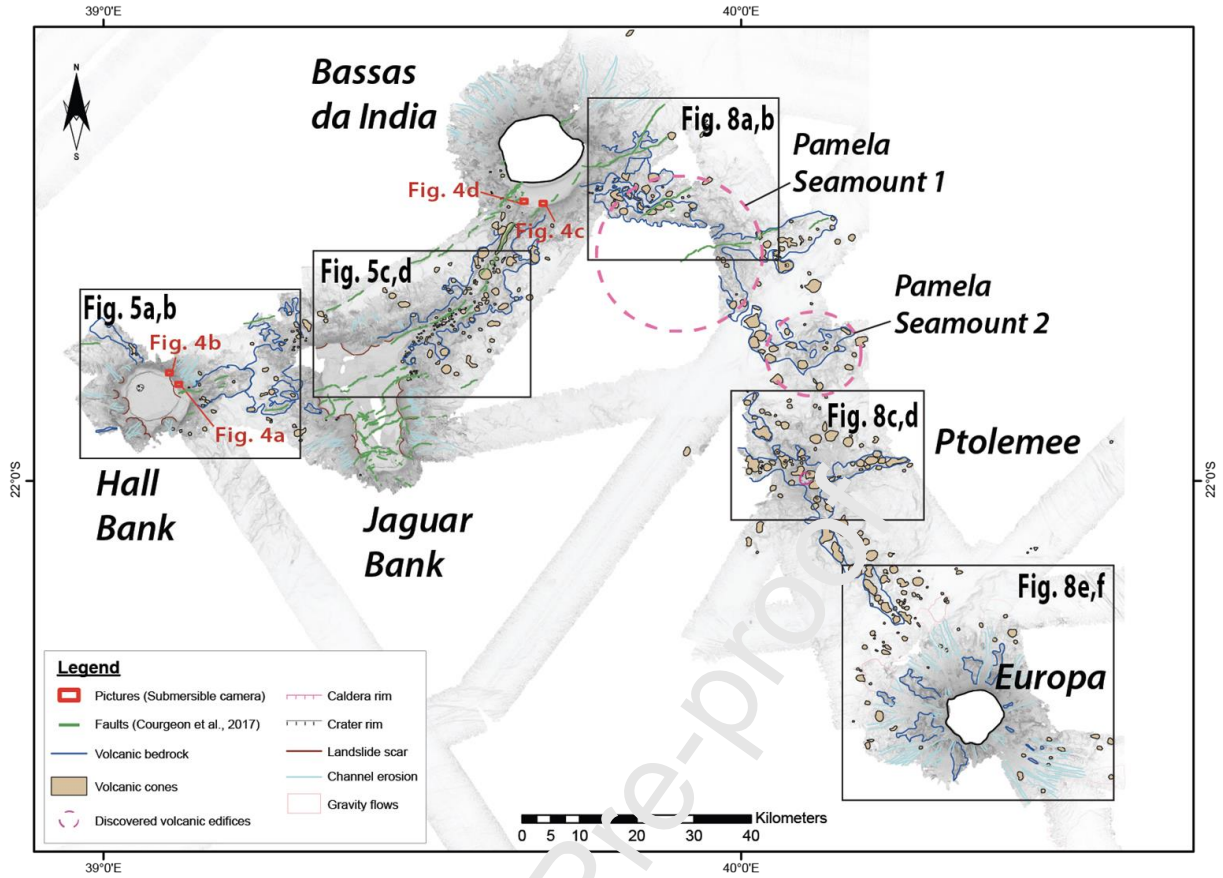


Figure 3

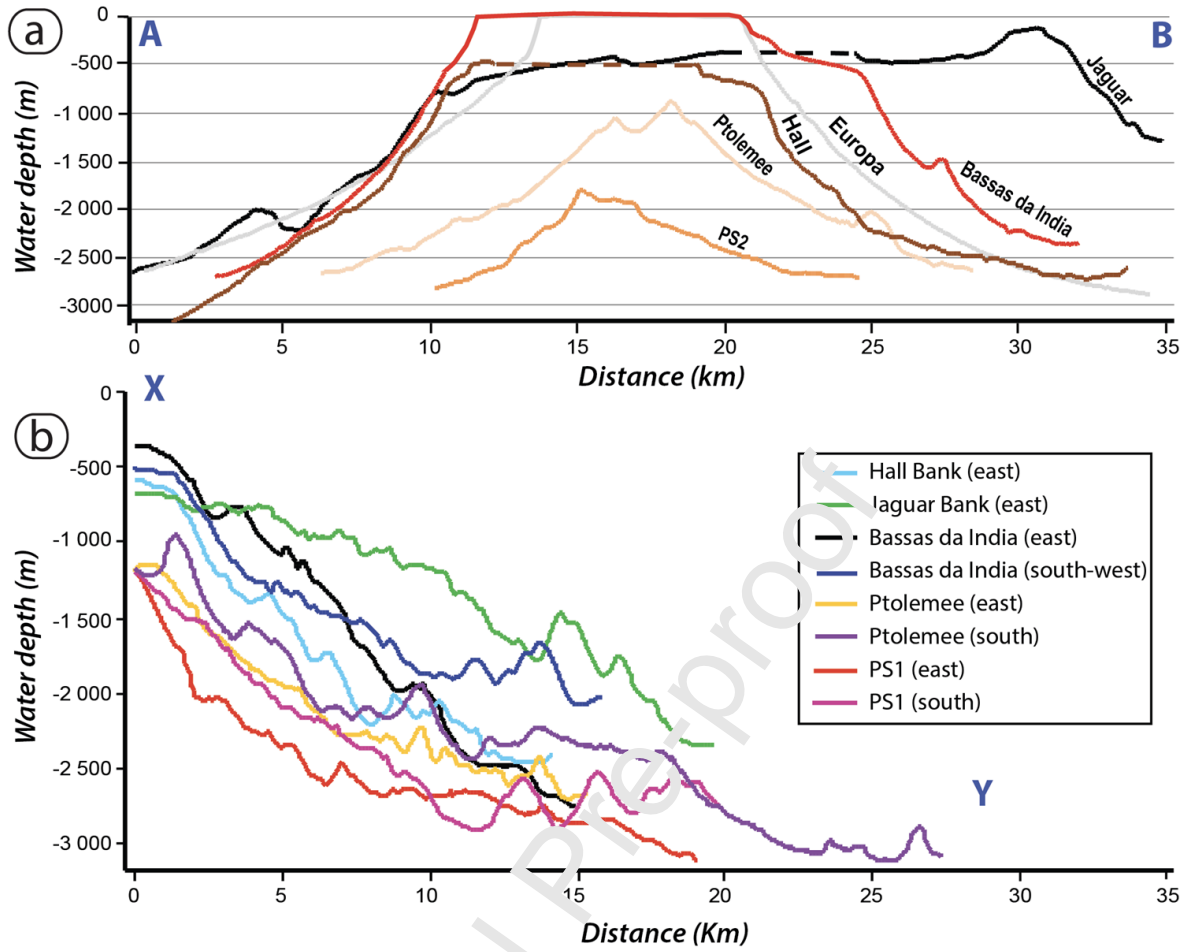


Figure 4



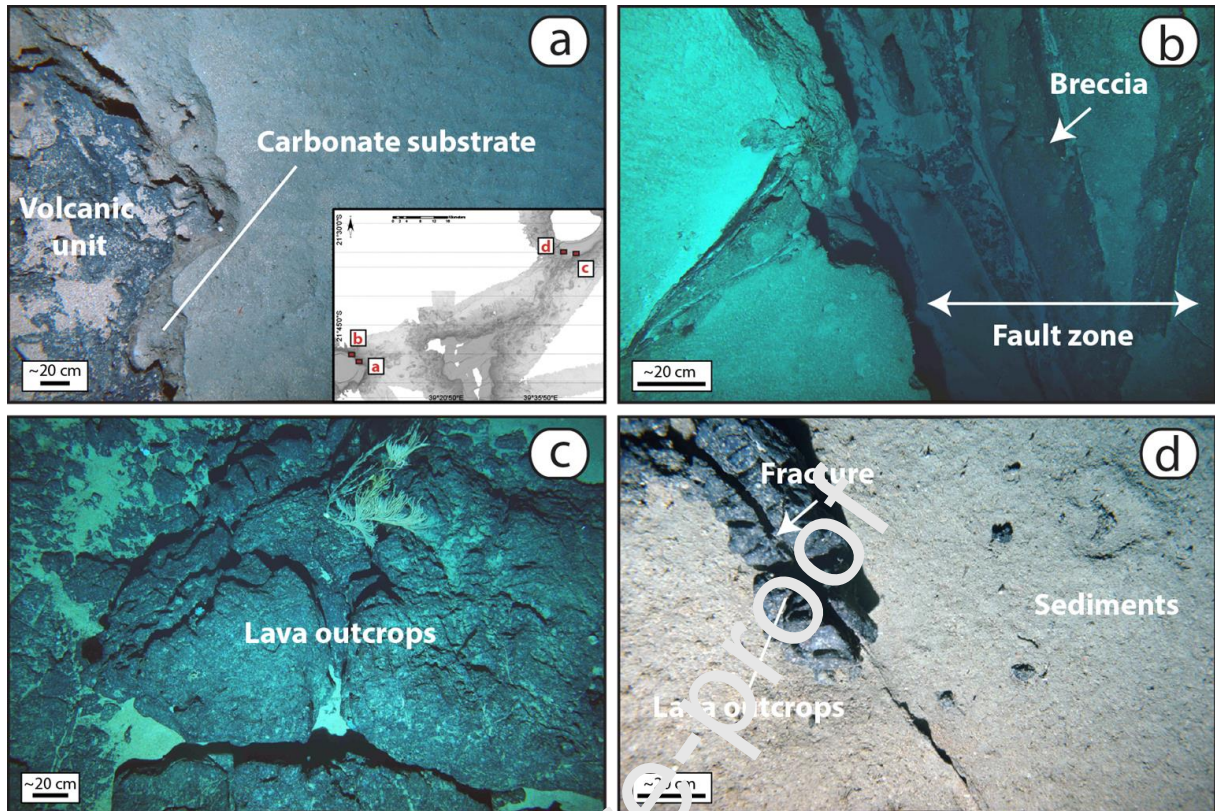
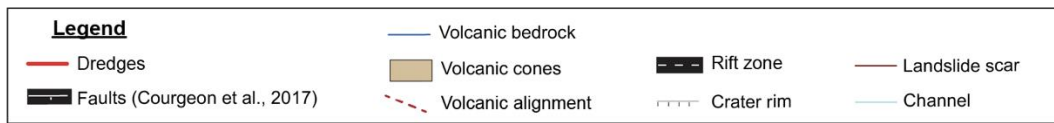
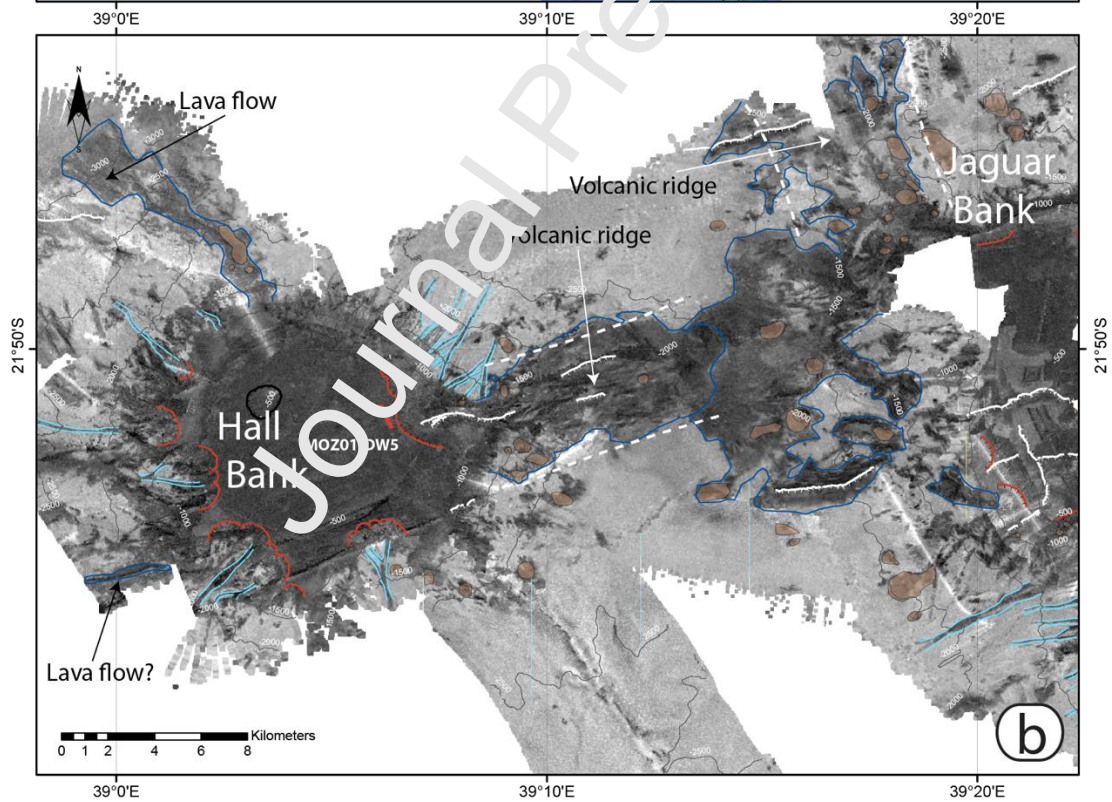
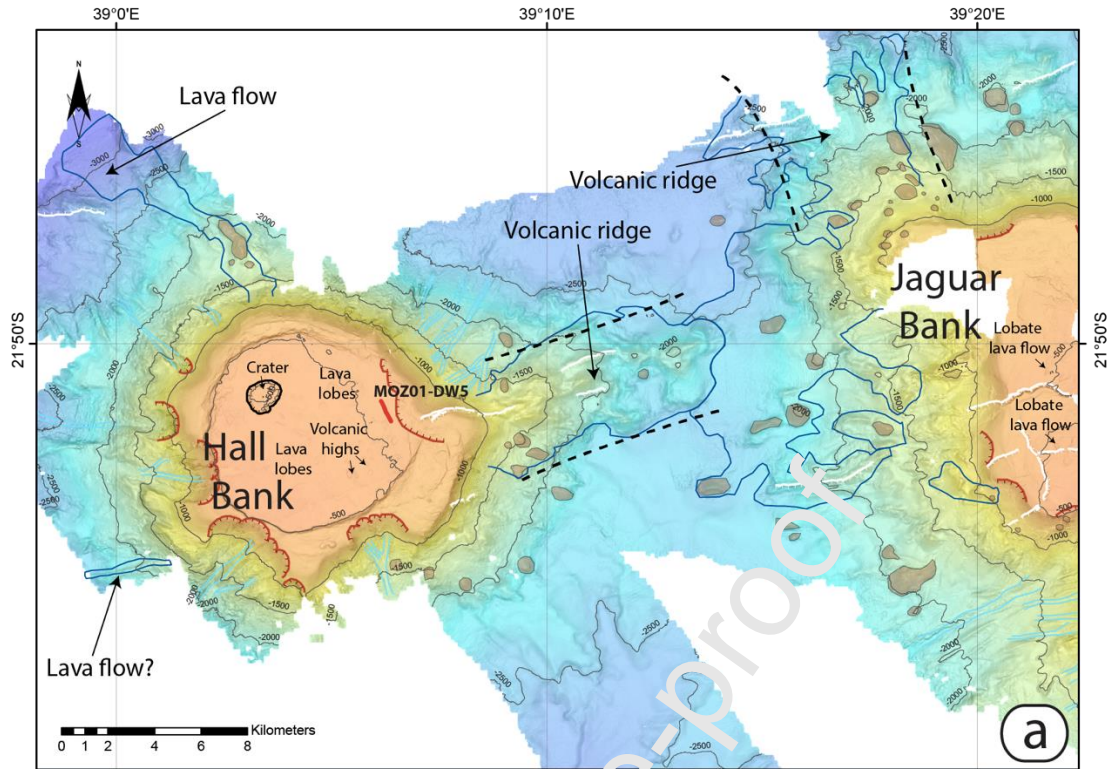


Figure 5



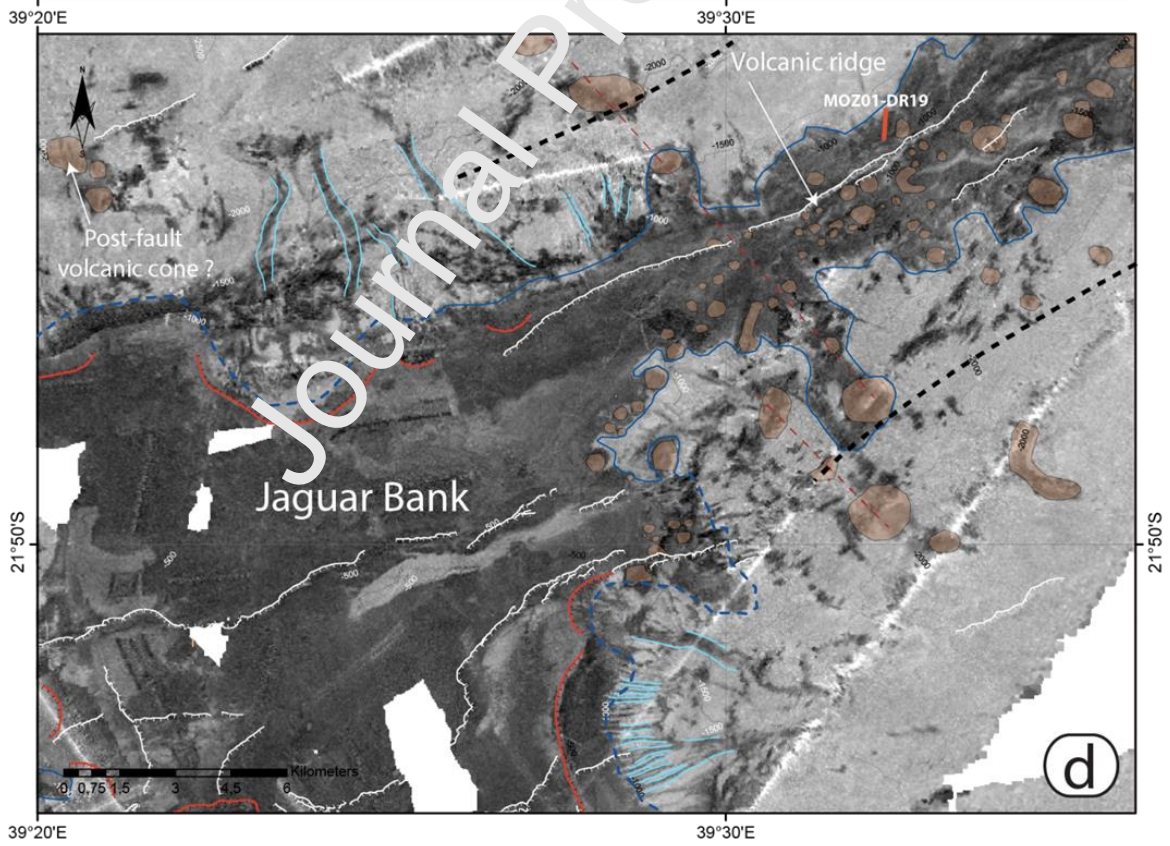
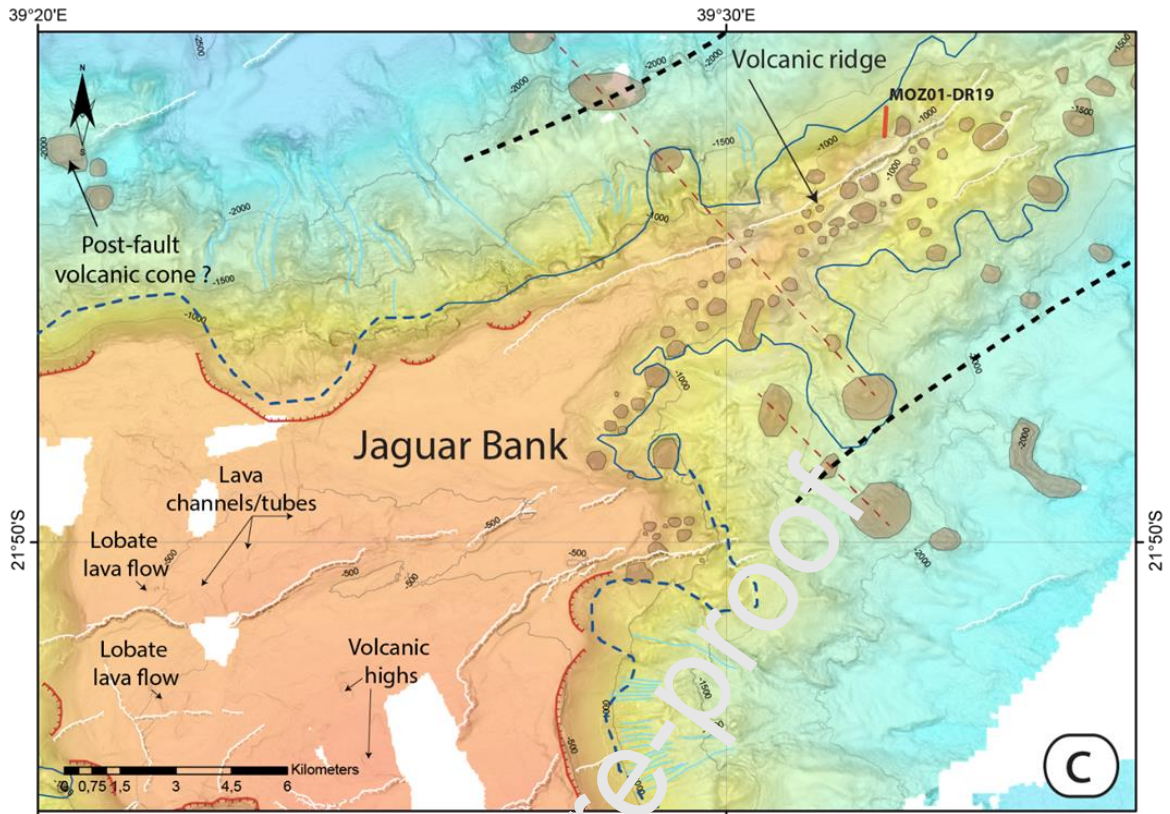


Figure 6

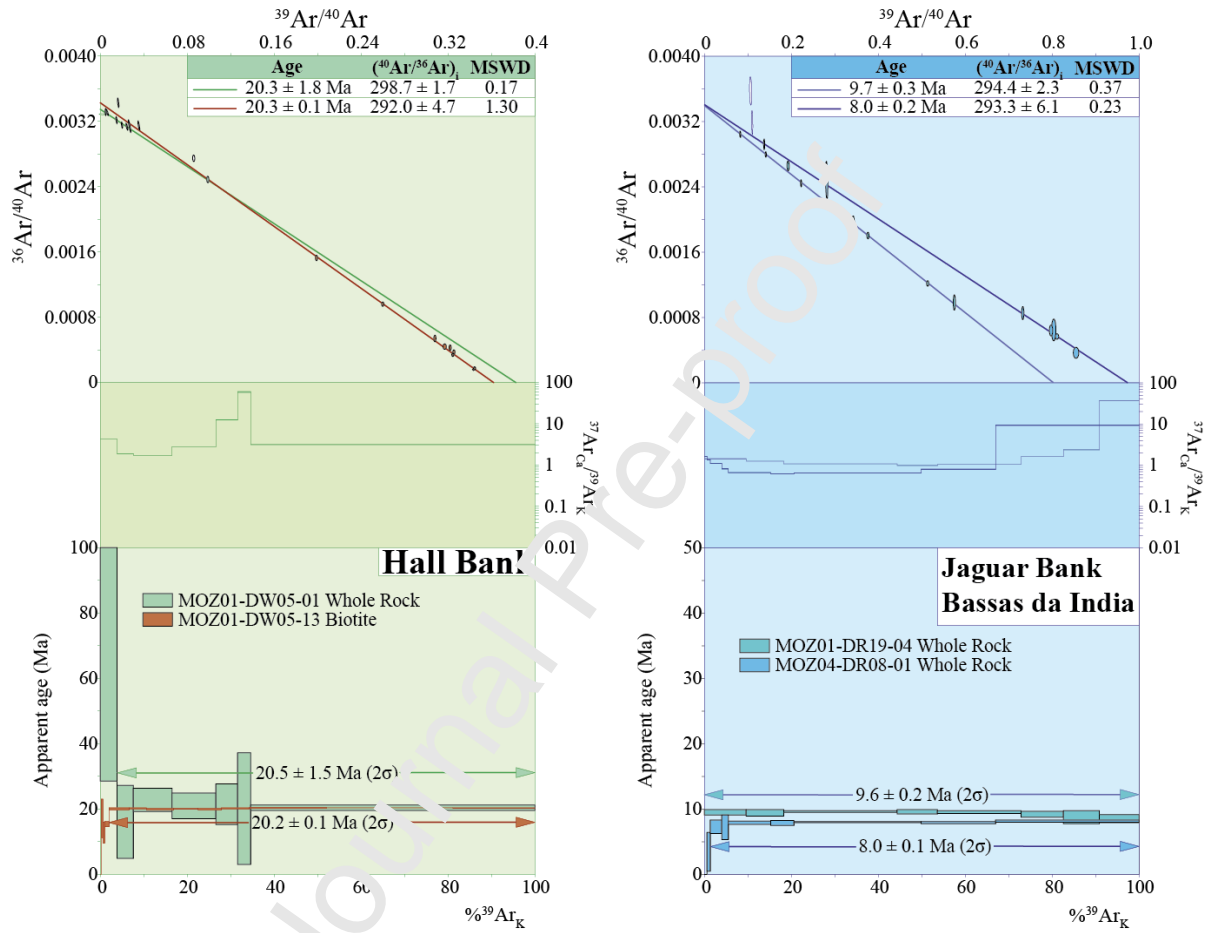


Figure 7

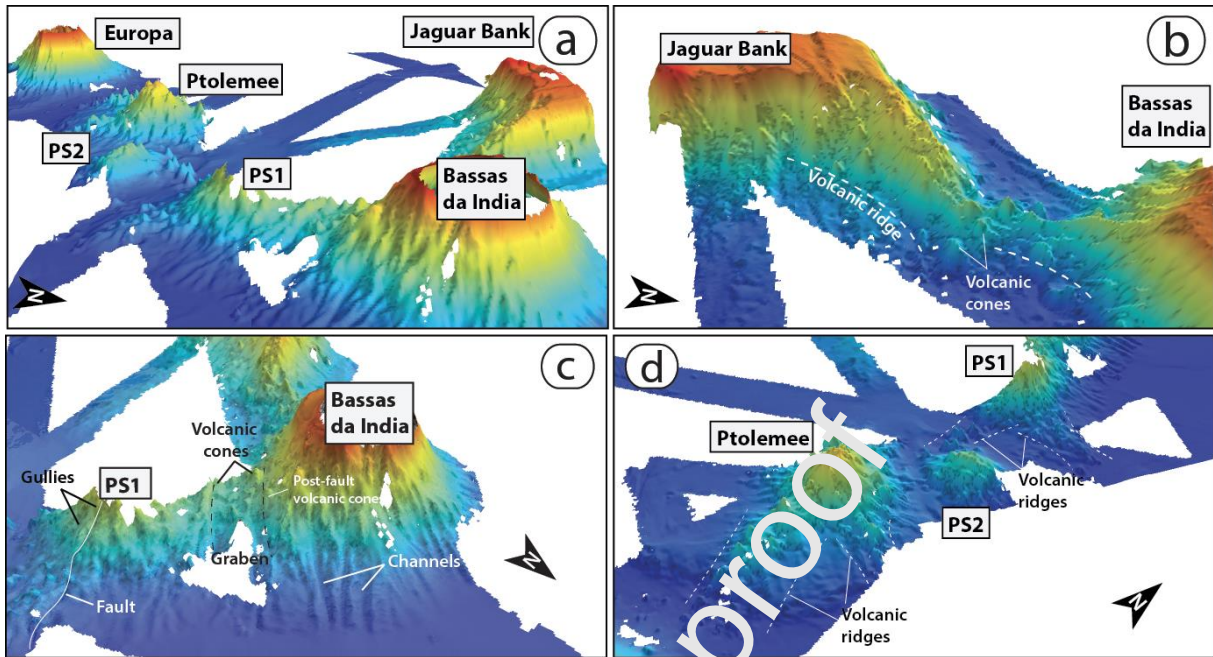
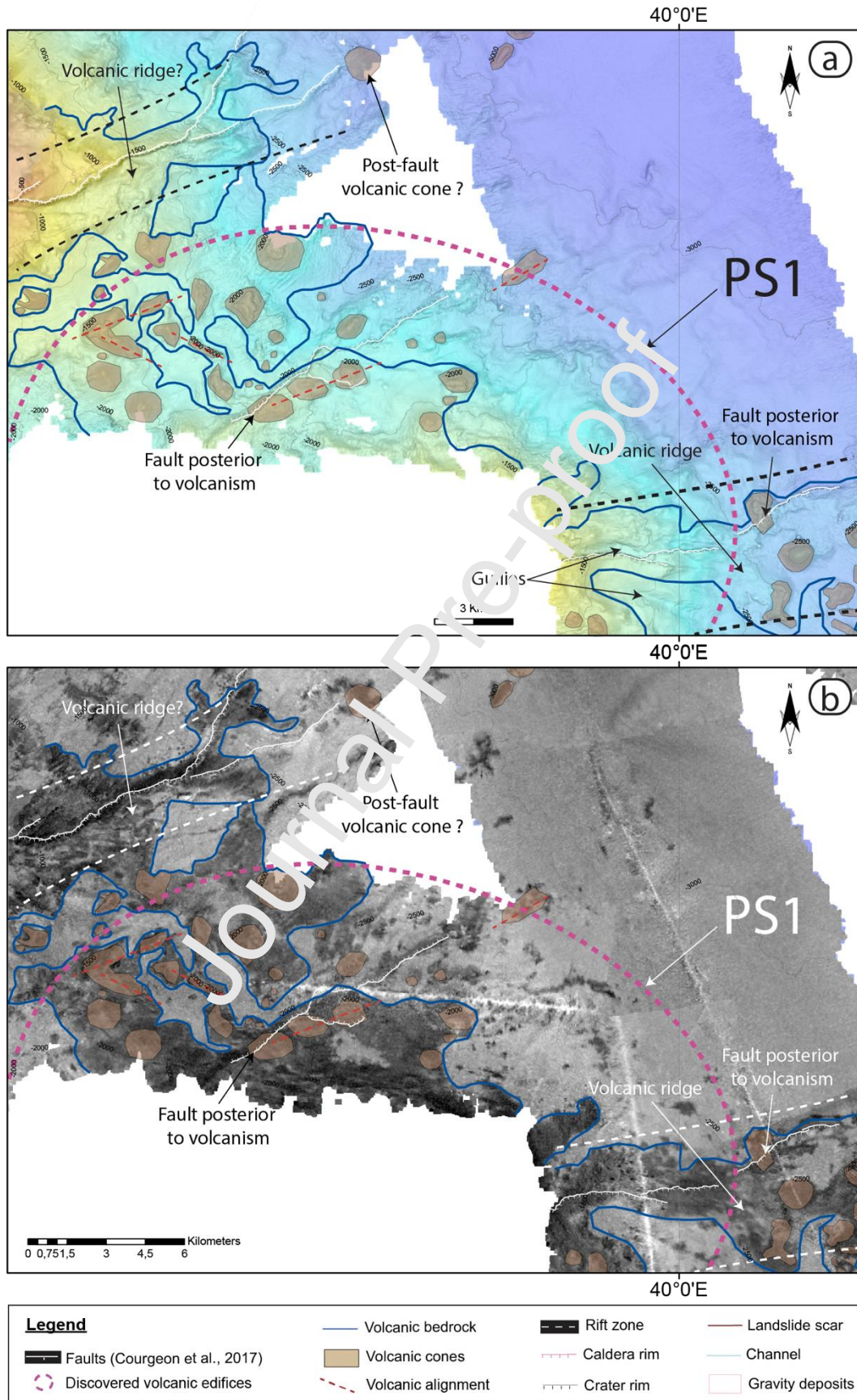
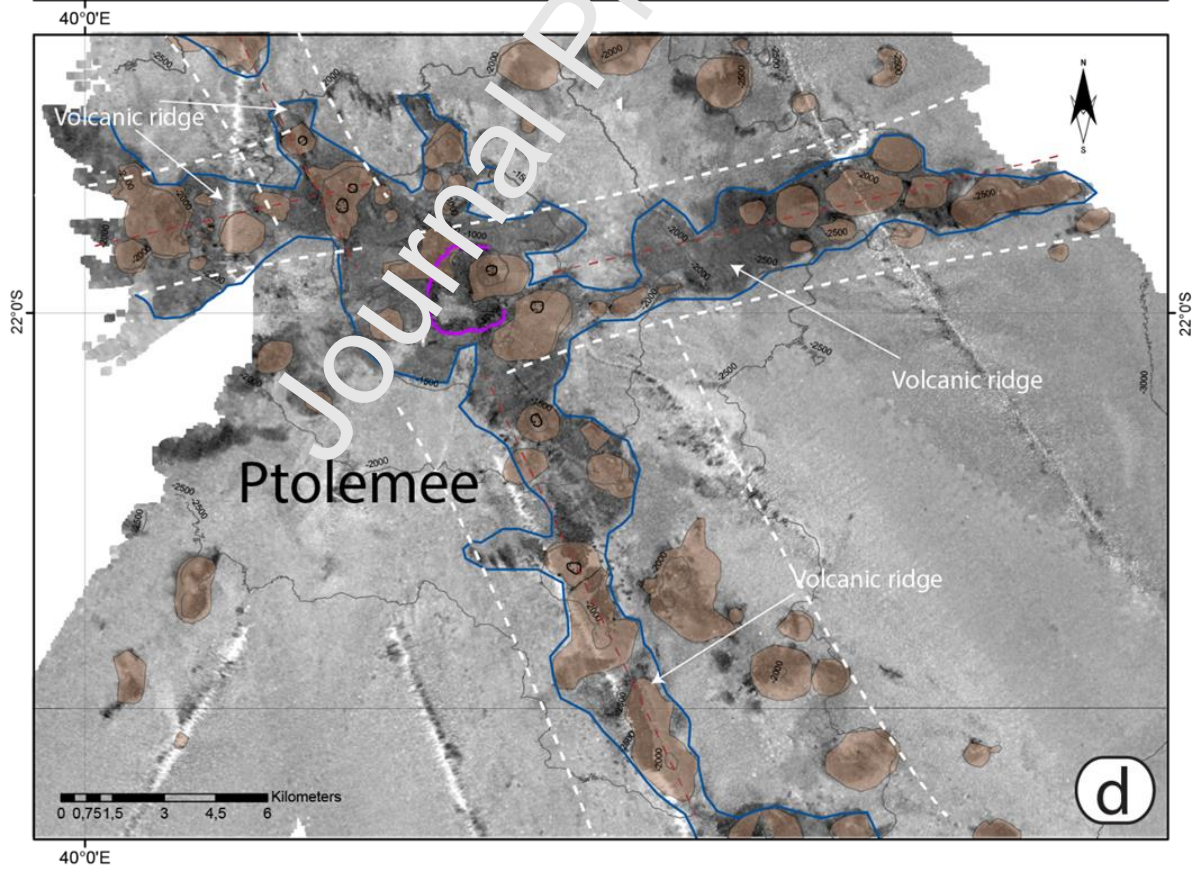
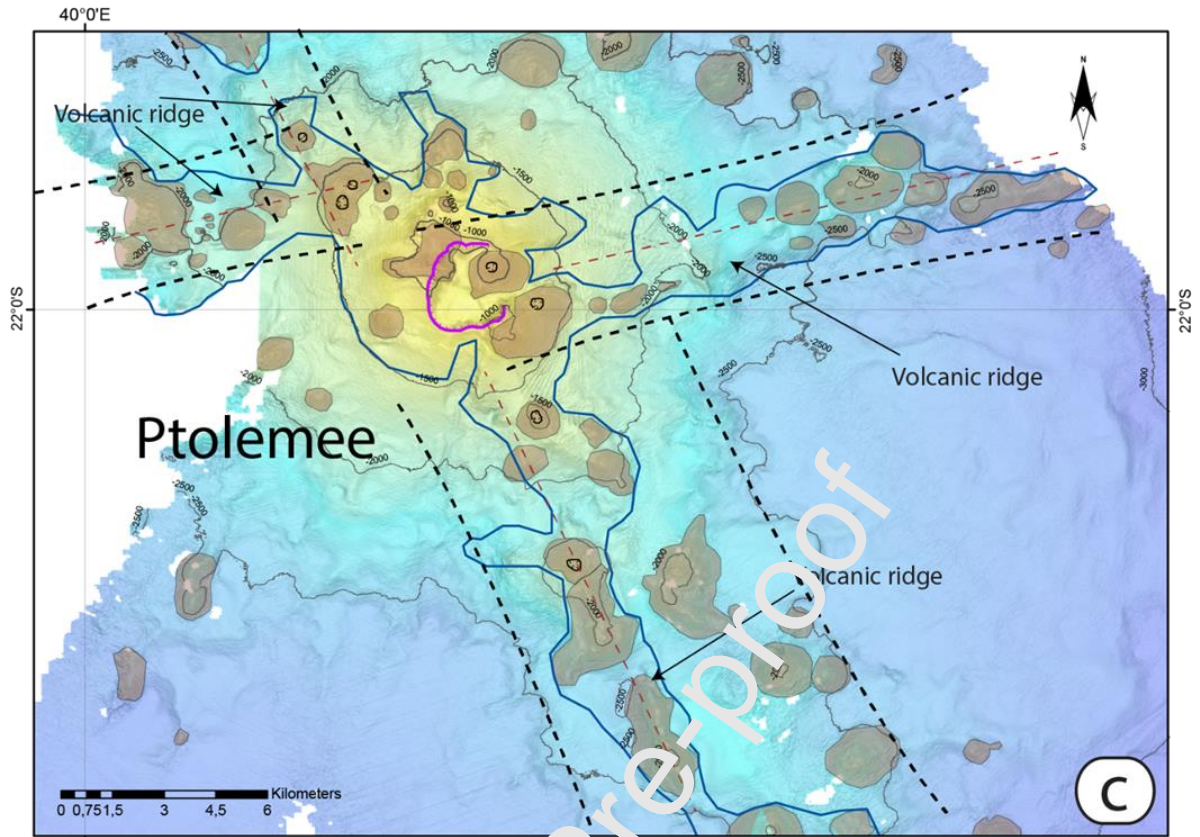


Figure 8





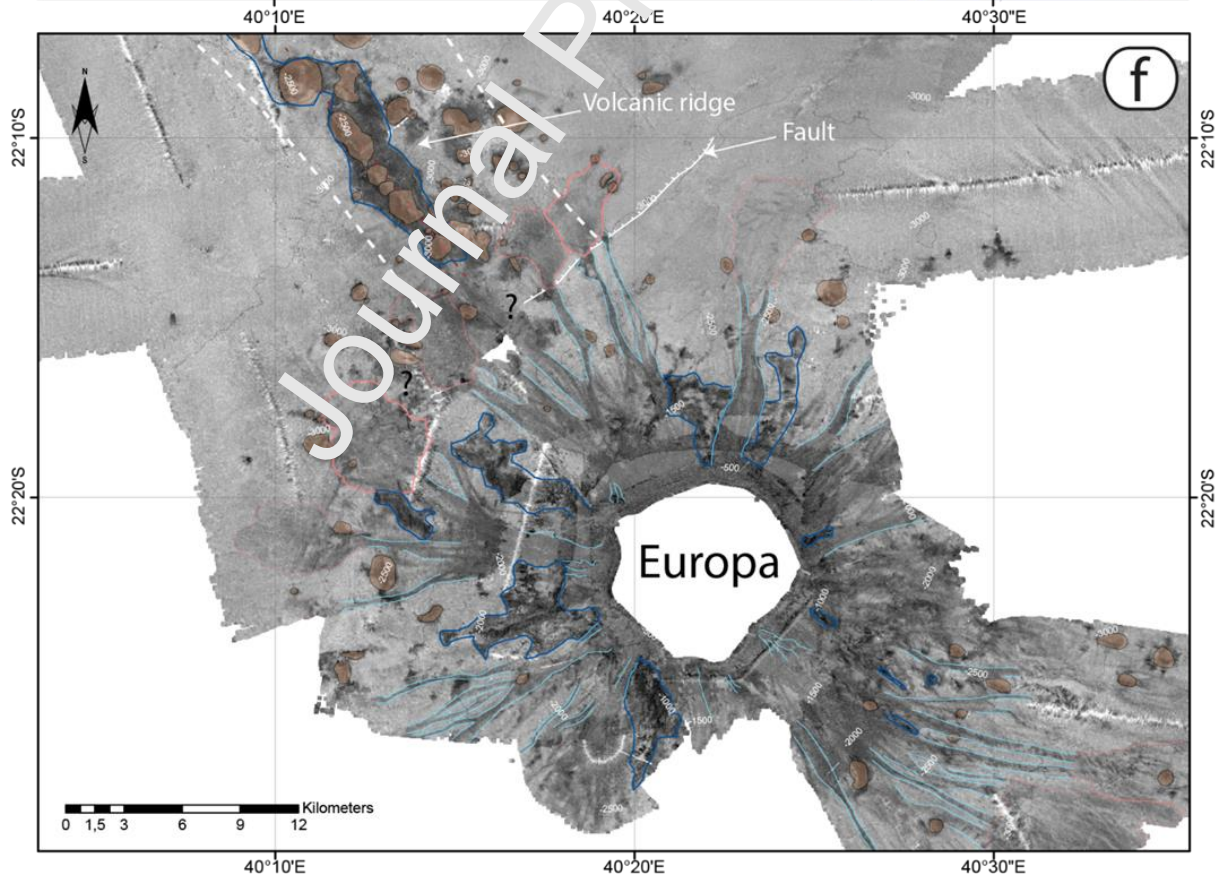
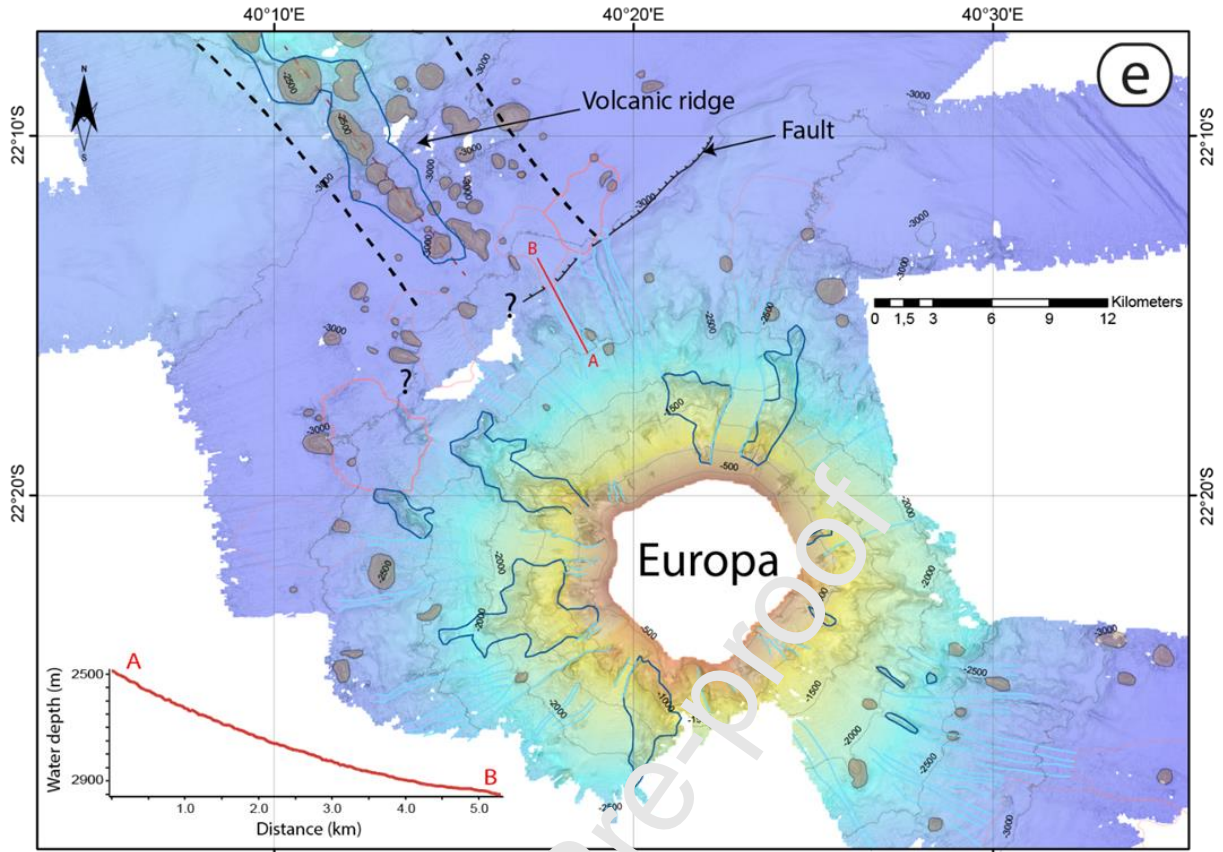




Figure 9

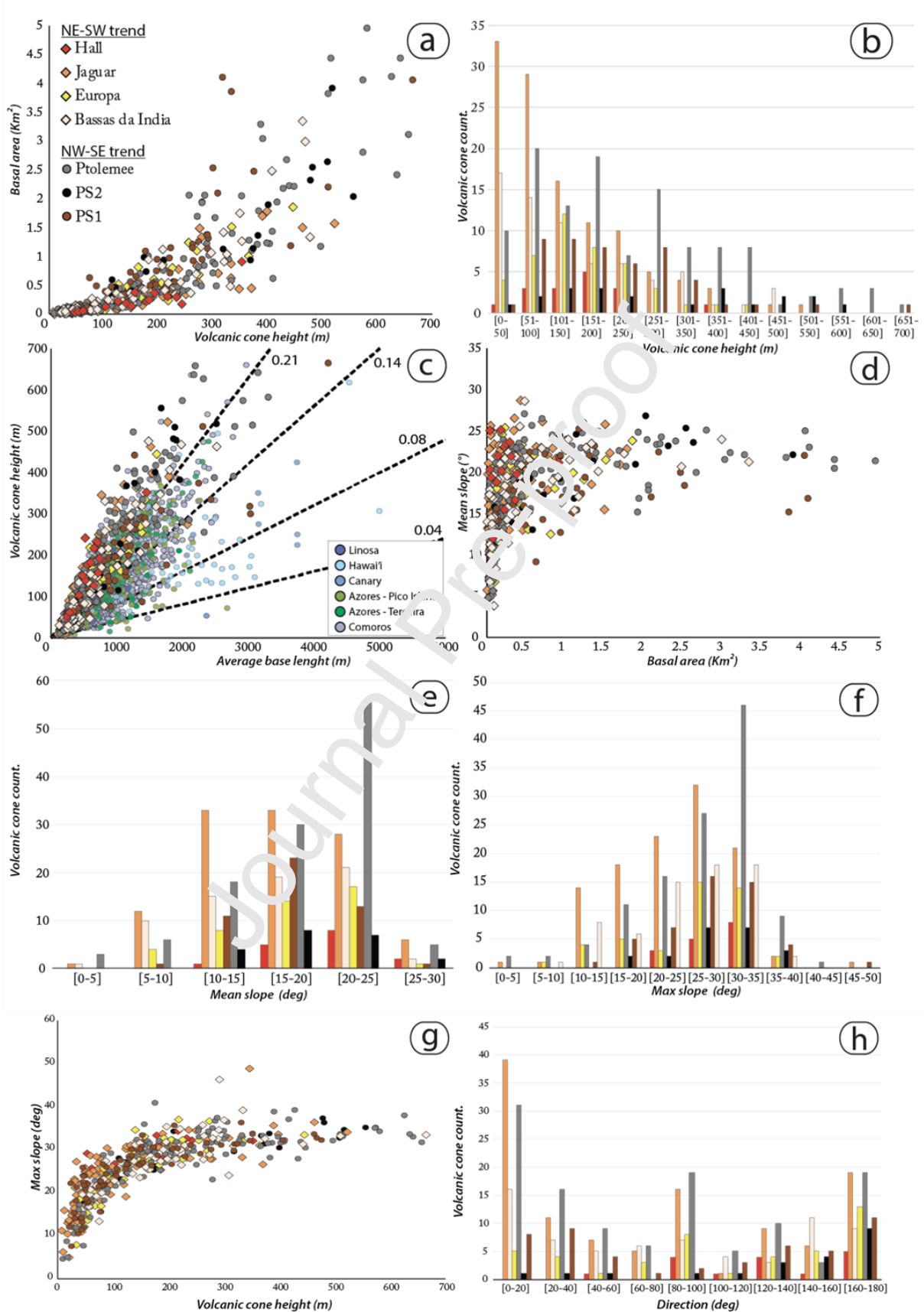


Figure 10

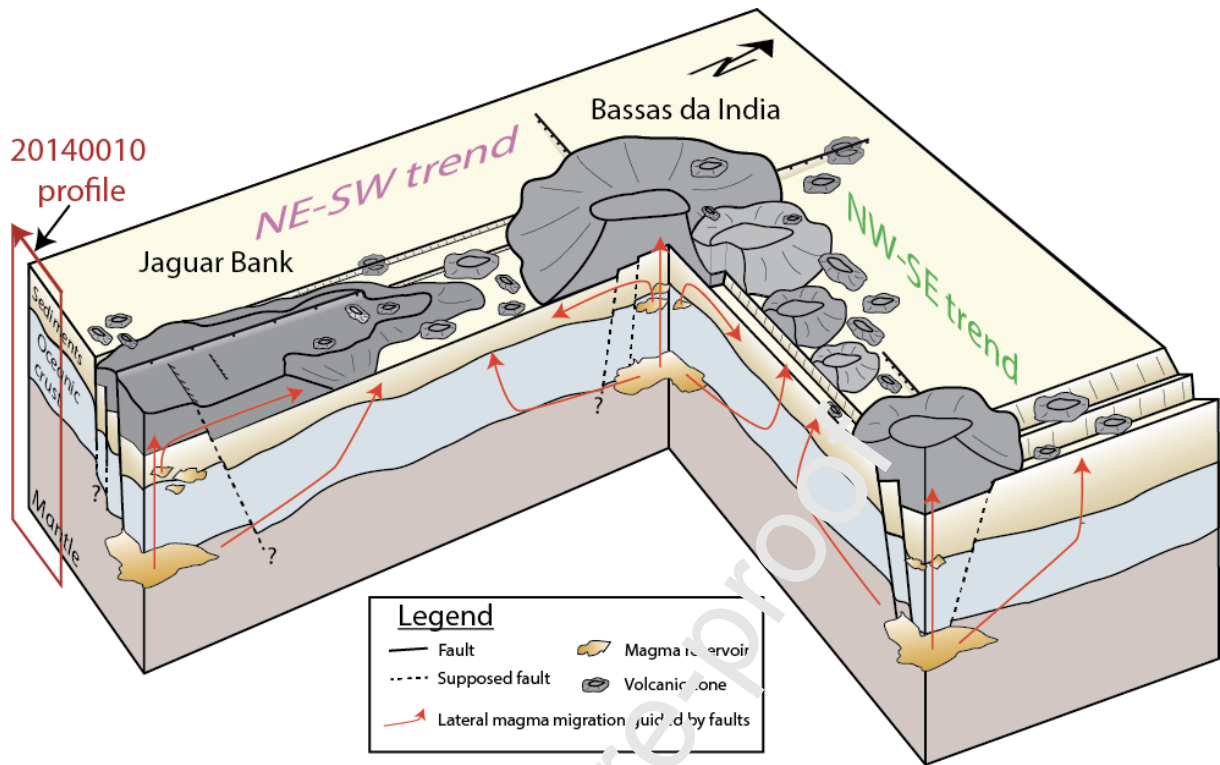
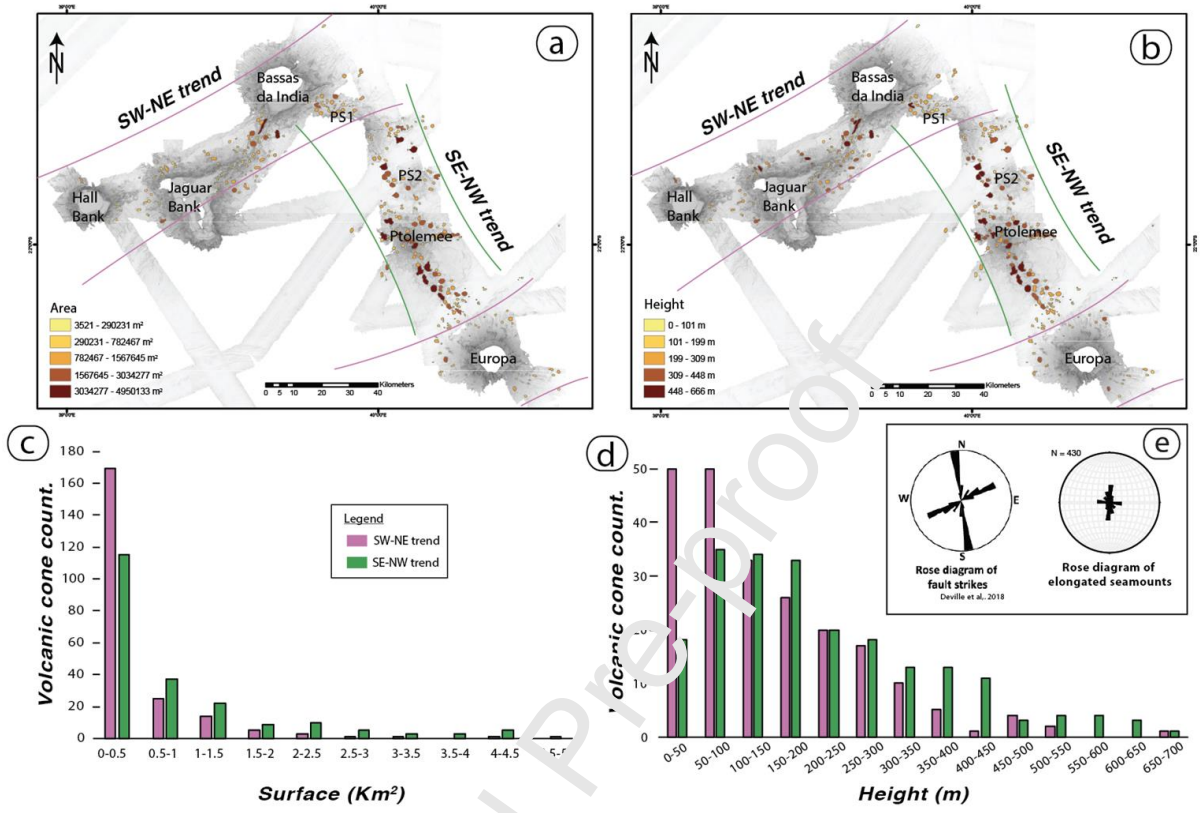
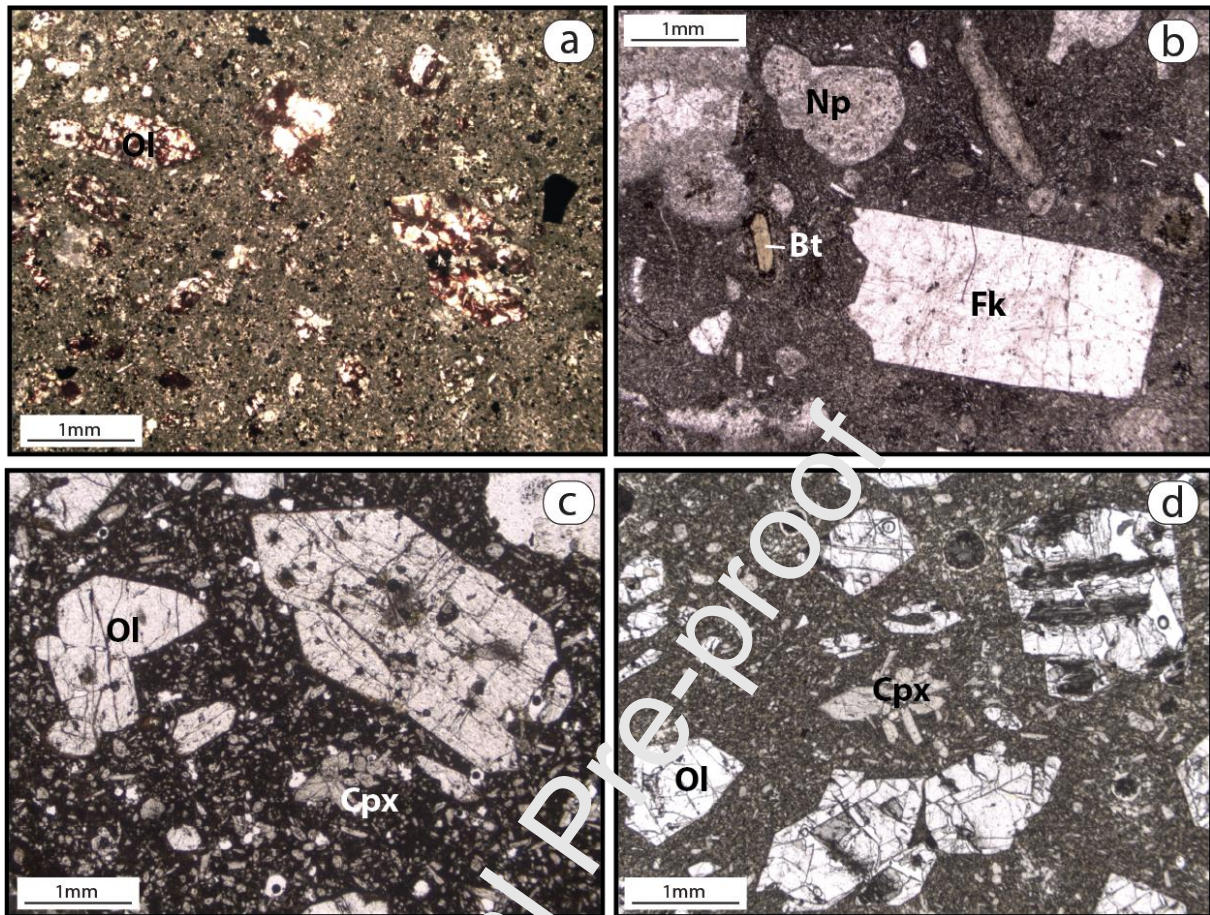


Figure 11



## 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  $\mu\text{m}$ ).

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



**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:

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### **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.

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