Revised version

Evidence of multi-phase Cretaceous to Quaternary alkaline magmatism on Tore-Madeira Rise and neighbouring seamounts from $^{40}Ar/^{39}Ar$ ages

Renaud Merle[a*], Fred Jourdan[b,c], Andrea Marzoli[a], Paul R. Renne[b,d], Marion Grange[e], Jacques Girardeau[f]

[a] Dipartimento de Geoscienze, Universita di Padova, Via Giotto 1, 35137 Padova, Italia.
[b] Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA 94709, USA.
[c] Western Australian Argon Isotope Facility, Department of Applied Geology and JdL-CMS, Curtin University of Technology, G.P.O. Box U1987, Perth, Western Australia 6845, Australia.
[d] Department of Earth and Planetary Science, University of California, Berkeley, California, 94720, USA
[e] Department of Applied Geology, Curtin University of Technology, G.P.O. Box U1987, Perth, Western Australia 6845, Australia.
[f] Laboratoire de Planétologie et Géodynamique, UMR-CNRS 6112, Université de Nantes, 2 rue de la Houssinère, 44322 Nantes cedex 3, France.

*Corresponding author.
Now at University of Western Australia, School of Earth and Geographical Sciences, 35 Stirling Highway Crawley, WA 6009, Australia.
Phone: +61 8 64882666. Fax: +61 8 64881037
E-mail : rmerle@cyllene.uwa.edu.au

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Abstract

The Tore-Madeira Rise (TMR) is a seamounts chain located 300 km off the Portugal and Morocco coasts attributed to a hot-spot activity. U-Pb ages of lavas from the northern and central TMR range between 103 and 80.5 Ma while $^{40}Ar/^{39}Ar$ ages from central and southern TMR yield ages ranging from 94.5 to 0.5 Ma. We performed new $^{40}Ar/^{39}Ar$ measurements in order to better understand the geodynamic history of the TMR. Plagioclase ages from Bikini Bottom and Torillon seamounts suggest ages of >90 Ma and ≥60 Ma respectively. Amphiboles from Seine seamount yield an age of 24.0 ± 0.8 Ma. Biotites from lavas of Ashton seamount give ages of 97.4 ± 1.1 Ma and 97.8 ± 1.1 Ma. The geochronological database available on TMR has been filtered on statistical criteria to eliminate unreliable ages. The resulting database reveals 3 pulses of alkaline magmatism on TMR at 103-80.5 Ma, at ~68 Ma and between 30 Ma to Present. The magmatism was continuous from 103 until ~68 Ma and from ~30 Ma until Present on the TMR, the surrounding seamounts and the Portuguese cost. We suggest that the space-time distribution of this magmatism results from the interaction between a wide thermal anomaly emitting magmatic pulses and the complex motion of the Iberian plate.

Supplementary material: Detailed Ar measurements data set is available at http://www.geolsoc.org.uk

The Tore-Madeira Rise (TMR) is a 1000 km long by 50 km wide seamount chain, oriented NNE-SSW along the Atlantic coast of Portugal and Morocco (Fig. 1a). It includes a dozen seamounts extending from the Tore seamount, located 300 km west of Lisbon, to the Madeira archipelago. For several decades, the nature of the rocks forming this aseismic ridge was almost unknown, and only very few samples were available. Two dredging campaigns were carried out in 2001 (R/V Meteor expedition M51/1; Tore-Madeira Rise cruise, R/V *Atalante*) to constrain the age and the main chemical characteristics of the rocks constituting the rise and to decipher the geodynamical process leading to the construction of the TMR. Abundant alkaline lavas displaying similar chemical characteristics were dredged along the whole rise in addition to surrounding alkaline magmatism occurrences (Fig. 1). Two sets of contrasting ages were obtained on lavas from seamounts along the whole rise. Titanite and zircon U-Pb ages from differentiated lavas of the northern and central part of the rise ranged between ~104 and ~80 Ma (Merle et al., 2006); $^{40}Ar/^{39}Ar$ measurements carried out on groundmass and mineral separates from central and southern TMR seamounts yielded Cretaceous (94 Ma) to Pleistocene ages (Geldmacher et al., 2005, 2006, 2008). All these studies argue for a hot-spot as the source of the TMR but it is still unclear if the TMR magmatism was related to the Madeira and/or Canary plumes (Geldmacher et al., 2006) or to a deep rooted thermal anomaly feeding the Azores, Madeira and Canaries hot-spots (Merle et al., 2006). Alternative hypotheses are accretion-related off-axis magmatic activity (Jagoutz et al., 2007) or shallow mantle upwelling (Geldmacher et al., 2008). These hypotheses are however closely dependent on the reliability of the ages of the various seamounts. Moreover, no ages are available for some seamounts, in particular those located slightly off the main TMR alignment. As a consequence, the geodynamic process that triggered the magmatism on the TMR and the surrounding area is still debated and additional geochronological data are required for the entire area.

The aim of this work is to document new $^{40}Ar/^{39}Ar$ dating performed on plagioclase, biotite and amphibole separates from lavas of four seamounts to improve the reliability of the two contrasting age sets mentioned previously. New and carefully selected published ages, and geochemical and isotopic data are discussed and combined together to obtain a more complete overview of the construction of the Tore-Madeira Rise. We give a new geodynamic interpretation of the TMR and the magmatic occurrences of this part of the Atlantic Ocean.

Geological setting

The Tore-Madeira Rise (TMR) ranges roughly from 40°20'N to 32°30'N and from 11°30'W to 17°40'W. It displays a NNE-SSW trending alignment of mounts which is surrounded by scattered seamounts (Fig. 1a). The northern limit of the rise is the ~2500 m high Tore seamount which rims an elliptic (120 km by 90 km) depression lying at 5000 m below sea level. The scattered seamounts occurring in the vicinity of the main alignment are the Bikini Bottom seamount, located to the NNW of Tore; Torillon, lying at around 100 km on the WSW of Tore; Unicorn and Seine seamounts (Fig. 1b). Most of the seamounts are at least 30 km in diameter (Seine reaches 48 km) for a height of over 3000 m above sea floor. Considering the dimension of the TMR (1000 km long by 50 km wide, 2 km high), the estimated volume of magma emitted could reach 10^5 km^3. The TMR has been considered as one of the main structures in the Northern Central Atlantic ocean.

The Azores-Gibraltar Fracture Zone (AGFZ), separating the Eurasian and African plates, is an important Atlantic transform fault which splits into three branches towards the Tore seamounts, Gorringe Bank, and Ampere-Coral Patch seamounts (e.g., Laughton et al., 1975; Jiménez-Munt et al., 2001; Fig. 1). Since Oligocene times, movements along the branches of the AGFZ seem to be transpressive, with a slight dextral component (Le Gall et al., 1997; Malod, personal comm.) while movements were very limited from Early Jurassic to Oligocene times (Olivet, 1996).

Seamounts to the North of the AGFZ lie along the J anomaly which is the first magnetic anomaly created by the Atlantic spreading centre along the Iberia margin (M0 to M3 magnetic anomalies, 125-130 Ma; Gradstein et al., 2004; Fig.1b). This anomaly corresponds to the boundary between true oceanic crust and a transitional domain composed of continental lithosphere peridotites exhumed during rifting and stretching of the Iberian margin (Boillot et al., 1989; Beslier et al., 1993; Girardeau et al., 1998). To the South beyond the central branch of the AGFZ, magnetic anomalies older than J seem to be present in the Seine Abyssal Plain (Roest et al., 1992) implying that some seamounts of the TMR could be emplaced onto oceanic lithosphere.

The geodynamical process leading to the construction of the TMR is still debated. Several explanations were put forward such as a hot-spot probably active coevally with spreading (Tucholke and Ludwig, 1982; Pierce and Barton, 1991; Geldmacher et al., 2006; Merle et al., 2006), accretion-related off-axis magmatic activity (Jagoutz et al., 2007) or shallow mantle upwelling (Geldmacher et al., 2008). It has been proposed that the TMR was built up by two magmatic phases, the earliest during Cretaceous times (Merle et al., 2006) constituting the basement of the rise capped by late Tertiary to recent magmas (Geldmacher et al., 2006). The magmas may have been focused along the lithospheric discontinuities which facilitated the magma ascent through the lithosphere (van der Linden, 1979; Geldmacher et al., 2006; Merle et al., 2006).

In the neighbouring region of the TMR (within < 1000 km; Fig. 1b), widespread alkaline magmatism occurs on Ormonde seamount (62-68 Ma, $^{40}Ar/^{39}Ar$ ages on both matrix and minerals; Féraud et al., 1982; 1986); Ampère-Coral Patch seamounts (~31 Ma, $^{40}Ar/^{39}Ar$ ages on whole-rock samples; Geldmacher et al., 2000) and on the continent (Serra de

Monchique complex: 69-70 Ma; Sines complex: 73-77 Ma; Sintra complex: 80-83 Ma; and Ribamar intrusion: ~88 Ma; U-Pb ages on titanite and zircon; Grange et al., 2007). All these magmatic occurrences as well as TMR samples display OIB-like geochemical characteristics, the specific positive Nb anomaly, in particular (Bernard-Griffith et al., 1997; Geldmacher et al., 2006; 2008; Merle, 2006). The isotopic characteristics of the TMR rocks and the surrounding alkaline occurrences are interpreted to be derived from the same OIB-type (mantle plume-like) source (Geldmacher and Hoernle, 2000; Geldmacher et al., 2006; Merle et al., 2006). However, isotopic heterogeneities exist between the different seamounts and within the same edifice. The isotopic compositions of the lavas from Godzilla seamount (Fig. 1) are clearly distinct from the compositions of the other seamounts of the TMR (see Geldmacher et al., 2006; 2008). The Cretaceous lavas display distinct isotopic characteristics from the Late Cenozoic volcanics (Geldmacher et al., 2006) and a significant variation of the isotopic signature is observed among the Seine seamount samples (Geldmacher et al., 2005).

Previous geochronological data from the TMR seamounts

As already emphasized, two datasets of contrasting ages were obtained on lavas along the whole rise (see Fig. 1b). All the previous $^{40}Ar/^{39}Ar$ measurements were performed using the Taylor Creek Rhyolite sanidine (TCRs) standard for which the authors adopted an age of 27.92 Ma (Dalrymple and Duffield, 1988; Duffield and Dalrymple, 1990). All the previous geochronological data from the TMR are given in Table A1 in online appendixes, together with analytical methods, rock types, material dated, ages with errors and standards used.

The lavas from the northern seamounts Tore, Sponge Bob and Ashton seamounts are dated by U-Pb methods on titanite and zircon from 80.5 ± 0.9 Ma to 104.4 ± 1.4 Ma (Merle et al., 2006).

In the central part of the rise, evolved lavas from Gago Coutinho seamount (also named Teresa by Geldmacher et al., 2006) have been dated between 92.3 ± 3.8 Ma and 94.5 ± 0.4 Ma (Geldmacher et al., 2006; Merle et al., 2006). Basic rocks dredged on Josephine North (Fig. 1) are dated by $^{40}Ar/^{39}Ar$ on whole-rock between 0.5 ± 0.1 Ma and 7.4 ± 0.5 Ma (Geldmacher et al., 2006) and those from Josephine seamount yielded ages between 8.2 ± 0.2 Ma and 15.8 ± 0.9 Ma (Wendt et al., 1976; Geldmacher et al., 2006). The basaltic rocks dredged on the Jo Sister seamount (also named Erik by Geldmacher et al., 2006) dated by $^{40}Ar/^{39}Ar$ on matrix give an age of 3.62 ± 0.32 Ma (Geldmacher et al., 2006) while the dredged evolved lavas are dated between 86.5 ± 3.4 Ma and 89.3 ± 2.3 by U-Pb on titanate (Merle et al., 2006).

Seamounts from the southern part of the TMR have been dated by $^{40}Ar/^{39}Ar$, except the altered basaltic samples dredged on Lion seamount estimated by a foraminifera fauna at ~80 Ma (Geldmacher et al., 2006). The basaltic lavas dredged on Dragon seamount are dated between 3.9 ± 0.3 Ma and 1.18 ± 0.18 Ma (Geldmacher et al., 2006) and those dredged on Seine seamount, Unicorn and Godzilla seamounts yield $^{40}Ar/^{39}Ar$ ages of 21.7 ± 0.2 Ma, 27.4 ± 2.4 Ma and around 66 Ma respectively (Geldmacher et al., 2005; 2008).

The $^{40}Ar/^{39}Ar$ ages of whole rock and separated plagioclase grains from the Madeira archipelago lavas range from 14.3 ± 0.2 Ma to 0.2 ± 0.1 Ma (Geldmacher et al., 2000 and references therein).

Analytical procedures

Mineral and whole rock analyses

Electron microprobe analyses (EMPA) of magmatic phases were performed with a Cameca SX50 automated electron microprobe (Microsonde Ouest, Brest), using an acceleration voltage of 15 kV, a beam current of 15 nA, a counting time of 6 s and correction by the ZAF method. Concentrations of < 0.3 Wt % are considered qualitative. Major and trace element analyses were carried out by ICP-AES and ICP-MS at the University of Brest and the CRPG at Nancy (analytical procedures in Govindaraju and Mevelle, 1987 and Carignan et al., 2001). For the samples analysed at University of Brest, specific details for the analytical methods and sample preparation can be found in Cotten et al., 1995.

$^{40}Ar/^{39}Ar$ geochronology

Plagioclases were separated from either the 100-200 µm or the 200-315 µm fractions using a Frantz isodynamic magnetic separator. The plagioclases recovered in the 2 Amperes non-magnetic fraction were selected by grain-by-grain hand-picking under the binocular microscope. The amphibole and biotite grains were separated using heavy liquids (CH_3Br_3 and CH_2I_2 respectively) and were hand-picked using a binocular microscope. Plagioclase and amphibole were further leached using diluted HF (2N) for 5 minutes and thoroughly rinsed in distilled water. The samples were loaded into aluminium discs along with the Fish Canyon sanidine standard (FCs = 28.03 ± 0.08 Ma, Jourdan and Renne, 2007) and irradiated for 10 h in the CLICIT facility at the TRIGA reactor, Oregon.

$^{40}Ar/^{39}Ar$ analyses were performed at the Berkeley Geochronological Center. Both single-grain and multi-grain aliquots were degassed by step heating using a CO_2 laser with focused lenses and beam-integrator lens, respectively. Ar isotopes were measured in static mode using a MAP 215-50 mass-spectrometer. Mass discrimination was monitored several times a day and yields a mean D-value of 1.00633 ± 0.00175 per AMU based on a power-law correction. Blank measurements were generally obtained after every three sample runs. *J*-values were calculated as the mean and standard deviation of the wells bracketing the samples (see for example, Jourdan and Renne, 2007) and yield a value of 0.002630 ± 0.000014 (0.54%, see online appendixes, Table A2). Ages were calculated using the decay constant recommended by Steiger and Jäger (1977) and step-heating details are given in online appendixes (Table A2) along with Ar isotopic data corrected for blank, mass discrimination and radioactive decay. Individual errors in online appendixes (Table A2) are given at 1σ level.

Our criteria for the determination of plateau ages are as follows: plateaus must include at least 70% of the ^{39}Ar released; they should be distributed over a minimum of 3 consecutive steps indistinguishable at 95% confidence level and satisfied a probability of fit of at least 0.05. Plateau ages are given at the 2σ level and are calculated using the mean of all the plateau steps, each weighted by the inverse variance of their individual analytical error. Integrated ages (2σ) are calculated using the total gas released for each Ar isotope. Inverse isochrons include the maximum number of consecutive steps with a probability of fit ≥0.05. The uncertainties on the $^{40}Ar^{*}/^{39}Ar^{*}$ ratios of the monitor are included in the calculation of the plateau age uncertainties but not the errors on the age of the monitor and on the decay constants (internal errors only).

Results

This work presents new ages for four samples dredged during the Tore-Madeira Rise cruise. They come from Bikini Bottom, Torillon, and Seine seamounts, located off the main trend of the TMR. In addition, biotites from a trachyte dredged on the Ashton seamount have also been dated to test a previous U-Pb age obtained on possibly inherited zircon grains (Merle et al., 2006) given that Ashton seamount is located on the very edge of the continental lithosphere (Fig. 1b). Coordinates and water depths of sampling sites are given in Table 1.

Petrological notes

The EMPA of mineral phases from the TMR samples are available in online appendixes (Table A3). All but one sample (Ashton trachyte; TMD 14-9) display evidence of seawater interaction occurring as carbonate, Fe-Mn hydroxides, brown-green clays and rare zeolites (K-zeolites: phillipsite and erionite) invading the groundmass and filling cracks and vesicles. However, it is worth noting that the phenocrysts are usually well preserved. The sample from Bikini Bottom (TMD 2-1) is a slightly altered basaltic trachyandesite containing well preserved phenocrysts of abundant (30% modal) plagioclase (2-8 mm in size), rare clinopyroxene (<1 mm), Fe-Ti oxides and iddingsitized olivine (1-2 mm in size). The groundmass is composed of feldspar laths and Fe-Ti oxides grains. The basic sample from Torillon seamount (TMD 12b-1) contains phenocrysts of iddingsitized olivine and scarce well preserved plagioclase (>10 mm-size). The groundmass is composed of feldspar laths, Fe-Ti oxides grains and altered rare olivine grains. The TMD 14-9 sample is a fresh highly porphyritic trachyte containing K-feldspars subordinate biotite and sparse clinopyroxene and Fe-Ti oxides. The groundmass is composed by the same minerals (Merle et al., 2006). The detailed description of this sample can be found in Merle et al. (2006). Sample TMD 21-2 from Seine seamount is a basanite containing phenocrysts of clinopyroxene (~5% modal), iddingsitized olivine (~5% modal), microphenocrysts of Fe-Ti oxides and subordinate brown amphibole (~1% modal) reaching 4 mm-size. The groundmass is composed of feldspar laths, clinopyroxene, Fe-Ti oxides grains and olivine.

Major and trace elements

The whole-rock analyses of the samples TMD 2-1, TMD 12b-1 and TMD 21-2 are given in Table 2. The sample TMD 14-9 has been documented by Merle et al. (2006). It is a very well-preserved trachyte (LOI = 2 wt %) whose incompatible elements patterns display Ba, Sr and Ti negative anomalies due to feldspar and Fe-Ti oxides fractionation. Apart from this sample, the others show moderate to high loss on ignition (LOI = 3.0 to 11.0 wt %). Samples TMD 2-1 and TMD 21-2 having less than 4.5 wt % of LOI can be more confidently plotted in the TAS diagram (not shown) and plot in the field of basaltic trachy-andesite and basanite, respectively. However, this result should be considered with caution since the seawater alteration has probably modified the chemistry of the rocks, especially the potassium content (see discussion below). All the samples documented here display steep multi-element patterns with an important enrichment in the most incompatible elements (LREE, LILE, Th, Nb), typical of OIB-type lavas (Fig. 2). Sample TMD 21-2 especially displays a positive Nb anomaly and its pattern shows similarities relative to the previously documented Seine samples (Geldmacher et al., 2005; Fig. 2). Generally, positive K and P anomalies such as observed in the pattern of the TMD 12b-1 sample (Fig. 2) could correspond to feldspar and apatite mineral accumulation but as neither of these minerals is observed, these anomalies are more likely related to seawater interaction. The data points from the studied samples plot in the field of the previously analysed TMR volcanics in the Zr/Y vs Th/Nb diagram (Fig. 3) suggesting that these rocks belong to the same magmatic events as those documented by Geldmacher et al. (2005, 2006).

$^{40}Ar/^{39}Ar$ geochronology

Summarized $^{40}Ar/^{39}Ar$ results are shown in Table 3.

Plagioclase analyses from TMD 2-1 (Bikini Bottom) show a U-shaped age spectrum with the oldest steps defining a weighted mean >90 Ma (Fig. 4a). The Ca/K ratio of this sample calculated from $^{37}Ar/^{39}Ar$ mimics the pattern of the age spectrum. The Ca/K of these plagioclase grains obtained by EMPA analyses is significantly higher which indicates the presence of a K-rich phase component in the $^{40}Ar/^{39}Ar$ results (Fig. 4a). These observations suggest that the plagioclase grains locally underwent partial alteration leading to recrystallization of a K-rich phase such as adularia. A minimum age of 90 Ma could be estimated upon the heating steps having the highest Ca/K (Fig. 4a). Similarly, $^{40}Ar/^{39}Ar$ measurements carried out on TMD 12b-1 (Torillon) plagioclase did not yield a plateau age (Fig. 4b). As for sample TMD 2-1, the Ca/K spectrum mimics the pattern of the age spectrum but displays only slight perturbation (Fig. 4b). The EMPA analyses yielded a mean Ca/K value well within error of the Ca/K ratio derived from the Ar experiments and suggest only negligible perturbation. Nevertheless, sample TMD 12b-1 failed to provide a plateau age and based on steps associated with the highest Ca/K ratio, can only be interpreted as a minimum age of ~60 Ma (Fig. 4b).

Two statistically indistinguishable biotite plateau ages have been obtained for sample TMD 14-9 (Ashton). We obtained an age of 97.4 ± 1.1 Ma (MSWD = 1.07; P = 0.38) on a single biotite grain and 97.8 ± 1.1 Ma (MSWD = 0.8; P = 0.78) on a multi-grain aliquot (Figs. 4c and 4d). These two $^{40}Ar/^{39}Ar$ ages are indistinguishable from the U-Pb age at 96.30 ± 1 Ma obtained by Merle et al. (2006) on titanite and zircon fractions from the same sample. $^{40}Ar/^{39}Ar$ dating of amphibole crystals from sample TMD 21-1 from Seine seamount yielded three indistinguishable plateau ages at 24.4 ± 0.4 Ma (MSWD = 0.23; P = 1.0) and 24.4 ± 0.5 Ma (MSWD = 1.24; P = 0.26) for the single grain measurements (Figs. 4e and 4f) and 24.8 ± 0.3 Ma (MSWD = 1.72; P = 0.13) for the multi-grains aliquot measurements (Fig. 4g). These ages are slightly older than the previous age at 22.0 ± 0.2 Ma (recalculated using an age of 28.34 Ma for the TCs standard; Renne et al., 1998) obtained on groundmass by Geldmacher et al. (2005). For the two first aliquots, the $^{40}Ar/^{36}Ar$ intercept values on the inverse isochron diagrams are similar to the atmospheric ratio. The third aliquots displays a value higher than the atmospheric ratio and a much greater scatter of the data suggesting that some heterogeneously distributed excess $^{40}Ar^*$ might be present (Fig. 4-5). The third aliquot is therefore not included in the mean age calculation of TMD 21-1 (Table 4).

Discussion

Significance of the new $^{40}Ar/^{39}Ar$ ages

The activity on the northernmost Bikini Bottom seamount estimated at >90 Ma may be related to the Cretaceous phase already pointed out by the previous studies (Geldmacher et al., 2006; Merle et al., 2006) but the poor age data quality prevent us from further speculation. Similar poor data quality for the Torillon seamount suggests a magmatic activity at ≥60 Ma in this locality. The $^{40}Ar/^{39}Ar$ biotite ages obtained from the trachyte TMD14-9 sampled on the Ashton seamount are indistinguishable from the U-Pb age (96.3 ± 1.0 Ma, Merle et al., 2006) yielded by titanite and zircon fractions extracted from the same rock. This implies that the zircon grains extracted from this alkaline lava have a magmatic origin as proposed by Merle et al. (2006) and are not inherited from the continental lithosphere. Nevertheless, this does not exclude the occurrence of the continental lithosphere beneath the seamount since Ashton is located at its very edge (Fig. 1b). Considering that the $^{40}Ar/^{39}Ar$ ages only marginally allow the expected ~1% intercalibration bias with U-Pb ages within errors (Min et al., 2000; Mundil et al., 2006), the data also seem to indicate minimal pre-eruptive magma residence times (e.g.

Simon et al., 2008). Our new ages obtained on the lavas from the Seine seamount (24.4 ± 0.5 Ma) are reliable for sub-million year high-precision geochronology and confirm the occurrence of a magmatic activity during the Late Oligocene.

TMR and surroundings age reliability

Precise and accurate radio-isotopic data play a critical role in obtaining the timing, duration, and rates of magmatic processes occurring on the TMR. The new data documented here confirm a long lasting and geographically extended magmatic activity during the Cretaceous and the early Palaeocene. However, any geodynamical discussion must be based on a reliable age database and must be filtered from statistically and geologically untrustworthy measurements. The calculation of the alteration index (A.I., Baski, 2007) to test the accuracy of the $^{40}Ar/^{39}Ar$ measurements was impossible since the detailed $^{40}Ar/^{39}Ar$ dataset (%^{39}Ar released, $^{40}Ar^*/^{39}Ar_K$, apparent age for each step) of the previously dated samples (Geldmacher et al., 2005, 2006, 2008) were not published.

$^{40}Ar/^{39}Ar$ geochronology performed on whole rock and groundmass may be an interesting alternative when K-rich phenocryst phases are absent (Sharp et al., 1996), providing that whole rock acid etching is performed before measurements. This technique can in some case yield good results (e.g. Pringle et al., 1991). Nevertheless, it becomes increasingly clear that K-Ar and $^{40}Ar/^{39}Ar$ measurement on groundmass displays technical limitations for high-precision and accuracy geochronology (except when rocks are only a couple of m.y. old; e.g., Hofmann et al., 2000; Baksi et al., 2006; Jourdan et al., 2007a). These limitations are:

(1) Untestable freshness of the samples using the Ca/K ratio, because different minerals with different chemical compositions and activation energies will degas their Ar at various temperatures yielding complex Ca/K spectra.

(2) $^{40}Ar/^{36}Ar$ fractionation in the extraction line and sample chamber which is known to yield older apparent ages (McDougall and Harrison, 1999).

(3) Existence of fast neutron activation-induced ^{39}Ar and ^{37}Ar recoil and possible ejection (Turner & Cadogan, 1974) creating significant ^{39}Ar and ^{37}Ar loss at the edge of a grain. In most cases, this will result in apparent older age due to the dominant effect of the ^{39}Ar loss (e.g. Onstott et al., 1995; Paine et al., 2006; Jourdan et al., 2007b) but for samples with high Ca/K and significant atmospheric contamination, the recoil of ^{37}Ar may produce younger apparent ages due to recoil fractionation of Ca-derived ^{37}Ar and ^{36}Ar (e.g., Jourdan et al., 2007b). The recoil phenomenon may also involve a complex re-distribution of the daughter atoms in different lattice sites.

Basaltic groundmass samples are generally enriched in potassium relative to the high Ca/K plagioclase phases, yielding age with better precision compared to mineral separates (due to low Ca interference correction and the larger Ar-ion beam). This is evidenced by our amphibole age (24.4 ± 0.4 Ma) from Seine seamount (Figs. 1 and 4) which is less precise than the earlier matrix age (22.0 ± 0.2 Ma; Geldmacher et al., 2005). However, it has been shown than in most cases for rocks older than a couple of Ma, the accuracy of the age obtained on the groundmass might be questionable (e.g. Hofmann et al., 2000; Jourdan et al., 2007a). Here, we suggest that the age at ~22 Ma of Geldmacher et al. (2005) is ~2 Ma younger due to the occurrence of cryptic alteration phases in the groundmass.

Furthermore, in basaltic rocks, the fine-grained groundmass carries most of the potassium (Mankinen and Dalrymple, 1972) and thus renders the K-Ar and $^{40}Ar/^{39}Ar$ measurements largely dependent on the mobility of potassium during any geological event.

This limitation is exacerbated for dredged rocks because they are highly suspected to have undergone severe and pervasive rock-seawater interactions for millions of years leading to a systematic chemical effect on the rock chemistry. This effects are illustrated by the geochemical composition of the TMR samples in which the pervasive seawater-rock interaction led to crystallization of potassium rich secondary phases such as zeolites (erionites, phillipsites), clay-minerals (celadonite-dioctaedric clays mixture) and carbonates in voids and groundmass of the rocks (Fig. 6; Merle, 2006). The crystallization of these alteration phases (brownstone facies, Cann, 1979) implies an overall hydration of the samples and the mobility of the alkaline elements such as potassium (e.g. Honnorez, 1981). The potassium behaviour can be monitored in the TMR samples by a K_2O *vs* LOI diagram in which the LOI values can be used as a proxy for alteration index. For a LOI value higher than 4.5%, the K_2O content of the TMR rocks displays a positive co-variation with increasing LOI (Fig. 7). Such kind of co-variation trend has already been documented in submarine samples and interpreted as a potassium accumulation from seawater in the samples (e.g. Honnorez, 1981). Therefore, the potassium content of the groundmass of TMR samples might reflect both magmatic composition and seawater interactions. The potassium mobility in basaltic rocks related to seawater interaction might occur even for LOI values lower than 2% (Caroff et al., 1995). As illustrated by the TMR samples, the most careful selection of fresh rock fragments based on optical methods is inadequate since alteration phases are almost inevitably present (see Fig. 6). The effects of pervasive seawater alteration may affect the chemistry of the rocks so deeply that they are unlikely removed by any acid etching compromising groundmass K-Ar and $^{40}Ar/^{39}Ar$ analyses.

Filtered age database and standard recalibration

In order to produce a robust age database to support the geodynamical discussion, $^{40}Ar/^{39}Ar$ total fusion measurements as well as K-Ar ages are rejected since there is no mean to check the validity of the age with internal criteria (e.g., age spectrum). Since our new step-heating Ar-Ar amphibole age from Seine is close to the previously published step-heating Ar-Ar matrix age, we consider that the step-heating matrix $^{40}Ar/^{39}Ar$ ages, even if unreliable for high-precision geochronology might have a geological significance and are taken into consideration. We only take into account the $^{40}Ar/^{39}Ar$ plateaus (>70% of ^{39}Ar released) and mini-plateaus (between 50 and 70% of ^{39}Ar released). $^{40}Ar/^{39}Ar$ step-heating measurements having less than 50% of ^{39}Ar are considered as invalid (e.g. Baksi, 1999, McDougall and Harrison, 1999) and are rejected.

U-Pb and $^{40}Ar/^{39}Ar$ age data where tested using the goodness of fit parameters such as the mean squared weighted deviation (MSWD) and probability of fit (P). These parameters were calculated when lacking and are reported in Table 4 along with the filtered database. Interestingly, all the groundmass $^{40}Ar/^{39}Ar$ measurements fit the statistical test, however, as stated before, they still have to be considered with caution. In the following geodynamical discussion, groundmass $^{40}Ar/^{39}Ar$ data will be considered as good estimate, but care must be taken if these data need to be used for very high-precision geochronology. All the $^{40}Ar/^{39}Ar$ data reported in Table 4 are calculated for an age of 28.03 Ma for FCs (Jourdan and Renne, 2007) corresponding to an age of 28.34 Ma for TCs.

Age and duration of magmatic activity on the TMR and surroundings

Considering the available filtered TMR age database, 3 pulses of alkaline magmatism seem to occur from the end of the Early Cretaceous until the Late Paleogene (Fig. 8). The oldest magmatic phase occurred between 103 and 80.5 Ma (magmatic phase 1) in the northern and the central part of the TMR (Fig. 1). The activity on the northernmost Bikini Bottom seamount estimated at ~90 Ma could be related to this phase. It is also possible that this magmatic phase occurred in the southern part of the TMR since the age of the Lion seamount has been estimated at ~80 Ma (Geldmacher et al., 2006).

A second pulse of magmatism occurred on the TMR during the Late Cretaceous-Early Paleocene (magmatic phase 2) between ~70 and ~60 Ma (Fig. 8). This phase would be localised on the southern part of the TMR and on the Godzilla seamount but could have also taken place on the northern part of the TMR since the magmatic activity on the Torillon seamount has been estimated to be ≥60 Ma (Fig. 1). However, the existence of this phase is based on relatively few data and additional data with a similar age are desirable to constrain the timing and duration of this phase as a significant magmatic event at the TMR scale. Considering the few samples collected, we do not exclude that continuous magmatism could occur from 103 to around 60 Ma with a lack of sampling for the 80-60 Ma period.

The last magmatic phase on the TMR (magmatic phase 3) began around 28 Ma in the southern part of the TMR (Seine-Unicorn area, Figs. 1 and 8). The duration of this magmatic pulse relies upon a number of groundmass $^{40}Ar/^{39}Ar$ analyses and seems to persist until present in the central part (Josephine area, Fig. 1) and southern part of the rise, leading to the construction of the Madeira archipelago.

Considering the magmatic activity that occurred between 88 and 69 Ma (n = 10) on the coast of Portugal (Grange et al., 2007) and at 65-62 Ma (n = 3) on Ormonde seamount (Féraud et al., 1982, 1986; Table 4), magmas were emitted continuously from 103 to 62 Ma in the northern central Atlantic (Fig. 1). An U-Pb age of 77 Ma was obtained on a diorite from Ormonde (Schärer et al., 2000) which is significantly older than the numerous previous $^{40}Ar/^{39}Ar$ ages (Féraud et al., 1982, 1986). This sample was collected on the top of Ormonde seamount among drop-stones of various continental petrographic types (Schärer et al., 2000) and displays geochemical characteristics (similar REE and multi-element patterns, same initial Hf isotopic composition) and age (within uncertainties) similar to the diorites of the Sines complex documented by Grange et al. (2007). As a consequence, this sample is most likely a drop-stone from the Sines complex, not related to the alkaline activity on Ormonde seamount. Magmatic activity might have occurred around 32 Ma on the Ampere-Coral Patch seamounts. However, this age was obtained on groundmass of a dredged sample (Geldmacher et al., 2000) and would require confirmation by $^{40}Ar/^{39}Ar$ on mineral separates. It emerges from this age compilation that a gap in magmatic activity occurred between around 60 and 32 Ma, at least considering the available dataset.

Refining the geodynamical model of the TMR origin

An OIB-type origin for the TMR

All the studied TMR lavas have unambiguous OIB-type geochemical characteristics. The enriched nature of the magmatism is likely to be inherited from the melting of enriched mantle domains (Geldmacher et al., 2005, 2006, 2008; Merle, 2006). Such a geochemical signature argues for a hot-spot-like nature for the origin of TMR (Geldmacher et al., 2006; Merle et al., 2006). An OIB-type magmatism rules out any accretion-related off-axis magmatic activity (Jagoutz et al., 2007), as this model suggests the shallow melting of asthenosphere-like depleted mantle source. Moreover, the emplacement of the TMR seamounts postdates by at least 20 Ma the activity of the accreting centre in the region.

Considering that the TMR magmatism is volumetrically important (~100 x 10^3 km^3) and comparable to the Canary Archipelago magmatism (150 x 10^3 km^3), it is unlikely that it originates from shallow melting processes, such as edge driven convection or adiabatic partial melting of magma occurring along transform faults. Furthermore, edge-driven convection would require thick cratonic lithosphere in the vicinity (King and Ritsema, 2000), which has not been evidenced beneath Iberia and north-western Africa.

During the TMR magmatic activity (103 Ma – Present), this part of the Iberian margin and the adjacent oceanic area underwent a wide compression (e.g. Olivet, 1996; Sibuet et al., 2004b). A strong heat source is then required to maintain a melting anomaly over the entire region during more than 100 Ma. In the case of a Hawaiian hot-spot model, an increase of the ages along the seamounts chain is expected. In the TMR case, this simple feature is most probably complicated by the complex motion of the Iberian plate since the Early Cretaceous.

Problems about the previous models proposed for the TMR origin

The lack of a clear space-time correlation over the whole area (although local trends may exist) and the simultaneous magmatic activity observed at several places, such as on Tore and Jo Sister seamounts and on the continent (Ribamar intrusion) at ~ 88 Ma, seem to exclude a simple Hawaiian-type hot spot for the origin of the TMR. A recent study proposes that the TMR would have been built during two phases of magmatism, the oldest one during the Cretaceous later capped by a Miocene-Pleistocene phase (Geldmacher et al., 2006). The first phase would be due to the interaction between the Canary hot-spot and the Mid-Atlantic Ridge (MAR), leading to the construction of an oceanic plateau, together with the J-Anomaly Ridge (JAR, located on the south of the Grand Banks of Newfoundland). The TMR and the JAR would constitute the basement of the second Miocene-Pleistocene magmatic phase induced by the activity of the Madeira hot-spot (Geldmacher et al., 2006). In spite of the advantage of giving an attractive geodynamical interpretation, this model presents some problems. (1) According to this model, the Cretaceous basement would correspond to the deepest part of the TMR and then all the Miocene-Pleistocene rocks would be dredged from shallower depths. However, the dredging depth can not be used to postulate any stratigraphic relations between Cretaceous and Miocene-Pleistocene rocks. Moreover, Cretaceous rocks were sometimes recovered at shallower depth than Miocene-Pleistocene rocks. For instance, the samples from Jo Sister (86-89 Ma) documented by Merle et al. (2006) were dredged between -2224 and -1960 m while the rocks from the eastern slope of the Josephine seamount (14-16 Ma) were dredged between -3600 and -3000 m. (2) The TMR and the JAR would be formed near the ridge axis around 125-130 Ma. Even if the possibility of an interaction with the MAR has been suspected for the oldest part of the TMR (Sponge Bob seamount, Merle et al., 2006), the magmatic activity exclusively younger than 103 Ma documented on the TMR post-dates the spreading of the Atlantic ridge by at least 22 Ma. Moreover, the age of the emplacement of the JAR is not constrained by any isotopic age data. (3) The main problem of this model concerns the seamounts located on the North of the AGFZ, which are not taken into account in the proposed geodynamical interpretation of Geldmacher et al. (2006). If they are included in the proposed plate reconstruction, these seamounts would be in a position to originate from the Madeira hot-spot and not from the Canary hot-spot as proposed, thus contradicting the interpretation of the isotopic signatures (see Fig. 9 in Geldmacher et al., 2006 and discussion concerning the isotopic data). Therefore, if the magmatism of the northern part of the TMR is taken into account, it is necessary to consider the kinematics of the Iberian plate that would necessarily influence the spatial distribution of the seamounts since they lie on the Iberian plate. (4) At last, this model does not include the magmatic alkaline activity occurring on the Portugual coast between 88 and 69 Ma.

A wide, deep rooted thermal anomaly located beneath the Azores, the Canaries and Madeira (Montelli et al., 2004) that could possibly have fed the TMR has also been proposed as a possible source of magmas leading to the construction of the TMR (Merle et al., 2006). This model however gives no details concerning the space-time related emission of magmas.

New interpretation of the TMR geodynamics

Considering that three temporally and spatially distinct magmatic phases occurred on the TMR and display heterogeneous isotopic signatures (Geldmacher et al., 2005; 2006; 2008; this study), we suggest that short-lived, small-sized (less than 100 km) magma pulses were emitted from a thermal anomaly located under the TMR-Azores-Madeira-Canary area. These magmatic pulses do not seem to be emitted randomly since two local trends are observed between Sponge Bob and Jo Sister seamounts (103-86 Ma) and between Ribamar and Serra de Monchique on the continent (88-69 Ma; Fig. 1b). The oceanic trend is oriented NE-SW suggesting a north-eastward motion of the Iberian plate. The continental trend is oriented NNW-SSE, suggesting a NNW motion of the Iberian plate. The movement of the Iberian plate since the Late Jurassic has been debated for three decades. However, a recent comprehensive geodynamical reconstruction of the Iberia plate motion and the Pyrenees orogenic formation (Sibuet et al., 2004b) suggests a plate motion toward the NE from 125 to around 83 Ma and toward the NNW from 83 Ma until Present (Fig. 9a). This model reconciles the onland data from the Pyrenees orogen formation and the offshore data from the Iberian margin and the Bay of Biscay. It suggests that part of the Neo-Tethys ocean was located between Iberia and Europe during the Late Jurassic-Early Cretaceous. This geodynamical reconstruction of the Iberian region (Sibuet et al., 2004b) together with our data allow us to propose a geodynamical model that involves an interaction between a thermal anomaly emitting magmatic pulses and the motion of the Iberia plate.

Stage 1 – 103 to 88 Ma: the Iberia plate moved in a NE direction due to the subduction of the Neo-Tethys Ocean beneath Europe (Fig. 9a). During this period, the Iberia behaved as a part of the African plate and the plate boundary was located in the Bay of Biscay and the Pyrenees. The emission of a magmatic pulse during this period yields to the formation of the age trend observed from Sponge Bob to Jo Sister (Fig. 9b) corresponding to the magmatic phase 1 on the TMR.

Stage 2 – ~88 to 81 Ma: the kinematics of the Iberian plate changed drastically around 83 Ma. The spreading of the Bay of Biscay ceased and the subduction of the Neo-Tethys ocean was achieved (Fig. 9a). The motion of the Iberia plate shifted from SW-NE to SSE-NNE leading to little or no movement during this stage. This change would need several million years to be effective, which led to a heat accumulation in the underneath mantle by the blanketing effect of the lithosphere. As a consequence, the thermal anomaly becomes hotter. It induced the emission of several magmatic pulses on distinct locations on the TMR as well as the Portugal coast. This may explain the occurrence of randomly-located magmatism between 88 and 81 Ma which ended the magmatic phase 1 on the TMR (Fig. 9b). It is possible that the lithospheric structures may have drained the ascending magmas.

Stage 3 – 80 to 69 Ma: as the continental subduction of Iberia under Europe initiated, the Iberian plate started moving toward the NNW (Fig. 9a). The magmatic pulse already emitted during the previous stage along the Portugal coast produced an age trend from the Ribamar intrusion to the Serra de Monchique complex (Fig. 9b, Grange et al., 2007).

Stage 4 – ~68 to 60 Ma: a second period of randomly-located magmatism occurred, corresponding to the magmatic phase 2 on the TMR (Fig. 9b). As for stage 2, this phase could be associated with a period of quiescence in the motion of the Iberia plate, leading again to the accumulation of heat under the lithosphere and emission of several magmatic pulses. Such a motionless phase has not been described in the model proposed by Sibuet et al. (2004b; see

Fig. 9a). However, considering the duration of the NNW motion phase in this model (~85 Ma to Present), a brief motionless period may have occurred as identified between 69 and 56 Ma by Roest & Srivastava (1991).

Stage 5 – 56 to 33 Ma: during this period, no magmatism is identified either on the continent or in the oceanic domain (Fig. 9b). This period corresponds to the main compression phase of the Pyrenees orogenesis (Olivet, 1996; Sibuet et al., 2004b). During this period, a 90 km-long slab of the oceanic lithosphere of the Bay of Biscay was subducted beneath the northern coast of the Iberian peninsula, along the North Iberian trough (Olivet, 1996 and references included). This subduction led to a thrust zone extending from the Pyrenees oceanward to the side of the Galicia bank (e.g. Olivet, 1996; Thinon et al., 2001). It is likely that a wide and strong compression affected both oceanic and continental lithospheres located on the south of the Galicia bank, as evidenced by the northward thrust of the Gorringe bank on the Tagus Abyssal Plain in the Early Tertiary times (Olivet, 1996; Le Gall et al., 1997). This wide compression that affected both oceanic and continental lithospheres may have prevented the ascent of the magmas toward the surface.

Stage 6 – ~32 Ma to present: The Pyrenees orogen is built and the plate boundary between the European and African plates is now the AGFZ (Fig. 9a). The Iberian plate consequently behaved as part of the European plate. The convergence between Europe and Africa, which involved an overall compression on the Iberia peninsula, is still ongoing (Jiménez-Munt, 2001). This period is related to another phase of randomly emitted magmatic pulses. This magmatic activity corresponds to the magmatic phase 3 on the TMR. The compression state on Iberia may have prevented the emission of the magma at the surface and may explain the localization of magmatism on the African plate. The very slow motion of the African plate (< 2mm/yr; Stich et al., 2006) may favour heat accumulation under the lithosphere by a shield effect and lead to an increase of magmatic pulse emissions. The position of the magmatic occurrences close to the branches of the AGFZ (Fig. 9b) suggests that these lithospheric structures may have played a role of conduits to drain the magmas to the surface.

Considering the geochronological, geochemical and isotopic data published on the TMR and the new $^{40}Ar/^{39}Ar$ data presented here, the magmatic phases on the TMR are mirrored by the interaction of a wide thermal anomaly beneath the lithosphere and the Iberia Plate motion driven by orogenic and tectonic activity of the Pyrenees. This model satisfies the geodynamical constraints imposed by the kinematics of the Iberia plate.

A single magmatic province in the Northern central Atlantic?

On the American plate, several seamount groups (Corner seamounts: 80-76 Ma; Newfoundland seamounts: 98 Ma; sills drilled on the ODP leg 210, site 1276: 105-98 Ma and New England seamounts: 103-82 Ma) had magmatic activity contemporaneous with that of the TMR (Fig. 10) and were located at that time less than 1000 km from the TMR. Although most of these ages were obtained by either K-Ar or $^{40}Ar/^{39}Ar$ on groundmass, they suggest that a wide magmatic activity occurred around 105 Ma on the northern central Atlantic. It is not excluded that the Azores Archipelago (from ~85 Ma to Present) and the Canary magmatic province (from 55 Ma and possibly 68 Ma to Present; Geldmacher et al., 2005) were also active at the same time as the TMR (Fig. 10). All these magmatic occurrences have previously been considered as independent magmatic provinces. They are relatively close in space to one another (less than 500 km) and seem to emplace during the same period. Recent geochemical studies have put forward that these provinces may share similar isotopic characteristics and thus, similar mantle source. For instance, the isotopic compositions of Madeira and Canary archipelagos, New England seamounts and some TMR lavas tend to converge to a restricted composition corresponding to a HIMU-like mantle component (Low Velocity Component: LVC defined by Hoernle et al., 1995; Taras and Hart, 1987; Geldmacher and Hoernle, 2000; Geldmacher et al., 2006). Similar source and coeval period of magmatic activity in the Northern Central Atlantic ocean together with the thermal anomaly imaged by seismic tomography (Montelli et al., 2004) argue for a single magmatic province fed by a wide thermal anomaly as previously proposed for the SW Portugal-Canary-Madeira magmatism (Hoernle et al., 1995; Lustrino and Wilson, 2007).

However, an isotopic heterogeneity is observed between the different provinces but also within a given province, e.g., strong isotopic heterogeneity on São Miguel Island in the Azores (Widom et al., 1997); EMI signature for Godzilla but HIMU for Josephine on the TMR (Geldmacher et al., 2006, 2008); clear EMII component in the ODP leg 210 sills (Hart and Blusztajn, 2006). A hypothesis to reconcile these data is to invoke a wide mantle plume/thermal anomaly which produced scattered magmatic pulses over a very large area yet constituting a single large volcanic province.

Conclusions

Our new $^{40}Ar/^{39}Ar$ measurements of plagioclase, amphibole and biotite separates from the Bikini Bottom, Torillon, Ashton and Seine seamounts give new constraints on the construction of the TMR. The filtered database argues for three magmatic phases on the TMR (103-80 Ma, ~68 Ma and from ~28 Ma until Present). Considering the magmatism that occurred on the Ampere-Coral Patch seamounts, Ormonde seamount and on the Portugal coast, the magmatic activity was continuous from 103 until ~60 Ma and from ~32 Ma until Present. Based on the space and time distribution of the magmatism on the TMR and surroundings, we suggest that the TMR magmatism resulted from interaction between the complex motion of the Iberian plate due to the Pyrenees formation and a wide thermal anomaly located beneath the Canary-Madeira area. This thermal anomaly produced short-lived, small-scale (> 100km) magmatic pulses which created seamount alignments during the phases of motion of the Iberian plate between 103 and 80 Ma and between 80 and 70 Ma. Instead, during the periods of quiescence of the Iberian plate, the shield effect of the lithosphere (continental and/or oceanic) would involve an accumulation of heat in the mantle leading to an increase of magma emissions. These periods correspond to randomly spatial occurrence of magmatism between 88 and 81 Ma, 67 and 60 Ma and from 31 Ma until Present. During the main compression phase associated with the Pyrenees formation, between 56 and 33 Ma, no magmatism occurred. The overall compression that affected the Iberian plate would prevent magma emission on the surface.

The TMR magmatism could be related to the same geodynamic process that led to the genesis of several magmatic provinces on the northern central Atlantic such as Newfoundland, Corner and New England seamounts, Azores and Canary Archipelagos which emplaced during the same period. All these magmatic occurrences could be the surface expressions of the thermal anomaly now located beneath the Canary-Azores area.

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Appendices

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Figures captions

Figure 1: (a) Bathymetric map of the East northern central Atlantic (From Sibuet et al., 2004a). TAP: Tagus abyssal plain. (b) Bathymetric map of the study region distinguishing the main structural units. Solid lines represent faults, and dashed lines inferred faults. AGFZ: Azores-Gibraltar Fracture Zone. Triangles indicate seamounts where dating has been performed. Ages of Ormonde, Monchique, Madeira, Porto Santo, Desertas Islands, Ampere, Josephine, Unicorn

and Seine from Wendt et., 1976: Féraud et al., 1982; 1986; Bernard-Griffiths et al., 1997; Geldmacher et al., 2000; 2005, 2006; 2008; Merle et al., 2006). The geochronological data from this study are indicated in bold. Location of the J anomaly after Olivet (1996).

Figure 2: Primitive mantle-normalized trace elements patterns. Normalization values from Sun and McDonough (1989). Average N-MORB pattern from Sun and McDonough (1989). Pattern of previously studied samples from Seine seamount after Geldmacher et al. (2005).

Figure 3: Zr/Yb vsTh/Nb plot for the data-points of the TMR samples. Fields of Canary Archipelago and Madeira Archipelago basalts and Atlantic N-MORBs from Georoc and PetDB databases. Field of previously studied TMR samples from Geldmacher et al. (2005; 2006; 2008).

Figure 4: Plagioclase, biotite and amphibole $^{40}Ar/^{39}Ar$ apparent age and related Ca/K ratio spectra of the plagioclase separates versus the cumulative percentage of ^{39}Ar released. Errors on plateau (>70% ^{39}Ar released) and mini-plateau (50-70% ^{39}Ar released) ages are quoted at 2σ and do not include systematic errors (i.e. uncertainties on the age of the monitor and on the decay constant). MSWD and probability are indicated. Ages in bold represent the most reliable ages for each sample.

Figure 5: Inverse correlation isochron plot of $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ for two step-heated samples. MSWD and probability, and $^{40}Ar/^{36}Ar$ intercept are indicated. Excluded steps are indicated in gray.

Figure 6: Photographs of thin sections of basic and less evolved lavas dredged on the TMR. The vesicles are filled by clay minerals, zeolites and carbonates. The groundmass display also overall oxidation due to seawater percolation.

Figure 7: Variation of potassium content as function of seawater alteration expressed as LOI (Loss on Ignition). The discrepancy observed for LOI higher than 4.5 % is related to potassium mobility.

Figure 8: Age frequency histogram (error bars not included) and probability density distribution diagram (PDD; error bars included in the curve calculation; PDD increment: 0.5 Ma) for the TMR lavas.

Figure 9: Geodynamical model for the space-time repartition of magmatism on TMR and surroundings. (a): Locations of the Iberian Plate since 125 Ma relative to Europe considered to be fixed (adapted from Sibuet et al., 2004b). The light gray domains are areas in extension and dark gray domains are areas under compression. The double lines in the Bay of Biscay at 83 Ma indicate the proto-ridge. J, A33 and A 34 are magnetic anomalies. The black arrows indicate the direction of convergence and the white arrows, the direction of extension. EU: Europe plate; IB: Iberian plate; NA: North America plate. Pyr suture: Pyrenees suture. NGFZ: Newfoundland Gibraltar fracture zone. (b) Interpretation of magmatic activity on the TMR and surroundings as different stages corresponding to the phases of the Iberian plate motion and Pyrenees orogenesis. Gray arrows indicate the magmatic trends.

Figure 10: Location of the different magmatic occurrences in the Northern Central Atlantic Ocean close to the TMR area at the time of its activity. Estimation of the volcanic activity of Azores from Gente et al. (2003); age of the ODP 210 sills from Hart and Blusztajn (2006);

age of the New England seamounts from Duncan (1984); Newfoundland seamounts from Sullivan and Keen (1977). Range of the magmatic activity on the Canaries from Geldmacher et al. (2001).

Tables

Table 1: Sampling sites and dredging operations parameters.

Table 2: Major and trace elements analyses of TMR.

Table 3: $^{40}Ar/^{39}Ar$ results.

Table 4: Filtered geochronological data from TMR and surroundings.

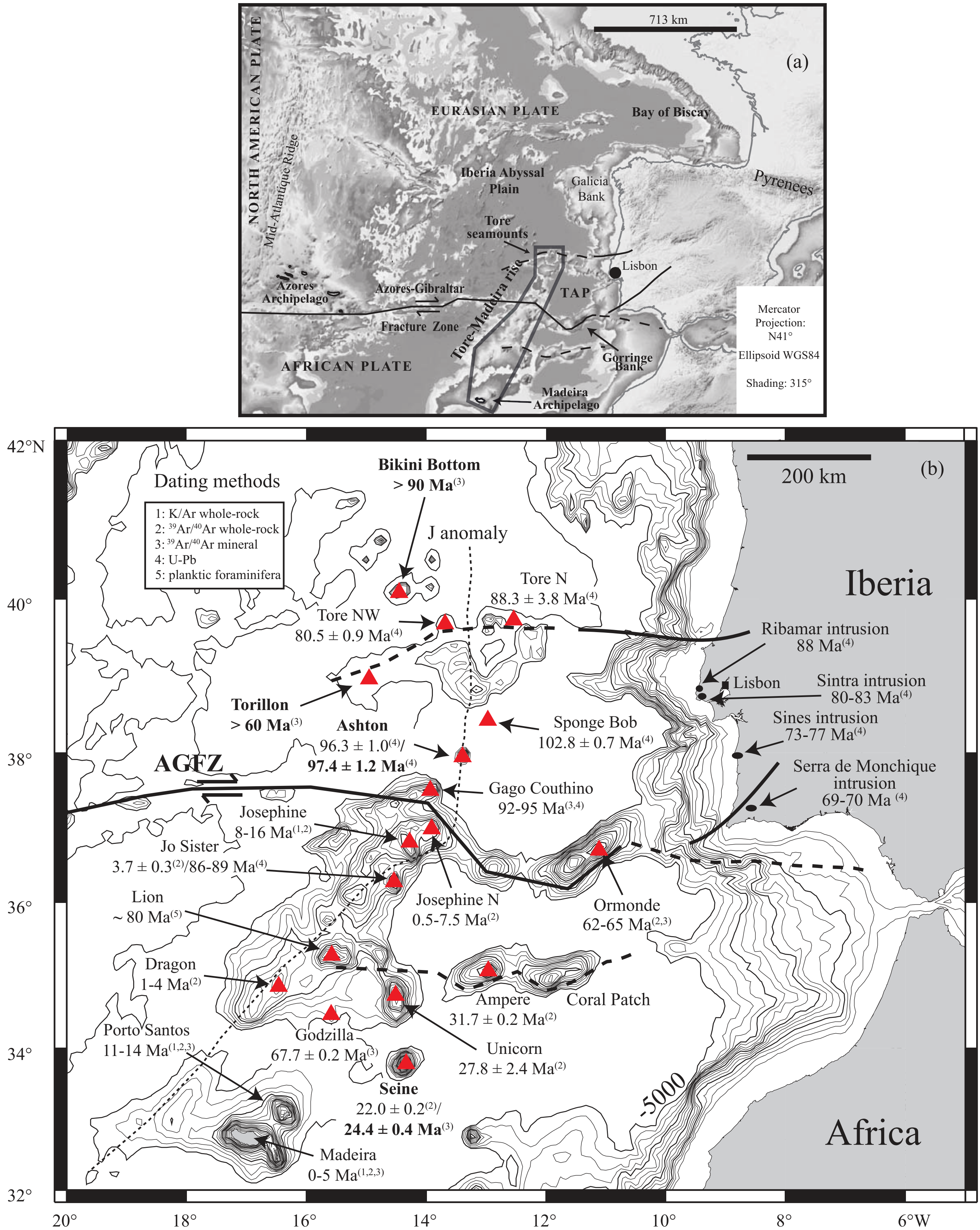
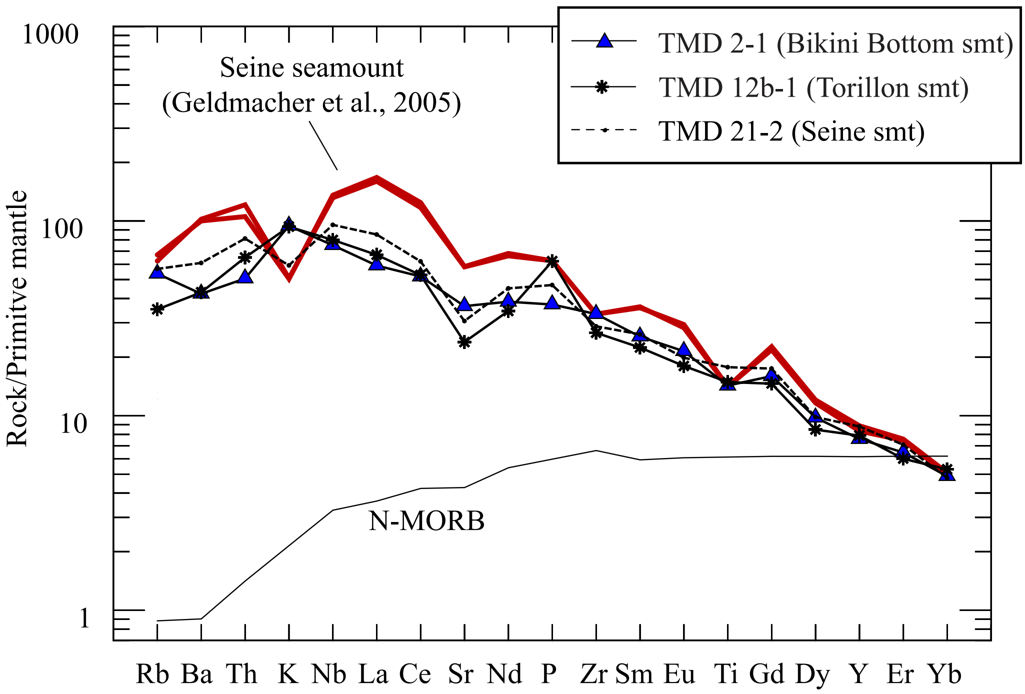

713 km
(a)
NORTH AMERICAN PLATE
Mid-Atlantique Ridge
EURASIAN PLATE
Bay of Biscay
Iberia Abyssal Plain
Galicia Bank
Pyrenees
Tore seamounts
Lisbon
Azores Archipelago
Azores-Gibraltar
Fracture Zone
TAP
Tore-Madeira rise
AFRICAN PLATE
Gorringe Bank
Madeira Archipelago
Mercator Projection: N41°
Ellipsoid WGS84
Shading: 315°
(b)
200 km
Dating methods
1: K/Ar whole-rock
2: 39Ar/40Ar whole-rock
3: 39Ar/40Ar mineral
4: U-Pb
5: planktic foraminifera
Bikini Bottom
> 90 Ma(3)
J anomaly
Tore N
88.3 ± 3.8 Ma(4)
Iberia
Tore NW
80.5 ± 0.9 Ma(4)
Ribamar intrusion
88 Ma(4)
Lisbon
Sintra intrusion
80-83 Ma(4)
Torillon
> 60 Ma(3)
Ashton
96.3 ± 1.0(4)/
97.4 ± 1.2 Ma(4)
Sponge Bob
102.8 ± 0.7 Ma(4)
Sines intrusion
73-77 Ma(4)
AGFZ
Gago Couthino
92-95 Ma(3,4)
Serra de Monchique intrusion
69-70 Ma (4)
Josephine
8-16 Ma(1,2)
Jo Sister
3.7 ± 0.3(2)/86-89 Ma(4)
Josephine N
0.5-7.5 Ma(2)
Ormonde
62-65 Ma(2,3)
Lion
~ 80 Ma(5)
Dragon
1-4 Ma(2)
Ampere
31.7 ± 0.2 Ma(2)
Coral Patch
Porto Santos
11-14 Ma(1,2,3)
Godzilla
67.7 ± 0.2 Ma(3)
Unicorn
27.8 ± 2.4 Ma(2)
Seine
22.0 ± 0.2(2)/
24.4 ± 0.4 Ma(3)
-5000
Madeira
0-5 Ma(1,2,3)
Africa
42°N
40°
38°
36°
34°
32°
20°
18°
16°
14°
12°
10°
8°
6°W

Figure 1



TMD 2-1 (Bikini Bottom smt)
TMD 12b-1 (Torillon smt)
TMD 21-2 (Seine smt)
Seine seamount
(Geldmacher et al., 2005)
N-MORB
Rock/Primitve mantle
1000
100
10
1
Rb Ba Th K Nb La Ce Sr Nd P Zr Sm Eu Ti Gd Dy Y Er Yb

Figure 2

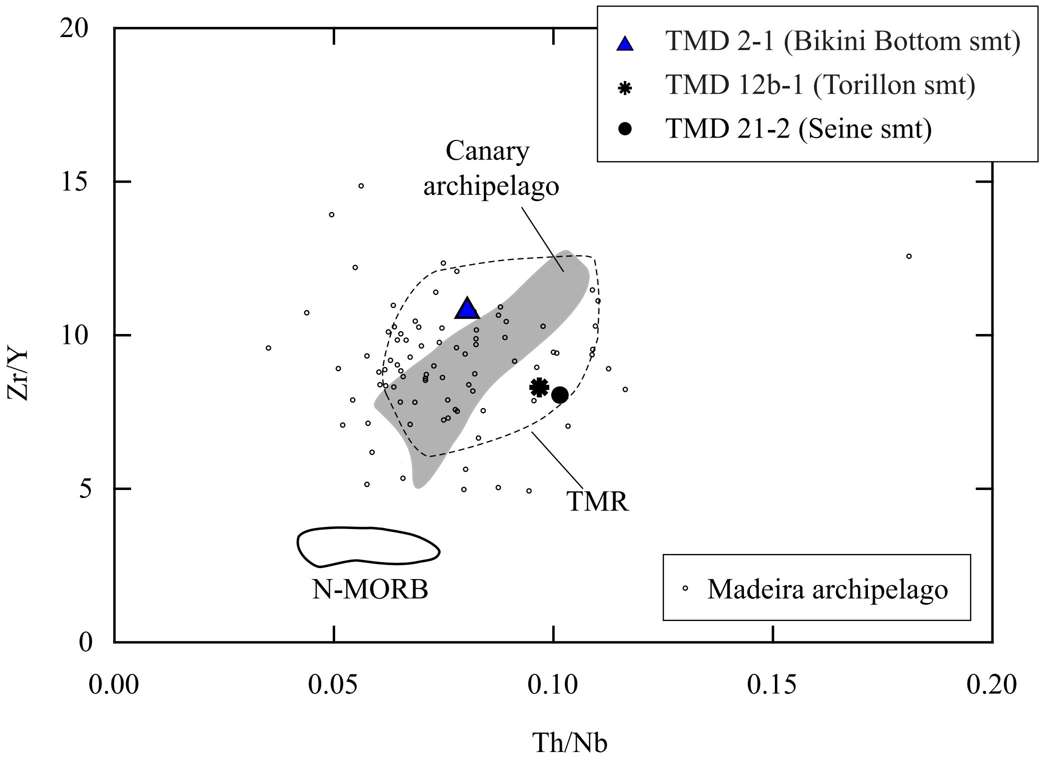

TMD 2-1 (Bikini Bottom smt)
TMD 12b-1 (Torillon smt)
TMD 21-2 (Seine smt)
Canary archipelago
TMR
N-MORB
Madeira archipelago
Zr/Y
Th/Nb
0
5
10
15
20
0.00
0.05
0.10
0.15
0.20

Figure 3

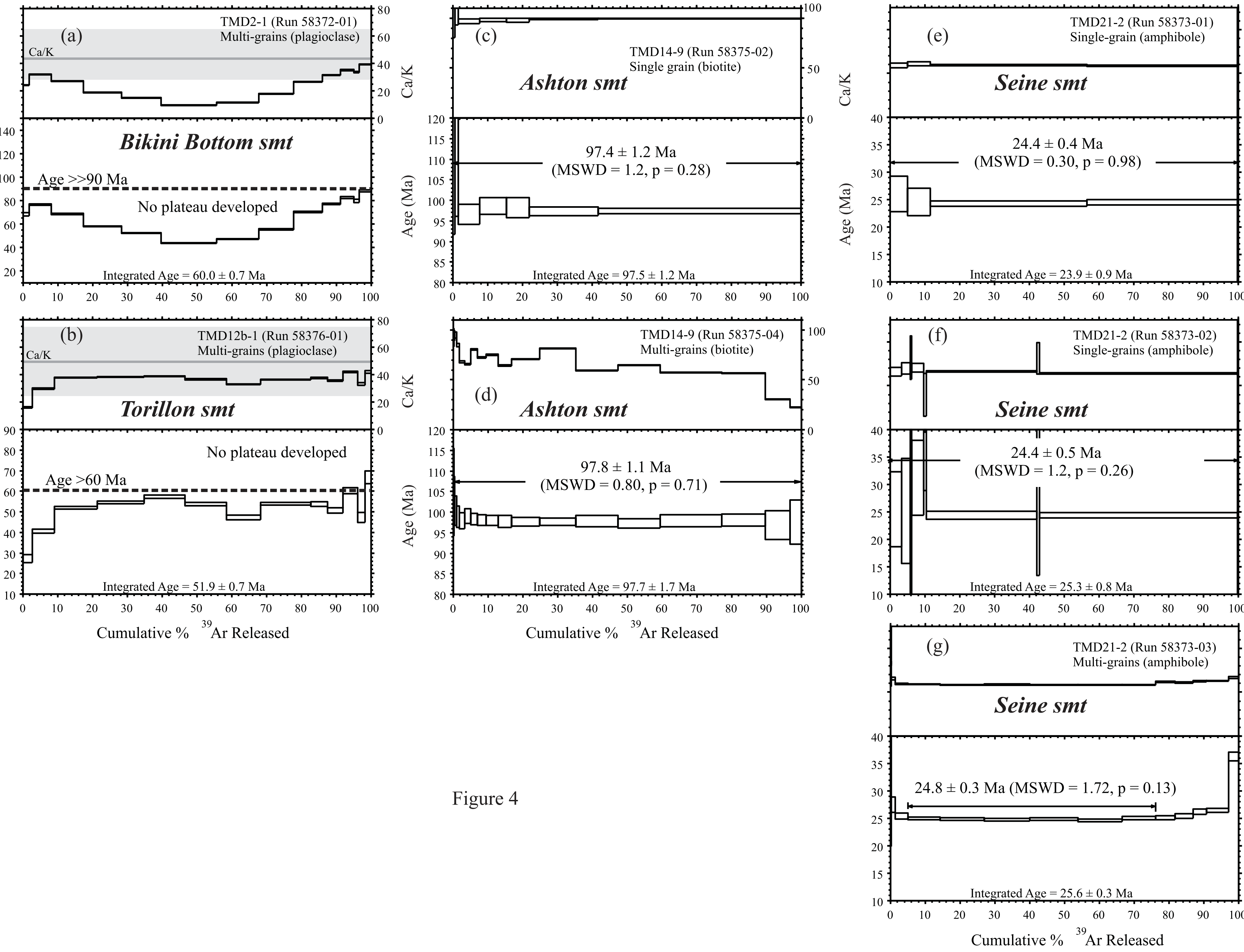
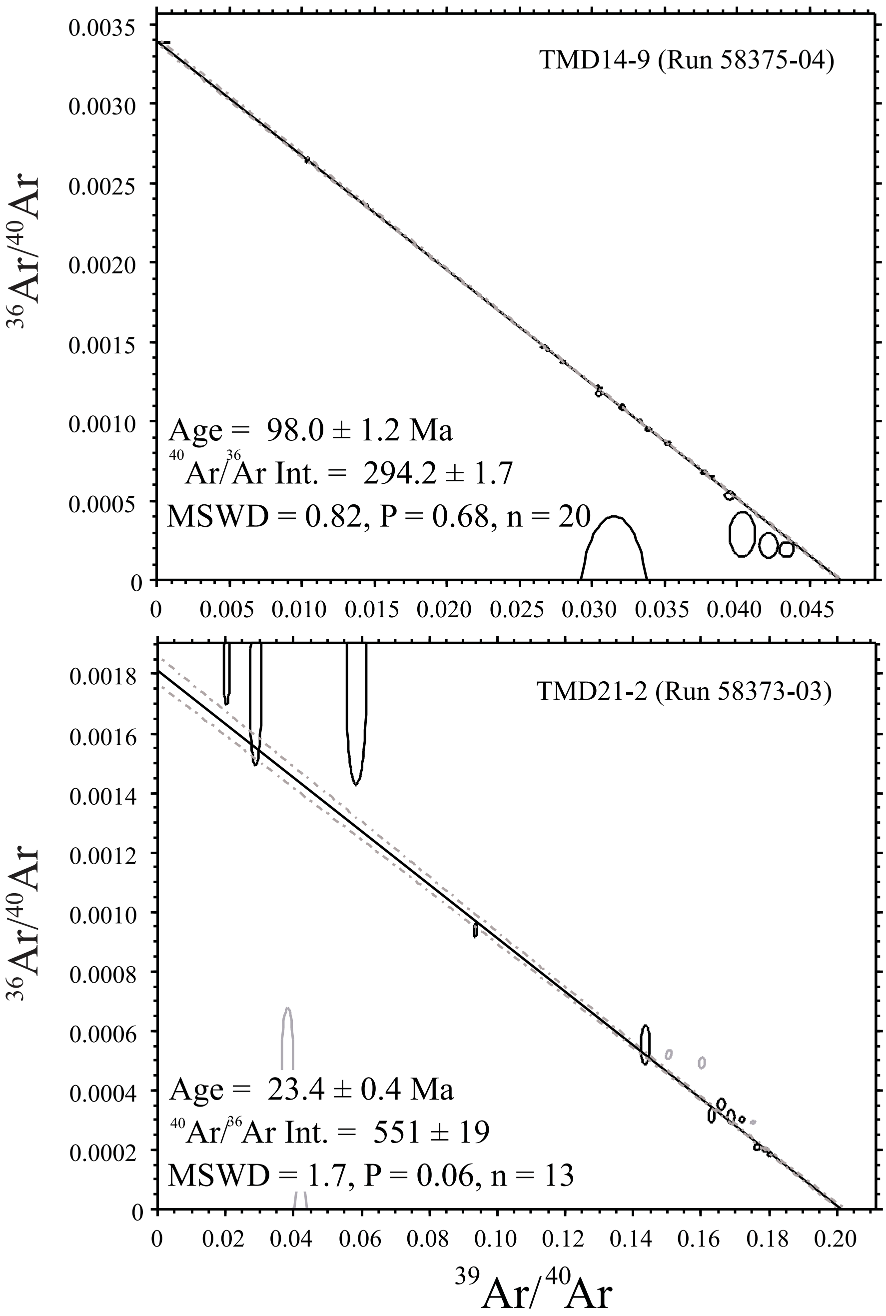

(a)
TMD2-1 (Run 58372-01)
Multi-grains (plagioclase)
Ca/K
Bikini Bottom smt
Age >>90 Ma
No plateau developed
Integrated Age = 60.0 ± 0.7 Ma
(b)
TMD12b-1 (Run 58376-01)
Multi-grains (plagioclase)
Torillon smt
No plateau developed
Age >60 Ma
Integrated Age = 51.9 ± 0.7 Ma
(c)
TMD14-9 (Run 58375-02)
Single grain (biotite)
Ashton smt
97.4 ± 1.2 Ma
(MSWD = 1.2, p = 0.28)
Integrated Age = 97.5 ± 1.2 Ma
(d)
TMD14-9 (Run 58375-04)
Multi-grains (biotite)
Ashton smt
97.8 ± 1.1 Ma
(MSWD = 0.80, p = 0.71)
Integrated Age = 97.7 ± 1.7 Ma
(e)
TMD21-2 (Run 58373-01)
Single-grain (amphibole)
Seine smt
24.4 ± 0.4 Ma
(MSWD = 0.30, p = 0.98)
Integrated Age = 23.9 ± 0.9 Ma
(f)
TMD21-2 (Run 58373-02)
Single-grains (amphibole)
Seine smt
24.4 ± 0.5 Ma
(MSWD = 1.2, p = 0.26)
Integrated Age = 25.3 ± 0.8 Ma
(g)
TMD21-2 (Run 58373-03)
Multi-grains (amphibole)
Seine smt
24.8 ± 0.3 Ma (MSWD = 1.72, p = 0.13)
Integrated Age = 25.6 ± 0.3 Ma
Ca/K
Age (Ma)
Cumulative % 39Ar Released

Figure 4



TMD14-9 (Run 58375-04)
Age = 98.0 ± 1.2 Ma
40Ar/36Ar Int. = 294.2 ± 1.7
MSWD = 0.82, P = 0.68, n = 20
36Ar/40Ar
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0
0 0.005 0.010 0.015 0.020 0.025 0.030 0.035 0.040 0.045
TMD21-2 (Run 58373-03)
Age = 23.4 ± 0.4 Ma
40Ar/36Ar Int. = 551 ± 19
MSWD = 1.7, P = 0.06, n = 13
36Ar/40Ar
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0
0 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20
39Ar/40Ar

Figure 5

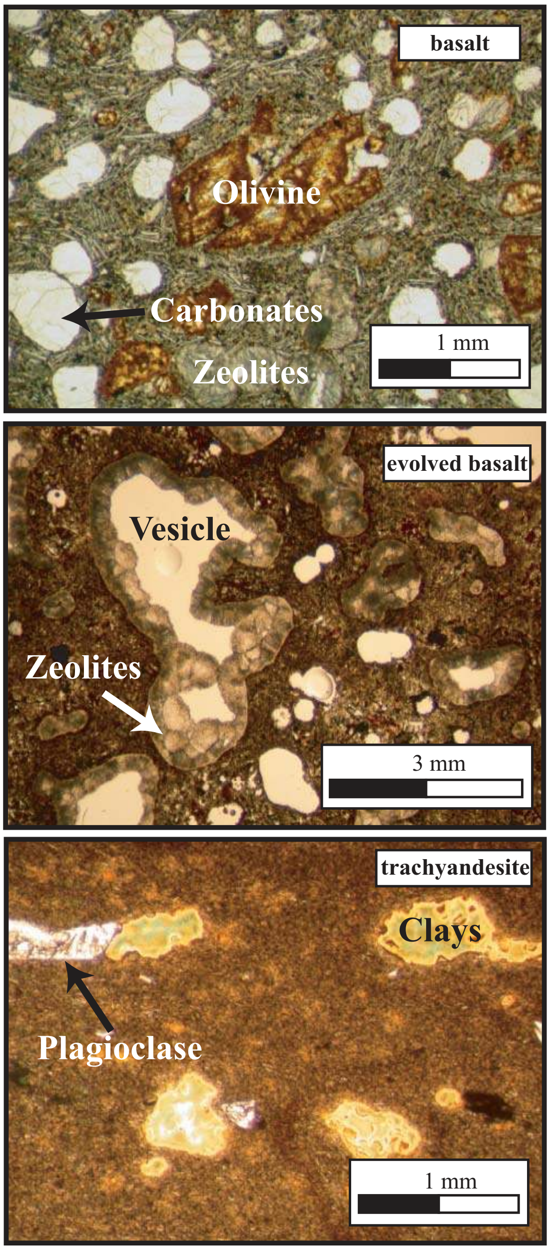

basalt
Olivine
Carbonates
Zeolites
1 mm
evolved basalt
Vesicle
Zeolites
3 mm
trachyandesite
Clays
Plagioclase
1 mm

Figure 6

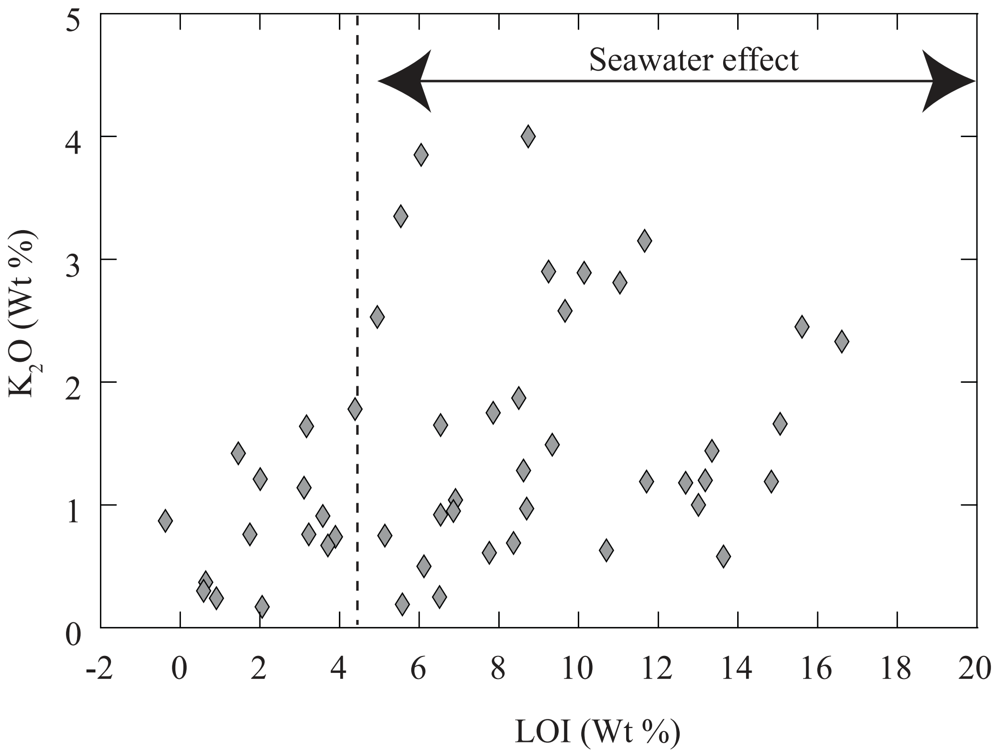


Figure 7

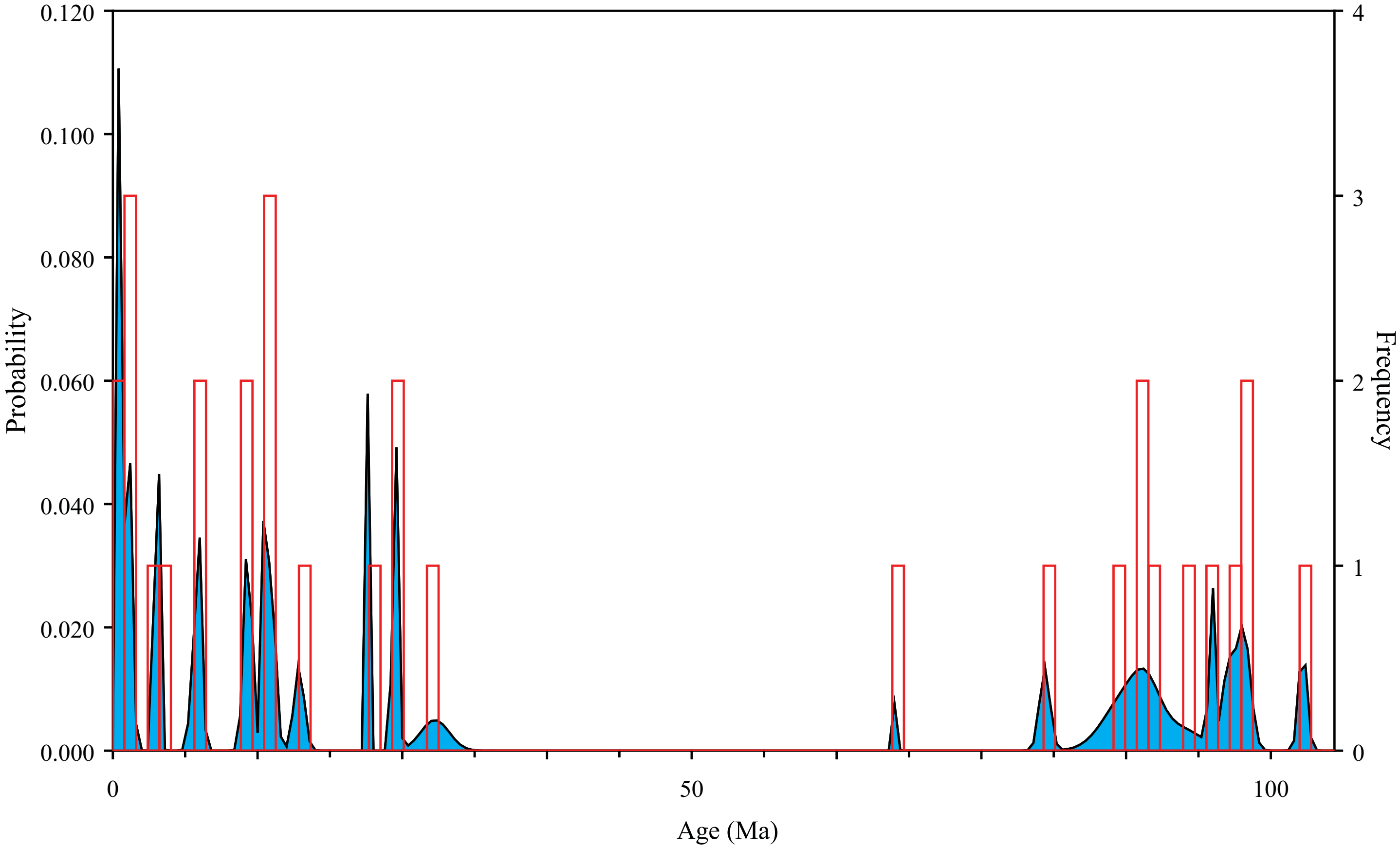

0.120
0.100
0.080
0.060
0.040
0.020
0.000
Probability
4
3
2
1
0
Frequency
0
50
100
Age (Ma)

Figure 8

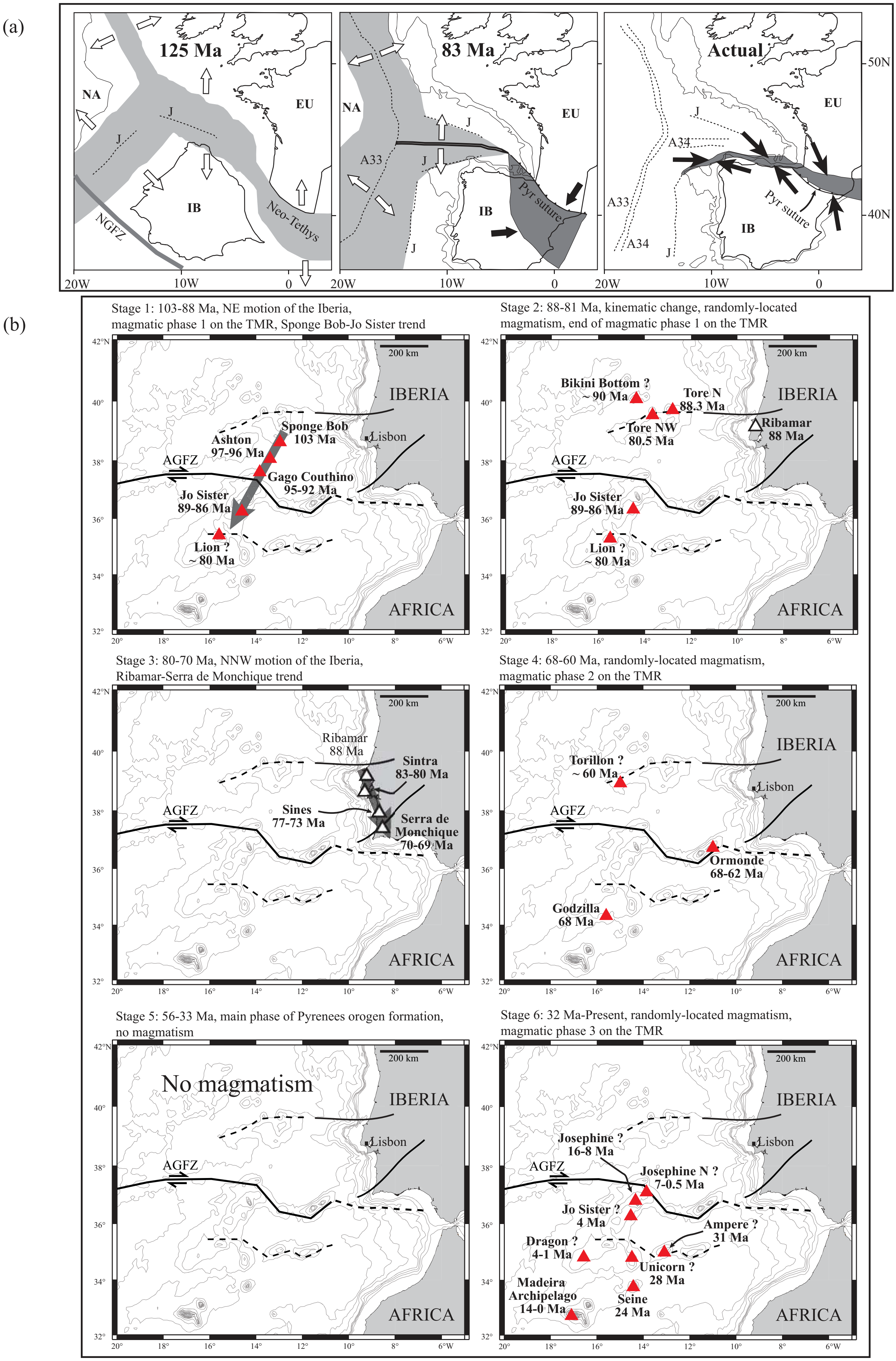

(a)
125 Ma
NA
EU
IB
J
NGFZ
Neo-Tethys
83 Ma
A33
Pyr suture
Actual
A34
50N
40N
20W
10W
0
(b)
Stage 1: 103-88 Ma, NE motion of the Iberia,
magmatic phase 1 on the TMR, Sponge Bob-Jo Sister trend
Stage 2: 88-81 Ma, kinematic change, randomly-located
magmatism, end of magmatic phase 1 on the TMR
Stage 3: 80-70 Ma, NNW motion of the Iberia,
Ribamar-Serra de Monchique trend
Stage 4: 68-60 Ma, randomly-located magmatism,
magmatic phase 2 on the TMR
Stage 5: 56-33 Ma, main phase of Pyrenees orogen formation,
no magmatism
Stage 6: 32 Ma-Present, randomly-located magmatism,
magmatic phase 3 on the TMR
200 km
IBERIA
AFRICA
AGFZ
Lisbon
Sponge Bob
103 Ma
Ashton
97-96 Ma
Gago Couthino
95-92 Ma
Jo Sister
89-86 Ma
Lion ?
~ 80 Ma
Bikini Bottom ?
~ 90 Ma
Tore N
88.3 Ma
Tore NW
80.5 Ma
Ribamar
88 Ma
Sintra
83-80 Ma
Sines
77-73 Ma
Serra de
Monchique
70-69 Ma
Torillon ?
~ 60 Ma
Ormonde
68-62 Ma
Godzilla
68 Ma
No magmatism
Josephine ?
16-8 Ma
Josephine N ?
7-0.5 Ma
Jo Sister ?
4 Ma
Ampere ?
31 Ma
Dragon ?
4-1 Ma
Unicorn ?
28 Ma
Madeira
Archipelago
14-0 Ma
Seine
24 Ma
42°N
40°
38°
36°
34°
32°
20°
18°
16°
14°
12°
10°
8°
6°W

FIGURE 9

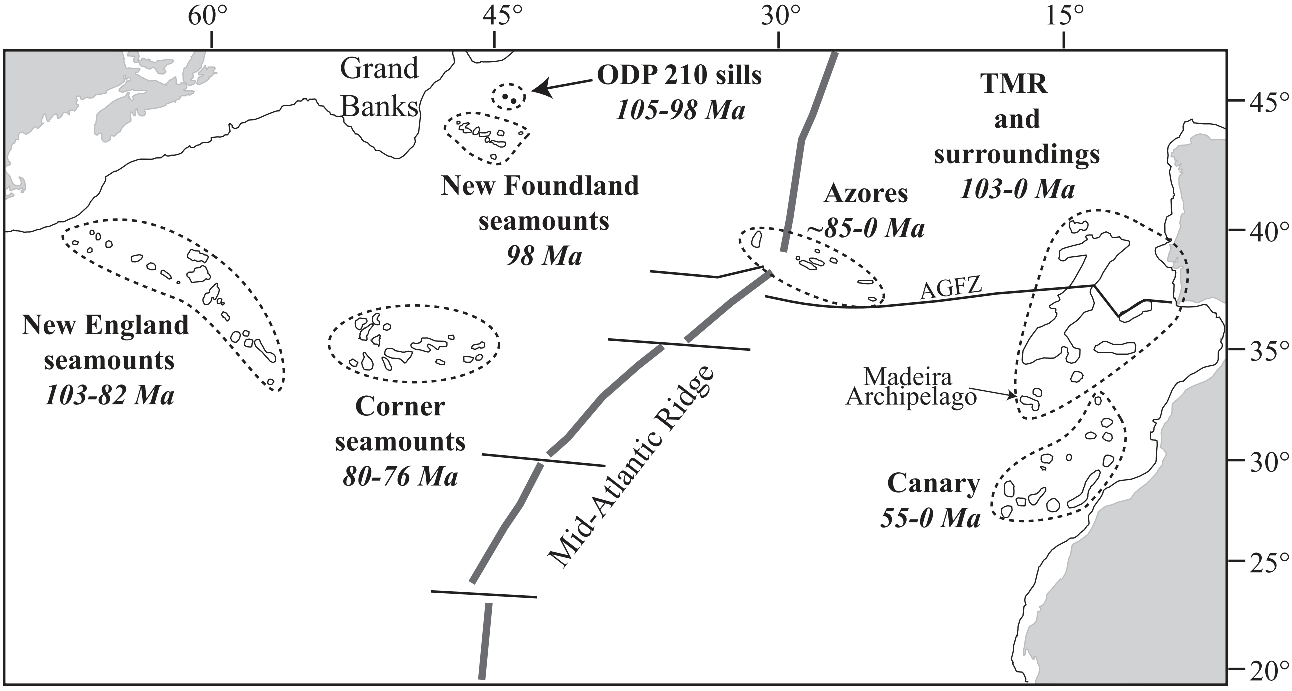

60°
45°
30°
15°
45°
40°
35°
30°
25°
20°
Grand
Banks
ODP 210 sills
105-98 Ma
New Foundland
seamounts
98 Ma
TMR
and
surroundings
103-0 Ma
Azores
~85-0 Ma
AGFZ
New England
seamounts
103-82 Ma
Corner
seamounts
80-76 Ma
Mid-Atlantic Ridge
Madeira
Archipelago
Canary
55-0 Ma

Figure 10

Table 1: Sampling sites and dredging operations parameters

Seamount	dredge	Beginning		End		Depth (m)		Distance covered (m)	Height covered (m)
		Lat. (N)	Long. (W)	Lat. (N)	Long. (W)	max	min		
Bikini Bottom	TMD 2	40°03.74'	14°24.50'	40°07.90'	13°39.31'	3514	2234	4074	1280
Torillon	TMD 12b	39°10.63'	15°12.81'	39°11.75'	15°10.51'	3884	3126	2960	758
Ashton	TMD 14	38°01.29'	13°23.71'	38°01.54'	13°22.66'	2803	2395	3900	408
Seine	TMD 21	33°50.83'	14°15.71'	33°51.18'	14°17.22'	1975	1677	1020	298

Table 2: Major and trace elements analyses of TMR

Samples	**TMD2-1**	**TMD 12b-1**	**TMD21-2**
Petrographic type	Basaltic trachy-and	basalt	basanite
(%Wt)			
SiO_2	48.50	40.22	41.10
TiO_2	3.09	3.22	3.84
Al_2O_3	19.20	18.21	13.50
Fe2O3*	10.86	13.38	14.10
MnO	0.20	0.16	0.15
MgO	0.93	1.29	5.75
CaO	6.40	5.58	11.25
NaO	3.79	2.66	2.62
K_2O	2.84	2.81	1.78
P_2O_5	0.81	1.35	1.02
LOI	3.03	11.04	4.39
total	99.65	99.92	99.50
(ppm)			
Rb	34.0	22.3	36.0
Sr	770	503	645
Ba	295	300	425
Sc	15.8	-	26.0
V	220.0	276	368.0
Cr	17.0	93.8	272.0
Co	17.00	33.4	34.50
Ni	9.5	66	112.0
Y	34.5	35.9	40.0
Zr	372	298	322
Nb	53.5	56.9	68.0
La	40.5	46	58.5
Ce	92.0	93.6	110.0
Nd	52.0	46.6	61.0
Sm	11.3	9.92	11.6
Eu	3.60	3.02	3.33
Gd	9.50	8.7	10.40
Dy	7.20	6.24	7.25
Er	3.10	2.88	3.40
Yb	2.41	2.61	2.36
Th	4.30	5.51	6.90

Major and trace elements of samples TMD 2-1 and TMD21-2 were obtained by ICP-AES at Brest (Université de Bretagne Occidentale) following the method described in Cotten et al. (1995). Relative standard deviations are < 2% for major elements, Rb and Sr, and < 5% for other trace elements. Analyses of sample TMD12b-1 were performed at Nancy (SARM, CRPG-CNRS). Major elements were obtained by ICP-AES following the method described in Govindaraju and Mevelle (1987) and trace elements by ICP-MS following the method in Carignan et al. (2001). Analytical precision is at 1-5% for major elements, except for MnO, MgO, Ca_2O and P_2O_5 (10%). For trace elements, analytical precision is in the range 5-10% for abundances > 50 ppm, 5-15% between 50 and 10 ppm, 5-20% between 10 and 1 ppm and 5-25% for abundances < 1 ppm. Fe_2O_3*: total iron expressed as Fe_2O_3. LOI: Loss on ignition. BE-N, AC-E, PM-S and WS-E materials were used as standards.

Table 3: $^{40}Ar/^{39}Ar$ results

General characteristics				Plateau characteristics					Isochron characteristics				
Sample N°	Mineral	Lab N°	Integrated age (Ma, ±2σ)	Plateau age (Ma, ±2σ)	Total ^{39}Ar released (%)	MSWD	P	Mean age* (Ma, ±2σ)	Isochron age (Ma, ±2σ)	n	$^{40}Ar/^{36}Ar$ intercept (±1σ)	MSWD	P
TMD14-9	Biotite	58375-02	97.5 ± 1.2	**97.4 ± 1**	100%	1.2	0.28	**97.7 ± 1.2**	-	-	-	-	-
		58375-04	97.7 ± 1.7	**97.8 ± 1.1**	100%	0.80	0.71		98.0 ± 1.2	20	294.2 ± 1.7	0.82	0.68
TM12b-1	Plagioclase	58376-01	51.9 ± 0.7	-	-	-	-	-	-	-	-	-	-
TMD2-1	Plagioclase	58372-01	60.0 ± 0.7	-	-	-	-	-	-	-	-	-	-
TMD21-2	Amphibole	58373-01	23.9 ± 0.9	**24.4 ± 0.4**	100%	0.3	0.98	**24.4 ± 0.4**	24.4 ± 0.4	16	292 ± 3	0.35	0.99
		58373-02	25.3 ± 0.8	**24.4 ± 0.5**	100%	1.2	0.26		-	-	-	-	-
		58373-03	25.6 ± 0.3	24.8 ± 0.3	71%	1.7	0.13	(excess ^{40}Ar*)?	23.4 ± 0.4	13	551 ± 19	1.7	0.06

Summary table indicating integrated, plateau/mini-plateau and isochron ages for the Tswaing impact glass samples. A (*) indicates mini-plateau ages. MSWD for plateau and isochron, percentage of ^{39}Ar degassed used in the plateau calculation, number of analysis included in the isochron, and $^{40}Ar/^{36}Ar$ intercept are indicated. Plateau age calculated using trapped $^{40}Ar/^{36}Ar$ is indicated. Analytical uncertainties on the ages are quoted at 2 sigma (2σ) confidence levels and at 1σ for the $^{40}Ar/^{36}Ar$ intercept. Bold data indicate the accepted age for a given sample. Italic data indicate rejected analyses.

Table 3: Merle et al.

Table 4: Filtred geochronological data from TMR and surroundings

Reference	Sample name	Location	Phase analyzed	Age (Ma)	Errors (2σ) Ma	MSWD	P
This study	TMD2-1	Bikini Bottom	plag	~ 90			
Merle et al., 2006	TMD10c-1	Tore N	titanite	**88.30**	**3.30**	0.34	0.89
Merle et al., 2006	TMD10c-2	Tore N	titanite	**88.30**	**3.80**	1.01	0.39
Merle et al., 2006	TMD3b-2	Tore NW	titanite+zrc	**80.48**	**0.90**	0.86	0.54
This study	TMD 12b-1	Torillon	plag	~ 60			
Merle et al., 2006	TMD4-3	Sponge Bob	titanite+zrc	**102.77**	**0.71**	0.38	0.91
Merle et al., 2006	TMD14-9	Ashton	titanite+zrc	**96.30**	**1.00**	0.60	0.81
This study	TMD14-9	Ashton	biot	**97.40**	**1.20**	1.20	0.28
This study	TMD14-9	Ashton	biot	**97.80**	**1.10**	0.80	0.71
Merle et al., 2006	TMD15-5	Gago Coutinho	titanite	**92.30**	**3.70**	0.25	0.91
Geldmacher et al., 2006	403 DR-5	Gago Coutinho	hbl	**94.90**	**0.44**	2.00	0.05
Geldmacher et al., 2006	399 DR-1	Josephine N (Pico Pia)	mtrx	0.53	0.45	0.60	0.83
Geldmacher et al., 2006	406 DR-7	Josephine N (Toblerone Ridge)	gls	1.42	0.61	0.70	0.74
Geldmacher et al., 2006	406 DR-7	Josephine N (Toblerone Ridge)	mtrx	0.47	0.13	1.50	0.07
Geldmacher et al., 2006	407 DR-4	Josephine N (Pico Julia)	mtrx	7.09	0.72	0.70	0.74
Geldmacher et al., 2006	407 DR-4	Josephine N (Pico Julia)	mtrx	7.50	0.47	0.60	0.80
Geldmacher et al., 2006	408 DR-2	Josephine	mtrx	16.08	0.87	1.00	0.45
Geldmacher et al., 2006	408 DR-2	Josephine	mtrx	13.83	0.65	1.40	0.14
Geldmacher et al., 2006	409 DR-1	Josephine	mtrx	11.75	0.73	1.30	0.22
Geldmacher et al., 2006	409 DR-1	Josephine	mtrx	11.59	0.65	0.50	0.89
Geldmacher et al., 2006	410 DR-4	Josephine	mtrx	13.35	0.63	0.70	0.78
Geldmacher et al., 2006	410 DR-4	Josephine	mtrx	13.14	0.30	1.60	0.07
Merle et al., 2006	TMD16-1	Jo Sister	titanite	**86.50**	**3.40**	0.13	0.97
Merle et al., 2006	TMD16-2	Jo Sister	titanite	**89.30**	**2.30**	0.76	0.64
Geldmacher et al., 2006	412 DR-2	Jo Sister	mtrx	3.67	0.32	1.70	0.07
Geldmacher et al., 2006	429 DR-1	Dragon	mtrx	1.45	0.43	0.90	0.57
Geldmacher et al., 2006	429 DR-1	Dragon	mtrx	1.14	0.20	0.60	0.73
Geldmacher et al., 2006	431 DR-1	Dragon	mtrx	4.00	0.30	1.30	0.19
Geldmacher et al., 2007	428 DR-1	Godzilla	biot	**67.68**	**0.17**	2.10	0.05
Geldmacher et al., 2005	423 DR-1	Unicorn	mtrx	27.81	2.44	0.70	0.73
Geldmacher et al., 2005	426 DR-1	Seine	mtrx	22.03	0.20	1.20	0.29
This study	TMD21-1	Seine	plag	**24.40**	**0.40**	0.30	0.98
This study	TMD21-1	Seine	plag	**24.40**	**0.50**	1.20	0.26
Geldmacher et al., 2000	DS-797-1	Ampere	mtrx	31.67	0.20	1.33	0.19
Féraud et al., 1982	DR-06-03	Ormonde	biot	**64.30**	1.10	0.65	0.74
Féraud et al., 1982	DR-06-18	Ormonde	mtrx	61.60	**2.40**	0.26	0.91
Féraud et al., 1986	CY14-2	Ormonde	biot	**65.07**	**0.65**	1.30	0.25

The age results reliable for sub-million year high-precision geochronolgy are reported in bold.

Zrc: zircon, biot: biotite, hbl: hornblende, gls: glass, mtx: matrix, plag: plagioclase

Table A1: Geochronological database from TMR and surroundings.

Reference	Sample name	Location	rock type	technique	Phase dated	Age (Ma)	Errors (2σ)	Standard type and age (Ma)
Merle et al., 2006	TMD10c-1	Tore N	trachy-andesite	U-Pb (ID)	titanite	88.30	3.30	-
Merle et al., 2006	TMD10c-2	Tore N	trachy-andesite	U-Pb (ID)	titanite	88.20	3.90	-
Merle et al., 2006	TMD3b-2	Tore NW	trachyte	U-Pb (ID)	titanite+zrc	80.50	0.90	-
Merle et al., 2006	TMD4-3	Sponge Bob	trachyte	U-Pb (ID)	titanite+zrc	102.80	0.70	-
Merle et al., 2006	TMD4-8	Sponge Bob	trachyte	U-Pb (ID)	titanite+zrc	104.40	1.40	-
Merle et al., 2006	TMD14-9	Ashton	trachyte	U-Pb (ID)	titanite+zrc	96.30	1.00	-
Merle et al., 2006	TMD15-5	Gago Coutinho/Teresa	trachyte	U-Pb (ID)	titanite	92.30	3.80	-
Geldmacher et al., 2006	403 DR-5	Gago Coutinho/Teresa	trachyte	$^{40}Ar/^{39}Ar$ (StH)	hbl	94.50	0.43	TCs =27.92
Geldmacher et al., 2006	403 DR-1	Gago Coutinho/Teresa	trachyte	$^{40}Ar/^{39}Ar$ (TF)	hbl	92.50	0.40	TCs =27.92
Geldmacher et al., 2006	399 DR-1	Josephine N (Pico Pia)	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	0.52	0.44	TCs =27.92
Geldmacher et al., 2006	406 DR-7	Josephine N (Toblerone Ridge)	basalt	$^{40}Ar/^{39}Ar$ (StH)	gls	1.40	0.60	TCs =27.92
Geldmacher et al., 2006	406 DR-7	Josephine N (Toblerone Ridge)	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	0.46	0.13	TCs =27.92
Geldmacher et al., 2006	407 DR-4	Josephine N (Pico Julia)	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	6.98	0.71	TCs =27.92
Geldmacher et al., 2006	407 DR-4	Josephine N (Pico Julia)	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	7.39	0.46	TCs =27.92
Geldmacher et al., 2006	408 DR-2	Josephine	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	15.84	0.86	TCs =27.92
Geldmacher et al., 2006	408 DR-2	Josephine	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	13.62	0.64	TCs =27.92
Geldmacher et al., 2006	409 DR-1	Josephine	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	11.58	0.72	TCs =27.92
Geldmacher et al., 2006	409 DR-1	Josephine	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	11.42	0.64	TCs =27.92
Geldmacher et al., 2006	410 DR-4	Josephine	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	13.15	0.62	TCs =27.92
Geldmacher et al., 2006	410 DR-4	Josephine	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	12.94	0.30	TCs =27.92
Wendt et al., 1976	9-101aKD	Josephine	basalt	K-Ar	mtrx	10.10	0.30	-
Wendt et al., 1976	9-101aKD	Josephine	basalt	K-Ar	mtrx	9.30	0.30	-
Wendt et al., 1976	9-123AT2	Josephine	basalt	K-Ar	mtrx	8.70	0.20	-
Wendt et al., 1976	9-123AT2	Josephine	basalt	K-Ar	mtrx	8.20	0.20	-
Wendt et al., 1976	9-123AT2	Josephine	basalt	K-Ar	mtrx	8.90	0.20	-
Wendt et al., 1976	9-123AT2	Josephine	basalt	K-Ar	mtrx	8.40	0.20	-
Wendt et al., 1976	9-127KD2	Josephine	basalt	K-Ar	mtrx	11.50	0.30	-
Wendt et al., 1976	9-127KD2	Josephine	basalt	K-Ar	mtrx	11.60	0.40	-
Wendt et al., 1976	9-133TD	Josephine	basalt	K-Ar	mtrx	9.60	0.40	-
Wendt et al., 1976	9-133TD	Josephine	basalt	K-Ar	mtrx	10.10	0.40	-
Wendt et al., 1976	9-133TD2	Josephine	basalt	K-Ar	mtrx	12.60	0.40	-
Wendt et al., 1976	9-133TD2	Josephine	basalt	K-Ar	mtrx	12.40	0.40	-
Merle et al., 2006	TMD16-1	Jo Sister/Erik	trachy-andesite	U-Pb (ID)	titanite	86.50	3.40	-
Merle et al., 2006	TMD16-2	Jo Sister/Erik	trachy-andesite	U-Pb (ID)	titanite	89.30	2.30	-
Geldmacher et al., 2006	412 DR-2	Jo Sister/Erik	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	3.62	0.32	TCs =27.92
Geldmacher et al., 2006	429 DR-1	Dragon	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	1.43	0.42	TCs =27.92
Geldmacher et al., 2006	429 DR-1	Dragon	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	1.12	0.20	TCs =27.92
Geldmacher et al., 2006	431 DR-1	Dragon	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	3.94	0.30	TCs =27.92
Geldmacher et al., 2007	428 DR-1	Godzilla	trachy-andesite	$^{40}Ar/^{39}Ar$ (TF)	hbl	66.20	0.50	TCs =27.92
Geldmacher et al., 2007	428 DR-1	Godzilla	trachy-andesite	$^{40}Ar/^{39}Ar$ (StH)	biot	66.69	0.17	TCs =27.92
Geldmacher et al., 2005	423 DR-1	Unicorn	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	27.40	2.40	TCs =27.92
Geldmacher et al., 2005	426 DR-1	Seine	basalt	$^{40}Ar/^{39}Ar$ (StH)	mtrx	21.70	0.20	TCs =27.92

ID: isotopic dilution; TF: total fusion; StH: step heating