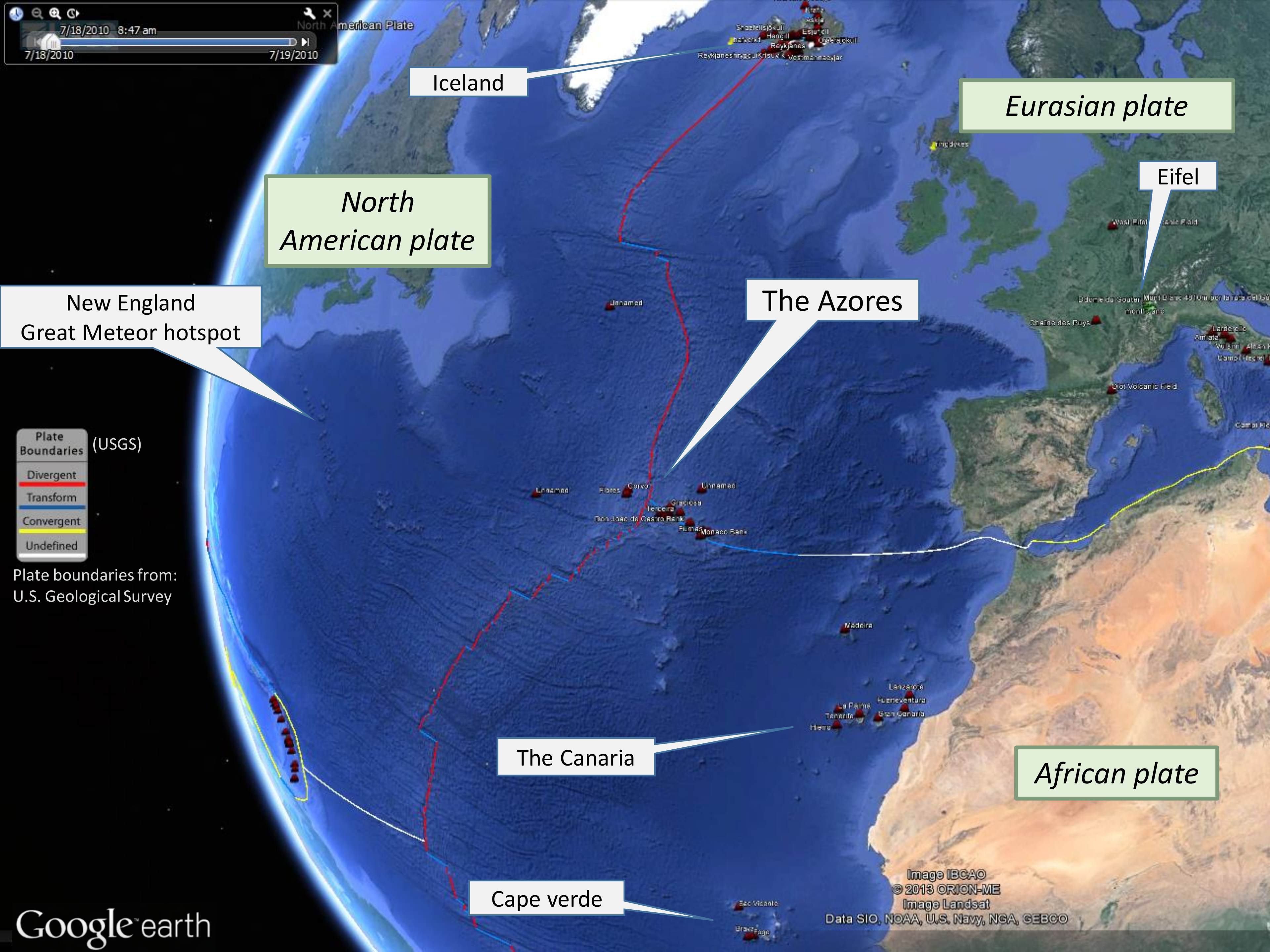


The Azores – A Triple Junction on a Hot Spot

Einar Ragnar Sigurðsson – 04.11.2013

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North American Plate
Iceland
Eurasian plate
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Great Meteor hotspot
The Azores
Madeira
Plate
Boundaries
(USGS)
Divergent
Transform
Convergent
Undefined
Plate boundaries from:
U.S. Geological Survey
The Canaria
African plate
Cape verde
Image IBCAO
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Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth

The Azores

- The archipelago consists of nine islands
- Located on both sides of the Mid Atlantic Ridge
- Located at the triple junction of the North American Plate, Eurasian Plate and African Plate
- The archipelago covers an triangular area 400 thousands square km
- Linear structure trending ESE-WNW
- Oceanic intra plate basaltic (OIB) developing close to mid oceanic ridge and is a typical example of hotspot-ridge interaction
- Mainly alkaline basalt volcanism.

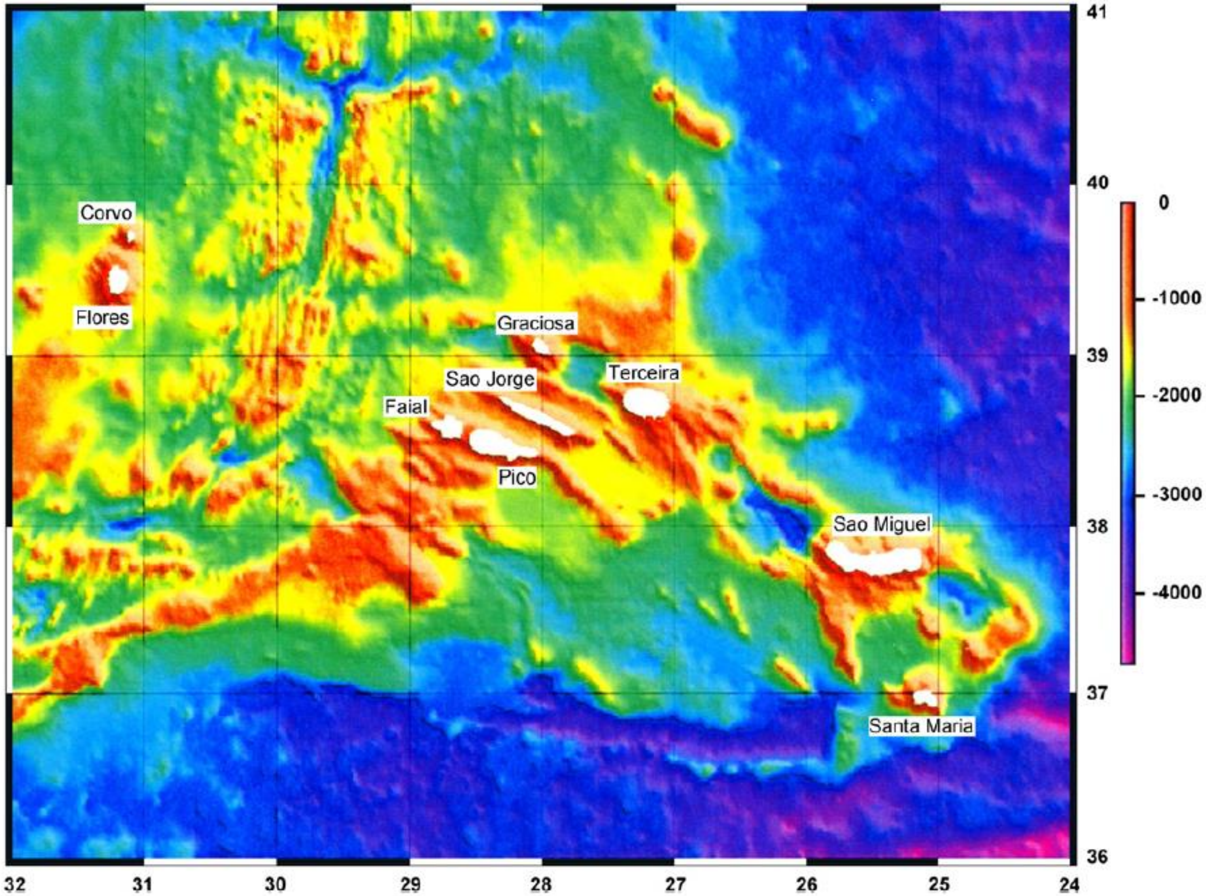


Fig. 1. Bathymetry of the Azores Plateau and location map of the nine islands of the Azores archipelago (Lourenço et al., 1998).

(Quartau, 2007; Babtiste et al, 2009)

(Babtiste et al, 2009)

Active volcanism

- The formation of the Azores Platform may have started 36Ma ago
- Azores basaltic province has been a region of major ocean floor uplift, intense seismicity and extensive volcanism since about 10 to 5Ma ago
- More than 20 volcanic eruptions have occurred since 15th century
- The last eruption from years 1998 to 2001 offshore close to Terceira island.
- The oldest rock is from 8.12 Ma

(Quartau, 2007; Babtiste et al, 2009)

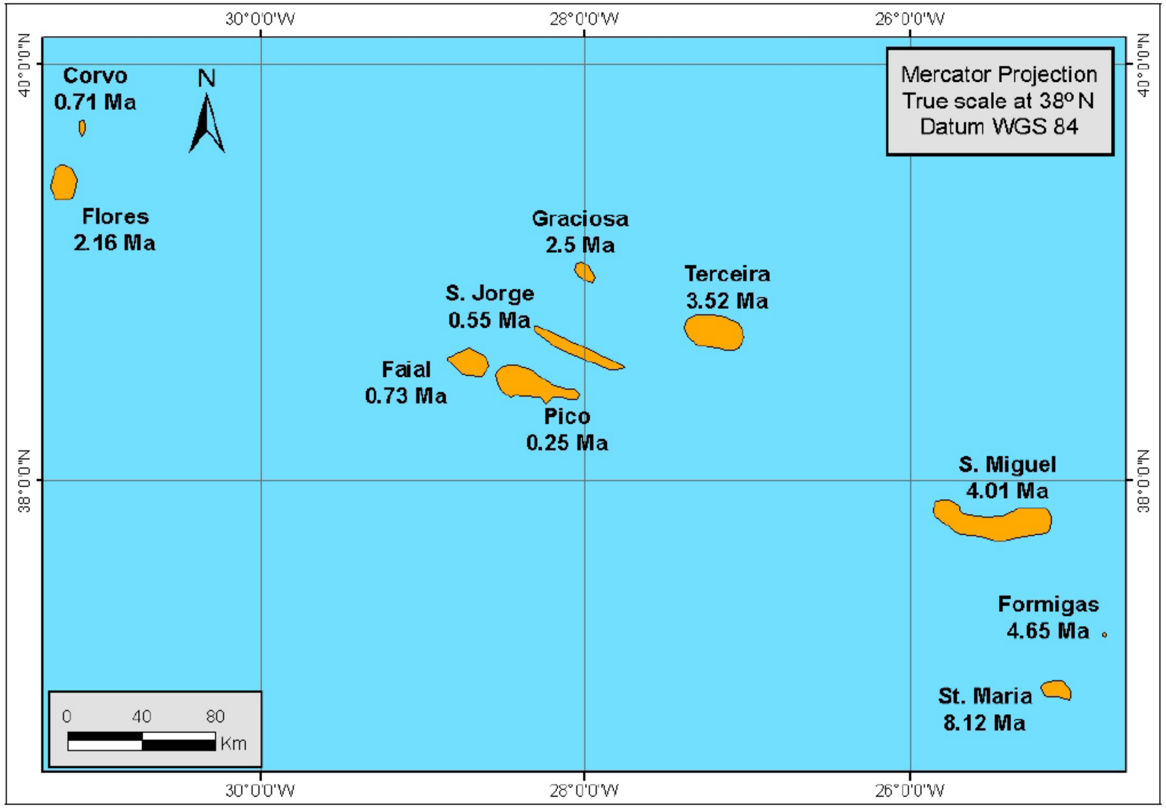


Figure 21 - Oldest radiometric ages (Ma) for each island (data collected from Abdel-Monem et al., 1968; Abdel-Monem et al., 1975; Azevedo et al., 2003; Azevedo et al., 1991; Chovelon, 1982; Feraud et al., 1980; Feraud et al., 1984; Ferreira and Martins, 1983; Forjaz, 1988; data collected from White et al., 1976).

(Quartau, 2007)

Age distribution of rocks

- Combined image from Quarto (2007) showing tectonic setting of the Azores archipelago and isometric age lines of oldest rock on each island or sets of islands

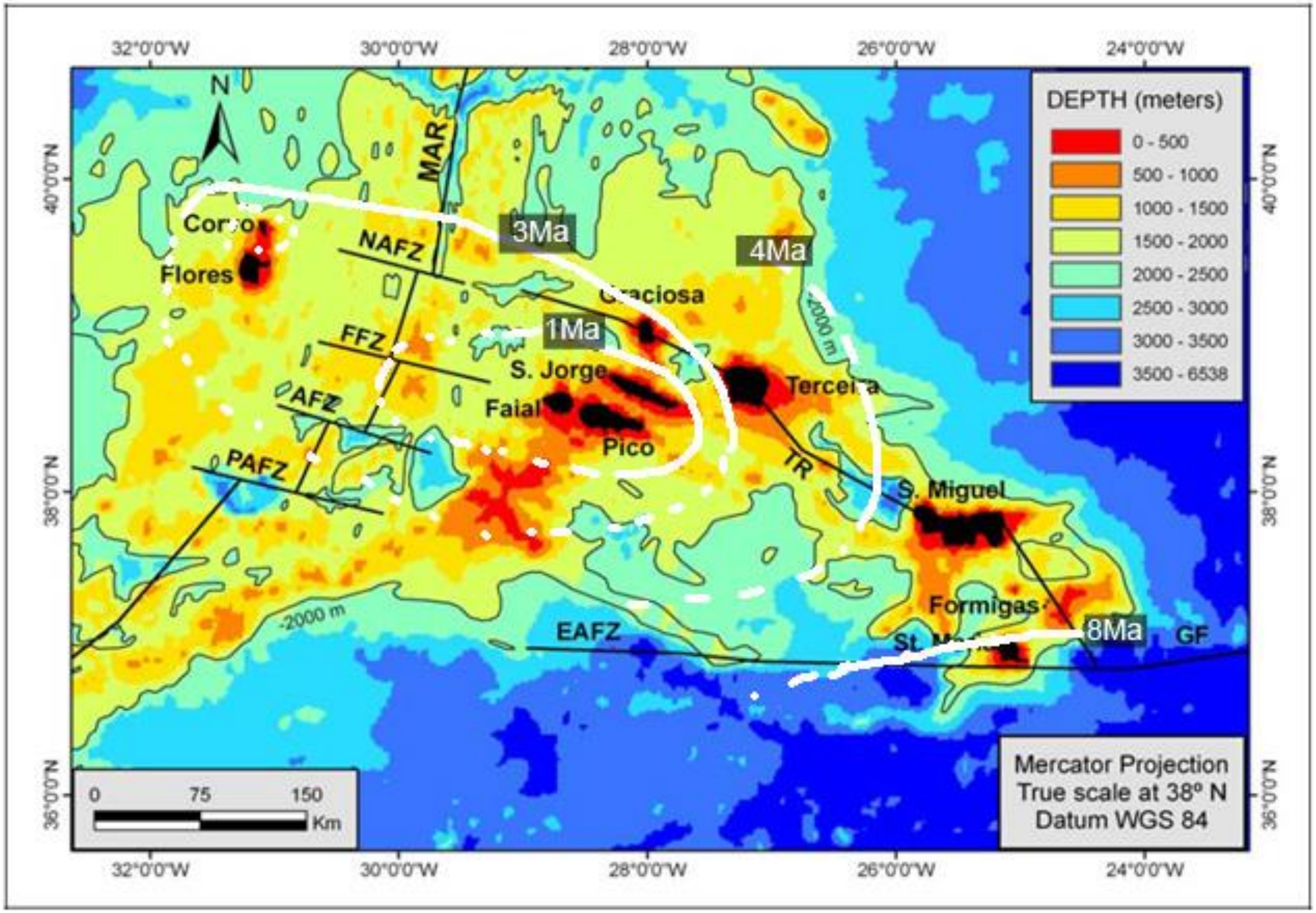


Figure 18 – Tectonic setting of the Azores archipelago (MAR modified from Luis et al., 1994; SJLT modified from Vogt and Jung, 2004). AFZ= Açor Fracture Zone; EAFZ= East Azores Fracture Zone; FFZ= Faial Fracture Zone; GF= Gloria Fault; MAR= Mid-Atlantic ridge; NAFZ= North Azores Fracture Zone; PAFZ= Princesa Alice Fracture Zone; TR= Terceira Rift. Bathymetry of the Azores archipelago from GEBCO (IOC IHO and BODC, 2003).

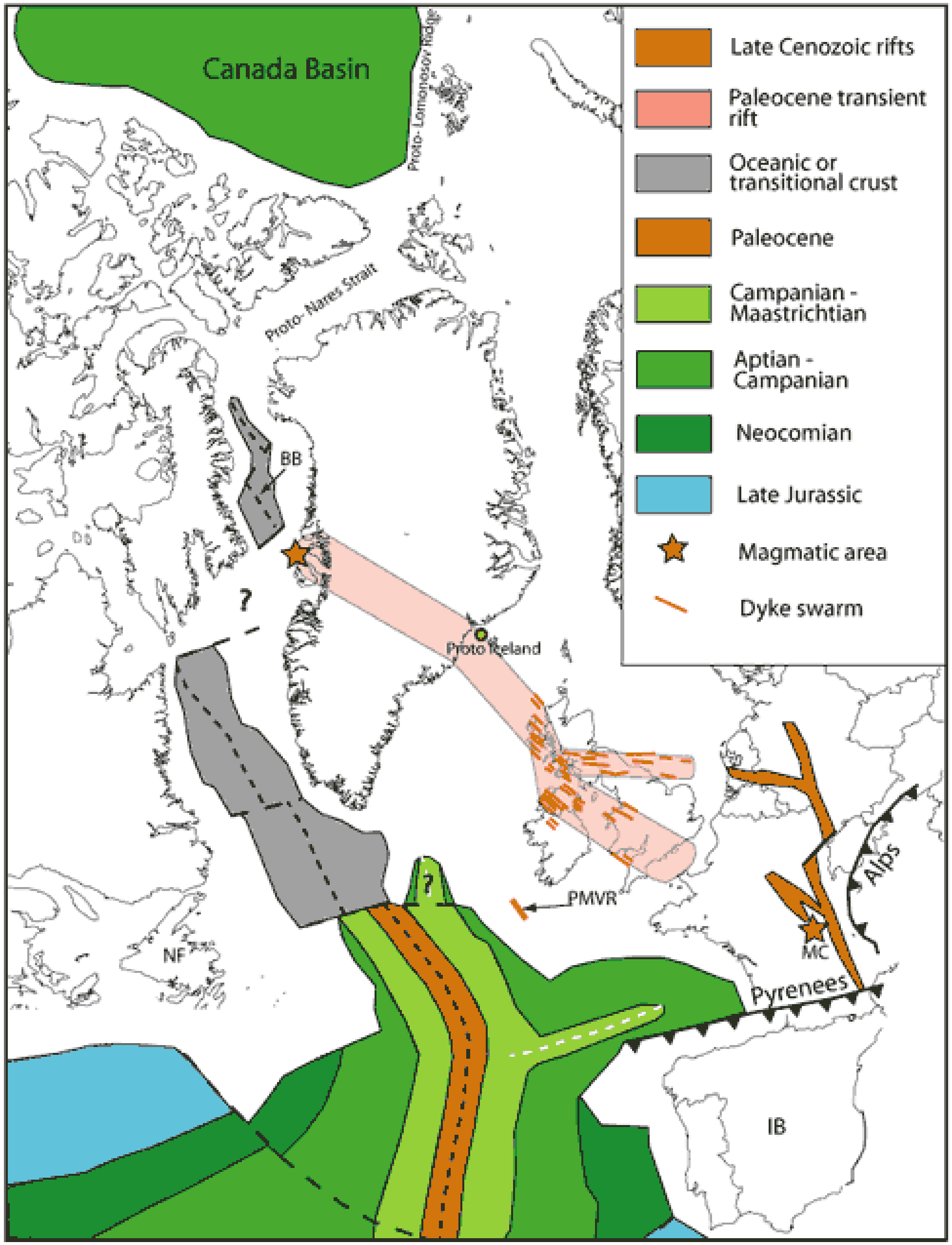
(Image: Quartau, 2007)

Age of rocks: Einar Ragnar)

Before the arrival of the ‘mantle plume’

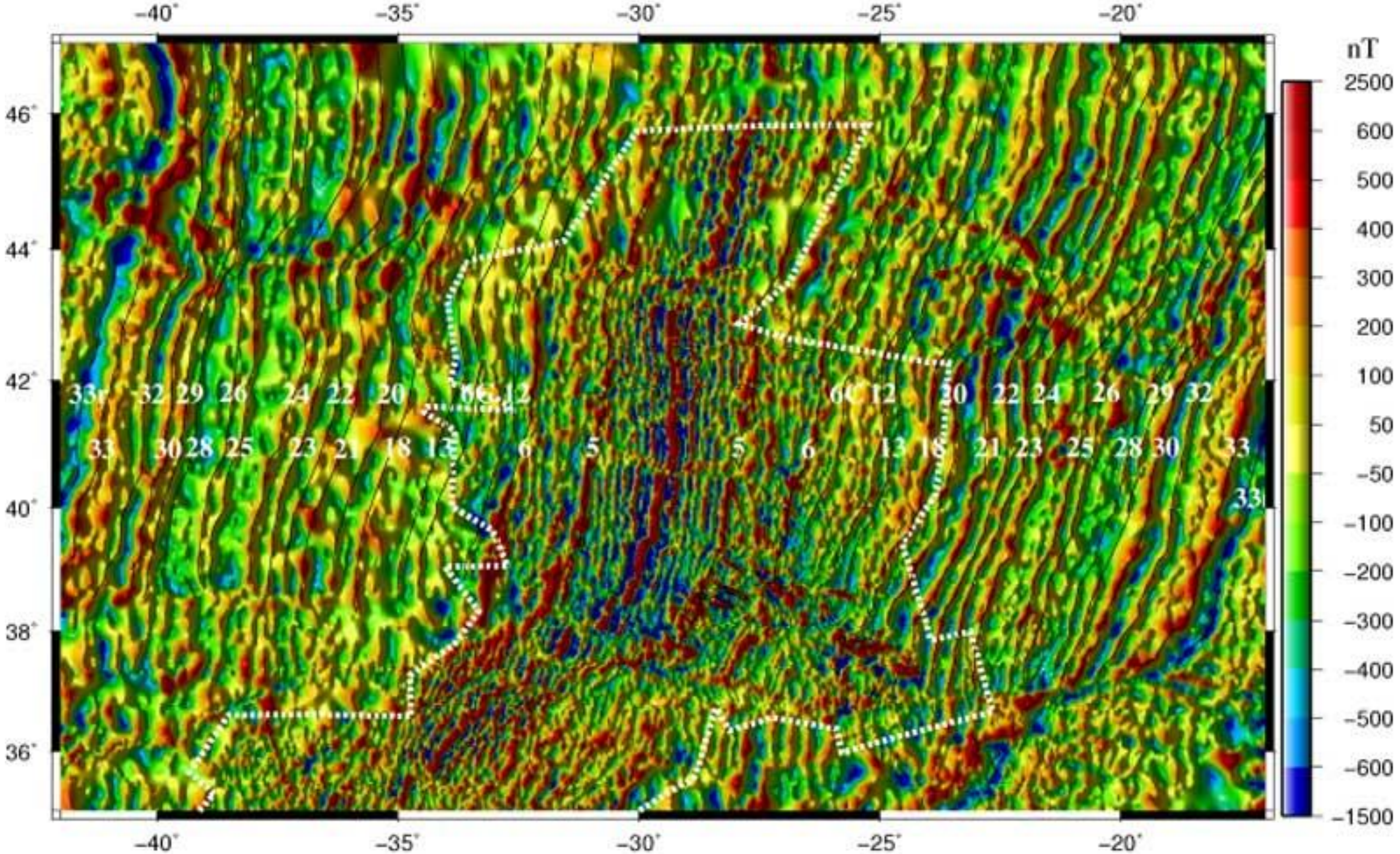
Plate reconstruction to 60 Ma (Trond Torsvik, pers. com. 2003) with simplified seafloor. The main dike trend in the British Volcanic Province schematically shown to extend to the West Greenland magmatic area, is invoked to utilize a zone of weak extension. The Late Cenozoic European rift system (from Ziegler, 1992) is included in order to illustrate a more evolved stage extension, also related to compression in the Pyrenees and the Alps. NF: Newfoundland, BB: Baffin Bay, IB: Iberia

(Lundin and Doré, 2004)



Magnetic anomalies

Magnetic anomalies continuously reduced to the pole. Overlain are the polylines whose vertices correspond to the anomaly picks along the magnetic isochrones. White dashed line encompasses the area where new magnetic data have been added to the existing compilation.



(Luis and Miranda, 2008)

Azores is a hotspot yes….
But is it a mantle plume ?

Hotspot

- Intense volcanism
- High heat flow
- High topography
- Sometimes trail

Hotspot is something you can see on the earth's surface.

Mantle plume

- Plume of solid, but hotter material rising by buoyancy from depth in the mantle
- Melt formed near the surface, feeds volcanoes of hotspot

Mantle plume is something you can only see deep in the mantle.

(Páll Einarsson, presentation 2012 in Current crustal)

Hypotheses proposed for the plateau formation

Tectonic origin

- The enhanced upwelling and magmatism driven by plate-boundary forces.
- The northward jump of the triple junction that this mechanism is a result of small changes in the relative motion between the three megaplates (Luis et al 1994)

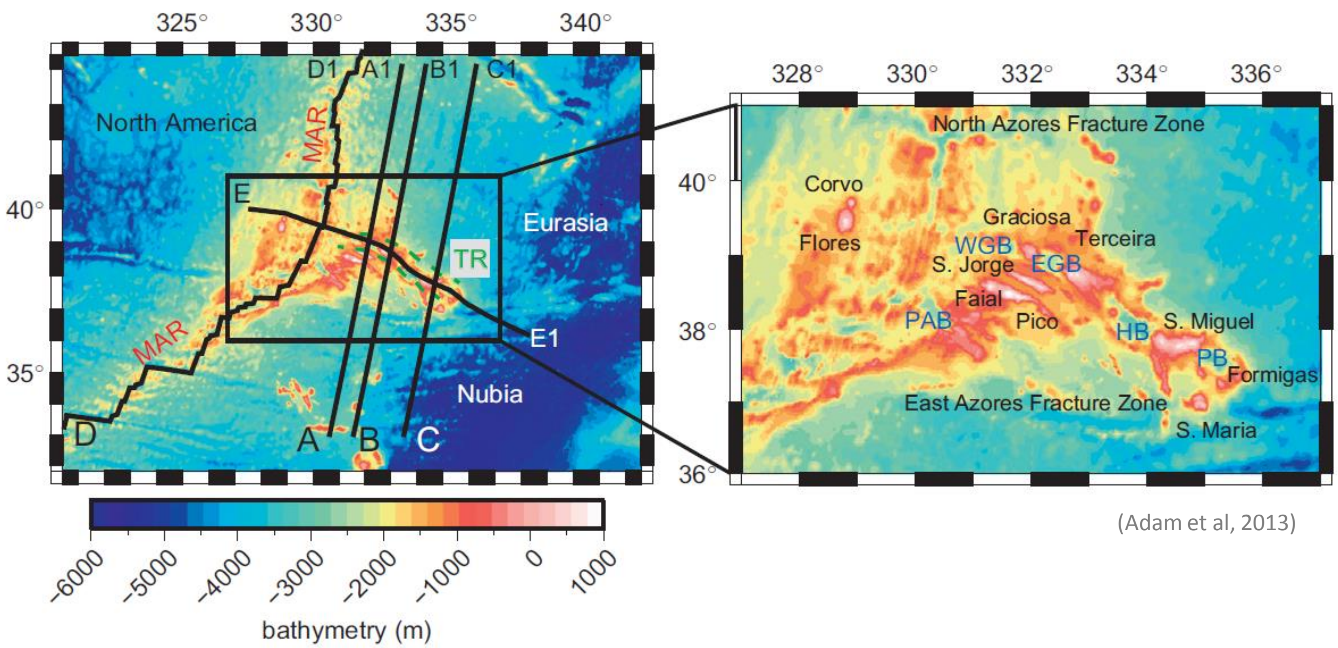
Mantle plume origin

- Other (Yang et al, 2006; Vogt and Jung, 2004) assume a mantle plume is necessary to explain the plateau formation.
- The northward jump of the triple junction is then a result of relative motion of the plates and the mantle plum.
- For Gente et al. (2003), the plateau results from the interaction between the MAR and the plume, followed by the progressive southward rifting of the plateau after 7 Ma.

(Adam et al, 2013)

Looking inside the mantle

- The plume has been imaged by several tomography models.
- The characteristics of the plume vary according to different models concerning the wavelength and amplitude of the velocity anomalies, as well as the depth of the root.
- Is the 'Azores plume' a shallow feature of the upper mantle or does it extend to the whole mantle?
- We will first look into models from Adam et al (2013)
- See images for profile lines.



(Adam et al, 2013)

Location of transections described on previous slide

Looking inside the mantle

The model points out two main low shallow (depth < 200km) velocity anomalies.

- One located under the islands Faial, Pico, S. Jorge, and Graciosa
- Other located under the area between the Terceira and S. Miguel islands

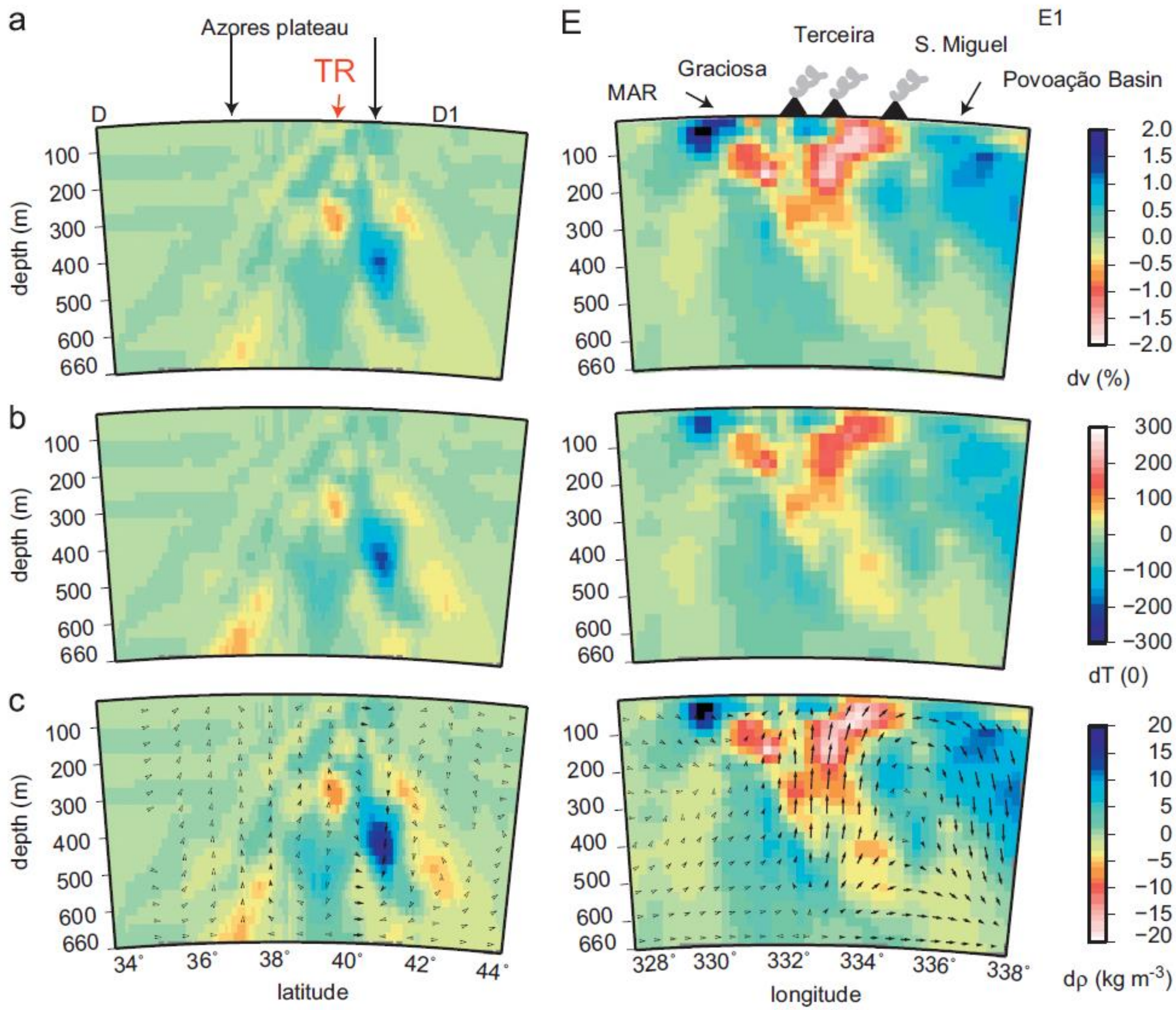
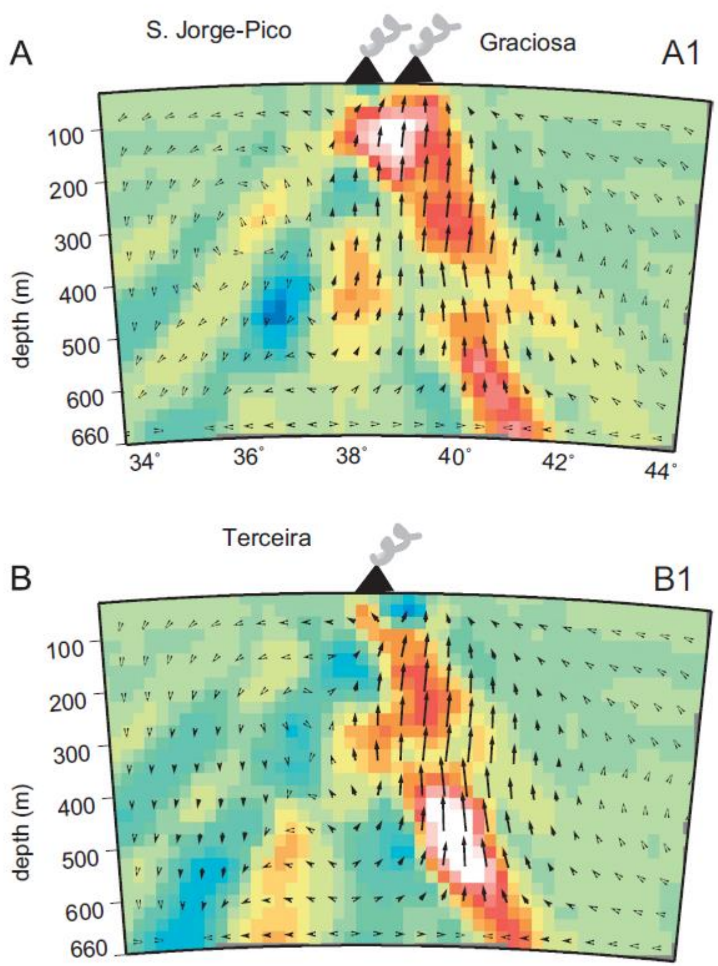


Fig. 2. Depth cross sections along the MAR (left panels) and the TR (right panels); (a) tomography model (Yang et al., 2006); (b) temperature anomalies deduced from the tomography model; (c) density anomalies deduced from the tomography model; the arrows represent the convection driven by these density anomalies.

(Adam et al, 2013)

Looking inside the mantle



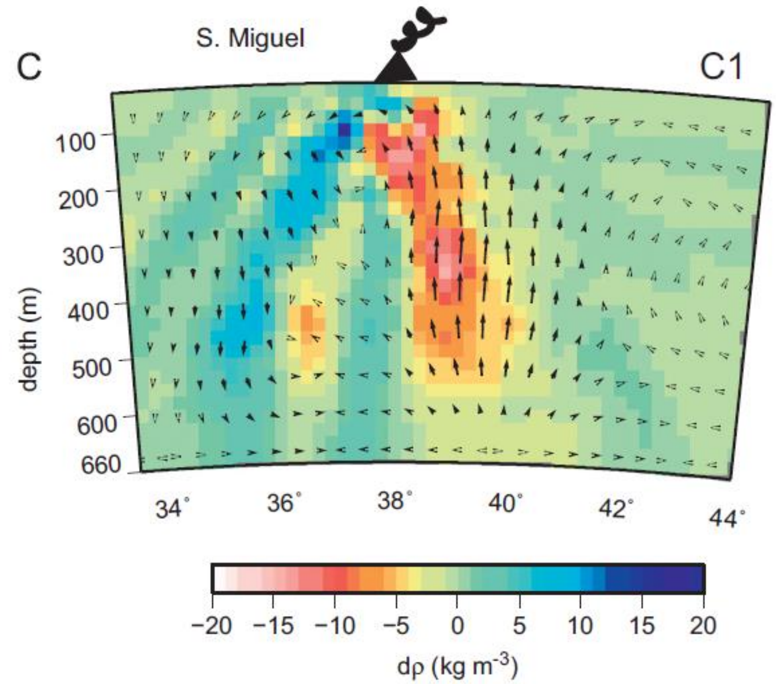


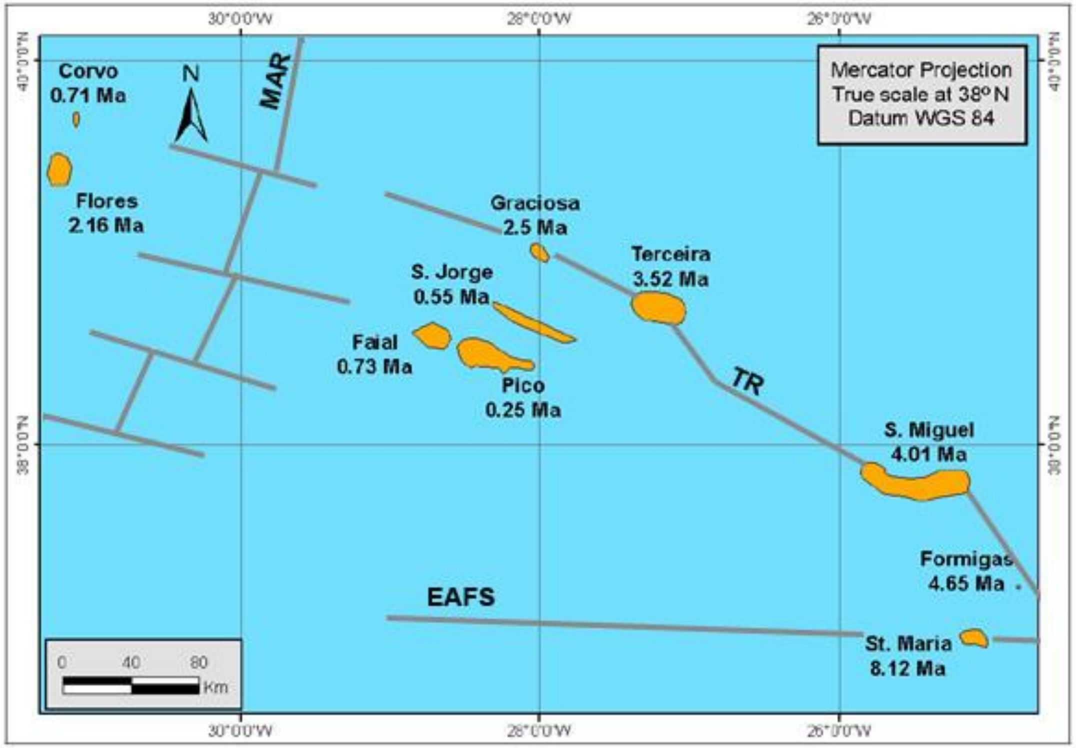
Fig. 3. Depth cross sections along the profiles AA1, BB1, CC1. The color map represent the density anomaly deduced from Yang et al. (2006) tomography model. The arrows represent the convection driven by these density anomalies.

Location of transections described on previous slide

(Adam et al, 2013)

Research on Helium isotopes in hydrothermal fluids of the Azores archipelago

- Very wide range of the $^3He/^4He$ ratio
  - Lower-than-MORB values (5.23–6.07 Ra) on central Sao Miguel, (normalized to the air ratio, Ra)
  - MORB values on Faial (8.53 Ra) and Flores (8.04 Ra) – either side of MAR
  - Plume-type values on Graciosa (11.2 Ra) and Terceira (13.5 Ra), where free gases also display ten times higher-than-MORB $CO_2/^3He$ ratios ($1.8–2.6×10^{10}$).



- The simultaneity of both elevated $CO_2/^3He$ and $^3He/^4He$ ratios is best explained by a ^3He-rich contribution from the lower mantle diluted in a CO_2-rich feeding plume that contains a recycled altered oceanic plate component.

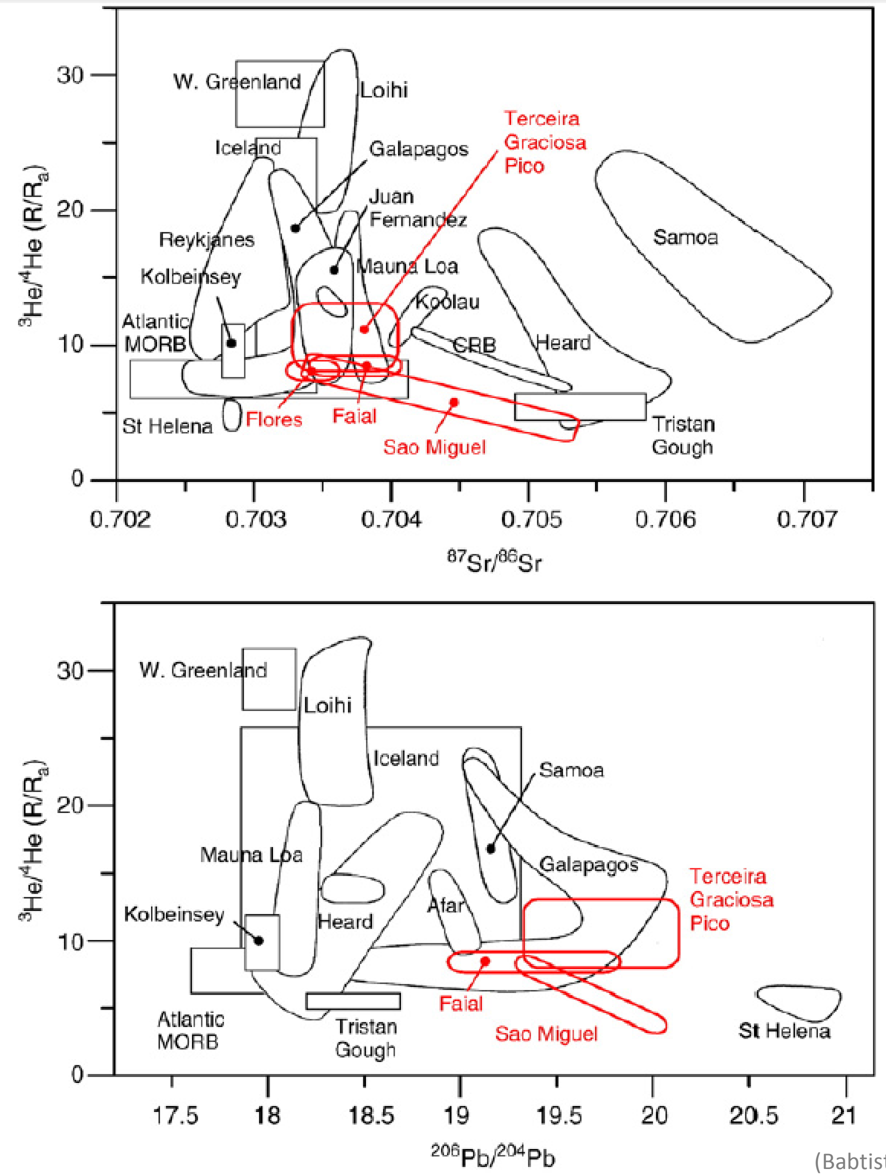
(Babtiste et al, 2009)

In relation to other areas

The observed isotopic variations require a mixing with at least two other mantle components:

(i) normal MORB mantle similar to that feeding the nearby Mid-Atlantic Ridge, and

(ii) a plumetype component with moderately high $^{3}He/^{4}He$ ratio and intermediate $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ values compared to themost ‘primitive’ endmember feeding Iceland or Loihi seamount in Hawaii



(Babtiste et al, 2009)

Fig. 4. He–Sr and He–Pb isotopic relations for Azores volcanic products (adapted from Graham et al., 1998). The helium isotope data set includes our present results for Azores fluids and those for volcanic rocks from Kurz (1991), Moreira et al. (1999), Madureira et al. (2005). Sr–Pb isotope data for Azores lavas are from White et al. (1976), Hawkesworth et al. (1979), Dupré et al. (1982), Davies et al. (1989), Widom et al. (1997), Turner et al. (1997), Moreira et al. (1999), França et al. (2006), and Beier et al. (2007).

Longitudinal distribution

The highest values (and plume-type) of $^3He/^4He$ ratios in fluids and rocks of the central volcanic islands demonstrates that the Azores plume component is concentrated under the central part of the archipelago.

However, the actual centre of the "high" $^3He/^4He$ plume might well be located beneath the island of Sao Jorge, just south of Terceira, where one rock sample with a ratio as high as 15.9 Ra has been reported.

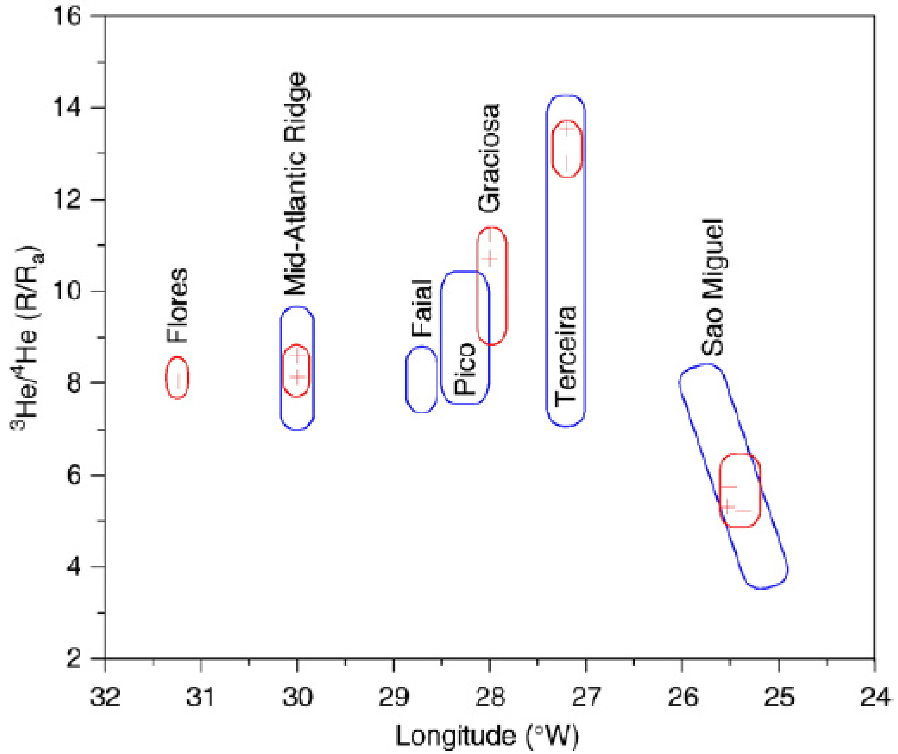


Fig. 5. Longitudinal distribution of $^3He/^4He$ ratios in Azores volcanic fluids and rocks. Rock data (in blue) are from Kurz (1991), Moreira et al. (1999) and Madureira et al. (2005). Our gas data are in red. Data for the Mid-Atlantic Ridge (37°N–40°N) rocks are from Moreira and Allègre (2002) and those for submarine hydrothermal fluid venting are from Jean-Baptiste et al. (1998) and Charlou et al. (2000).

(Babtiste et al, 2009)

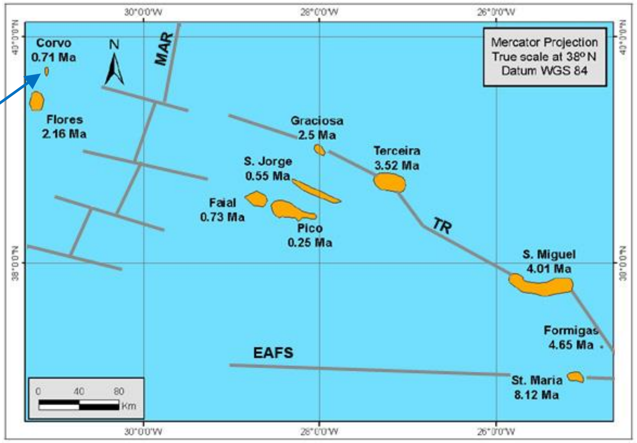
Geochemical composition:
TAS Diagram

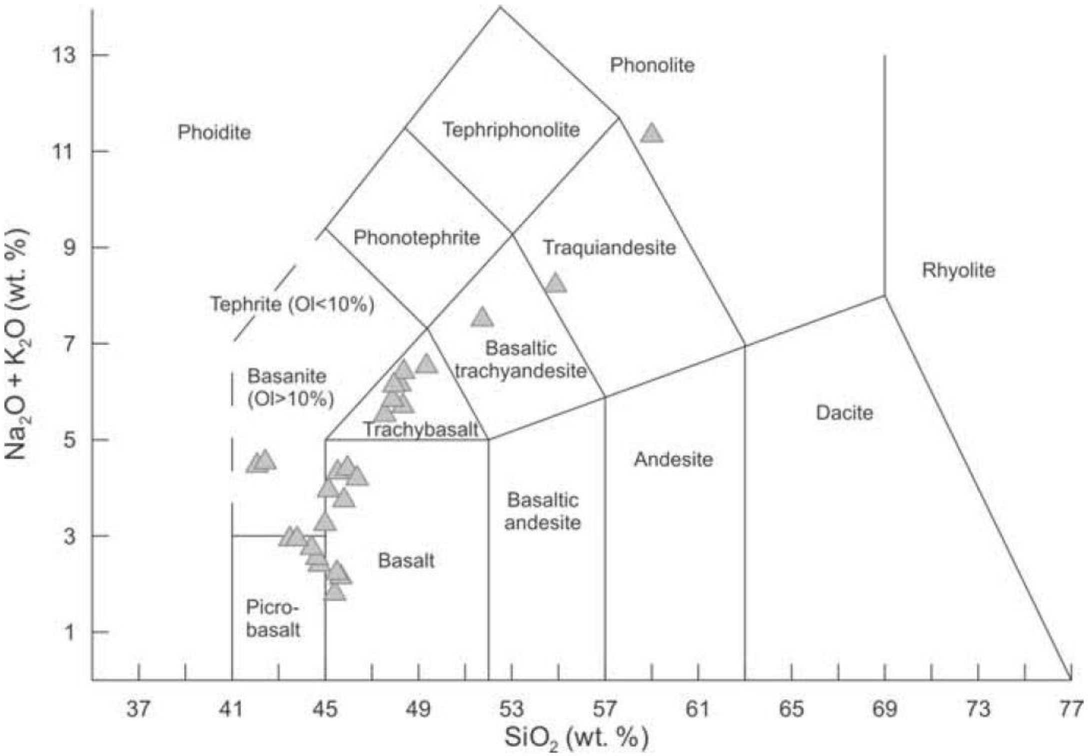
The data is for Corvo Island (the small island on the American plate).

According to Franca et al (2006) the geochemical composition for the Corvo island area nearly equivalent for other islands in the archipelago.

It seem to be above the Hawaiian line.

Described by the author as a material from a mantle plume with a significant HIMU (high time-integrated $^{238}U/^{204}Pb$ or high μ) contribution as the geodynamic scenario for the genesis of the magmas.





(França et al, 2006)

Fig. 2.- TAS diagram for 49 volcanic rocks of the Corvo island.

Looking inside the mantle

Based on gravity study:

a) Bathymetry: Seafloor depth
b) Bouguer gravity anomaly
c) Residual
d) Relative crustal thickness, should be interpreted as upper bounds.

Seismic and gravity data suggest plateau crustal thicknesses of ~8 km or more

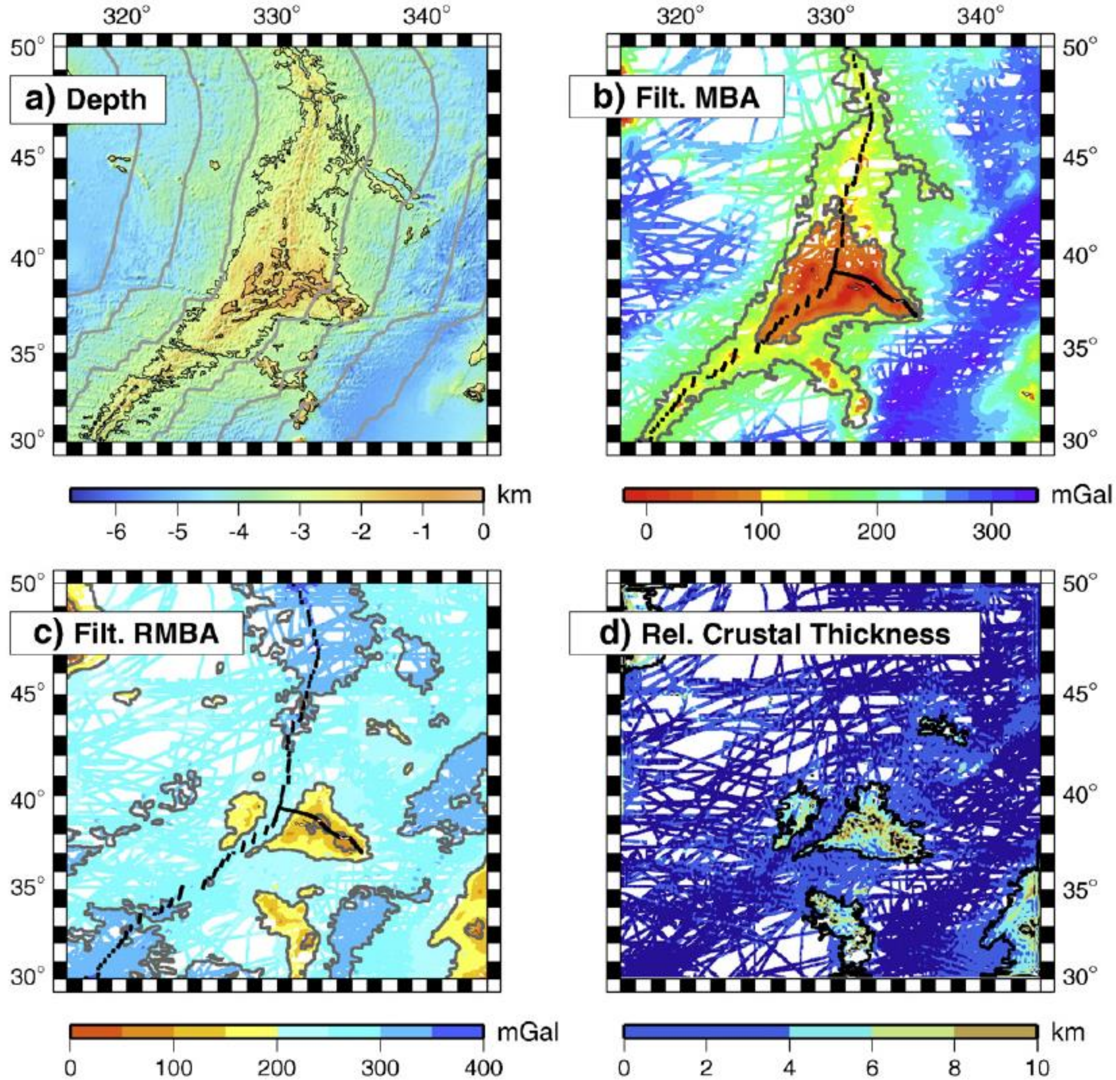
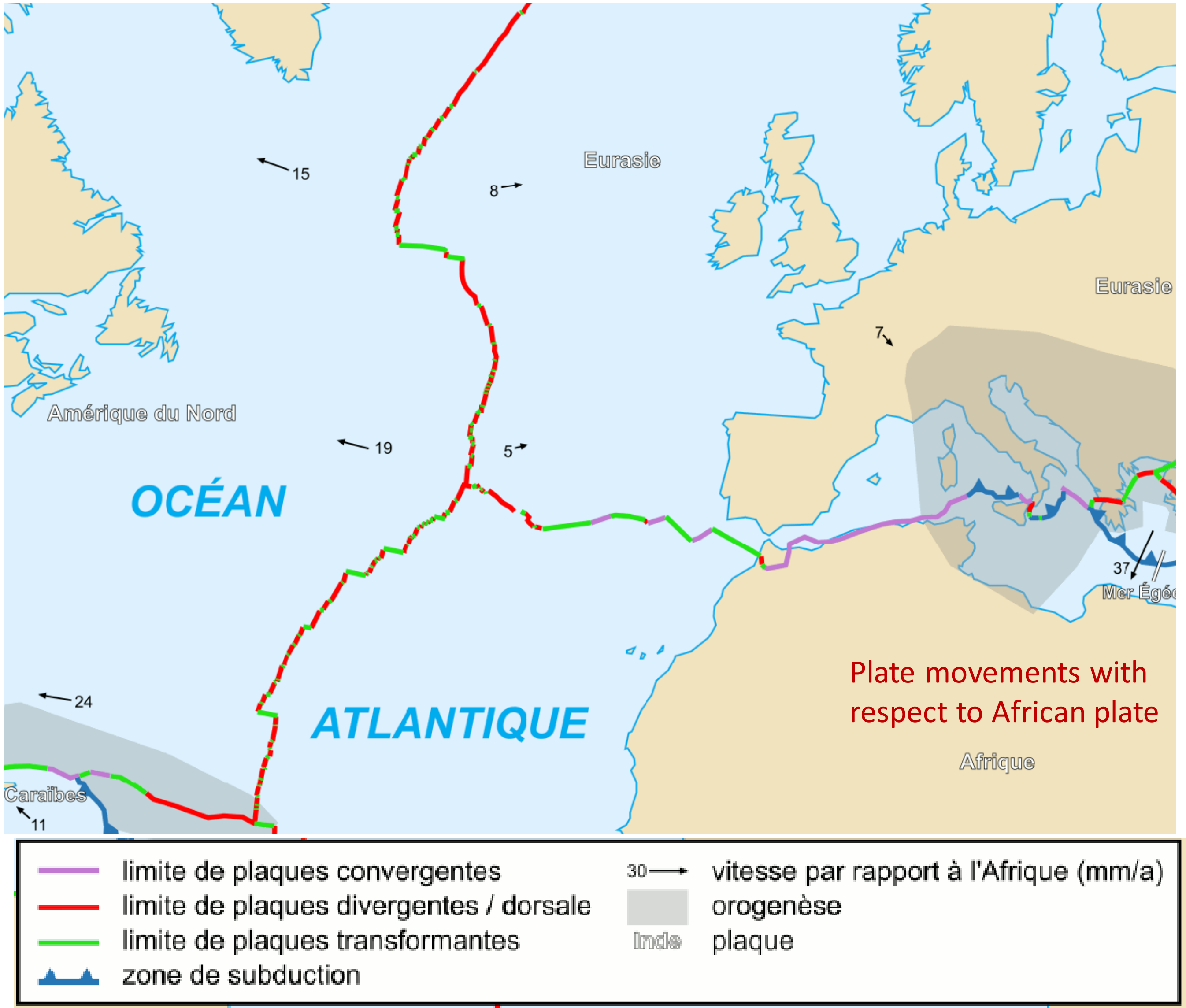


Fig. 3. (a) Seafloor depth, (b) mantle Bouguer anomaly, (c) residual mantle Bouguer anomaly, and (d) gravity-inferred relative crustal thickness variations for the Azores Triple Junction region. Data sources, data set resolution, and calculation methods are described in the text. Contours are plotted at (a) 1.5 km depth, (b) 100 and 160 mGal, (c) 100 mGal, and (d) 3 km. In (a), thick gray lines show 25 Myr isochrons (Müller et al., 2008). In (b), (c), and (d), regions farther than 10′ from a shiptrack are masked with white to visually deter interpretation of areas without data control. MBA and RMBA are filtered with a lowpass filter with cutoff wavelength of 40 km.

(Georgen & sankar, 2010)

Plate tectonics

- The Azor Triple Junction: Ridge-Ridge-Ridge
- But: According to data from USGS used in Google klm file available on the internet it is Rige-Ridge-Transform triple junction



(Páll Einarsson, presentation 2012 in Current crustal)

TER: Terceira Rift

- The precise nature of the TER has been debated
  - Some investigations describe the boundary as a zone of distributed deformation or as an extensional strike-slip fault [e.g., Luis et al., 1998].
  - Other [Vogt and Jung 2004] treats the TER as an ultra-slow diverging ridge with a half-rate of 0.4 cm/yr.

(Georgen, 2011)

- Slowest spreading rate on Earth?
  - The Gakkel Ridge in the Arctic area: 7-13mm/a
  - SW Indian Ridge: 15-16mm/a
  - Terceira Ridge: 4mm/a
- Topography of the ridge, Interpreted simply as volcanically ‘unfilled’ rift valley segments:
  - the interisland basins (e.g. the 3200 m deep Hirondelle Basin) are slightly wider (30-60 km), but not significantly deeper (1000-2200 m) than the Mid-Atlantic Ridge (MAR) median valley (20-28 mm/a)

(Vogt & jung, 2004)

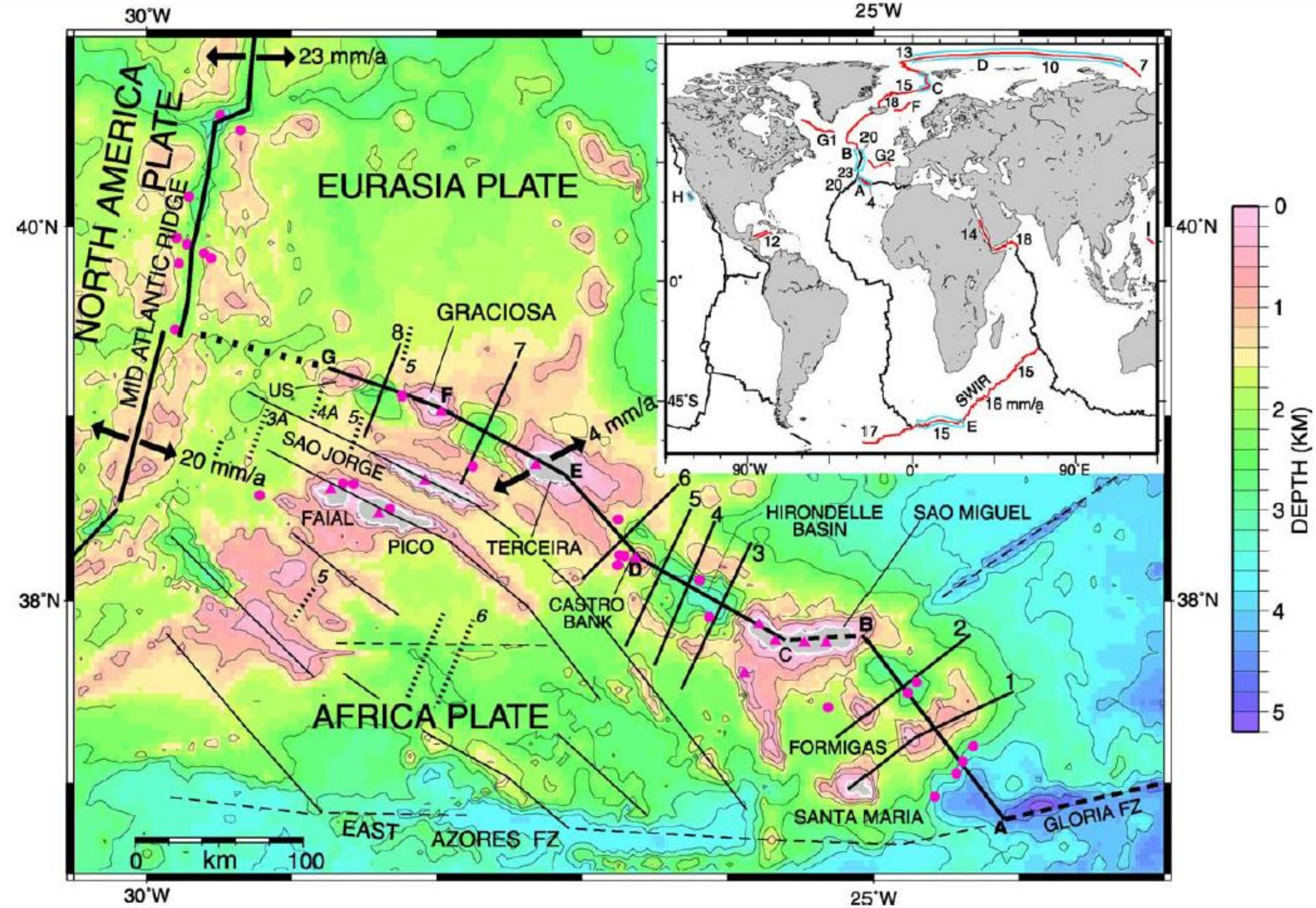


Fig. 1. Bathymetry of Azores Plateau area (from [32]), showing interpreted Terceira Rift and Mid-Atlantic Ridge plate boundaries (solid, spreading ridges; dashed, transform faults; dotted, uncertain boundary). Red dots are teleseisms (courtesy of National Geophysical Data Center) and triangles are active and dormant volcanoes. Thin solid and dashed lines show possible extinct, pre-TR plate boundaries. Dotted lines are sea-floor spreading type magnetic lineations (modified from [20]). Numbered lines show locations of bathymetric profiles, and letters denote points along longitudinal profile (Fig. 2). Inset map shows world's major spreading boundaries, with total opening rates (mm/a) for slow ridges. Lettered blue boxes outline locations of ridge segments reproduced in Fig. 4 and others discussed in text: A, Terceira Rift; B, Mid-Atlantic Ridge; C, Mohns–Knipovich Ridge; D, Gakkel (Nansen) Ridge; E, Southwest Indian Ridge; F, extinct Aegir Ridge; G1, extinct Mid-Labrador Sea Ridge; G2, King's Trough; H, Guadalupe Island and extinct axis; I, extinct West Philippine Sea axis.

(Vogt & jung, 2004)

Seismicity 1973-2008

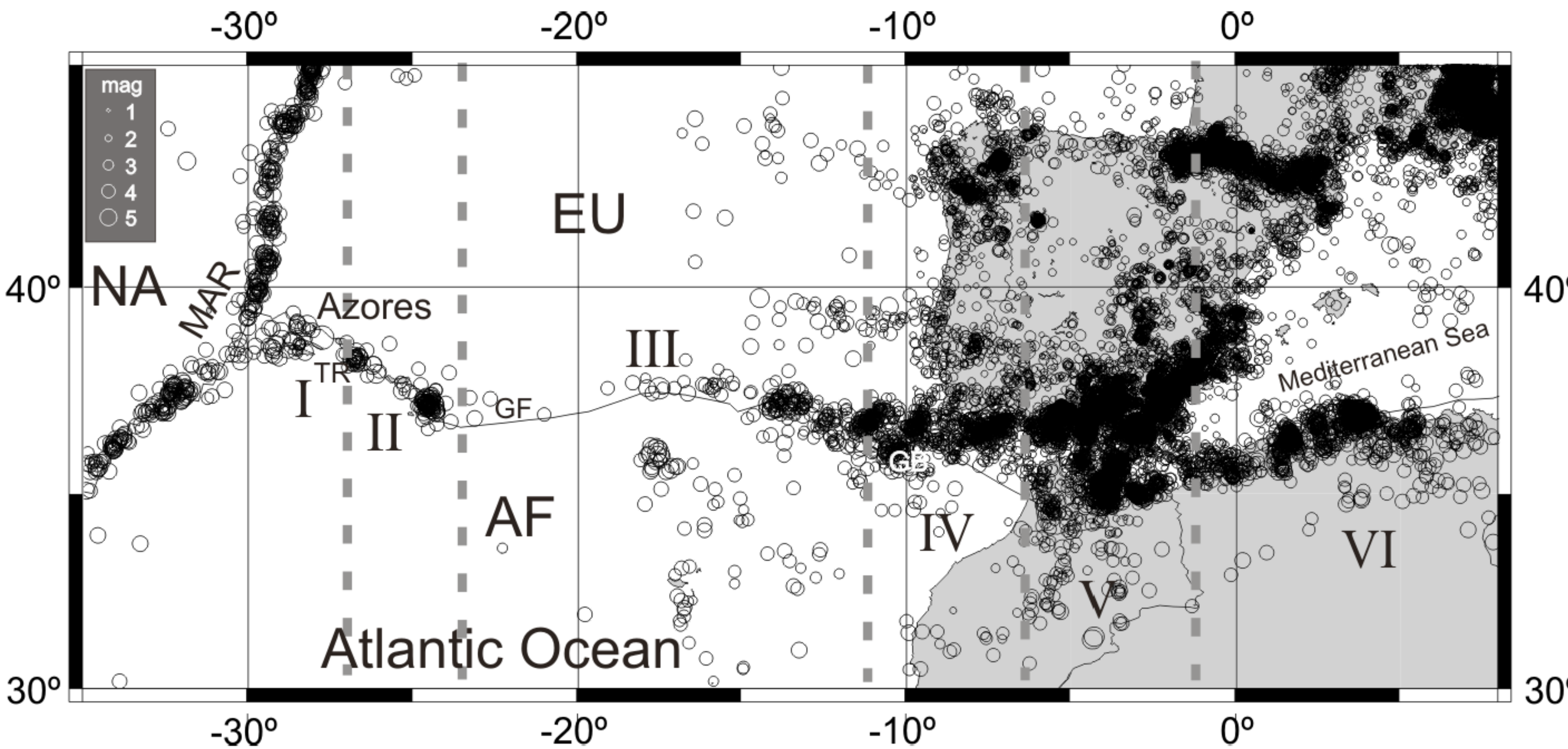


Fig. 1: Seismicity for the western part of the Eurasia-Nubia plate boundary for the period 1973-2008 for magnitude M≥ 1.0 (NEIC Data File). MAR = Middle Atlantic Ridge; TR = Terceira Ridge; GF = Gloria Fault; GB = Gorringe Bank; NA = North American plate; EU = Eurasian plate; AF = African plate; P = Portugal; S = Spain; M = Morocco; A = Algeria. The roman numbers (from I to VI) indicates the six zones studied and described in the text.

(Bezzeghoud et al, 1998)

Seismicity

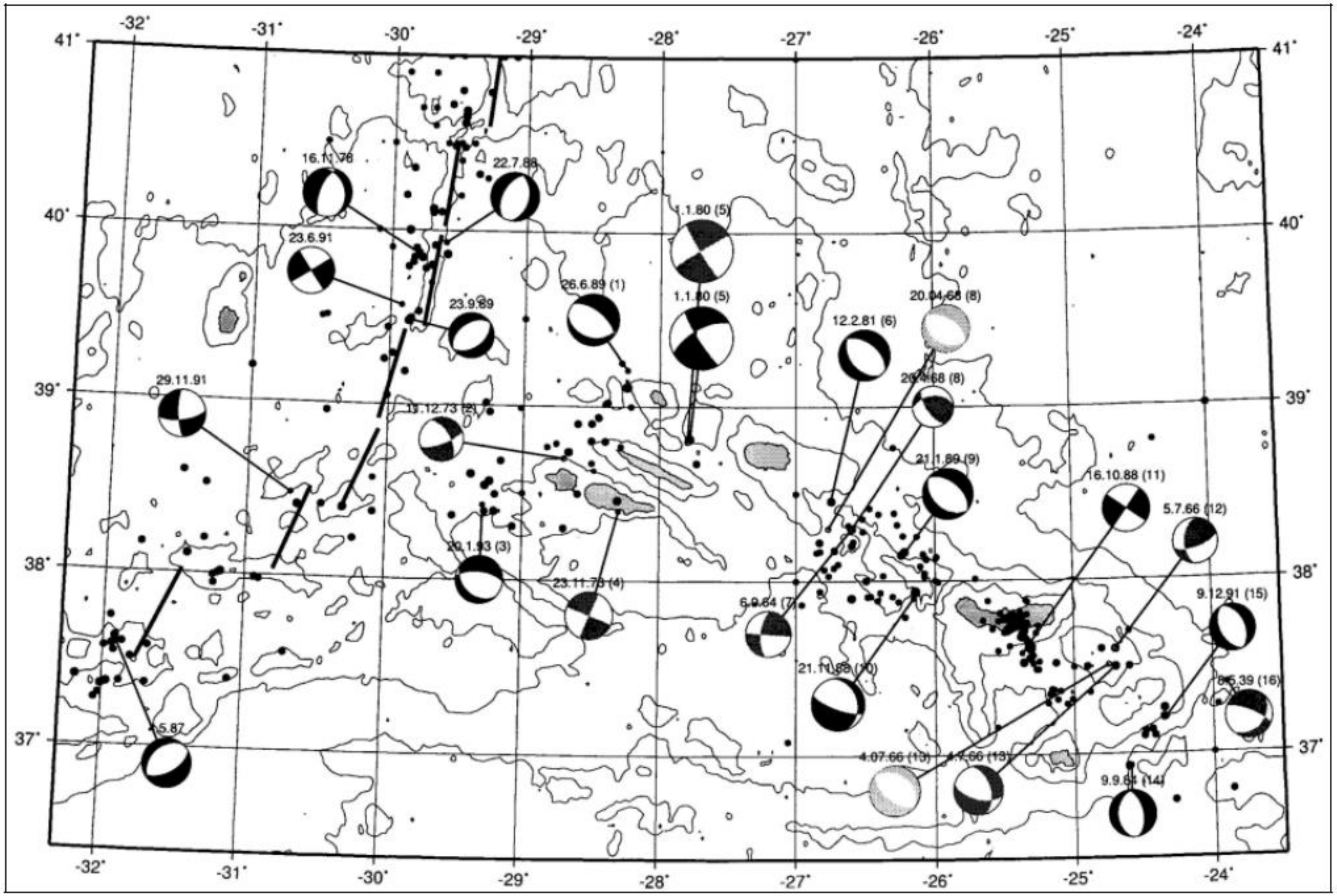


Figure 20 - Seismicity map (M>4) of the Azores plateau from 1928 until 1998, retrieved from the USGS database (Lourenço et al., 1998).

(Quartau, 2007)

GPS Measurements

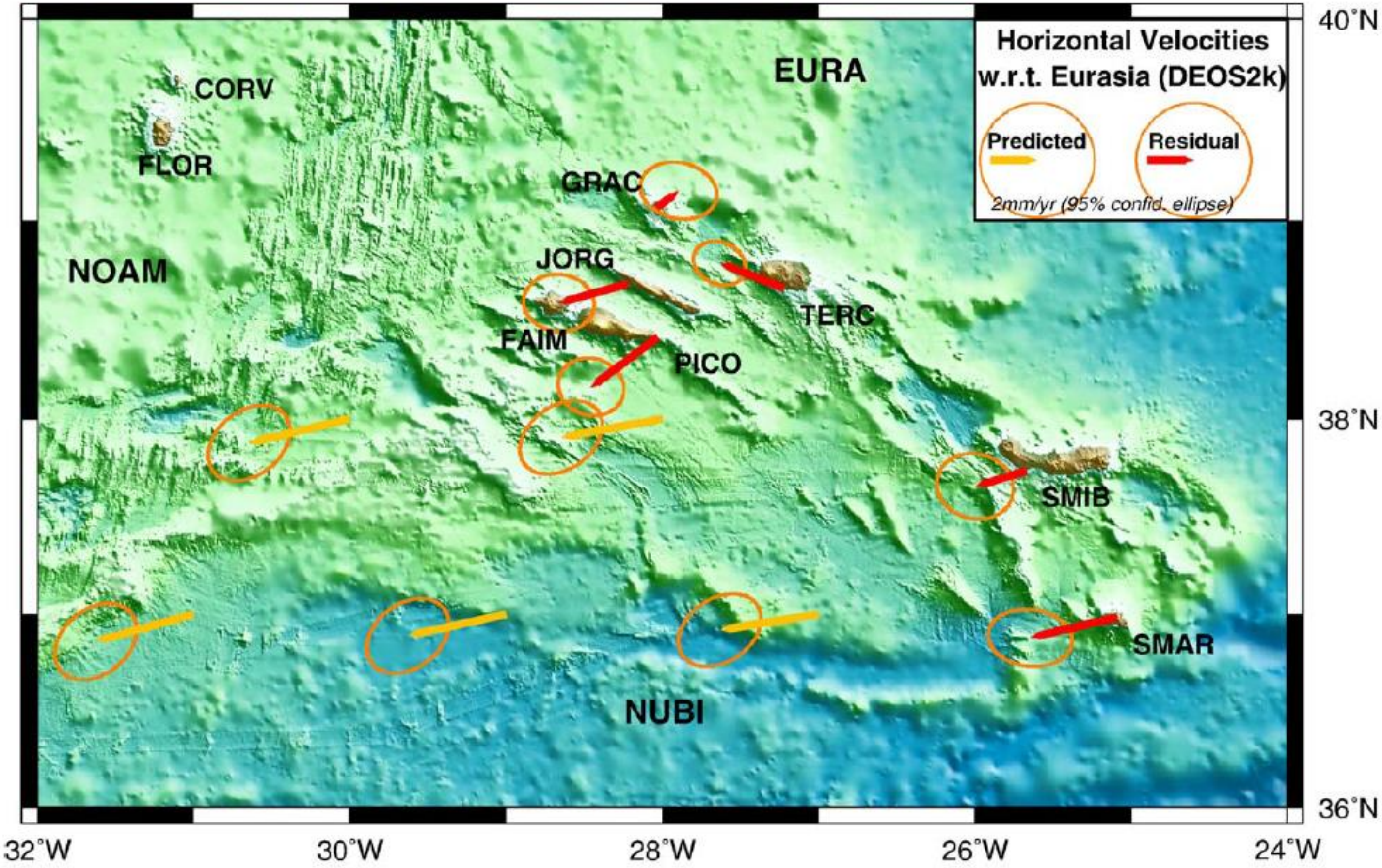


Fig. 4. Relative motions with respect to stable Eurasia (as predicted by DEOS2k). Residual motions (observations minus predictions) for the initial TANGO sites in the Central and Eastern groups (red). Predicted relative motions for points located in stable Nubia (purple). On the background is shown the bathymetry from Lourenço et al. (1998). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For discussion

- Is the Terceira Rift the slowest rift on Earth?
- What will be the future of the Terceira Rift?
- Do we have a mantle plume at Azores – and even 2 of them?
- Why is much more volcanic material above sea level in Iceland than in the Azores?

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