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# Conditions of melting beneath the Azores

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ABSTRACT

The depth and temperatures of melting beneath Ocean Islands provide important constraints on mantle melting dynamics. The central Azores islands of Faial, Pico, Graciosa and São Jorge are ideally suited for calculating depth and temperatures of melting because they are situated orthogonal to the slow spreading Mid-Atlantic Ridge and thus supposedly on variable lithosphere thicknesses which allow to constrain on the influence of lithosphere thickness on average melting depth. The dataset presented here is used to test the spatial pattern of potential temperature anomalies in the Azores mantle plume. Trace elements indicate comparable degrees of partial melting for all three islands, while Sr–Nd–Pb isotope ratios and incompatible trace element ratios imply only small-scale source heterogeneity that is not related to the major element systematics. Thus, the observed differences in calculated, primary $SiO_2$, $FeO^T$ and $TiO_2$ (and $Al_2O_3$) are inferred to reflect changes in melting pressures and temperatures that are independent of source composition. Melting temperatures in the Azores are lower and melting starts deeper than at other mantle plumes (e.g., Hawaii). This implies that the smaller size of the Azores compared to other mantle plumes might be the result of a much smaller anomaly with a large variability of depths and temperatures of melting even on the scale of an individual island. This small-scale variability is of importance when comparing pressures and temperatures between different islands or even globally. The Azores lavas have temperatures lower than predicted for a dry mantle solidus indicating the presence of at least 200 ppm $H_2O$ in the Azores mantle source.


## 1. Introduction

Lavas erupted on the ocean floor, i.e. along spreading axes (Mid Ocean Ridge Basalts, MORB) or within oceanic plates (Oceanic Island Basalts, OIB), provide important information on melting processes, melt movement and the composition of the Earth's mantle. The occurrence of ocean islands such as the Azores has been commonly attributed to the presence of thermal anomalies in the Earth's mantle (Montelli et al., 2004; Morgan, 1971; Ritsema and Allen, 2003) but it remains a matter of debate as to whether it is solely increased temperature that results in magmatism ("hotspot" Morgan, 1971). Alternatively, heterogeneity, in the form of enriched mantle and/or volatiles plays an important role in triggering melting (e.g. volatiles, "wetspot" Bonatti, 1990). These effects may also be combined in the form of heterogeneous thermochemical piles (e.g., Farnetani and Samuel, 2005; Sobolev et al., 2005). It is generally accepted that the mantle is heterogeneous on scales from centimeters to 1000 km in terms of incompatible elements and Sr, Nd, Pb and Hf isotopes (see review by Hofmann, 2003 and references therein). Most OIB are geochemically distinct from MORB (Schilling, 1975b; Schilling et al., 1985; White, 1985) and show evidence of significant time-integrated incompatible element enrichment compared to MORB (White and Hofmann, 1982; Zindler and Hart, 1986). However, the major element heterogeneity of the mantle is poorly understood and much of the major element variation observed in fractionation-corrected MORB is attributed to variable degrees and depths of partial melting (Klein and Langmuir, 1987). Compared to MORB, the interpretation of OIB is more complicated because they form (a) beneath variably thick lithosphere (Haase, 1996; Lee et al., 2009) and (b) from highly variable mantle sources as implied by their incompatible element and Sr, Nd, Pb, Hf isotope ratios. For a given thermal structure, the total extent of melting is likely to be greatest beneath the thinnest lithosphere. Recently, it has been argued that there are correlations between isotopes and major element compositions in OIB (Dasgupta et al., 2010; Jackson and Dasgupta, 2008). However, an important prerequisite for constraining melting temperatures and pressures is determining the composition of a primary melt from whole rock or glass compositions (Green et al., 2001; Herzberg and Asimow, 2008; Langmuir and Hanson, 1981; Putirka, 2005).

The lavas from the Azores archipelago exhibit extreme incompatible element and isotope heterogeneity with large variations observed even within a single island (Moreira et al., 1999a; Turner et al., 1997; White et al., 1979). The MORB along the adjacent Mid-Atlantic Ridge (MAR) have trace element and isotopic signatures believed to reflect an enriched mantle plume (Schilling, 1975a) and

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they also have high volatile contents argued to reflect a wetspot (Asimow et al., 2004; Schilling et al., 1980). The presence of young, recent volcanism on nearly every island spanning the MAR is not easily explained by a deep mantle plume. The tectonic situation is also complicated by the ultraslow spreading Terceira Rift situated in the north of the Azores Plateau (Beier et al., 2008; Vogt and Jung, 2004). Consequently, the Azores volcanism offers a possibility to study the mantle heterogeneity and its possible co-variation with potential temperature.

Here, we present new major element, trace element and Sr–Nd–Pb isotope data for whole rocks and glasses as well as olivine xenocryst compositions from three Azores islands (Faial, Pico, São Jorge) and compare these with published data from the islands of Graciosa, Terceira and São Miguel. These are used to investigate the causes of melting and whether there is any spatial variation in the inferred depth and temperature of melting with lithospheric thickness or inferred source composition. Based on mineral and lava compositions we calculate the composition of primary melts to determine the mantle potential beneath the islands. We find that, although the different islands have variable isotope signatures, the major element and Rare Earth Element compositions are far less variable implying comparable degrees of partial melting. We infer a slight increase in mantle potential temperature and the average depth of melting with increasing distance from the MAR implying a lithospheric control on melting dynamics. The Azores melting temperatures and pressures are lower than predicted by the dry peridotite solidus and indicate at least 200 ppm $H_2O$ in the Azores mantle plume.

## 2. Geologic background

The Azores Plateau contains two main tectonic structures: a) the Mid-Atlantic Ridge (MAR), separating the platform into a larger eastern and a smaller western part and b) the NW–SW trending ultraslow spreading Terceira Rift (2–4 mm/a) at the northern boundary of the plateau (Fig. 1a; Vogt and Jung, 2004). The rift comprises the islands of Graciosa, Terceira, the seamount João de Castro and the island of São Miguel (from west to east) where trace elements and isotopes provide evidence for short length-scale heterogeneity in the mantle (Beier et al., 2008; Beier et al., 2010a). In particular, there have been debates as to whether the trigger for melting beneath the islands is thermal or chemical in character (i.e. wetspot versus hotspot; Bonatti, 1990; McKenzie and O'Nions, 1995; Montelli et al., 2004).

Faial and Pico islands are situated some 65 km south of the recently active Terceira Rift with São Jorge located half way between (Fig. 1c). Faial, Pico and the submarine Pico Ridge form a volcanic lineament ~160 km length striking parallel to the Terceira Rift in a NW–SE direction (Fig. 1b,c).

Faial and Pico are separated from each other by narrow (~6 km) deep non-magmatic basin comparable to the structures recently observed along the Terceira Rift (Beier et al., 2008; Vogt and Jung, 2004). Geophysical investigations in the vicinity of Faial and Pico have revealed steep submarine flanks containing large lava flows and caves (Mitchell et al., 2008). Pico island has a large stratovolcano (Mt. Pico) in the west and a series of small scoria cones toward the east continuing submarine for at least 60 km East of Pico (Fig. 1b).

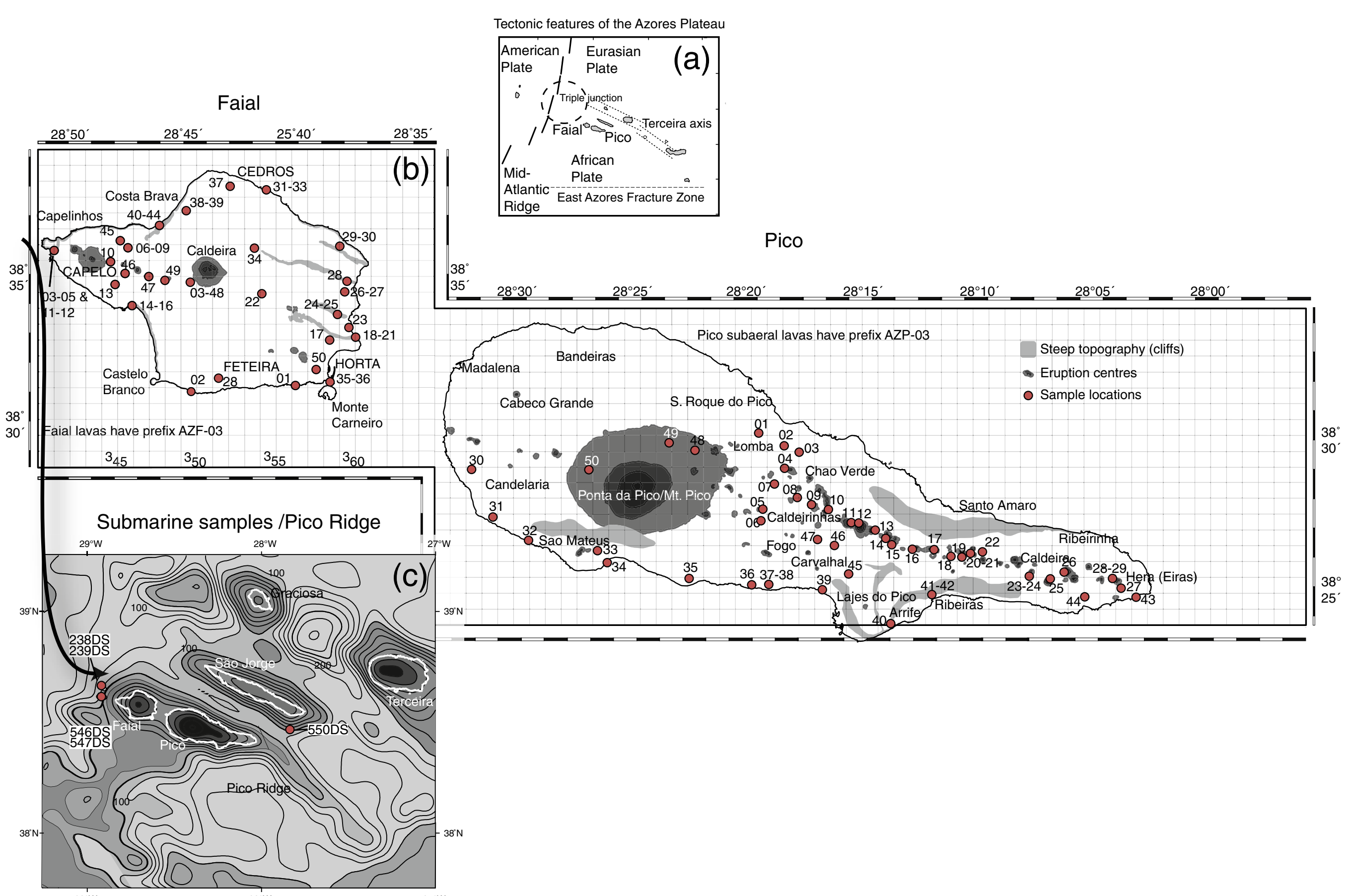


**Fig. 1.** A) Main tectonic features of the Azores Plateau with the Mid-Atlantic Ridge (MAR) in the west, the East Azores Fracture Zone in the south and the ultraslow spreading Terceira Rift in the north. B) Islands of Faial and Pico. Maps are based on topographic maps from the Instituto Geografico Portugues. Bright gray shows steep topographic sections, dark gray fields indicate main eruptive centers. Note that the steep section on the eastern coastline of Faial is a horst-and-graben structure. C) This panel shows bathymetric map of São Jorge, Pico and Faial with dredge sample locations of cruises POS232 and POS286. For Graciosa data see Beier et al. (2008).