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Geochemical and geophysical estimates of lithospheric thickness variation beneath Galápagos

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Active volcanism in Galápagos is far more widespread (>40,000 km^2) than in other hotspot-related archipelagos, such as Hawaii (~20,000 km^2). Here we employ both geochemical and geophysical models to constrain the causes of this large spatial extent of melt generation and the diverse compositions of erupted basalts. Insight in to the physical as well as the chemical nature of the melting regime beneath Galápagos –– and the cause of the relatively widespread, non-linear age-progressive distribution of volcanism – is provided by incompatible-trace-element ratios of basaltic magmas. Whilst variations in these (and isotopic) ratios of basalts from individual Galápagos volcanoes are limited, considerable differences have been observed in basalts erupted across the archipelago. We have used rare-earth-element inversion modelling for basalts dominated by "plume" and depleted MORB mantle components to constrain the depth to the top of the melt column beneath different Galápagos volcanoes. By converting S-wave data from a recently published tomographic experiment [Villagomez, D.R. *et al.*, 2007. Upper mantle structure beneath the Galápagos Archipelago from surface wave tomography. J. Geophys. Res. 112] to temperature we have been able to map the base of the Galápagos lithosphere, *i.e.* where the geotherm, with a mantle potential temperature of 1315 °C, intersects the anhydrous peridotite solidus.

An excellent correlation exists between the results of our geophysical and geochemical models. These predict that lithospheric thickness varies from ~60 km beneath islands in the south west of the Galápagos Archipelago (*e.g.* Fernandina and Isabela) to ~45 km below those in the northeast (*e.g.* Genovesa, Marchena, eastern Santiago and northern Santa Cruz). The thinner lithosphere away from the postulated site of the present-day plume axis, combined with the lateral deflection of the plume, is responsible for active volcanism over a relatively large area. Non-uniform variations in lithospheric thickness relative to distance from the Galápagos Spreading Centre are consistent with the complex nature of the oceanic lithosphere beneath this part of the Pacific, perhaps due to ridge jumps.

1. Introduction

Decades of successively more detailed research on ocean-island basalts (OIBs) have revealed that their parental melts result from the interaction of complex physical and chemical processes in the Earth's convecting mantle and overlying lithosphere. In most cases, melt is believed to be generated by adiabatic decompression in upwelling mantle plumes with potential temperatures greater than those of ambient mantle. Melting is initiated when the mantle adiabat intersects the solidus and continues until upwelling is inhibited by rigid lithosphere. Most geochemical models of melting beneath oceanic islands involve either: (i) forward modelling of whole-rock concentrations of major elements and mineral chemistry; or (ii) forward or inverse modelling of rare-earth-element ratios, *e.g.* Herzberg and Asimow (2008), Herzberg and Gazel (2009), Langmuir et al. (1992), McKenzie and O'Nions (1991, 1995), Putirka (1999, 2005). These models yield predictions of the depth to the base and top of the melt column, degree of partial melting and mantle potential temperature (T_P). The algorithms used in these calculations require estimates of the composition of the mantle source region(s), the composition of primary melts, and an assumption of the physical processes involved in melt separation from the mantle, *i.e.* isentropic batch or incremental–fractional melting.

There have been relatively few attempts to assess how estimates of physical parameters determined by numerical modelling of geochemical data for OIBs correlate with the results of geophysical studies of the Earth's mantle and local differences in tectonic setting. This primarily reflects the limited amount of high-resolution seismic imaging available for individual archipelagos in which narrow chains of islands and lack of ocean-floor seismometers restrict two-dimensional geographic coverage. Here we compare the results of quantitative modelling of whole-rock geochemical data for high-MgO

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Galápagos basalts with the findings of a recent broadband seismic investigation of the archipelago (Hooft et al., 2003; Villagomez et al., 2007). We have used the large published geochemical database for Galápagos basalts together with new analyses (Supplementary Dataset) to estimate the onset and cessation of adiabatic decompression melting. In order to minimize the effects of different mantle compositions, we focus on basaltic melts from recent eruptions in the central, western and eastern zones of the Galápagos Archipelago, where the contributing melts are predominantly derived from 'depleted' and 'plume' regional mantle components (Harpp and White, 2001; White et al., 1993). The latter resembles the common global plume component frequently referred to as "C" or "FOZO" (Hanan and Graham, 1996; Harpp and White, 2001; Hart et al., 1992; Stracke et al., 2005), whereas the former has been attributed to the upper mantle (Geist et al., 1988) or part of a zoned plume (Hoernle et al., 2000). There is no attempt to model compositions found in the northern and southern archipelago that contain different isotopic components (Harpp and White, 2001). The wide geographic coverage of the seismic data together with the broad distribution of active volcanism and small range isotopic- and incompatible-trace-element composition of magma erupted from individual volcanoes makes the Galápagos Archipelago ideally suited to a comparative geochemical and geophysical study.

2. The Galápagos lithosphere

The Galápagos Archipelago resides on a submarine platform of oceanic crust which ranges in thickness from ~10 km on the margins to 18 km beneath southeast Isabela (Feighner and Richards, 1994). Feighner and Richards (1994) proposed that the central part of the platform is underlain by lithosphere with an elastic thickness of <6 km and is in Airy compensation whereas the western and southern parts are flexurally supported by lithosphere with an effective elastic thickness of ~12 km. They further suggested that the change in lithospheric strength is abrupt and postulated the presence of a major fault passing along the Wolf–Darwin lineament and through the central archipelago at a longitude of ~91°W, before trending approximately east through Floreana and Española in the southern archipelago (Fig. 1). Feighner and Richards (1994) used a half-space conductive-cooling model to predict that the oceanic lithosphere to the west of the fault is ~10 km thicker than that to the east. There is, however, no direct surface evidence of a major fault, and magnetic stripes indicate that the 91°W transform has existed for <3 million years (Wilson and Hey, 1995).

The surface wave tomography of Villagomez et al. (2007) has helped constrain the thickness of the lithosphere beneath Galápagos. They observed a sharp change in seismic velocity at a depth varying from 40 km below the northeast to 70 km beneath the southwest of the archipelago. At greater depths they found a continuous region of anomalously low velocity extending to >150 km. Villagomez et al. (2007) interpreted the marked change in seismic velocity as the base of the oceanic lithosphere. They inferred that the presence of a thick (70 km) high-velocity lid beneath the zone of most active volcanism (Fernandina and Isabela) is caused by the presence of dehydrated residue from melting.

3. The Galápagos mantle plume

The presence of thick oceanic crust, a slow-seismic velocity-zone that extends through the upper mantle, thinning of the transition zone, and basalts with high $^{3}He/^{4}He$ ratios (up to 30.3 times atmospheric R_a) and primordial neon isotopic ratios suggest that melt generation beneath Galápagos is associated with an upwelling mantle plume (Feighner and Richards, 1994; Graham et al., 1993; Hooft et al., 2003; Kurz and Geist, 1999; Kurz et al., 2009; Villagomez et al., 2007). A region with an anomalously thin mantle transition zone, with a 100 km radius, has been located 40 km southwest of Fernandina (Fig. 1) and is believed to represent the present-day plume axis (Hooft et al., 2003).

Historic volcanism has occurred on at least seven emergent Galápagos volcanoes and extends over an area of >40,000 km^2. The most active volcanism occurs in the west of the archipelago, close to the geophysically determined plume axis. Historic eruptions on Fernandina and Isabela together with those on Santiago and Marchena (Simkin and Siebert, 1994) define a 150 km wide zone of active volcanism that extends north and east from the axis of plume upwelling towards the adjacent Galápagos Spreading Centre (GSC; Fig. 1). The influence of the plume on the GSC is evident from the presence of incompatible-trace-element and isotopically 'enriched' basalts together with thickened crust and elevated topography in a 1000 km wide zone centered at 91°W along the ridge (Schilling et al., 1982). Some have proposed that the distribution of active volcanism is related to the horizontal deflection of the Galápagos plume head towards the GSC, and volcanism is more widespread than usual owing to the young, thin, and extended lithosphere in the region (Harpp and White, 2001; Richards and Griffiths, 1989; White et al., 1993). The Galápagos plume is believed to be relatively 'weak', having a low buoyancy flux (1 to 2.5 Mgs^{-1}) that is similar to the present-day Iceland plume (1.4 Mgs^{-1}) (Ribe, 1996; Sleep, 1990).

Villagomez et al. (2007) noted that average seismic velocities are lowest beneath the southwest of the archipelago and, at depths greater than 100 km, lower than those observed beneath regions of comparable age in the Pacific. Between 40 and 120 km depth Galápagos seismic velocities are similar to those in the mantle under Iceland but at greater depths are higher than those observed beneath Hawaii. Villagomez et al. (2007) inferred that the convecting mantle beneath Galápagos is 30 °C to 150 °C warmer than ambient mantle (*i.e.* 1345 °C to 1465 °C for ambient $T_P = 1315$ °C), and the range of V_S can be explained by lateral temperature variations of ~50 °C. The Galápagos T_P estimates calculated from seismic data are similar to those derived from geophysical and petrological investigations (Asimow and Langmuir, 2003; Courtier et al., 2007; Herzberg and Asimow, 2008; Ito et al., 1997).

4. Spatial variations in Galápagos basalt geochemistry

Previous studies have shown that basalts erupted from western and northern Galápagos volcanoes are remarkably uniform in terms of their incompatible-trace-element and isotopic ratios (Table 1). In contrast, volcanoes in the eastern and southern part of the archipelago have experienced relatively long periods of volcanism (several million years) and are built of interspersed 'depleted' (MORB-like) and 'enriched' (alkaline) rocks. Indeed on Santiago, in the centre of the archipelago, both isotopically 'depleted' and 'enriched' basalts have erupted from different monogenetic vents in the past 300 years.

Incompatible-trace-element and Sr-, Nd-, Pb-, and Hf- isotopic ratios of Galápagos basalts define a broad east-facing 'horseshoe', which consists of a rim of basalts with 'enriched' isotope- and trace-element signatures surrounding a central core of more 'depleted' basalts, *e.g.* Blichert-Toft and White (2001), Geist et al. (1988), Harpp and White (2001), Kurz and Geist (1999), White et al. (1993). Harpp and White (2001) showed that the regional isotopic variations are due to the following 4 geographically restricted mantle reservoirs (Fig. 2):

(i) The southern HIMU-like enriched plume component (known as FLO) which is prevalent on Floreana, nearby seamounts, and to a lesser extent on Española and southern Isabela (Fig. 1).
(ii) A "C"-like central plume component, which is proportionally most significant in magmas erupted at large shield volcanoes on central and northern Isabela (*e.g.* Volcans Darwin and Ecuador) and Fernandina in western Galápagos.