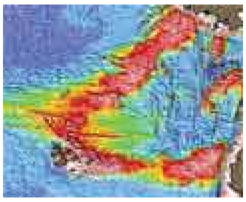

Crustal seismology helps constrain the nature of mantle melting anomalies: The Galápagos Volcanic Province

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Abstract

In this paper we advocate the combination of crustal seismology and gravity with petrology as a promising approach to help constrain the nature of mantle melting anomalies. We compare seismic velocity and density models of the crust and uppermost mantle along five transects crossing the Cocos, Carnegie, and Malpelo ridges in the Galápagos Volcanic Province (GVP). A remarkable, systematic observation in the velocity profiles is an overall anti-correlation between lower-crustal velocity and crustal thickness. Velocity-derived density models account for the gravity and depth anomalies assuming uniform mantle densities, indicating that the ridges are isostatically compensated at the base of the crust. A 2D steady-state mantle melting model is applied to illustrate that it is difficult to account for the seismic structure of the ridges if it is assumed that the main source of the Galápagos hotspot is a thermal anomaly, even if vigorous mantle upwelling coupled with deep, damp melting is included in the model. It is easier to account for the observations if a major element heterogeneity, is also considered. We thus suggest that the primary source of the Galápagos hotspot may be a compositional heterogeneity, possibly a mixture of depleted mantle and recycled oceanic crust. Such a mantle source explains well the isotope and trace element patterns showed by GVP basalts.

This webpage is a summary of the work described in Sallarès et al. (2005).

1. Introduction

The origin of large igneous provinces is usually explained by hot mantle plumes rising from the deep mantle, whose surface imprint is referred to as a "hotspot" (*Morgan*, 1971). The thermal plume model asserts that a hot, rising plume enhances mantle melting, and that the excess melting is mostly emplaced as igneous crust (*White & McKenzie*, 1989). The primary support for this hypothesis is the thick crust of igneous provinces when compared with normal oceanic crust. Additional arguments supporting the plume model include the composition of hotspot basalts, which is akin with that expected for melting of hotter-than-normal mantle (*e.g., White et al.*, 1992), the high-velocity crustal roots frequently found beneath oceanic plateaus, volcanic margins (*e.g., Kelemen & Holbrook,* 1995), and low-velocity anomalies extending from the surface to the lower mantle shown in global tomography models (*e.g., Montelli et al.*, 2004).

Despite the wide acceptance of the thermal plume model, several alternatives have been proposed. The "small-scale convection" model postulates that systems cooled from above feature lateral temperature contrasts which result in small-scale convection up to an order of magnitude faster than plate motions (Korenaga & Jordan, 2002). It has been also demonstrated that rifting may induce dynamic convection within the mantle as well (Boutillier & Keen, 1999). Mantle plumes may also include a significant proportion of lower melting components, such as eclogite derived from recycled oceanic crust (*e.g., Campbell*, 1998). The importance of major-element source heterogeneity in accounting for the excess melting has been highlighted for a number of hotspots (*e.g., Hauri*, 1996). Moreover, recent seismic experiments show that high-velocity crustal roots are absent in several cases (*e.g.,* Korenaga et al., 2000), and no local tomography studies yet performed in Iceland show compelling evidence for a velocity anomaly extending deeper than the mantle transition zone (*e.g.,* Foulger et al., 2001).

The GVP constitutes a well-studied example of an igneous province generated by the interaction between the Galápagos hotspot (GHS) and the Cocos-Nazca Spreading Center (CNSC). Different geophysical studies based on gravity analysis, seismic data, and numerical modelling suggest that the GHS is a thermal anomaly (*e.g.,* Ito et al., 1997; Canales et al., 2002), and receiver-function analysis claims that the associated mantle plume extends deeper than the mantle transition zone (Hooft et al., 2003). Available global tomography models do not show, however, any Galápagos-linked anomaly going deeper than the base of the upper mantle (*e.g.,* Montelli et al., 2004). In this paper, We first show seismic tomography models along two profiles acquired in the GVP (Figure 1). Velocity-derived density models are subsequently constructed to determine the mantle density structure that best fits gravity and topography data. We finally develop a 2D steady-state mantle melting model that has been used to infer the nature of the GHS based on the velocity models.

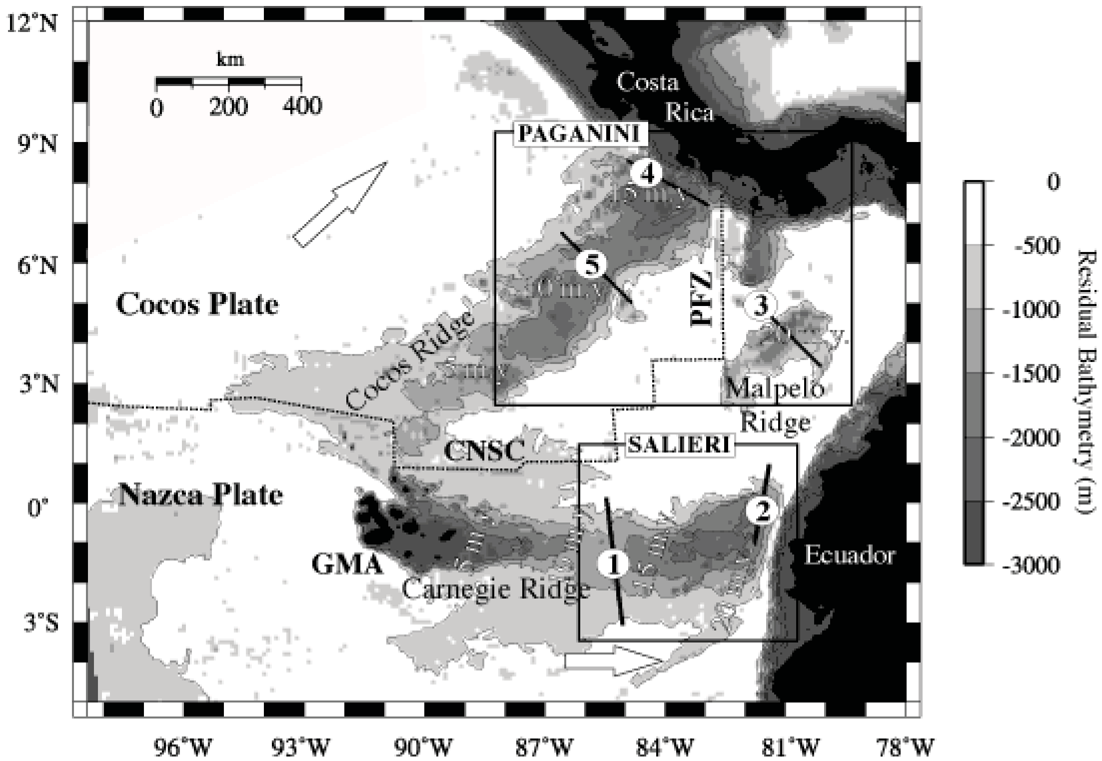

Figure 1. Location map of the study zone showing the residual bathymetry derived from seafloor age. Numbers show crustal ages of the ocean floor at 5 Ma intervals. Large arrows indicate plate motions. Black lines show locations of the wide-angle seismic profiles (P1: W Carnegie, P2: E Carnegie, P3: Malpelo, P4: N Cocos, P5: S Cocos). Boxes outline the seismic experiments PAGANINI-1999 and SALIERI-2001. CNSC: Cocos-Nazca Spreading Centre, GHS: Galápagos hotspot, PFZ: Panama Fracture Zone.

2. Seismic tomography

The seismic data set used in this study comprises two wide-angle profiles crossing the Carnegie Ridge acquired during the SALIERI-2001 experiment (*Flueh et al.*, 2001), and three other transects crossing Cocos and Malpelo, acquired in the PAGANINI-1999 survey (Figure 1). All lines were covered by densely spaced OBS/H. Two-dimensional (2D) velocity models were estimated using the joint refraction and reflection traveltime inversion method of *Korenaga et al.* (2000). The uncertainties in the model parameters were estimated by performing a Monte Carlo-type analysis described by *Sallarès et al.* (2005).

The velocity structure obtained is very similar along all the profiles (*Sallarès et al.*, 2003, 2005). The velocity of Oceanic Layer 2 shows a prominent vertical gradient, but velocity is much more uniform in Layer 3. This layer accommodates most of the crustal thickening. Surprisingly, the lowest Layer 3 velocities are systematically found where the crust is thickest. Maximum crustal thickness is ~13 km along profile 1, ~19 km along profile 2 (Figure 2), and ~16.5 km and ~19 km respectively along their conjugate profiles. Crustal thickness variations reveal that the magmatic rate of the GHS on both sides of the CNSC changed with time, and allow temporal variations in the relative distance between the GHS and the CNSC to be calculated (*Sallarès & Charvis*, 2003). The velocity uncertainties estimated from the Monte Carlo analysis are lower than 0.1 km/s in most parts of the models, and the depth uncertainties are generally lower than 0.3-0.4 km. The accuracy of the results was checked by repeating the inversion twice using only half the data in each case. Both solutions are very similar, confirming the consistency of the data set. The velocity anomalies are thus real features and inversion artefacts, if present, are minor.

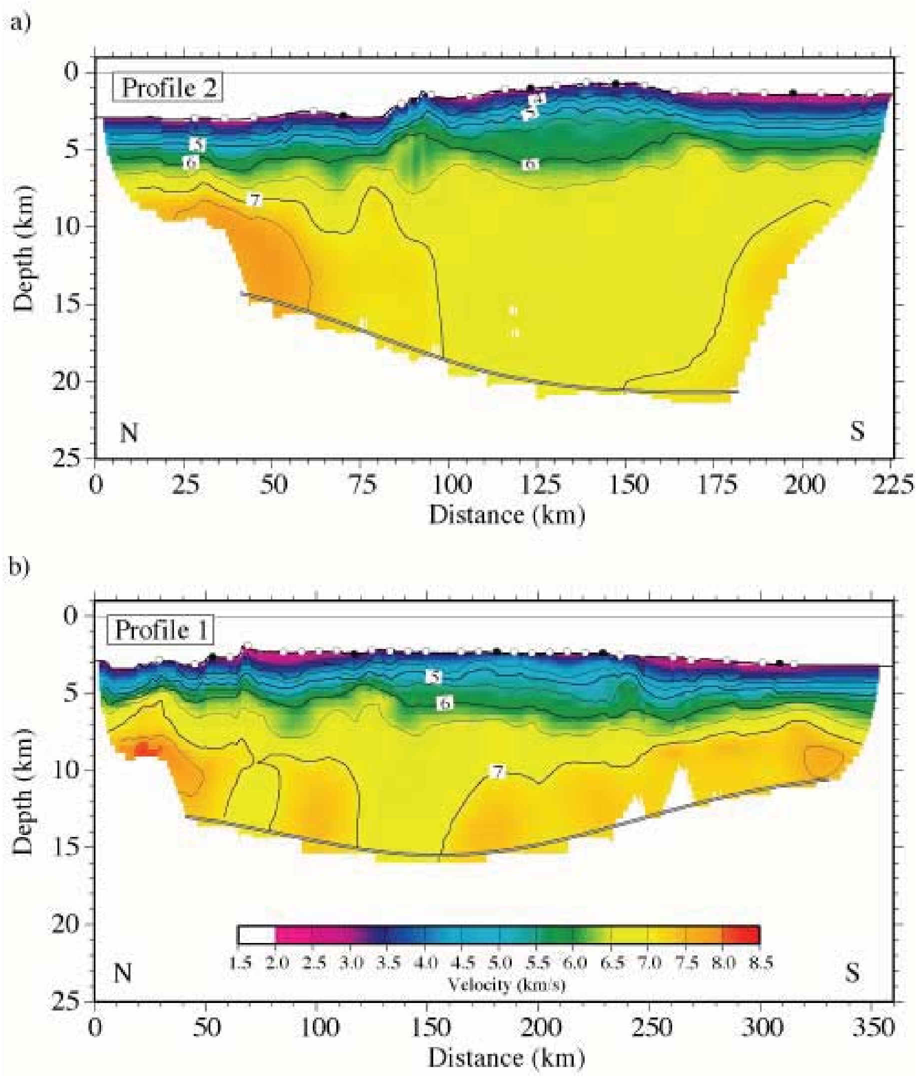

Figure 2. Seismic tomography results. Final averaged velocity models from 100 Monte Carlo ensembles. Open circles indicate OBS/OBH locations along profiles. (a) P2, and (b) P1, in Figure 1.

3. Gravity and compensation of topography

Gravity analyses were performed along profiles 1, 3 and 5 (Figure 1) to calculate the velocity-derived crustal density structure and the range of mantle density anomalies required to explain the gravity and topography data. Gravity profiles were constructed using available marine gravity data based on satellite altimetry (*Sandwell & Smith*, 1997). A method based on the spectral method of *Parker* (1972) was employed to calculate the gravity anomaly produced by a heterogeneous 2D density model. Velocity was converted to density using different empirical conversion laws for sediments and oceanic crust (*Carlson & Herrick*, 1990). The velocity-derived density models explain well the observed gravity anomaly along all the profiles, indicating that the velocity model is compatible with the gravity data without requiring mantle density anomalies.

A bathymetric data analysis was performed subsequently. Topography compensation studies assume isostatic equilibrium either as a result of crustal thickness variations, mantle density variations, or, more likely, a combination of both. Lateral crustal density variations contribute significantly to the gravity anomaly, so these were included in the calculations (*Sallarès et al.*, 2005). The results show that the contribution of lateral crustal density variations to the depth anomaly is also significant. Predicted mantle density anomalies for the variable crustal density models along the transects are negligible for a wide range of compensation depths, indicating that swell anomalies are isostatically compensated at the base of the crust (Figure 3). Mantle density anomalies, if present, are beneath the uncertainty threshold of the method.

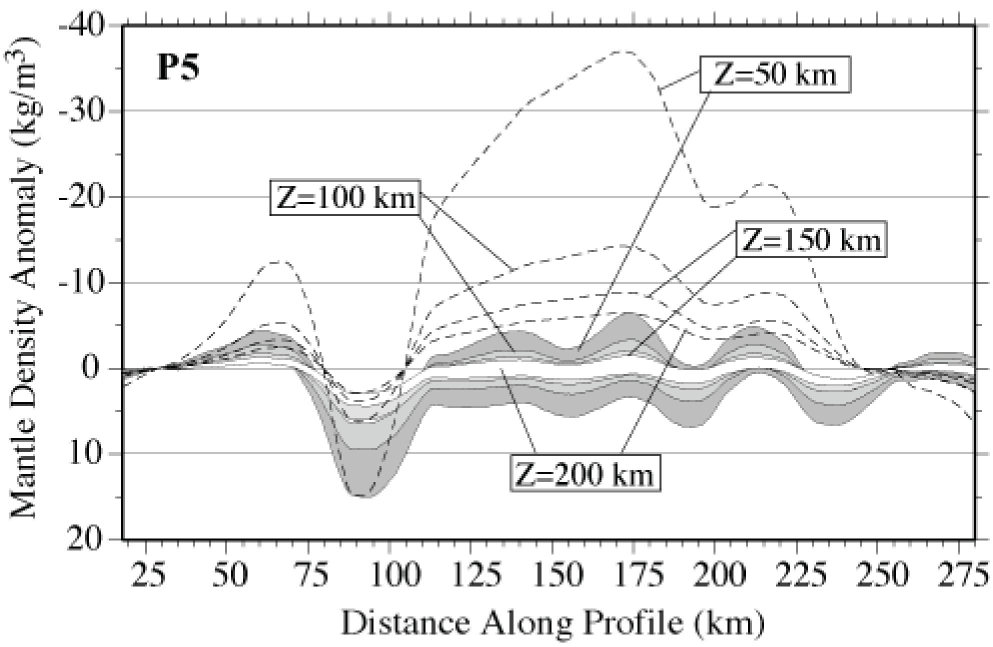

Figure 3. Mantle density variations along transect P5, inferred from the isostasy model, for different compensation depths (Z=50, 100, 150, 200 km). Shaded stripes show mantle density uncertainties for each compensation depth. Dashed lines correspond to uniform crustal density models (2800 kg/m^3) with the same Moho geometry.

4. Mantle melting model

McKenzie & Bickle (1988) demonstrated that the 6-7 km thick, MORB-like composition oceanic crust that normally is produced at spreading centers is the result of decompression melting of a ~1300°C potential temperature dry pyrolite mantle source. Higher mantle temperatures or compositional anomalies may cause buoyant upwelling of the mantle, enhancing melting and producing, eventually, a thicker crust. It has also been suggested that deep, damp melting of a volatile-bearing mantle may produce a significant part of the total volume of melt, even if the melting rate is an order of magnitude lower than that of shallow, dry melting (*Braun et al.*, 2000), if it is coupled with vigorous upwelling at the base of the melting zone (*e.g.*, *Maclennan et al.*, 2001).

A 2D steady-state mantle melting model that includs the effect of mantle temperature, deep damp melting, active upwelling beneath the dry solidus, and mantle source composition, was developed in order to quantify the relative importance of the melting parameters to the seismic structure of the resultant igneous crust. The model is based on the 1D model of *Korenaga et al.* (2002), in which a connection between mantle melting parameters and resultant crustal structure is established on the basis of an empirical relationship between crustal velocity and mean pressure and degree of melting. A description of the method and the different parameters can be found in *Sallarès et al.* (2005). Several sample calculations were performed that consider different values for the parameters involved (Figure 4). The different panels of Figure 4 correspond to so-called H-Vp diagrams. These display the predicted velocity obtained using the multilinear regression method of *Korenaga et al.* (2002) and the mean depth and fraction of melting derived from our model, versus crustal thickness, as a function of mantle potential temperature and upwelling ratio. Crustal thickness and lower crustal velocity values obtained along the profiles are superimposed. The main conclusion is that the results cannot be explained by deep damp melting coupled with active upwelling only. Low mantle potential temperatures are always required to account for the observed H/Vp anti-correlation, which is both counter-intuitive and difficult to justify. It is thus necessary to consider alternatives to the homogeneous, hot mantle model in order to explain this observation.

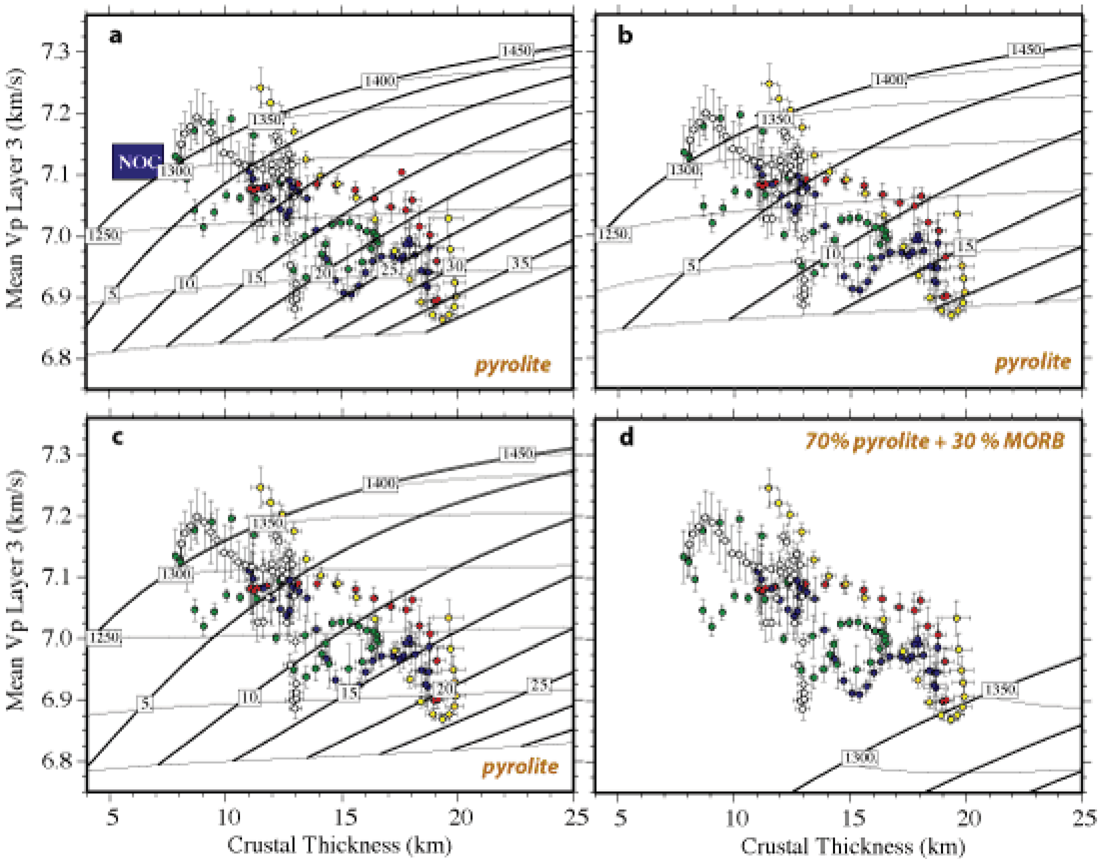

Figure 4. H-Vp diagrams corresponding to different melting parameters. Crustal thickness is plotted versus mean Layer 3 velocity. Values are taken from the velocity models along the five profiles: P1 (blue), P2 (white), P3 (red), P4 (yellow), P5 (green). Thin lines indicate mantle potential temperatures, and thick lines indicate upwelling ratio. Melting parameters: (a) Γd=15 %/GPa, Γw=1 %/GPa, α=0.25, ΔZ=50 km, pyrolite, (b) Γd=15 %/GPa, Γw=2 %/GPa, α=1, ΔZ=50 km, pyrolite, (c) Γd=20 %/GPa, Γw=1 %/GPa, α=0.25, ΔZ=75 km, pyrolite, (d) same as (c) but with a source composed by 30% MORB and 70% depleted mantle. NOC: Normal CNSC-oceanic crust.

An alternative model to be examined is the possible presence of compositional anomalies in the mantle source, as indicated by isotopic and trace element geochemistry of basalt samples from the Galápagos platform (*e.g., White et al.*, 1993), the axis of the CNSC (*e.g., Schilling et al.*, 2003), and the aseismic ridges (*e.g,. Hoernle et al.*, 2000). However, too few melting experiments with source compositions other than pyrolite exist to develop a quantitative model including the effect of source heterogeneities. Following Korenaga et al. (2002), a test was performed that considered a hypothetical source composed of 70% pyrolite and 30% MORB, combined with higher melt productivity and a 50°C lower temperature in the solidus to reflect Fe enrichment (Figure 4d). The results indicate that the seismic structure of the thickest crustal segments are more easily explained by passive to moderately active upwelling of normal temperature but fertile mantle rather than by a hot (or wet) homogenous pyrolitic mantle. Melting of recycled subducted oceanic crust could explain the observed isotope and trace element patterns, as well as the crustal thickening and the anti-correlation between crustal thickness and seismic velocity, without need for anomalously high mantle temperatures. A contribution of extra melting from a deep, hydrous root is probably needed (Cushman et al., 2004). Melting experiments to study mantle source compositions different from dry pyrolite are required, however, to quantify the relative significance of "fertile" versus "damp" melting in the source of the GVP.

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