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Small-scale sublithospheric convection reconciles geochemistry and geochronology of 'Superplume' volcanism in the western and south Pacific

Maxim D. Ballmer [a,*], Garrett Ito [b], Jeroen van Hunen [c], Paul J. Tackley [a]

[a] Institute of Geophysics, ETH Zürich, Sonneggstrasse 5, 8092 Zürich, Switzerland
[b] School of Ocean and Earth Sciences and Technology, University of Hawaii, 1680 East-West Road, Honolulu, USA
[c] Department of Earth Sciences, Durham University, DH1 3LE, Durham, UK

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A B S T R A C T

Cretaceous volcanism in the West Pacific Seamount Province (WPSP), and Tertiary volcanism along the Cook-Australs in the South Pacific are associated with the same broad thermochemical anomaly in the asthenosphere perhaps related to the Pacific 'Superplume.' Abundant volcanism has usually been attributed to secondary plumelets rising from the roof of the Superplume. The Cook-Australs display distinct geochemical trends that appear to geographically project, backward in time, to corresponding trends in the WPSP. However, the implied close proximity of source regions (i.e., ~1000 km) with very different geochemical fingerprints and their longevity over geological time (>100 Myrs) appear to be at odds with the secondary plumelet hypothesis, a mechanism with a typical timescale of ~30 Myrs. Moreover, ages sampled along the individual volcano chains of the Cook-Australs, and of the WPSP violate the predictions of the plumelet hypothesis in terms of linear age–distance relationships.

Our numerical models indicate that small-scale sublithospheric convection (SSC) as likely triggered by the thermochemical anomaly of the 'Superplume' instead reconciles complex age–distance relationships, because related volcanism occurs above elongated melting anomalies parallel to plate motion ('hot lines'). Furthermore, SSC-melting of a mantle source that consists of pyroxenite veins and enriched peridotite blobs in a matrix of depleted peridotite creates systematic geochemical trends over seafloor age during volcanism. These trends arise from variations in the amount of pyroxenite-derived lavas relative to peridotite-derived lavas along a 'hot line,' therefore stretching between the geochemical end-members HIMU and EMI. These predicted trends are consistent with observed trends in radiogenic isotopic composition from the Wakes, Marshalls, Gilberts (i.e., the individual volcano groups of the WPSP) and the Cook-Australs. For increasing mantle temperatures, volcanism is further predicted to occur at greater seafloor ages and with a more EMI-like signature, a result that can explain many of the observed systematics. Thus, SSC explains many of the geochemical observations with long-term temporal variations in mantle temperature, instead of persistent intermediate-scale (~1000 km) compositional heterogeneity.

1. Introduction

The origin of oceanic intraplate volcanism is still debated today. While classical plume theory successfully explains many observations at some long-lived volcano chains with a linear age–distance relationship (Morgan, 1972), it does not give an explanation for the spectrum of observations at many short-lived volcano chains (e.g., Courtillot et al., 2003). While these discrepancies have urged some authors to abandon plume theory altogether (Anderson, 2000; Foulger, 2007), others invoke a variety of mechanisms to account for the spectrum of intraplate volcanism. Short-lived chains were attributed to secondary plumelets that detach from the top of a major diffuse upwelling (i.e., a Superplume) (Davaille, 1999), or to various non-hotspot mechanisms (King and Ritsema, 2000; Koppers et al., 2003; King, 2007; Clouard and Gerbault, 2008a; Ballmer et al., 2009). Illuminating the geodynamical mechanisms and the related processes of partial melting is essential in order to understand the observed geochemical characteristics of ocean island basalts (OIBs), and ultimately the composition of the mantle source.

The South Pacific (SP) is an unusual location, where multiple active parallel volcano chains with a short lifetime (~30 Myrs) are concentrated. Geochemical arguments (Staudigel et al., 1991), constraints from seismic tomography (e.g., Ritzwoller and Lavely, 1995), and most importantly, a broad topographic swell (McNutt and Fisher, 1987) suggest that the region is underlain by a thermochemical anomaly, possibly the expression of a giant diffuse mantle upwelling — the SP Superplume (Larson, 1991).

The West Pacific Seamount Province (WPSP) includes the Wakes, Marshalls and Gilberts and is located on the topographical swell of the

* Corresponding author. Tel.: +41 44 632 0244; fax: +41 44 633 1065.
E-mail address: ballmer@tomo.ig.erdw.ethz.ch (M.D. Ballmer).

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Darwin Rise, a feature that has been interpreted as the Cretaceous analogue of the SP Superswell (McNutt and Fisher, 1987; Wolfe and McNutt, 1991; Ritzwoller and Lavely, 1995). In further support of this notion is the suggestion that volcanoes in the Cretaceous WPSP and the Tertiary Cook-Australs (a double chain located at the southern edge of the SP Superswell) share a common mantle source, both geographically (Larson, 1991; Konter et al., 2008) and geochemically (Davis et al., 1989; Staudigel et al., 1991; Janney and Castillo, 1999; Koppers et al., 2003). Thus, the WPSP and the Cook-Australs likely originated from similar geodynamic processes perhaps related to the Superplume.

The geochemical link between the WPSP and the Cook-Australs is an important clue to the originating processes. Geochemical compositions of Cook-Austral basalts project along distinct trends between the geochemical end-members EM1 and HIMU, as well as DMM and C/FOZO (Zindler and Hart, 1986; Staudigel et al., 1991; Hart et al., 1992; Hanan and Graham, 1996; Bonneville et al., 2006). Accordingly, these trends span almost the whole OIB array on an area that covers only ~0.14% of the Earth's surface. Distinct geochemical trends of the Cook-Australs appear to geographically project, backward in time, to corresponding trends in the WPSP (Konter et al., 2008). The implied spatial longevity of very distinct geochemical sources over geological time (>100 Myrs) has been ascribed to a strongly heterogeneous mantle domain within the Superplume, which rose from the lowermost mantle (e.g., subduction graveyard) (Konter et al., 2008). However, it appears to be unlikely that the close proximity (<1000 km) and the longevity (>100 Myrs) of the geochemical anomalies may be explained by a mechanism with a typical timescale of ~30 Myrs such as secondary plumelets.

Moreover, the predictions of the plumelet hypothesis appear to be very difficult to reconcile with volcano ages sampled. To explain all sample ages at the Cook-Australs, at least three (Bonneville et al., 2006) or likely even more plumelets (McNutt et al., 1997; Clouard and Bonneville, 2005; Clouard and Gerbault, 2008b) would have to be invoked. For each individual chain of the WPSP, recent $^{39}Ar/^{40}Ar$ dating reveals highly complex and irregular age–distance relationships (Koppers et al., 2003, 2007), while the plumelet hypothesis implies short but regular age progressions coinciding with plate motion.

Small-scale sublithospheric convection (SSC) is one, among several non-hotspot processes proposed to create intraplate oceanic volcanism (e.g., see discussion in Ballmer et al., 2009). SSC evolves from instabilities of the cold and dense thermal boundary layer at the bottom of the oceanic lithosphere. Once evolved, SSC tends to organize as 'Richter' rolls that align with plate motion (Richter and Parsons, 1975). SSC typically establishes itself beneath oceanic seafloor of age ~70 Myrs (Parsons and McKenzie, 1978; Fleitout and Yuen, 1984; Stein and Stein, 1992; Doin and Fleitout, 2000), but it may be triggered significantly earlier in the presence of unusually low ambient mantle viscosity or lateral density heterogeneity (Huang et al., 2003; Dumoulin et al., 2008). The SP Superplume provides both these triggers (Staudigel et al., 1991; Cadek and Fleitout, 2003) therefore potentially giving rise to SSC (Griffiths and Campbell, 1991; Keller and Tackley, 2009). Such a situation may spawn decompression melting within the upwelling limbs of SSC (Fig. 1) (Bonatti and Harrison, 1976; Buck and Parmentier, 1986; Ballmer et al., 2007, 2009). Ballmer et al. (2007, 2009) showed that SSC of a homogeneous peridotitic mantle can create volcanoes of heights comparable to those in the WPSP and Cook-Australs in regions with low asthenospheric viscosity. However, such a peridotitic source alone is unable to produce parental melts for ocean island basalts (Niu and O'Hara, 2003).

In order to further examine the SSC hypothesis for 'Superplume' volcanism, we build upon our prior work (Ballmer et al., 2007, 2009) by exploring melting of a lithologically heterogeneous (i.e., veined) mantle. We compare model predictions in terms of isotope compositions of magmas produced, and age–distance relationships of volcanism to observations from the Wakes, Marshalls, Gilberts, and Cook-Australs. Finally, we discuss the role of thermal and compositional heterogeneity in the mantle source.

2. Methods and model description

We perform 3D-thermochemical numerical experiments using an extended version of the finite element code CITCOM (Moresi and Gurnis, 1996; Zhong et al., 2000). We solve the equations of mass, momentum, and energy of an incompressible, infinite Prandtl-number fluid, and use the extended Boussinesq approximation in order to consider the effects of latent heat of melt (with the specific latent heat $L = 560$ kJ/kg), adiabatic heating (with the adiabatic gradient $\gamma = 0.38882$ K/km), and viscous dissipation (Christensen and Yuen, 1985). Details of the numerical method used, and any unreported parameters are equivalent to those in Ballmer et al. (2009).

Calculations are performed in a Cartesian box cooled from above and heated from below. We impose a velocity boundary condition of +65 km/Myr at the top side in order to simulate Pacific plate motion. To accommodate the resulting flow, we allow inflow at the front side, which is parallel to, but 1170–2080 km away from the mid-ocean ridge (MOR), and outflow at the back side. The box is 3400 km long, 400 km deep, and 520 km wide using 448x56x64 elements. We impose +10 km/Myr at the bottom boundary to simulate a small amount of motion relative to the lower mantle (which is conceptually at 660, and not at 400 km depth). We close the bottom to prevent artificially large vigor, and long wavelength SSC. The plate motion parallel sides are free-slip boundaries.

Following the mantle marble-cake hypothesis, we model melting of a veined mantle source consisting of multiple lithologies (Allègre et al., 1984; Phipps Morgan, 2001; Ito and Mahoney, 2005a,b; Sobolev et al., 2007). We consider a lithological assemblage that consists of veins of pyroxenite (PX) and blobs of geochemically enriched peridotite with high volatile content ('enriched component,' EC)

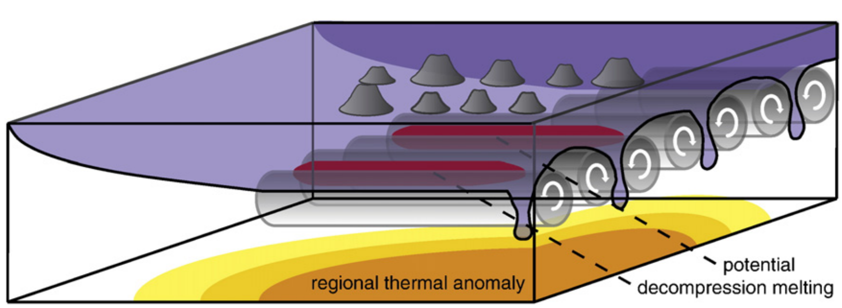

Fig. 1. Small-scale sublithospheric convection (SSC) spontaneously evolves at the bottom of mature oceanic lithosphere with a preferred geometry of rolls parallel to plate motion. SSC may be triggered earlier than elsewhere by influence of a regional thermal anomaly. Such a situation potentially yields decompression melting along the upwelling limbs of SSC, something that spawns 'hot line' volcanism.