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Speculations on the nature and cause of mantle heterogeneity☆

Don L. Anderson

Seismological Laboratory 252-21, Div. of Geological and Planetary Sci., California Institute of Technology, Pasadena, CA 91125, United States

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Abstract

Hotspots and hotspot tracks are on, or start on, preexisting lithospheric features such as fracture zones, transform faults, continental sutures, ridges and former plate boundaries. Volcanism is often associated with these features and with regions of lithospheric extension, thinning, and preexisting thin spots. The lithosphere clearly controls the location of volcanism. The nature of the volcanism and the presence of 'melting anomalies' or 'hotspots', however, reflect the intrinsic chemical and lithologic heterogeneity of the upper mantle. Melting anomalies—shallow regions of ridges, volcanic chains, flood basalts, radial dike swarms—and continental breakup are frequently attributed to the impingement of deep mantle thermal plumes on the base of the lithosphere. The heat required for volcanism in the plume hypothesis is from the core. Alternatively, mantle fertility and melting point, ponding and focusing, and edge effects, i.e., plate tectonic and near-surface phenomena, may control the volumes and rates of magmatism. The heat required is from the mantle, mainly from internal heating and conduction into recycled fragments. The magnitude of magmatism appears to reflect the fertility, not the absolute temperature, of the asthenosphere. I attribute the chemical heterogeneity of the upper mantle to subduction of young plates, aseismic ridges and seamount chains, and to delamination of the lower continental crust. These heterogeneities eventually warm up past the melting point of eclogite and become buoyant low-velocity diapirs that undergo further adiabatic decompression melting as they encounter thin or spreading regions of the lithosphere. The heat required for the melting of cold subducted and delaminated material is extracted from the essentially infinite heat reservoir of the mantle, not the core. Melting in the upper mantle does not requires the instability of a deep thermal boundary layer or high absolute temperatures. Melts from recycled oceanic crust, and seamounts—and possibly even plateaus—pond beneath the lithosphere, particularly beneath basins and suture zones, with locally thin, weak or young lithosphere. The characteristic scale lengths—150 to 600 km—of variations in bathymetry and magma chemistry, and the variable productivity of volcanic chains, may reflect compositional heterogeneity of the asthenosphere, not the scales of mantle convection or the spacing of hot plumes. High-frequency seismic waves, scattering, coda studies and deep reflection profiles are needed to detect the kind of chemical heterogeneity and small-scale layering predicted from the recycling hypothesis.

Keywords: Eclogite; Mantle; Plumes; Ocean islands; Heterogeneity

1. Mantle homogeneity; the old paradigm

The large scale structure of mantle convection is controlled by surface conditions—including continents, effects of pressure on material properties, recycling and the mode of heating (Anderson, 2001, 2002a,b; Tackley,

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E-mail address: dla@gps.caltech.edu.

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1998; Phillips and Bunge, 2005). Global tomography and the geoid characterize the large scale features. Higher frequency and higher resolution techniques are required to understand the smaller scale features (e.g., Fuchs et al., 2002; Thybo et al., 2003), and to integrate geophysics with tectonics and with mantle petrology and geochemistry.

Numerous papers have addressed the role of the lithosphere in localizing volcanism and creating volcanic chains (Jackson and Shaw, 1975; Jackson et al., 1975; Favela and Anderson, 2000; Natland and Winterer, 2004). The lithosphere is heteorogeneous in age, thickness and stress and this plays a large role in the localization of magmatism. On the other hand, the upper mantle is generally regarded as being extremely homogeneous (e.g., Hofmann, 1997; Helffrich and Wood, 2001). The intrinsic chemical heterogeneity of the shallow mantle, however, is now being recognized (Fitton, 1980; Niu et al., 2002; Korenaga and Kelemen, 2000; Lassiter and Hauri, 1998; Janney et al., 2000). This heterogeneity is recognized as contributing to the isotopic diversity of magmas. I take the next step and attribute melting anomalies themselves to lithologic heterogeneity and variations in fertility. The volume of basalt is related more to lithology of the shallow mantle than to absolute temperature. Thus, both the locations of volcanism and the volume of volcanism are attributed to shallow-lithospheric and asthenospheric-processes, processes that are basically athermal and that are intrinsic to plate tectonics. This is such a dramatic shift from current orthodoxy that I include Speculations in the title.

Much of mantle geochemistry is based on the assumption of chemical and mineralogical homogeneity of the shallow mantle, with so-called Normal Midocean Ridge Basalt (N-MORB) representative of the homogeneity and depletion of the entire upper mantle source ("the convecting upper mantle") (DePaolo and Wasserburg, 1976; White and Hofmann, 1982). The entire upper mantle is perceived to be a homogeneous depleted olivine-rich lithology approximating pyrolite (pyroxene–olivine-rich rock) in composition. All basalts are formed by melting of such a lithology. Venerable concepts such as isolated reservoirs, plumes, temperature–crustal thickness correlations and others are products of these perceived constraints. Absolute temperature, not lithologic diversity, is the controlling parameter in current models of geochemistry and geodynamics, and in the visual or intuitive interpretations of seismic images (e.g., Albarede and van der Hilst, 1999).

The perception that the mantle is lithologically homogeneous is based on two assumptions: 1) the bulk of the upper mantle is roughly isothermal (it has constant potential temperature) and 2) midocean ridge basalts are so uniform in composition ("the convecting mantle" is geochemical jargon for what is viewed as "the homogeneous well-stirred upper mantle") that departures from the basic average composition of basalts along spreading ridges and within plates must come from somewhere else. The only way thought of to do this is for narrow jets of hot, isotopically distinct, mantle to arrive from great depths and impinge on the plates.

The fact that bathymetry follows the square root of age relation is an argument that the cooling plate is the only source of density variation in the upper mantle. The scatter of ocean depth and heat flow—and many other parameters—as a function of age, however, indicates that something else is going on. Plume influence is the usual, but non-unique, explanation for this scatter. Lithologic (major elements) and isotopic homogeneity of the upper mantle are two of the linchpins of the plume hypothesis and of current geochemical reservoir models. Another is that seismic velocities, anomalous crustal thicknesses, ocean depths and eruption rates are proxies for mantle potential temperatures. I suggest in this paper that the asthenosphere is variable in melting temperature and fertility (ability to produce magma) and this is due, in part, to recycling of delaminated continental crust and lithosphere and anomalous oceanic crust. In addition, seismic velocities are a function of lithology, phase changes and melting and are not a proxy for temperature alone. Some lithologies melt at low temperature and have low seismic velocities without being hotter than adjacent mantle. Dense eclogite, for example, can have appreciably lower shear velocities than peridotite at the same temperature.

2. Background

The apparent isotopic homogeneity of MORB has strongly influenced thinking about the presumed homogeneity of the upper mantle and the interpretation of 'anomalous' sections of midocean ridges (e.g., Goslin et al., 1998). The homogeneity of MORB does not, however, imply a homogeneous well-stirred upper mantle (e.g., Meibom and Anderson, 2003). The need to subdivide MORB [N-MORB, T-MORB, E-MORB, and P-MORB, for example] and the numerous 'plume-influenced' or 'anomalous' sections of ridges, are indications that the basalts erupting along the global spreading ridge system are not completely uniform. It is common practice to avoid 'anomalous' sections of the ridge when compiling MORB properties, and to attribute anomalies to 'plume-ridge interactions'. In