Stretching chemical heterogeneities by melt migration in an upwelling mantle: An analysis based on time-dependent batch and fractional melting models

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ABSTRACT

The source region of basalt in the upper mantle is heterogeneous and may consist of depleted background mantle and blobs of enriched mantle. The size, shape, and distribution of the enriched blobs in the upper mantle are unknown but may play an important role in controlling variations in isotope ratios and trace element abundances in basalts and residual peridotites. During decompression melting, the mass flux of interstitial melt increases while the mass flux of residual solid decreases upward from the solidus, resulting in an acceleration of the effective transport velocity for an incompatible trace element in the residue. Consequently, a blob of chemical heterogeneity is stretched during its transit through the melting column. Here we quantify the melt migration induced size change by allowing trace element abundances and isotope ratios in the mantle source to vary as a function of time and space. We use simple analytical solutions for the time-dependent batch melting and fractional melting models to illustrate how a trace element or an isotope ratio varies spatially and temporally in an upwelling and chemically heterogeneous melting column. We show that an enriched blob as marked by isotope or incompatible trace element anomaly is variably stretched along the direction of melt flow during its transit through the melting column. The amount of stretching depends on the extent of melting, style of melt extraction (batch vs. fractional), porosity of the melting column, and partition coefficient, and can be quantified by a dimensionless parameter called the stretching factor. For radiogenic isotopes U, Th, Pb, Sr, Nd, and Hf, a factor of $2 \sim 8$ stretching is expected for the residue and a factor of at least 30 is found for the channel melt. For near fractional melting beneath mid-ocean ridge, an enriched Nd isotope signal takes approximately 10 times more time to transit through the low-porosity matrix than through the high-porosity channel. Hence chemical heterogeneities observed in residual peridotites and extracted melts are decoupled both spatially and temporally, which has important implications for the interpretation of isotope and trace element characteristics of the basalts and residual peridotites.

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1. Introduction

Models for trace element fractionation during partial melting and melt migration are essential to the interpretation of igneous rocks. Simple melting models that have been widely used in the geochemical literature include batch melting, fractional melting, and dynamic melting models (Albarède, 1995; Shaw, 2006; Zou, 2007). These melting models were derived under the assumption of local chemical equilibrium between the partial melt and residual solid. The main difference among the three models is how much melt produced during melting remains in residual solid (also

referred to as matrix hereafter). In the context of concurrent melting and melt extraction in a one dimensional (1D) steady-state upwelling column, batch melting corresponds to an endmember case in which all the melt generated in the solid matrix percolates upward through the upwelling melting column (Ribe, 1985a; Spiegelman and Elliott, 1993; Asimow and Stolper, 1999). Perfect fractional melting corresponds to an endmember case in which melt generated at any point in the upwelling column is completely and instantaneously removed from the solid matrix. In a physically more realistic setting, a fraction of melt is left behind in the melting column. In the standard treatment of dynamic or continuous melting, one assumes that a constant and small fraction of melt is retained in the residual solid (Langmuir et al., 1977; McKenzie, 1984; Albarède, 1995; Zou, 1998; Shaw, 2000). For melting in an upwelling column, the steady-state version of the dy-

namic melting model has the same algebraic expression for the melt composition as the standard dynamic melting model if one replaces the melt fraction in the latter by the ratio between the mass flux of the melt and the mass flux of the solid in the melting column (Liang, 2008). The melt-to-solid mass flux ratio is constant and uniform in the steady-state dynamic melting model. During concurrent melting and melt migration in a 1D steady-state upwelling column, porosity and melt velocity, hence the mass flux of the melt, increase as a function of the degree of melting or the height measured from the base of the melting column, whereas the mass flux of the solid decreases upward (Ribe, 1985a; Spiegelman and Elliott, 1993; Asimow and Stolper, 1999; Hewitt and Fowler, 2008). Iwamori (1993b, 1994) unified the steady-state batch and fractional melting models by allowing part of the melt generated in the partially molten residual mantle to segregate into its neighboring channels. The style of melting is encapsulated by a dimensionless melt suction rate ($\mathbb{R}$), defined as the rate of melt extracted from the matrix to the channel ($\dot{S}$) relative to the rate of matrix melting (Γ_m), viz.,

$$\mathbb{R} = \frac{\dot{S}}{\Gamma_m(1 - \psi)}, \tag{1}$$

where ψ is the volume fraction of melt conduits or high-porosity channels in the upwelling column (Iwamori, 1994; Ozawa, 2001; Liang and Peng, 2010). For a constant melt suction rate, concentration of a trace element in the matrix melt in the melting column (C_f^m) is given by the simple expression (Iwamori, 1994)

$$C_f^m = \frac{C_s^0}{k_m}\left[\frac{k_m + (1 - k_m - \mathbb{R})F}{k_m}\right]^{\frac{k_m - 1}{1 - k_m - \mathbb{R}}}, \tag{2a}$$

where C_s^0 is the solid concentration at the onset of melting; k_m is the bulk solid–melt partition coefficient for the trace element of interest in the matrix. The degree of melting experienced by the solid matrix, F, increases upward along the melting column. For constant melting rate, we have

$$F = \frac{\Gamma_m z}{\rho_s V_s^0}, \tag{2b}$$

where z is the vertical coordinate with origin at the bottom of the melting column and V_s^0 is the solid upwelling rate at the onset of melting ($z = 0$). Eq. (2a) recovers the batch melting model and the perfect fractional melting model when $\mathbb{R} = 0$ and $\mathbb{R} = 1$, respectively. Ozawa (2001), Liang and Parmentier (2010), and Liang and Peng (2010) further generalized Eq. (2a) by including additional sources and sinks and by considering spatially variable melt suction rate. Applications of Eq. (2a) and its more generalized versions to REE variations in clinopyroxenes in abyssal peridotites demonstrate that $\mathbb{R}$ is typically greater than 0.8 (Iwamori, 1994; Lundstrom, 2000; Ozawa, 2001; Liang and Peng, 2010), i.e., the style of melting is near fractional as originally suggested by Johnson et al. (1990).

A feature common to the aforementioned melting models is the constant and uniform source composition (C_s^0). These simple melting models are only suitable for studying melting a compositionally homogenous mantle. For example, C_s^0 could be the concentration of a trace element in the depleted MORB mantle (DMM) or an enriched mantle (EM), but not both. For melting a two-component mantle (e.g., DMM and EM), the standard geochemical treatment is mixing, either before (i.e., mixing the two sources) or after melting calculations (mixing melts derived from the two components). There is no spatial or temporal information in the mixing model. For melting an upwelling and spatially inhomogeneous mantle, such as the one shown in Fig. 1, one must
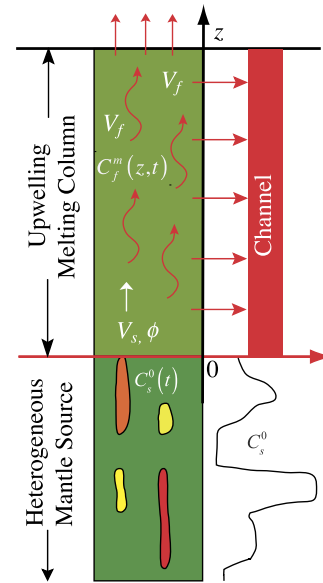

Fig. 1. Schematic diagram showing the model setup. The base of the melting column is at $z = 0$ where chemically heterogeneous sources are introduced. The background or ambient mantle source is shown in green, while the chemically heterogeneous mantle sources are marked by red, orange, and yellow blobs below the melting region ($z < 0$). Melt generated at $z \geq 0$ is allowed to segregate both vertically through the overlying melting column (matrix) and horizontally into neighboring channels. Modified after Liang (2008). (For interpretation of the colours in the figure, the reader is referred to the web version of this article.)

consider variable or time-dependent source compositions, as different sources feeding into the melting column at different times.

Richter and Daly (1989) were among the first to examine the consequences of melting a heterogeneous mantle column through time-dependent numerical simulations. DePaolo (1996) and Liang (2008) generalized the steady-state dynamic melting model by allowing trace element abundance in the source region to vary as a function of time and space. Results from these studies showed how initially correlated isotope and trace element ratios for two elements of different compatibility (e.g., Sr and Nd) are phase-shifted (in time) or decoupled (in space) as a result of chromatographic fractionation in the melting column. Under the condition of local chemical equilibrium, the effective transport velocity (V_{eff}) for a trace element in the upwelling melting column depends on solid–melt partition coefficient (k_m) and is given by the expression (McKenzie, 1984)

$$V_{eff} = \frac{\rho_f \phi_m V_f^m + \rho_s(1 - \phi_m)V_s^m k_m}{\rho_f \phi_m + \rho_s(1 - \phi_m)k_m}, \tag{3}$$

where ρ is density; V is velocity; and ϕ is the porosity or volume fraction of the melt in the matrix; superscript m refers to residual solid matrix; subscripts f and s stand for melt and solid, respectively. (Key symbols are listed in Table 1.) In the models of DePaolo (1996) and Liang (2008), as well as most geochemical studies of mantle chromatography (e.g., Navon and Stolper, 1987; Bodinier et al., 1990; Hauri, 1997), V_{eff} is constant and uniform in the melting column as spatial variations in porosity and melt and solid velocities are not considered. Hence the size of a chemical heterogeneity does not change during dynamic or continuous mantle melting.

In general, porosity, melt and solid velocities vary systematically during melting and melt migration in an upwelling mantle column (Ribe, 1985a; Spiegelman and Elliott, 1993; Jull et al., 2002; Hewitt and Fowler, 2008). Fig. 2a shows spatial variations of matrix porosity for several choices of the dimensionless melt suction rate