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Petrological geodynamic modeling of mid-ocean ridges

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ABSTRACT

Mid-ocean ridges are the primary location where the Earth's oceanic crust is formed. Beneath spreading ridges several processes such as dynamic melting and partial crystallization modify the petrology of the upper mantle and affect the Earth's global geochemical evolution. A unified picture of the temporal and spatial evolution of melt and residual mantle, as well as crustal production and melt dynamics requires a comprehensive model that takes into account simultaneously the complexity of the physical processes involved and the petrological variations of the ridge system. Here we present the first results of a 2-D numerical approach applied to a spreading ridge that fully couples a two-phase flow model for melt and solid mantle and a chemical thermodynamic model which provides a spatial and temporal description of the minerals and melt abundance and composition. The most significant features found by this study are the following. (1) Accumulation of melt is observed at the base of the lithosphere in the off-axis region (<~50 km from the ridge axis). (2) Crustal production (thickness) shows temporal variations which are mainly induced by periodic discharge of the melt accumulated underplate. (3) Magma waves develop between 10 and 30 km depth in proximity of the ridge axis. However to accurately resolve melt fluctuations, the grid size must be smaller than the compaction length for porous flow. Since in this study the compaction length decreases with depth, we have used a simplified 1-D melt model incorporating the two-phase flow dynamics and the thermodynamic formulation to show that the depth at which magma waves start to form increases by increasing the numerical resolution. Despite the limitation of the numerical grid resolution, we have observed that variations of the melt content do not appear to have significant influence on major elements composition of the residual solid and melt. (4) In the initial stage of the ridge evolution, a melting area detaches from the main melting region around the ridge axis. It is possible that this type of development may repeat over time beyond the duration of the simulation model of this study (~15 Ma). Sluggish coupling between the dynamics of the lithosphere and the asthenospheric mantle flow suggests that accretion of the lithosphere by conductive cooling away from the ridge center involves portions of the upper mantle that not necessarily passed through the spreading ridge. (5) During the development of the spreading ridge, the asthenosphere affected by the melting process deflects downwards, creating in this way a chemical heterogeneity in the large mantle circulation. (6) Composition of major elements in the residual solid after partial melting is in agreement with the chemical pattern observed in abyssal peridotites. However, in order to explain the large variation of major elements content found in abyssal peridotite, a consistent petrological and geodynamic model of the evolution of the mid-ocean ridge, requires that partial crystallization of small amount of melt refertilizes the depleted mantle. The petrological model presented in this study accounts for the complexity of polybaric dynamic melting and the continuous reactions between the residual solid and melt, but it is limited by the assumption of local thermodynamic equilibrium within a domain defined by the numerical grid size. The interpretation of the petrological results needs to be carefully evaluated to ensure that the time and space scale of the numerical model complies with the constraints provided by solid–melt reactive experiments and the spatial scale of the petrological structures observed in mid-ocean ridges. (7) Melt distribution and thermal structure are revealed by the seismic shear wave map computed from the numerical model. Certain observations, such as the extent of the melting region, overall agree quite well with the evidences from seismic studies from various ridge settings.

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1. Introduction

Current understanding of mantle processes under mid-ocean ridges relies on geophysical and geochemical observations. Interpretation of seismological data along with electrical conductivity and magnetotelluric data provide detailed information on the presence of a magma chamber, the internal structure of the crust and upper mantle and the extent of the melting region (e.g. Sinton and Detrick, 1992; Zhang et al., 1994; Cannat, 1996; Tucholke et al., 1997; Canales et al., 1998; Forsyth et al., 1998; Toomey et al., 1998; Webb and Forsyth, 1998; Evans et al., 1999; Canales et al., 2000; Dunn et al., 2000; Dunn and Forsyth, 2003; Dunn et al., 2005; Evans et al., 2005; Nedimović et al., 2005; Baba et al., 2006; Yang et al., 2007). Using gravity and bathymetric data, it was also inferred that crust thickness varies with time (Pariso et al., 1995; Tucholke et al., 1997; Heinson et al., 2000; Bonatti et al., 2003; Lizarralde et al., 2004). The observation was also supported by petrological evidence (Cipriani et al., 2009). The general interpretation is that the temporal variations are related to the velocity of the spreading plate and melt production or some mechanism associated with melt extraction. Extensive information stored in the PetDB database (www.petdb.org) is available on the composition of MORB melt and abyssal peridotites collected from the bottom of the ocean floor (e.g. Dick and Fisher, 1984; Michael and Bonatti, 1985; Shibata and Thompson, 1986; Klein and Langmuir, 1987; Dick, 1989; Johnson et al., 1990; Johnson and Dick, 1992; Niu and Batiza, 1993; Baker et al., 1995; Seyler and Bonatti, 1997; Michael and Cornell, 1998; Yang et al., 1998; Niu, 2004; Bodinier and Godard, 2005; Workman and Hart, 2005; Eason and Sinton, 2006; Rubin and Sinton, 2007; Dick et al., 2008; Niu and O'Hara, 2008). Petrological studies on ophiolites, which represent displaced portions of ancient ridge structures, reveal a complex stratigraphic sequence of ultramafic and mafic rocks, ranging from peridotites that experienced various degrees of depletion to dunites and gabbros (e.g. Jousselin et al., 1998; Godard et al., 2000; Braun and Keleman, 2002; Girardeau et al., 2002; Le Mée et al., 2004). Quantitative interpretations of these observations are based either on petrological models or on physical descriptions of magma transport. Empirical parameterization of melting, petrological considerations and thermodynamic formulation (Ghiorso and Sack, 1995; Ghiorso et al., 2002) are used to interpret the chemical evolution of MORB and other mafic and ultramafic formations associated to mid-ocean ridges and peridotite melting (Klein and Langmuir, 1987; McKenzie and Bickle, 1988; Johnson et al., 1990; Kinzler and Grove, 1992a; Kinzler and Grove, 1992b; Langmuir et al., 1992; Plank and Langmuir, 1992; Kinzler and Grove, 1993; Niu et al., 1997; Hirschmann et al., 1998; Asimow, 1999; Hirschmann et al., 1999a; Hirschmann et al., 1999b; Asimow and Stolper, 1999; Asimow et al., 2001; Asimow, 2002; Asimow and Langmuir, 2003; Herzberg, 2004). Essential information are provided by phase equilibrium experimental data on peridotite melting (e.g. Jaques and Green, 1980; Takahashi, 1986; Falloon et al., 1988; Hirose and Kushiro, 1993; Takahashi et al., 1993; Walter and Presnall, 1994; Walter, 1998; Gudfinnsson and Presnall, 2000; Presnall et al., 2002). The petrological models usually consider ideal cases, for instance assuming either fractional or batch melting. However it appears that the melt evolution under mid-ocean ridges is the result of more complex physico-chemical processes. Previous studies suggested that dunites are the mantle conduits of melt moving through the oceanic mantle which are developed through continuous reactions of dissolution and precipitation with the transient melt (Kelemen, 1990; Kelemen et al., 1997; Braun and Keleman, 2002). Experimental work and field observations revealed that melting of peridotite rocks is more likely associated with kinetic reactive processes and partial equilibration between melt and the mineral phases in the residual solid (Kelemen et al., 1990; Kelemen et al., 1992; Kinzler and Grove, 1992a; Wagner and Grove, 1998; Longhi, 2002; Morgan and Liang, 2005; Lambart et al., 2009; Van Den Bleeken et al., 2010). Recent petrological models are beginning to account for this more complex interaction between melt and the solid assemblage (Lissemberg and Dick, 2008; Lambart et al., 2009; Collier and Kelemen, 2010).

On the other hand, transport of melt in ridge settings has been extensively investigated by numerical methods using mainly a two phase flow formulation (e.g. Morgan, 1987; Spiegelman and McKenzie, 1987; Ribe, 1988; Scott and Stevenson, 1989; Sparks and Parmentier, 1991; Su and Buck, 1993; Braun et al., 2000; Ghods and Arkani-Hamed, 2000; Rabinowicz and Ceuleneer, 2005; Katz, 2008; Rabinowicz and Toplis, 2009). The melting process in these studies is usually based on simple models that not necessarily reproduce the petrological behavior of mantle rocks.

One of the most challenging questions related to mid-ocean ridges is the temporal and spatial relation between the dynamics of the oceanic mantle, crust and melt and the petrological evolution that leads to the formation of MORBs, depleted lherzolite, dunites and the emplacement of intrusive rocks such as gabbros. A combined petrological and geodynamic approach may be able to address such problem and, more in general, to provide a comprehensive description of the evolution of mid-ocean ridges. An early attempt in this direction (Cordery and Morgan, 1993) using the parameterization of Kinzler and Grove (1992a) for the melting process, simultaneously explored the chemical and dynamical evolution of melt in the steady state. The study was based on certain simplifications. It assumed that the assemblage opx-cpx-ol-sp was always present and that the composition of the system was controlled only by the dynamic evolution of the residual mantle. By linking the melt content to the residual solid composition, the model assumed fractional melting, but at the same time the melt formed locally was added to the existing melt in a way that resembled a incremental batch melting. Despite these assumptions, the model reproduced reasonably well the general trend of major elements in abyssal peridotites and MORB melts.

In alternative to a parameterized petrological model a thermodynamic formulation can be used instead. The main advantage of combining chemical thermodynamic principles with a dynamic model (Fullea et al., 2009; Tirone et al., 2009) is that petrological field observations can be related with the simulated results in a spatial and temporal setting and simultaneously the thermophysical properties that control the dynamics of the process are self-consistently incorporated in the procedure. For mid-ocean ridges the petrological observations should include MORBs, abyssal peridotites, depleted lherzolites and gabbros. A strong validation of the modelling work can be provided by a successful comparison of the petrological field evidences with the numerical computation together with a description of the thermal and dynamical evolution of the mid-ocean ridge.

2. Method

The governing equations of the transport model, a brief summary of the numerical procedure and the parameters used in this study are discussed in Sections 2.1 and 2.3. Abundance and composition of mantle minerals and melt are retrieved from a thermodynamic model that minimizes the Gibbs energy for a given local bulk composition pressure and temperature. Section 2.2 presents the thermodynamic database that has been developed for this work. The relevant thermodynamic parameters for melt and solid phases described in the simplified system Na_2O–CaO–MgO–FeO–Al_2O_3–SiO_2 are summarized in Table 1.

2.1. Summary of the petrological and geodynamical numerical approach

The numerical procedure used in this work consists of two parts. In the first part, a two-phase flow problem is solved by a set of