



An integrated kinematic and geochemical model to determine lithospheric extension and mantle temperature from syn-rift volcanic compositions

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ABSTRACT

We present an integrated kinematic and geochemical model that determines the composition of melts and their residual source rocks generated by decompression melting of the mantle during continental rifting. Our approach is to construct a unified numerical solution that merges an established lithospheric stretching model which determines the rate and depth at which melting occurs, with several compositional parameterisations of mantle melting to predict the composition of primary melts. We also incorporate a parameterisation for the rare earth elements. Using our approach, we are able to track the composition of the melt fractions and mantle residues as melting progresses. Our unified model shows that primary melt composition is sensitive to rift duration and mantle temperature, with rapid rifting and higher mantle temperatures producing larger melt fractions, at a greater mean pressure of melting, than slower/cooler rifting. Comparison of the model results with primitive basalts recovered from oceanic spreading ridges and rifted margins in the North Atlantic indicates that rift duration and synrift mantle temperature can be inferred independently from the appropriate geochemical data.

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1. Introduction

Melting of the mantle occurs at rifted continental margins in response to decompression as mantle rocks are brought toward the surface by lithospheric extension. This melting is controlled by several parameters including: the initial mantle temperature and source composition; the rate of continental extension; the final degree of lithospheric stretching (β_{\max}); and the initial lithospheric thickness (Bown and White, 1995). Several studies have attempted to estimate some of these parameters from estimates of rift-related magmatic volume (e.g., (White and McKenzie, 1989; Keen et al., 1994; Barton and White, 1997; Korenaga et al., 2000; Kelemen and Holbrook, 1995)). This volume is usually estimated from wide-angle seismic data. Igneous products, added to the lower crust (i.e., underplated or intruded complexes) are identified as regions of high seismic velocity (White and McKenzie, 1989) relative to normal continental crust (e.g., (Christensen and Mooney, 1995)). Extrusive volcanics (i.e., flood basalts) are identified as high amplitude seaward dipping reflector sequences on the continent-ocean transition. Examples of both intrusive and extrusive magmatic rocks are found on “volcanic”

margins such as the East Greenland margin (Korenaga et al., 2000); (Holbrook et al., 2001) the Faeroes margin and Hatton Bank (White et al., 2008). In contrast, such features are absent at “non-volcanic” rifted margins, and the presence at some of these margins of exhumed serpentinized mantle, well-documented by both geophysical studies and by direct sampling in the southern Iberia Abyssal Plain (e.g., (Dean et al., 1999); (Whitmarsh et al., 2001)), shows that melting can be suppressed by different syn-rift conditions.

In both types of rifted continental margin, there are difficulties in measuring accurately the volume of magmatic products using seismic reflection techniques alone. This is due to the high impedance contrast between magmatic intrusions and the surrounding lower continental crustal material, as well as limited spatial resolution, which makes it difficult to image small and discontinuous bodies of intruded material. However, it is possible to put constraints on the total intrusive volume from the average lower-crustal velocity if the end member velocities of the pre-existing crust and the intrusive rocks are known (White et al., 2008). More importantly, the volume of magmatic products is not constrained uniquely by the tectonic process alone; rather it is also subject to variations in mantle temperature, composition and strain rate.

An alternative approach to determining the rifting conditions (encompassing tectonic geometry, strain rate, mantle temperature and composition) is to use the composition of the volcanic products and, where available, upper mantle residues. (Williamson et al., 1995) showed, through modelling, how the rare earth element compositions of syn-rift volcanics on the Labrador margin of eastern Canada and the

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North Sea Rift are sensitive to mantle temperature, the degree of stretching and the duration of rifting. Using a similar principle, we have developed an integrated kinematic and geochemical model to determine the geochemical compositions of syn-rift melts and their residual mantle source rocks under a variety of rifting conditions. From this model, we demonstrate that the major, minor and rare-earth element geochemistry of the syn-rift melts and their mantle residues are sensitive independently to the extension history and mantle temperature. By inverting the approach, we compare the compositions of syn-rift volcanic products from around the North Atlantic margin with those predicted by our model and hence to infer the most probable rifting conditions prevalent during their genesis.

2. Rifted margin melting model

Various tectonic models for lithospheric stretching at continental margins have been proposed including pure shear models (McKenzie, 1978), simple shear models (Wernicke, 1985), and models involving depth-dependent stretching in different forms (e.g., (Davis and Kusznir, 2004)). The simplest models to account for the main features of most rifted margins assume pure shear at a uniform and finite rate. We employ one of these variants, the one-dimensional lithospheric stretching model of (Bown and White, 1995), which determines several key parameters during rifting: the temperature distribution throughout the lithosphere and asthenosphere and the quantity of melt generated at each increment of rifting and melting.

To determine the temperature distribution during rifting, we solve the advection-diffusion equation (Press et al., 1992):

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} - v \left(\frac{\partial T}{\partial z} + h \right),$$

where T is temperature, κ is the thermal diffusivity of the mantle, z is the vertical coordinate, v is the vertical velocity of the mantle, and h is the adiabatic temperature gradient. The temperature is corrected for the loss of latent heat of fusion using a method similar to that of (Watson and McKenzie, 1991), assuming a value for the entropy of fusion of $400 \text{ J kg}^{-1} \text{ K}^{-1}$, and invoking mantle melting under dry solidus conditions. The advection of heat with the melt and the latent heat released by solidification of the melt are ignored since this heat is released in the crust, not in the mantle source region, and its effect on melt generation is negligible (Bown and White, 1995). Our model is constructed from a series of depth regions, or cells, the thicknesses of which decrease as a function of rifting progress. Throughout rifting, we assume a constant strain rate, parameterised by the rift duration and the final degree of extension (β_{max}). We use a lithosphere with initial thickness of 125 km that is in thermal equilibrium with the asthenosphere at the start of rifting (Parsons and Sclater, 1977); (Pollack and Chapman, 1977). Asthenospheric temperature is assumed to be invariant during rifting. Other model parameters are as in Table 1 of (Bown and White, 1995).

The approach of (Bown and White, 1995) provides an ideal basis for modelling the melt product geochemistry: first, it allows us to test all the rifting parameters of interest while keeping the model simple; second, the melt chemistry parameterisations require calculations of

the degree of mantle depletion, temperature and pressure, all of which are tracked through time; third, the composition of the melt and the residue can be determined independently for each depth interval and at each time step in the model. To calculate compositions we assume fractional melting, where the liquid phase separates from the solid residue immediately after it has formed, followed by extraction and lithospheric pooling without further reaction, equilibration or refertilisation of the surrounding mantle matrix. While this assumption is probably a simplification, recent studies of mantle melting and melt extraction based on ^{238}U – ^{230}Th disequilibria find that incremental batch melting and rapid melt extraction is a good approximation of the actual melting process in sub-oceanic mantle (Condomines and Sigmarsson, 2000). Similarly U–Th–Pa–Ra studies of oceanic basalts (Stracke et al., 2006) find results that are consistent with rapid melt migration and extraction via high-porosity channels, with minimal melt-matrix interaction, as a general means of melt extraction from the upper mantle. In addition, the parameterisations we use here enable sequential integrated melting across phase boundaries in the mantle, accommodating melting in both the garnet and spinel lherzolite fields (e.g. Prinzhofer and Allègre, 1985)). These simplifications allow us to implement several melting schemes and parameterisations in our kinematic and thermal model for comparison.

3. Major element composition

Three different major element parameterisations have been implemented (Watson and McKenzie, 1991); (Niu and Batiza, 1991); (Niu, 1997). The first two use similar methods to determine melt composition from experimentally derived partition coefficients. In contrast, (Watson and McKenzie, 1991) use empirical fits to data, from laboratory melting experiments, to derive functions, thus describing effective bulk partition coefficients of each element and the source mantle mineralogy as melting proceeds.

3.1. Source composition

Before considering the compositions of the magmatic product predicted by our modelling, it is important to note that the composition of syn-rift melts are particularly dependent on the composition of the upper-mantle source. In our modelling, we use a selection of upper-mantle sources, chosen from a variety of studies of tholeiite sources, to both assess the effects of source composition on our results and to inform our choice of a source that yields melts that most closely resemble syn-rift volcanic products.

In their modelling, (Watson and McKenzie, 1991) use a 'Depleted Mantle' source (DM) made by removing 40% of the mass of a primitive mantle composition (McKenzie and O'Nions, 1991) by the production of average continental crust (after (Taylor and McLennan, 1985)). (Niu and Batiza, 1991) use three different sources: (i) 'Hawaiian Pyrolite' is a synthetic, enriched and fertile spinel lherzolite used in experimental studies of the genesis of Hawaiian tholeiite (after (Green, 1973)), that is consequently more fertile (i.e., cpx-rich) than 'DM'; (ii) 'Tinaquillo lherzolite' (Jaques and Green, 1980), a naturally occurring depleted or refractory spinel lherzolite that is generally more depleted in incompatible elements (except Al and Ca) than DM. 'Tinaquillo lherzolite' can be produced by invoking ~5% more melting of a primitive mantle composition than that which has been invoked to produce 'DM'; and (iii) MORB pyrolite 90, a synthetic MORB source calculated by adding 24% of a mixture comprising 83% N-MORB and 17% primitive olivine, to 76% harzburgite (Green et al., 1979). The (Niu, 1997) source is a naturally occurring depleted abyssal peridotite that is close to the MORB pyrolite 90 composition. Unlike the other sources mentioned here, it is a real rock, recovered from oceanic fracture zones and as such, it is attractive since it represents a relatively fertile upper-mantle composition.

Table 1
Major element source composition from (Condomines and Sigmarsson, 2000) and (Stracke et al., 2006)

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O
Hawaiian pyrolite	45.20	0.71	3.54	8.47	37.50	3.08	0.57	0.13
Tinaquillo lherzolite	44.95	0.08	3.22	7.66	40.03	2.99	0.18	0.02
MORB pyrolite 90	44.74	0.17	4.37	7.55	38.57	3.38	0.40	0.03
Niu (1997)	45.5	0.16	4.2	7.7	38.33	3.4	0.3	0.03

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