Earth and Planetary Science Letters 269 (2008) 248–258

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Modelling the composition of melts formed during continental breakup of the Southeast Greenland margin

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ARTICLE INFO

Article history:
Received 2 May 2007
Received in revised form 5 February 2008
Accepted 11 February 2008
Available online 4 March 2008
Editor: C.P. Jaupart

Keywords:
Southeast Greenland margin
major element composition
large igneous province
ridge–hotspot interaction

ABSTRACT

We have developed a generic dynamic model of extension of the lithosphere, which predicts major element composition and volume of melt generated from initial extension to steady state seafloor spreading. Stokes equations for non-Newtonian flow are solved and the mantle melts by decompression. Strengthening of the mantle due to dehydration as melting progresses is included. The composition is then empirically related to depletion. Using a crystallisation algorithm, the predicted primary melt composition was compared with mean North Atlantic mid-ocean ridge basalt (MORB). At steady state, using half spreading rates from 10 to 20 mm yr^{-1} and mantle potential temperatures of 1300 to 1325 °C we predict a major element composition that is within the variation in the mean of North Atlantic MORB.

This model is applied to the Southeast Greenland margin, which has extensive coverage of seismic and ODP core data. These data have been interpreted to indicate an initial pulse of magmatism on rifting that rapidly decayed to leave oceanic crustal thickness of 8 to 11 km. This pattern of melt production can be recreated by introducing an initial hot layer of asthenosphere beneath the continental lithosphere and by having a period of fast spreading during early opening. The hot layer was convected through the melt region giving a pulse of high magnesian and low silica melt during the early rifting process. The predicted major element composition of primary melts generated are in close agreement with primary melts from the Southeast Greenland margin. The observed variations in major element composition are reproduced without a mantle source composition anomaly.

1. Introduction

The volume and composition of melt generated by adiabatic decompression is influenced by the potential temperature and upwelling rate of the lithosphere (McKenzie and Bickle, 1988). The breakup of continents can lead to large amounts of magmatism giving large igneous provinces such as that formed around the North Atlantic in the early Tertiary (Barton and White, 1997; Fowler et al., 1989; Hopper et al., 2003). Various models for extension and rifting have been put forward: models in which stretching and buoyancy are imposed but the velocity field is not perturbed by buoyancy, e.g. (Bown and White, 1994; Bown and White, 1995; Williamson et al., 1995); and more dynamic models, in which the flow of material is subject to internal forces due to density gradients within mantle, e.g. (Scott, 1992; Ito et al., 1996; Boutilier and Keen, 1999; Nielsen and Hopper, 2004) Here we develop a two dimensional dynamic model of rifting that includes melt composition calculations. This model will be used to explore the evolution of volcanic margins and the thermal and chemical nature of the mantle beneath such margins. We shall examine the effect of the initial temperature structure, and early spreading rates upon the evolution of the Southeast Greenland margin, which is in the distal region of the possible Iceland plume track (Holbrook et al., 2001).

1.1. Breakup of the North Atlantic

The breakup of the North Atlantic is thought to have been influenced by the Iceland hotspot (White and McKenzie, 1989; Holbrook et al., 2001). In this article we are concerned with understanding the breakup of Southeast Greenland from the Hatton Bank off the west coast of Ireland and UK. The breakup of the North Atlantic took the following scenario: at 61 Ma a thermal plume impacted the margin and delivered warm mantle material to distal portions of the margin away from the plume impact area (Holbrook et al., 2001; Storey et al., 1998; Storey et al., 2007a). Warm mantle material drained along the sublithospheric topography spreading into the distal regions of the margin (Holbrook et al., 2001; Nielsen and Hopper, 2002). At breakup, between 56 and 53 Ma (Cande and Kent, 1995; Berggren et al., 1995; Storey et al., 2007a), the plume continued to feed excess melt generation and active upwelling in the proximal portion of the margin (Holbrook et al., 2001). In the distal regions, warm material was exhausted during breakup and the margin then evolved towards a steady state crustal thickness of between 8 and 11 km (Holbrook et al.,

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doi:10.1016/j.epsl.2008.02.024

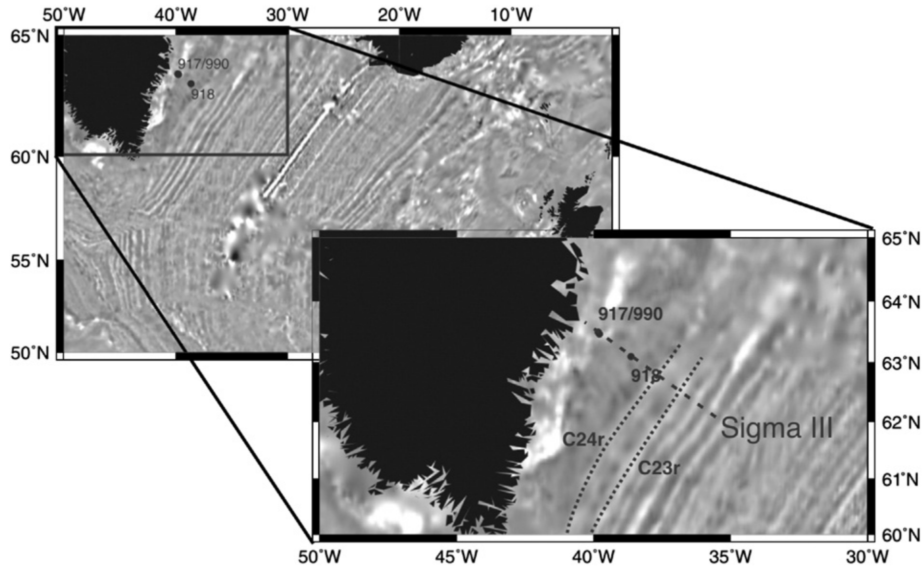

Fig. 1. The North Atlantic, ODP sites 917,918 and 990 are marked off Southeast Greenland. Inset shows approximate locations of magnetic chrons C24r and C23r and the Sigma III survey line. Shading shows magnetic anomalies (Verhoef et al., 1996).

2001). By 45 Ma excess magmatism was confined to regions around Iceland. Therefore the anomalously thick crust observed off Southeast Greenland (Hopper et al., 2003) is possibly explained by the presence of such a hot layer beneath the lithosphere.

Studies of global mid-ocean ridge basalt (MORB) find that mean primary magma has between 10 and 15% MgO, and that the primary magma compositions correlate with the axial depth of the ocean ridge (Klein and Langmuir, 1987). However, primary magmas from Southeast Greenland have MgO contents of up to 18% and high FeO contents of up to 14% (Larsen et al., 1998). Such melt compositions may be attributed to source heterogeneity associated with the ancestral Iceland plume, increased melt fraction due to the presence of a thermal anomaly, or both (Fram et al., 1998; Fitton et al., 2000).

1.2. Drilling off Southeast Greenland

The Ocean Drilling Program (ODP) cored the Southeast Greenland margin during legs 152 and 163 (see Fig. 1). The transition within site 917 from thick silicic flows through a sandstone layer to units of olivine basalt and picrite marks the final stage of breakup (Larsen et al., 1994; Fitton et al., 1995). Basalts from the upper series at site 917 have not been dated although the setting of this series suggests an age of 56 Ma or older (Larsen and Saunders, 1998; Sinton and Duncan, 1998). Basalts recovered from the upper series have high concentrations of magnesium oxide (see Table 1; Larsen et al., 1998) and have been inferred to be close to primary (Thy et al., 1998). It is believed that these units were rapidly erupted through a system of fissures rather than stored within magma chambers (Fitton et al., 2000). Furthermore it is suggested that such aphyric picrite with 18% MgO would have had an eruption temperature of 1380 °C, which implies a mantle potential temperature 1500 to 1600 °C (Nisbet et al., 1993; Fitton et al., 1995).

Site 990 lies fractionally further off-shore and was also emplaced at roughly 56 Ma (Tegner and Duncan, 1999). The composition of the primary magma from unit 990-7 has been calculated (Larsen et al., 1999) by back calculating along the crystallisation liquid lines of descent and is summarised in Table 1. From the crystallisation calculations used to generate the primary melt it was predicted that melting began at high temperatures (1460 to 1580 °C) and there were high degrees of melting (15–21%) (Larsen et al., 1999). The basalts sampled at site 918 were erupted when the rift had developed towards more steady rifting with more established magma reservoirs (Tegner and Duncan, 1999; Fitton et al., 2000).

2. Methods

2.1. Melt depletion and composition

We have developed a model that first calculates the amount of melt generated during the rifting of continents and then predicts the primary composition of that melt. The modelling procedure can be broken down into two steps: First the mantle flow is calculated using a modified version of *CitCom* (Moresi and Solomatov, 1995; Nielsen and Hopper, 2004), which predicts the amount of melt generated during rifting (see Appendix A for a description of the model equations). The amount of melt generated is sensitive primarily to the spreading rate and mantle temperature. The second step uses the fraction of melt generated, the temperature and pressure within the melt region to calculate the melt major element composition. We have based these calculations on the two empirical parameterisations of Watson and McKenzie (1991) and Niu (1997) outlined below. Therefore there are three variables within this model: the initial mantle temperature structure, the spreading rate and the choice of composition parameterisation.

We have focused on two major element composition parameterisations:

1. The major element composition of accumulated melt was linked to fraction of melt generated and pressure by fitting polynomial functions to large data sets from batch melting experiments (McKenzie and Bickle, 1988). Additional corrections to the iron and magnesium oxides to maintain consistency with the olivine/liquid

Table 1
Measured and calculate primary melt compositions from ODP leg 152, site 917 and ODP leg 163, site 990

Site–unit	SiO_2	TiO	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O
917–14	46.77	0.72	14.30	10.65	17.67	7.86	1.61	0.06
917–16	47.38	0.91	13.09	11.09	17.80	7.31	1.78	0.23
Calculated								
917–11R4	46.88	0.96	12.40	11.00	17.76	8.71	1.67	0.17
917–17	47.81	0.90	13.93	9.68	15.31	9.52	2.12	0.31
990–7	48.45	0.71	10.89	11.21	18.01	8.88	1.54	0.08

Units 917–14 and 917–16 from Larsen et al. (1998), 11R4 and 917–17 are estimated by Thy et al. (1998); unit 990–7 primary composition was estimated by Larsen at al. (1999).