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Melt evolution and residence in extending crust: Thermal modeling of the crust and crustal magmas

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ABSTRACT

Tectonic extension and magmatism often act in concert to modify the thermal, mechanical, and chemical structure of the crust. Quantifying the effects of extension and magma flux on melting relationships in the crust is fundamental to determining the rate of crustal melting versus fractionation, magma residence time, and the growth of continental crust in rift environments. In order to understand the coupled control of tectonic extension and magma emplacement on crustal thermal evolution, we develop a numerical model that accounts for extension and thermal-petrographic processes in diverse extensional settings. We show that magma flux exerts the primary control on melt generation and tectonic extension amplifies the volume of melt residing in the crustal column. Diking into an extending crust produces hybrid magmas composed of 1) residual melt remaining after partial crystallization of basalt (mantle-derived melt) and 2) melt from partial melting of the crust (crustal melt). In an extending crust, mantle-derived melts are more prevalent than crustal melts across a range of magma fluxes, tectonic extension rates, and magmatic water contents. In most of the conditions, crustal temperatures do not reach their solidus temperatures to initiate partial melting of these igneous lithologies. Energy balance calculations show that the total enthalpy transported by dikes is primarily used for increasing the sensible heat of the cold surrounding crust with little energy contributing to latent heat of melting the crust (maximum crustal melting efficiency is 6%). In the lower crust, an extensive mush region develops for most of the conditions. Upper crustal crystalline mush is produced by continuous emplacement of magma with geologically reasonable flux and extension rates on timescales of 10^6 yr. Addition of tectonic effects and non-linear melt fraction relationships demonstrates that the magma flux required to sustain partially molten regions in the upper crust is within the range of estimates of magmatic flux in many rifting regions ($\sim 10^{-4}$ to 10^{-3} km^3/yr) and at least an order of magnitude lower than previous modeling estimates. Our results demonstrate the importance of tectonics in augmenting melt production, composition, and crustal evolution in active magmatic systems.

1. Introduction

The combination of extensional tectonics and magmatic intrusion has long been recognized to alter the thermal and structural properties of the crust in rifting environments (e.g., Brown and Solar, 1998; Callot et al., 2001; Ebinger and Casey, 2001; McKenzie and Bickle, 1988; Mohr, 1982; Sengör and Burke, 1978). These two processes are strongly coupled because: 1) both crustal thinning and magmatic intrusions perturb the geothermal gradient, 2) tectonic extension favors vertical propagation of magma following the path perpendicular to the least principal stress direction (e.g., Anderson, 1951), and 3) extensional processes in the crust can control the growth and emplacement of magmatic bodies (e.g., Corti et al., 2003; Gudmundsson, 2006; Jellinek and DePaolo, 2003). However, the interplay of long-term crustal extension and magma intrusions and their exact control on crustal growth, compositional evolution, and thermal evolution remains poorly constrained (e.g., Dufek and Bergantz, 2005; Fitton et al., 1991; Karlstrom et al., 2010; Thompson and Connolly, 1995).

A key question is how the mass and energy are balanced in the crust in response to magma emplacement and extensional tectonics. In many rift environments, the origin, longevity, and location of melt in the crust remain controversial (e.g., Deering et al., 2011; Schmitt and Vazquez, 2006). Numerical and geochemical models have suggested either partial melting of the crust (e.g., Bindeman and Simakin, 2014; Conrad et al., 1988; Fyfe, 1973) or fractional crystallization of the parental magma (e.g., Baker et al., 1977; Barberi et al., 1975; Jagoutz, 2010; Mahood and Baker, 1986;

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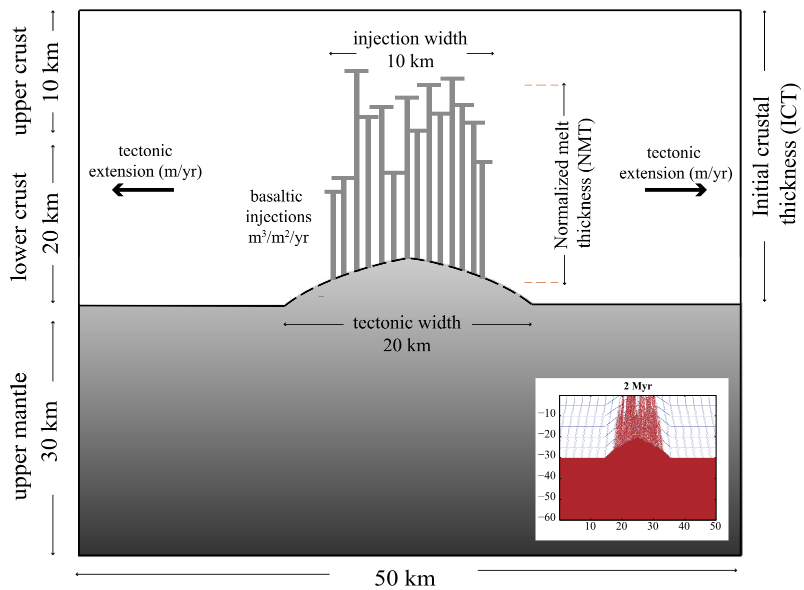

Fig. 1. Conceptual model for thermo-mechanical simulations. The computational domain is an idealized proxy for the crust and uppermost mantle and has three layers: 0–10 km is tonalite, 10–30 km is amphibolite and 30–60 km is peridotite. Diking is localized over the 10 kilometers on the crust–mantle boundary (injection width). Normalizing the two-dimensional area of melt in the domain by the total intrusion width is defined as the normalized melt thickness (NMT). The ratio 'R' represents the ratio of NMT to the initial crustal thickness (ICT). Sills are formed at the tip of the dikes. Emplacement of dikes and sills are accommodated by displacement of the crustal material to conserve mass. Crustal extension is given by a uniform displacement through the crustal column by a defined extension rate. Extension is accommodated by thinning of the crust near-axis (constrained to 10 km half-width) by conservation of mass and induces mantle upwelling. Extension of the crust and mantle upwelling promotes advection of heat in the crust. An example deformation of a regular grid due to extension is shown in the inset. Drawing is not to scale.

O'Hara, 1977) as the main process that explains crustal layering and petrologic diversity observed in volcanic settings. It is likely that both processes operate to different degrees (e.g., DePaolo, 1981b), but in many systems quantitative understanding can remain elusive. Understanding the physical parameters that determine crustal melting versus residence of mantle-derived magmas in the crust has a bearing on the mass balance of rifts and the generation of new crustal material (e.g., Condie, 1982; Rudnick and Fountain, 1995; White et al., 2006).

A closely related issue is that of melt residence time in crustal domains. Observational evidence from exposed plutons and erupted volcanics constrains our current understanding of crustal thermal evolution. Long residence times at low melt fractions have been often argued for crustal magmas (e.g., Bachmann et al., 2007; Hildreth, 2004; Reid et al., 1997). In opposition to this, others have argued that, if the magma bodies do not erupt on relatively short timescales, then they must completely solidify to form plutons (e.g., Glazner et al., 2004; Tappa et al., 2011). The key to understanding the generation and thermal and compositional evolution of crustal magmas is 1) determining the thermal budget of these systems, and 2) assessing the relative amount of crustal melt versus fractionated melt derived from the mantle.

Much of the energy driving these crustal processes derives from mantle melting. While there is a first-order understanding of the relationship between mantle upwelling and melt generation in the mantle, the amount of melt that enters the crust depends on complex non-linear dynamic processes during mantle melt generation, segregation, and transport (e.g., Liang and Parmentier, 2010). These processes are influenced by mantle heterogeneities and several other parameters such as rheology, rift duration, rifting velocity, mantle potential temperature, mechanical boundary layer thickness, decompression rate, presence of volatiles, strain rates, porosity, compaction length, separation velocity, rupture, and dike opening (e.g., Bialas et al., 2010; Brown and Solar, 1998; Buck, 2004; Foucher et al., 1982; McKenzie, 1985; McKenzie and Bickle, 1988; Pedersen and Ro, 1992; Ruppel, 1995; White et al., 1987; Ziegler and Cloetingh, 2004). The complex processes in the mantle lead to significant differences in the timing and volume of magmatism in different rifts and segments, ranging from minor magmatic contribution to intense volcanic activity (e.g., Ruppel, 1995). An open question is how this variability in tectonic rates and mass and energy flux affect the thermal and compositional evolution of crustal magma.

While in many settings both tectonics and magmatic intrusions clearly influence the thermal state of the crust, these processes are often treated in isolation. Geophysical and geodynamic models typically focus on deformation and thermal changes associated with intrusion events and extensional tectonics (e.g., Baer et al., 2008; Corti et al., 2003). Petrologic and thermodynamic studies often focus on the detailed thermal history of magmatic regions by constructing models that consider magmatic intrusion, differentiation, and crustal melting using either a single intrusion (e.g., Bergantz, 1989; Huppert and Sparks, 1988) or multiple intrusion events (e.g., Annen et al., 2006; Annen and Sparks, 2002; Dufek and Bergantz, 2005; Pedersen et al., 1998; Petford and Gallagher, 2001; Wells, 1980). However, the thermal state of the crust and crustal magmas have not been examined by models that include the interplay of varying tectonic extension rates and detailed thermodynamic and petrologic processes.

To investigate the long-term thermal evolution of the crust that is subjected to tectonic extension and dike injections derived from the mantle, we present a thermo-mechanical numerical model that solves for coupled kinematic and thermodynamic processes. This model is focused on crust–magma interaction, and we do not replicate detailed mantle processes including generation, segregation, and transport of the melt but rather we focus on the heat transfer processes in the crustal domain as a result of variable extension rates and magma input. We systematically examine a parameter space for magma flux and tectonic extension to quantify the length- and time-scales of magma–crust interaction. We also use two different magmatic water contents to examine crustal rifts both above relatively wet and dry mantle. The model accounts for crustal displacement due to intrusions and for extensional tectonics through a specified kinematic condition. In this way, our