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Relamination of mafic subducting crust throughout Earth's history

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A B S T R A C T

Earth has likely cooled by several hundred degrees over its history, which has probably affected subduction dynamics and associated magmatism. Today, the process of compositional buoyancy driven upwelling, and subsequent underplating, of subducted materials (commonly referred to as "relamination") is thought to play a role in the formation of continental crust. Given that Archean continental crust formation is best explained by the involvement of mafic material, we investigate the feasibility of mafic crust relamination under a wide range of conditions applicable to modern and early Earth subduction zones, to assess if such a process might have been viable in an early Earth setting.

Our numerical parametric study illustrates that the hotter, thicker-crust conditions of the early Earth favour the upward relamination of mafic subducting crust. The amount of relaminating subducting crust is observed to vary significantly, with subduction convergence rate having the strongest control on the volume of relaminated material. Indeed, removal of the entire mafic crust from the subducting slab is possible for slow subduction (∼2 cm/yr) under Archean conditions. We also observe great variability in the depth at which this separation occurs (80–120 km), with events corresponding to shallower detachment being more voluminous, and that relaminating material has to remain metastably buoyant until this separation depth, which is supported by geological, geophysical and geodynamical observations. Furthermore, this relamination behaviour is commonly episodic with a typical repeat time of approximately 10 Myrs, similar to timescales of episodicity observed in the Archean rock record. We demonstrate that this relamination process can result in the heating of considerable quantities of mafic material (to temperatures in excess of 900 °C), which is then emplaced below the over-riding lithosphere. As such, our results have implications for Archean subduction zone magmatism, for continental crust formation in the early Earth, and provide a novel explanation for the secular evolution of continental crust.

1. Introduction

The mechanisms that have led to the formation of the felsic continental crust (CC) from the mantle throughout Earth's history are still poorly understood, but the presence of subduction systems seems to be an essential component. Indeed, the composition of today's subduction related magmas shares many similarities with the CC (Rudnick, 1995; Jagoutz and Kelemen, 2015). This also applies to the most ancient CC (>2.5 Ga), however, there are systematic differences (Taylor and McLennan, 1995). In particular, certain geochemical features common of this early crust are widely recognized to be derived from mafic material at high pressure (Defant and Drummond, 1990; Foley et al., 2002; Alonso-Perez et al., 2009), but the particular processes that operated in the early Earth and led to the specificities of the early CC are still speculative.

A commonly accepted mechanism explaining the structure and composition of the CC is a basalt input model, where mantle derived basaltic arc magmas are differentiated into a felsic component, leaving an ultramafic to mafic cumulative counterpart that ultimately delaminates and is recycled back into the mantle (Rudnick, 1995). However, recent studies have argued for a simpler petrological model where buoyant diapirs of crustal material detach from the slab, pond beneath the over-riding plate and melt, feeding the lower crust with evolved magmas from below, a process commonly referred to as "relamination" (Hacker et al., 2011; Marschall and Schumacher, 2012; Castro et al., 2013; Kelemen and Behn, 2016). Based on the pervasiveness of a sedimentary signature in arc magma it is suggested that ∼27% of modern granulite terranes and ∼43% of ultra-high-pressure terranes have formed via such a crustal underplating mechanism (Behn et al., 2011). How-

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ever, when looking at Archean granulites this figure falls to 6% (Hacker et al., 2011) in accordance with the fact that the composition of Archean CC is best explained by the involvement of mafic, not just sedimentary, crustal material.

Secular changes in crustal composition suggest that CC formation differed from the modern day mechanism, but exactly how is debated (Condie, 2005; Van Hunen and Moyen, 2012). Whether subduction even played a role in the Earth's earliest history has been thrown into question (Davies, 1992; Sizova et al., 2010), although there is structural evidence for Archean subduction (Calvert et al., 1995; Stevens and Moyen, 2007). If subduction did occur in the early Earth, conditions within the subduction system are expected to have differed systematically from conditions today. In particular, mantle temperatures were probably higher (Herzberg et al., 2010), and oceanic crust was likely thicker as a result (Hoffman and Ranalli, 1988; Abbott et al., 1994). This oceanic crust may have differed compositionally from today's MORB (Herzberg et al., 2010) and, as such, may have had different physical properties. Moreover, it is debated whether subduction in the Archean was slower (Korenaga, 2006), faster (van Hunen and van den Berg, 2008), or comparable to today (Sleep, 1992) and perhaps occurred at a shallower angle (Abbott et al., 1994) although this point is also debated (van Hunen et al., 2004). All these differences may have affected the dynamics of the subduction interface and, in particular, allowed for the relamination of more of the subducting crust.

This leads to the hypothesis: if relamination of subducted felsic materials occurs in modern subduction zones then perhaps, under different, early Earth conditions, such a process may have been viable not only for subducted sediments, but for more of the mafic part of the subducting crust as well, thus producing the characteristics of Archean CC. In this paper we aim to constrain the conditions required for the relamination of the mafic subducting crust by using a thermo-mechanical numerical model of subduction, varying key parameters across a range of values deemed reasonable for the modern and Archean Earth. We show that under Archean conditions (i.e., with hotter mantle and thicker mafic crust), relamination of the mafic subducting crust is indeed viable under a wider range of subduction conditions. The observed dynamic behaviour can also account for other characteristics of Archean felsic terranes and related rocks, such as their episodic emplacement history (Moyen and Van Hunen, 2012), variable mantle signature (Smithies, 2000), and variable depth of primary melt formation, as well as the secular change of these properties throughout the Archean (Martin and Moyen, 2003).

2. Method

2.1. Model physics

A 2-D Cartesian version of the finite element code Citcom is used (Moresi and Gurnis, 1996; Zhong et al., 2000) to numerically solve the governing equations that ensure the conservation of mass, momentum, thermal energy, and composition:

$$\nabla \cdot \mathrm{u}' = 0$$

$$-\nabla P' + \nabla \cdot \left(\eta'\left(\nabla \mathbf{u}' + \left(\nabla \mathbf{u}'\right)^T\right)\right) + \left(Ra_T T' + Ra_C C\right)\hat{\boldsymbol{e}}_Z = 0$$

$$\frac{\partial T'}{\partial t} + \mathbf{u}' \cdot \nabla T' = \nabla^2 T'$$

$$\frac{\partial C}{\partial t} + \mathbf{u}' \cdot \nabla C = 0$$

where the primed variables represent dimensionless variables, non-dimensionalised as follows:

$$T' = \frac{T}{\Delta T} \qquad t' = \frac{\kappa}{h^2} t \qquad \mathbf{u}' = \frac{h}{\kappa}\mathbf{u}$$

$$P' = \frac{h^2}{\eta_0 \kappa}\left(P - \rho_0 g(h - z)\right) \qquad \eta' = \frac{\eta}{\eta_0}$$

and the thermal and compositional Rayleigh numbers, Ra_T and Ra_C, are defined as follows:

$$Ra_T = \frac{\rho_0 g \alpha \Delta T h^3}{\kappa \eta_0} \qquad Ra_C = \frac{\Delta \rho g h^3}{\kappa \eta_0}$$

All variables used in the above equations are defined in Table 1.

We use the Boussinesq approximation and assume incompressibility, with no shear, adiabatic or radiogenic heating, which reduces the complexity of the system in order to allow for the clearer investigation of its primary features.

We use a purely viscous, non-Newtonian rheology for all materials. Brittle behaviour is not included as it is deemed not to play a significant role in our region of interest: namely the subducting crust and mantle wedge, below the over-riding plate. Instead, we impose a maximum viscosity of 10^{24} Pa s, which limits the maximum stresses achievable within the rheologically stronger regions of the model. During preliminary work it was apparent that dislocation creep dominates throughout the model region. This is in line with the findings of Karato and Wu (1993) who put the dislocation–diffusion creep transition between 200 km and 300 km depth, and with the fact that dislocation creep is more likely to dominate in high-stress regimes such as around subduction zones. As such, the viscosity (η) is calculated as follows:

$$\eta = A^{\frac{1}{n}} \dot{\varepsilon}^{\frac{1-n}{n}} \exp\left(\frac{E}{nRT}\right)$$

All variables in the above equation are defined in Table 1.

The effect of pressure on viscosity is assumed to be negligible as the model domain is shallow, and is partly offset by the omission of adiabatic heating, which has an opposite effect on the rheology. It is expected that the inclusion of pressure effects and adiabatic heating, would increase the viscosity at the bottom of the model area by no more than a factor of 3.2 (based on an activation volume of 14×10^{-6} m^3 mol^{-1} for dislocation creep (Karato and Jung, 2003) and an adiabatic gradient of 7.8 °C/GPa). This is small compared to the viscosity uncertainties due to variations in flow law parameters arising from uncertainty in the subducting crustal composition as well as discrepancies between different rheological studies (see Fig. 2).

Material is defined to be either mantle or crust, both with different flow laws (A, E and n) and densities. The density of crust relative to mantle material ($\Delta\rho$) is assigned a fixed negative value above a certain "eclogitisation depth" and a fixed positive value below (see Table 1). This is included as a first order effort to simulate the effect of densifying phase changes (eclogitisation) expected to take place in the subducting crust (see Section 2.5 for details).

2.2. Model setup

The model domain is 450 × 150 km divided up into 512 × 256 finite elements. These elements are 600 × 600 m in a region of interest around the subducting slab and mantle wedge and 1200 × 600 m outside. The thermal and mechanical boundary conditions are illustrated in Fig. 1. The mechanical boundary conditions are as follows: $V_x = V_z = 0$ (no slip) on the surface boundary; $V_x = V_{trench}$ (see below) and $dV_z/dz = 0$ (stress free) on the bottom boundary at 150 km; $dV_x/dx = 0$ (stress free) and $V_z = 0$ (no slip) on the left hand side; and V_x is linearly interpolated between $V_x = 0$ at $z = d_{plate}$ and $V_x = V_{trench}$ at $z = h$ with $V_z = 0$ (no slip) on the right hand side. The thermal boundary conditions are: $T = 0$ (0 °C) at the surface; $T = 1$ (ΔT or mantle temperature, see Table 1) at 150 km; the left hand side boundary is given the thermal profile of a half-space which has been conductively