Earth and Planetary Science Letters 481 (2018) 73–79

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Thermal impact of magmatism in subduction zones

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ARTICLE INFO

Article history:
Received 7 July 2017
Received in revised form 26 September 2017
Accepted 5 October 2017
Available online xxxx
Editor: R. Bendick

Keywords:
magma transport
subduction zone
thermal model

ABSTRACT

Magmatism in subduction zones builds continental crust and causes most of Earth's subaerial volcanism. The production rate and composition of magmas are controlled by the thermal structure of subduction zones. A range of geochemical and heat flow evidence has recently converged to indicate that subduction zones are hotter at lithospheric depths beneath the arc than predicted by canonical thermomechanical models, which neglect magmatism. We show that this discrepancy can be resolved by consideration of the heat transported by magma. In our one- and two-dimensional numerical models and scaling analysis, magmatic transport of sensible and latent heat locally alters the thermal structure of canonical models by ∼300 K, increasing predicted surface heat flow and mid-lithospheric temperatures to observed values. We find the advection of sensible heat to be larger than the deposition of latent heat. Based on these results we conclude that thermal transport by magma migration affects the chemistry and the location of arc volcanoes.

1. Introduction

Petrological estimates of sub-arc temperature conditions in both continental and oceanic subduction zones are systematically higher than predicted by thermal models, typically by 200–300 K, at depths less than ∼70 km (Kelemen et al., 2003; Perrin et al., 2016). Similarly, measurements of geothermal heat flow in SW Oregon and NE Japan are higher than predicted by approximately 50–100 mW/m^2 near the volcanic arc (Kelemen et al., 2003; Furukawa, 1993). Geophysical evidence from seismic and magnetotelluric imaging of high temperatures and/or magma at depth under volcanic arcs (Zhao et al., 2007; Syracuse et al., 2008; Rychert et al., 2008; McGary et al., 2014) is consistent with the emerging consensus that the shallow arc temperatures in subduction zones are hotter than canonical models predict.

In canonical models, the thermal structure of subduction zones is calculated as a balance between thermal diffusion and advection. Heat is advected by the creeping solid mantle flow within the wedge-shaped region between the subducting slab and overriding lithosphere (McKenzie, 1969). Previous modelling efforts to resolve the discrepancy with observations have involved varying the prescribed geometry of subduction, the coupling between mantle and slab, and the rheological model of the mantle (Kelemen et al., 2003; Furukawa, 1993). Inclusion of frictional heating along the slab top in the seismogenic zone increases heat flow in the fore-arc (Gao and Wang, 2014). None of these efforts have been successful in explaining both the amplitude of the thermal observations and their position relative to the volcanic arc.

It is known that hydrous fluids are released from the subducting slab by de-volatilisation reactions (Schmidt and Poli, 2014) and percolate upward into the mantle wedge. There they reduce the solidus temperature, promote melting, and hence become silicic as they ascend. During their ascent, the magmas traverse from cooler mantle adjacent to the slab, to hotter mantle at the core of the wedge, to cooler mantle at the base of the lithosphere. They advect heat between these regions and consume or supply latent heat with melting and freezing. Despite the copious production of magma in subduction zones, these thermal processes have been neglected from almost all previous models. One exception, a scaling argument comparing advective heat transport by magma flow to thermal diffusion, suggests that magma flow may be significant (Peacock, 1990). Similarly, hydrothermal circulation in the crust may play a role in cooling the slab in the fore-arc region (Spinelli et al., 2016). In this paper we assess the role of magmatic processes in altering the thermal structure of the wedge and lithosphere. Our approach is based on theory for two-phase dynamics of the magma–mantle system (McKenzie, 1984). We quantify the magmatic transport of sensible and latent heat, focusing on the physical mechanisms and their controls, rather than on any particular subduction zone.

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https://doi.org/10.1016/j.epsl.2017.10.015
0012-821X/

2. Methodology

Magma migration in the mantle is a two-phase flow, governed by continuum equations of mass and momentum conservation for the solid (mantle) and melt (magma) (McKenzie, 1984; Rudge et al., 2011). The thermal and compositional structure is governed by equations of conservation of energy and chemical species. Our approach is to prescribe the magmatic flux and investigate how the thermal structure responds. This response is determined from energy conservation in the form of a heat equation:

$$\frac{\partial T}{\partial t} + \boldsymbol{v}_s \cdot \nabla T + \boldsymbol{v}_D \cdot \nabla T = \kappa \nabla^2 T - \frac{L}{\rho c_p}\Gamma, \qquad (1)$$

T denotes temperature, t time, κ thermal diffusivity, ρ density, c_p specific heat capacity, L latent heat, and Γ melting rate. We neglect differences between the thermal properties of the phases because these do not affect the solution at leading order. The velocity variables involved are: solid mantle velocity $\boldsymbol{v}_s$, liquid magma velocity $\boldsymbol{v}_l$, the Darcy (or segregation) flux $\boldsymbol{v}_D \equiv \phi(\boldsymbol{v}_l - \boldsymbol{v}_s)$, where ϕ is the porosity.

In the absence of magma, $\boldsymbol{v}_D = 0$ and $\Gamma = 0$, and eqn. (1) reduces to the heat equation used in canonical mantle convection calculations. In the presence of magma, two relevant terms are non-zero: first, an advective term associated with the segregation flux of magma $\boldsymbol{v}_D$; second, a latent heat sink associated with melting ($\Gamma > 0$), which becomes a source in the case of freezing ($\Gamma < 0$). The petrological model for Γ is described in Sec. S1, Supplementary Material, and was inspired by previous studies of mantle melting in the presence of water (Hirschmann et al., 1999; Katz et al., 2003; Keller and Katz, 2016).

By the considerations above and the results below, we emphasise that the latent heat of phase change is not the only thermal contribution from magmatism; there is also advective transport by the magma. In what follows, we consider the relative importance of these mechanisms.

3. Results

3.1. One-dimensional model

So-called ‘melting-column models’ have been used to understand mid-ocean ridge magmatism, where the main cause of melting is decompression of the upwelling mantle (Ribe, 1985; Asimow and Stolper, 1999; Hewitt, 2010). Subduction zones are a considerably more complex environment, but we adapt ideas from melting-column models to investigate how magmatism modifies their thermal structure. The column model is fully derived and described in more detail in Sec. S2, Supplementary Material. A one-dimensional, steady-state heat equation can be written

$$\rho c_p \overline{W_0} \frac{dT}{dz} - \rho c_p \Psi^* = \frac{d}{dz}\left(\rho c_p \kappa \frac{dT}{dz}\right) - L\Gamma, \qquad (2)$$

where Ψ^* is the dimensional version of the source term, discussed below. We rescale lengths by the height of the column H, velocities by the diffusive scale κ/H, and Ψ^* by κ/H^2. Then eqn. (2) becomes

$$\mathrm{Pe}\, T' - \Psi = T'' - \mathrm{Pe}\,\mathrm{St}\,(T' + \Delta T_H), \qquad (3)$$

where Ψ is the rescaled version of the source term, discussed below. ΔT_H is the adiabatic temperature drop between slab and surface; primes denote a derivative with respect to position (e.g., T' is a rescaled vertical temperature gradient). Two dimensionless numbers control the behaviour of the system: a Péclet number $\mathrm{Pe} = H\overline{W_0}/\kappa$ is the scaled volume flux at the base of the column; a Stefan number $\mathrm{St} = (L/c_p)\partial F/\partial T$ is the scaled isobaric productivity that quantifies the ratio of latent to sensible heat (F is the degree of melting). Hydrous flux melting has low isobaric productivity (Hirschmann et al., 1999) so the Stefan number is small.

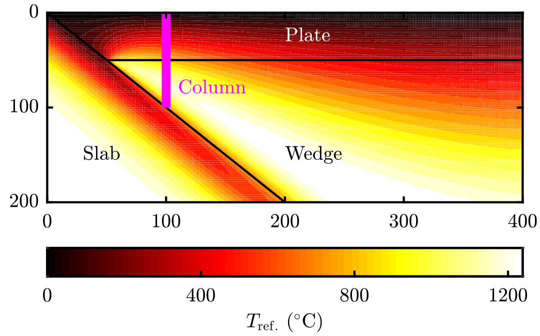

Fig. 1. Reference temperature field $T_{\mathrm{ref.}}$ from van Keken et al. (2008) using the parameter values listed therein. The dip angle, slab velocity and thickness of the overriding plate are prescribed. The solid velocity in the mantle wedge is calculated and coupled to the temperature through a temperature-weakening viscosity. A pink line indicates the position of an example column model. Axis label show distance from the trench in km. Only a subset of the model domain is shown; the full domain is 660 km wide and 600 km deep. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The mantle flow in subduction zones is far from one-dimensional; a corner flow is driven by the motion of the subducting slab (McKenzie, 1969). A key step in representing corner flow in a column model is to introduce a spatially variable, volumetric heating term Ψ that mimics the effects of large-scale mantle flow, which tends to supply heat into the column. We infer Ψ from a single-phase, two-dimensional thermomechanical reference model that is shown in Fig. 1; the domain geometry and temperature-dependence of viscosity are as given in a study that outlined broadly representative models of subduction (van Keken et al., 2008). From the reference model, we extract a vertical temperature profile at some position of interest $T_{\mathrm{ref.}}(z)$ and use it to calculate the source term $\Psi = -T''_{\mathrm{ref.}}$. The source term is constructed such that the solution of equation (3) in the absence of magma flow ($\mathrm{Pe} = 0$) is $T = T_{\mathrm{ref.}}$, i.e., the single-phase result. For $\mathrm{Pe} > 0$, this approach is reasonable provided melt does not drastically change the large-scale mantle dynamics, a prospect we consider later.

Fig. 2 shows results of the 1D column calculations. These are obtained for the column rising from slab where it is 100 km deep. This choice is roughly consistent with the observed mean slab depth beneath arc volcanoes (England et al., 2004; Syracuse and Abers, 2006). The flux at the base of the column is varied within the range suggested by a previous study (Wilson et al., 2014). Dimensionally, this range corresponds to fluxes between 0.2–2 m/kyr. Panel (a) shows profiles of the absolute temperature; panel (b) shows the temperature difference compared to the single-phase (magma-free) reference case. The change in temperature from the reference state increases with the imposed flux and is significant even at the lower end of the plausible range (Wilson et al., 2014). Immediately above the slab, upward flow reduces the mantle temperature as material is transported from the relatively cold slab. Nearer the surface, the effect is reversed as upward flow brings warm material from the mantle into the lithosphere. This effect is supplemented by latent heat associated with melting and solidification, shown in panel (c). Above the slab, melting of the mantle wedge facilitated by the presence of water consumes latent heat. Nearer the surface, solidification of the melt deposits latent heat. The maximum degree of melting (d) is increased because of the elevated temperatures, which will have a significant geochemical signature (Turner et al., 2016). It is interesting to note that the maximum degree of melting does not vary monotonically, but peaks at an intermediate Péclet number between 2 and 5.