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Mantle wedge temperatures and their potential relation to volcanic arc location

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ABSTRACT

The mechanisms underpinning the formation of a focused volcanic arc above subduction zones are debated. Suggestions include controls by: (i) where the subducting plate releases water, lowering the solidus in the overlying mantle wedge; (ii) the location where the mantle wedge melts to the highest degree; and (iii) a limit on melt formation and migration imposed by the cool shallow corner of the wedge. Here, we evaluate these three proposed mechanisms using a set of kinematically-driven 2D thermo-mechanical mantle-wedge models in which subduction velocity, slab dip and age, overriding-plate thickness and the depth of decoupling between the two plates are systematically varied. All mechanisms predict, on the basis of model geometry, that the arc-trench distance, D, decreases strongly with increasing dip, consistent with the negative D-dip correlations found in global subduction data. Model trends of sub-arc slab depth, H, with dip are positive if H is wedge-temperature controlled and overriding-plate thickness does not exceed the decoupling depth by more than 50 km, and negative if H is slab-temperature controlled. Observed global H-dip trends are overall positive. With increasing overriding plate thickness, the position of maximum melting shifts to smaller H and D, while the position of the trenchward limit of the melt zone, controlled by the wedge's cold corner, shifts to larger H and D, similar to the trend in the data for oceanic subduction zones. Thus, the limit imposed by the wedge corner on melting and melt migration seems to exert the first-order control on arc position.

1. Introduction

Two key outstanding questions surrounding arc volcanism at subduction zones are why it is focused along a narrow front that is usually <50 km wide (e.g. Schmidt and Poli, 2014), and what controls the position of that front. In this paper, we will focus on the second question. A clustering of slab depths 100–130 km below the arc (e.g. England et al., 2004; Syracuse and Abers, 2006; Schmidt and Poli, 2014) (Fig. 1), and correlations between subduction parameters (most notably slab dip) and arc-trench distance, D, or slab depth below the arc, H, have usually been taken as evidence that arc position is controlled by the slab-wedge system's physical state. Indeed, different studies have proposed that arc position is governed by: (i) the thermal state of the slab, which controls the dehydration of downgoing crust and mantle lithosphere; (ii) thermal conditions in the mantle wedge, which dictate where melting is possible and to what degree it occurs; and (iii) conditions in the wedge that control fluid and melt migration, or a combination of these (e.g. Tatsumi, 1986; Davies and Stevenson, 1992; Schmidt and Poli, 1998; Grove et al., 2009; England and Katz, 2010). An additional role for (iv) overriding-plate structure has also been suggested (e.g. for Indonesia and Central America: Phipps-Morgan et al., 2008; Pacey et al., 2013).

It is widely accepted that water is required to promote melting in the mantle wedge (e.g. Gill, 1981) and, accordingly, it was originally proposed that slab conditions (i) were the main control on arc position, with a particular pressure-sensitive dehydration reaction responsible for the narrow range of slab depths below the arc (e.g. Tatsumi, 1986). However, it has subsequently been demonstrated that there is a significant range of H (Fig. 1, England et al., 2004; Syracuse and Abers, 2006; Schmidt and Poli, 2014) as well as a range of depths over which dehydration reactions occur (e.g. Schmidt and Poli, 1998; Grove et al., 2009; Van Keken et al., 2011). Some recent numerical models predict that within this wider depth range, most fluid release occurs over a few (slab-temperature dependent) narrow depth intervals (e.g. Hebert et al., 2009; Van Keken et al., 2011), which could lead to focused fluid pathways through the wedge (e.g. Wilson et al., 2014;

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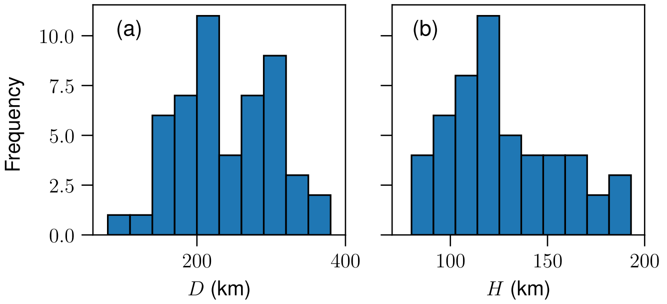

Fig. 1. (a) Distribution of arc-trench distances (D) – mean = 240 km, standard deviation = 62 km; (b) Distribution of slab depth (H) below the arc – mean = 127 km, standard deviation = 29 km. Data from compilation by Syracuse et al. (2010).

Cerpa et al., 2017). On the other hand, absorption of the slab-released fluids in hydrous minerals in the mantle wedge directly above the slab, and the subsequent downward advection of this material, would again distribute fluids over a wider depth range (Hebert et al., 2009) such that they do not act as a point source for volcanism. By combining thermal modelling with petrological experiments, Grove et al. (2009, 2012) propose that a combination of (i) slab temperatures, where fluids are released over a wide depth range, and (ii) wedge temperatures controlling melt evolution yields the observed negative correlation of D with slab dip. However, this model does not explain focusing along a narrow volcanic front.

Davies and Stevenson (1992) proposed that arc position is governed by (ii) wedge melting. Using thermo-mechanical models, they argue that the location of maximum melting is controlled by crossing of the amphibole-buffered solidus, which subsequently determines where the arc forms. Their modelling predicts a positive correlation between H and slab dip, consistent with the early subduction parameter database from Gill (1981). A subsequent compilation by England et al. (2004), however, displays a negative H-dip correlation, which England and Katz (2010) attribute to a combination of controls on melt generation (ii) and melt migration (iii). Based on analytical and numerical models, they propose that the location where the 'anhydrous' solidus (for 200–500 ppm of water, considered relatively dry for mantle wedge conditions) approaches the trench most closely, governs both maximum melt generation and, through the resulting melt porosity and viscosity variations, channels melt towards the arc. Wilson et al. (2014) also found that due to the effects of compaction, fluids/melts can be focused towards the trench, where the cold high-viscosity forearc corner limits trench-ward flow.

In stark contrast, Schmidt and Poli (2014) find no relation between H and subduction parameters like slab dip, subduction velocity or slab age, concluding that even though temperature must be important, correlations with subduction parameters may not be expected as subduction zones are unlikely to be in a steady-state. They also argue that small-scale convection (e.g. Honda and Saito, 2003; Le Voci et al., 2014; Davies et al., 2016) and thermo-chemical plumes (e.g. Gerya and Yuen, 2003; Zhu et al., 2009; Behn et al., 2011) will complicate wedge structure. Small-scale instabilities from the overriding plate can indeed locally suppress wedge melting (e.g. Le Voci et al., 2014; Davies et al., 2016; Lee and Wada, 2017). However, Davies and Stevenson (1992) argue that melt and fluid migration should have only a secondary effect on wedge thermal structure, due to their high velocities relative to solid-state mantle flow. This seems to be borne out by the thermal structure from a range of models that include fluid or melt migration and even low-density thermo-chemical plumes (e.g. Gerya and Yuen, 2003; Cagnioncle et al., 2007; Wilson et al., 2014; Cerpa et al., 2017).

Contrasting interpretations of relationships in global subduction parameters motivates the reanalysis of the sensitivity of wedge thermal structure to these parameters, specifically to compare the D and H trends observed (Syracuse and Abers, 2006; Syracuse et al., 2010) with those expected from parameter sensitivities. In the models presented herein, wedge thermal structures are a consequence of the mantle wedge's flow regime, which is driven by the downgoing plate. Our models incorporate a temperature, pressure and strain-rate dependent viscosity, and neglect viscosity variations associated with spatially variable hydration or melt porosity, or small-scale convective drips from the overriding plate. In this way, the setup is similar to those used in previous studies (e.g. Van Keken et al., 2002; Grove et al., 2009; Wada and Wang, 2009; Syracuse et al., 2010; England and Katz, 2010), where it was demonstrated that such models provide a sensible first-order reference for wedge thermal structure, compatible with a range of geophysical, geochemical and petrological constraints (e.g. Abers et al., 2006; Plank et al., 2009; Wada and Wang, 2009; Syracuse et al., 2010). We investigate what trends between D, H and subduction parameters are expected for a set of diagnostics we define for the three main processes that have been proposed to control arc position: (i) dehydration conditions; (ii) melting conditions; and (iii) a constraint on fluid/melt migration by wedge thermal structure, in particular the cold forearc corner.

1.1. Trends in global subduction data

Fig. 1 shows the distribution of arc-trench distances and slab depths below the arc from the data compilation we will compare our model trends to, the one by Syracuse et al. (2010). This data base uses well-constrained slab geometries and, accordingly, is the most comprehensive compilation available. There is a wide spread in arc-trench distances that appears somewhat bimodal, which is, in part, due to variations in slab geometry (e.g. flattened slabs below Alaska and Mexico fall within the second peak, at around 300 km distance). The depth of the slab below the arc forms a tighter distribution, with a single peak and a mean of 127 km.

In Fig. 2, we illustrate the main trends of D and H with subduction parameters in this database. Consistently, studies have found that arc-trench distance, D, correlates negatively with slab dip, δ (e.g. Gill, 1981; Jarrard, 1986; Syracuse and Abers, 2006; England et al., 2004; Schmidt and Poli, 2014). In the Syracuse database, this trend has a correlation coefficient of 0.62 with a probability, p, that the trend appears by chance of 0 (assuming such a trend is linear) (Fig. 2a). Another possibly significant trend in D is a negative correlation with subduction (convergence) velocity V_c (Fig. 2b) and, hence, various products of dip and convergence velocity, such as the descent velocity $V_c \sin(\delta)$ and thermal parameter (the product of subducting-plate age and $V_c \sin(\delta)$) also correlate with D. For intra-oceanic subduction zones, there is also a positive trend with overriding-plate age, A_{OP}, while there is no significant trend with subducting-plate age, A_{SP} (Fig. 2c–d).

For slab depth below the arc H, the database shows a positive trend with δ (Fig. 2e), A_{OP} (Fig. 2g), and a negative, but likely insignificant, trend with V_c (Fig. 2f). There is arguably a positive trend between H and subducting-plate age (Fig. 2h). England et al. (2004), on the other hand, found a negative H–δ trend, and a strongly significant negative trend with V_c (and, accordingly, significant trends with $V_c \sin(\delta)$). Gill (1981) found that H increases with increasing dip, which is consistent with the Syracuse database, whilst Schmidt and Poli (2014) do not find a $V_c \sin(\delta)$ trend with H. Syracuse and Abers (2006) confirm the trends of England et al. (2004) when they limit their analysis to the same subduction zones although they see no motivation for deselecting the zones excluded by England et al. (2004); they note that