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A numerical approach to melting in warm subduction zones

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ABSTRACT

The complex feedback between dehydration and melting in hot subduction zones is quantitatively addressed in this study. We present an integrated numerical tool that combines a high-resolution thermo-mechanical subduction model with a thermodynamic database that allows modeling metamorphic devolatilization, and subsequent re-hydration and melting reactions. We apply this tool to quantify how the hydration state of a lithologically layered subducting slab varies during interaction with the hot mantle wedge and how this affects any melting taking place in the subducting crust or the overlying mantle wedge. Total crustal dehydration is achieved before any crustal melting can occur, even in very young subducting slabs. Significant oceanic crust melting is only achieved if the metamorphic fluids from the dehydrating underlying subducting slab mantle are fluxed through the dry eclogites. But our models further demonstrate that even if the oceanic crust can melt in these specific conditions, the preceding crustal dehydration will simultaneously result in extensive mantle wedge melting at lower pressures than for colder slabs. The significant mantle wedge melting implies that also for hot subduction zones, most of the melt feeding the overriding plate is of mantle origin.

1. Introduction

Subduction zones are part of the geochemical cycle for volatiles, and are an essential site for the production of silica-rich magmas that contribute to the formation of continental crust (e.g. Arculus, 1981; Taylor and McLennan, 1995). Modern subduction zone magmatic processes are mainly driven by slab devolatilization that triggers flux melting of the metasomatized mantle wedge and strongly influences the geochemical characteristics of arc magmatism (Tatsumi and Kogiso, 1997; Ulmer, 2001). It is within the arc crust that most silicic-rich granitoids are formed, either by fractional crystallization of mantle wedge primitive parental melts, or, alternatively, by re-melting of previously crystallized primitive melts. But in an unusually warm subduction regime, e.g. in a young slab, water-present melting (water saturated melting) or water-absent melting (dehydration melting) of slab crust may take place, producing Na–Al rich dacitic melts, with high Sr/Y and La/Yb ratios (symptomatic of the presence of garnet and/or amphibole), commonly known as adakites (Moyen, 2009). This process has also been suggested to be at the origin of the early Earth's crust (e.g. Martin, 1999). High-Mg andesites with specific trace element ratios originally recognized in the Adak island of the Aleutian Arc (Kay, 1978) were subsequently termed adakites when interpreted to be slab melts. This terminology arose from Defant and Drummond (1990), who recognized that adakitic compositions from the Austral Andes are related to the subduction of a young (<25-Myr old) oceanic plate. But a considerable debate exists about the processes leading to an adakitic signature: in addition to mafic crust melting as a means to produce adakites (Rapp et al., 1991; Atherton and Petford, 1993), high pressure fractionation of water rich mantle melts also generates "adakitic" compositions (Macpherson et al., 2006; Alonso-Perez et al., 2009), as does the interaction between mantle wedge peridotite and slab partial melts (Rapp et al., 1999). This study intends to better constrain the possible source of an adakitic signal during the subduction of a young lithosphere and provide a better understanding of the magmatic outcome of a warm subduction zone.

Because the effect of metamorphic fluid advection has long been recognized as the primary factor for the generation of subduction zone magmas (Ringwood, 1974), significant effort has been put into constraining the distribution of water distilled from the descending slab. This has been widely investigated experimentally (e.g. Ulmer and Trommsdorff, 1995; Schmidt and Poli, 1998; Grove et al., 2006) and numerically (e.g. Iwamori, 1998; Rüpke et al., 2004; Arcay et al., 2005; Connolly, 2005; Hacker, 2008; Wada et al., 2012; Magni et al., 2014). Numerical models have simulated slab dehydration in warm regimes (Syracuse et al., 2010; van Keken et al., 2011; Magni et al., 2014), but much less attention has been given to the melting processes and the magmatic outcome in these systems.

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In this study, we use a numerical model that reproduces the thermo-mechanical essential characteristics of a subducting slab and computes the thermodynamic equilibrium parageneses at each pressure–temperature–composition (P–T–X) condition of the system at every time step. The resulting paragenetic map of a subduction system allows us to quantify the fate of water during dehydration and subsequent re-hydration or melting reactions. This study has two main objectives: (1) to model these processes envisioned to occur in an ordinary subduction zone, by examining a 40-Myr old subducting slab; and (2) to quantify the dehydration process and the occurrence of melting in a much hotter subduction zone. We show that oceanic crust melting can only be achieved if free water is supplied by dehydration reactions occurring deeper in the slab, but that extensive mantle wedge melting is still the main overriding plate supplier.

2. A dynamic solidus setup

We have developed a numerical tool that unifies a thermo-mechanical finite element model with a thermodynamic database, which allows us to model phase assemblages and the metamorphic evolution of a lithologically layered slab of a subduction zone system.

2.1. Combined thermo-chemical–mechanical model

We use the finite element code Citcom to calculate the flow field and temperature distribution inside a subduction system in a Cartesian geometry (Moresi and Gurnis, 1996; Zhong et al., 2000). Conservation of mass, momentum (which together define the steady state flow field) and conservation of energy (which defines a time-dependent temperature field) are solved assuming an incompressible flow and adopting the Boussinesq approximation, with an a posteriori adiabatic temperature correction of 0.5 K/km. Tracking of material properties and water content is performed using a second-order Runge–Kutta tracer particle technique. Further details on the governing equations and associated numerical methods are described in van Hunen and Allen (2011). For each tracer, the stable mineral phases are calculated using a Gibbs free energy minimization strategy (Connolly, 2005, 2009), see Section 2.2 below. Initially, water is only present within the slab on the left hand side of the model. It is subsequently carried deeper within the slab until dehydration occurs. If, according to Gibbs energy minimization, free water is one of the stable phases, it is collected for all tracers in each element, moved to and distributed over the tracers in the element above (Gerya et al., 2002; Arcay et al., 2005), where it is added to the composition to affect the stable mineral phases. This approach assumes that water percolation in the mantle occurs on time scales much shorter than mantle convection. We run our simulations long enough to reach a quasi-steady-state condition in the slab in which the dehydration processes do not change anymore with time.

The computational domain is 300 km deep and 600 km wide, with a grid resolution of about 0.6×0.6 km^2 (Fig. 1). We use a commonly applied model setup of a kinematically described subducting slab (e.g. Syracuse et al., 2010). Since slab deformation is not of first-order importance in this study, we use a straight slab (as e.g. in van Keken et al., 2008) subducting under a 30° angle with a constant velocity of 5 cm/yr. To allow subduction, a 4.5 km thick weak fault zone (with an effective, relatively low viscosity $\eta = 10^{21}$ Pa s) is imposed between the subducting and overriding plate. The temperature field is first computed in a model in which the subduction of oceanic lithosphere with a given age evolves until it reaches a quasi-steady-state condition. This thermal structure is subsequently used as the initial temperature field for further

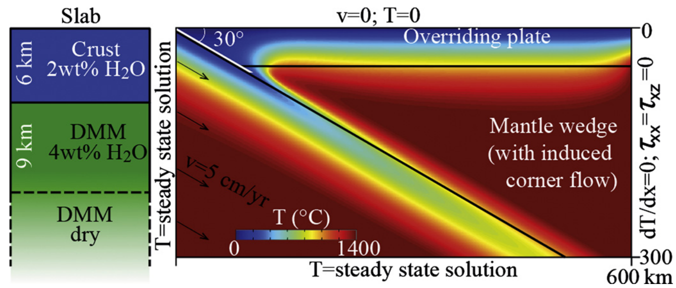

Fig. 1. Schematic representation of the computational model setup. A slab with constant dip angle enters the computational domain from the left with a fixed temperature (half-space cooling temperature for given plate age) and fixed velocity and leaves it from the bottom. The top boundary conditions are no-slip and zero surface temperature (0 °C). Stress free outflow and zero diffusional heat flow are the boundary conditions on the right-hand side boundary. The slab consists of a 6 km thick hydrated crust (2 wt% H_2O) and a 9 km underlying DMM mantle (either dry or hydrated to 4 wt% H_2O), and a dry DMM mantle underneath. The grey area between the plates shows the weak fault zone.

Table 1
Symbols, units and default model parameters.

Parameters	Symbols (unit)	Value
Temperature	T_{abs} (K)	–
Mantle potential temperature	T_m (K)	1623
Reference mantle viscosity	η_0 (Pa s)	10^{21}
Maximum mantle viscosity	η_{mm} (Pa s)	10^{24}
Lithosphere viscosity	η_l (Pa s)	10^{26}
Weak zone viscosity	η_w (Pa s)	10^{21}
Gas constant	R (J/mol/K)	8.3
Activation energy	E (kJ/mol)	360
Plate velocity	v (cm/yr)	5
Mesh resolution	km^2	0.6×0.6

model calculations. Temperature is prescribed at the top and inflow boundary, while a zero conductive heat flux applies on the right and bottom boundaries. The velocity boundary conditions are no-slip at the top, imposed velocity at the slab in- and outflow boundary, and stress free flow at the right boundary. The mantle wedge flow is kinematically driven by the slab descent. We use a temperature-dependent rheology in the mantle wedge, in which the deformation is accommodated by diffusion creep (Table 1):

$$\eta_{diff} = \eta_0 \exp\left(\frac{E}{RT_{abs}} - \frac{E}{RT_m}\right)$$

Plates have a constant viscosity of 10^{26} Pa s. A maximum viscosity of 10^{24} Pa s is imposed for the mantle wedge. The obtained slab temperatures in our models are within the range of those proposed for such conditions (Gerya et al., 2002; van Keken et al., 2008; Syracuse et al., 2010). At each time step, which corresponds to about 3000 yrs, the obtained pressure, temperature and composition are used to compute the stable phases from the thermodynamic database (see below).

2.2. Thermodynamical model set-up

We investigate the petrological processes involved in intermediate-to-warm subduction zones using compositions for the crust and mantle lithologies that have been widely used previously, and that can be considered as benchmark compositions. In these models, the slab crust is a 6-km compositionally homogeneous hydrated (2 wt% H_2O) layer representing the bulk of the igneous oceanic crust (sample LTBC, Poli, 1993; Poli and Schmidt, 1995; Schmidt and Poli, 1998). Underneath is a depleted lithospheric mantle (DMM, Workman and Hart, 2005) with or without a hydrated shallow part (9 km, with 4 wt% H_2O) representing serpentinized mantle. Such slab compositions are considered