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The global range of subduction zone thermal models

Ellen M. Syracuse[a,*], Peter E. van Keken[b], Geoffrey A. Abers[c]

[a] Department of Geoscience, University of Wisconsin, 1215 W. Dayton St., Madison, WI 53706, USA
[b] Department of Geological Sciences, University of Michigan, 1100 North University Avenue, Ann Arbor, MI 48109-1005, USA
[c] Lamont-Doherty Earth Observatory, Columbia University, PO Box 1000, 61 Rte 9W, Palisades, NY 10964, USA

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ABSTRACT

We model 56 segments of subduction zones using kinematically defined slabs based on updated geometries from Syracuse and Abers (2006) to obtain a comprehensive suite of thermal models for the global subduction system. These two-dimensional thermal models provide insight to the dehydration and melting processes that occur in subduction zones. Despite the wide range of slab geometries, ages, convergence velocities and upper plates the predicted thermal structures share many common features. All models feature partial coupling between the slab and the overriding plate directly downdip of the thrust zone, invoked to replicate the cold nose observed in measurements of heat flow and seismic attenuation. We test four separate assumptions about the causes of the partial coupling: (1) the downdip end of the partial coupling is at a constant depth, (2) it is at constant distance trenchward from the arc, (3) it is defined by a critical surface slab temperature, or (4) it is adjusted such that the hottest part of the mantle wedge beneath the arc is at a constant temperature for all subduction zones. In all of these models, slabs reach temperatures where the top of the oceanic crust and sediments dehydrate before they reach subarc depths, and the overlying mantle wedge is too hot for hydrous minerals to be stable at subarc depths. By contrast, the interior of the oceanic crust and underlying mantle within the downgoing plate remains cold enough for hydrous phases to be stable beyond the arc in all but the hottest subduction zones, allowing water to be carried beyond the arc in the slab.

1. Introduction

Subduction zones and the volcanic arcs formed above them extend across approximately 40,000 km of the Earth's surface. Their thermal structure affects the processes that contribute to the dehydration of subducting crust and mantle, the generation of intermediate-depth earthquakes, melt production in the overlying mantle wedge and the formation of arc volcanoes. Given the large variation in slab input parameters (age, speed), geometry (slab dip, trench advance or roll-back) and overriding plate structure the full range of these thermal structures is not well understood.

Previous numerical models of subduction zone temperatures have often focused on comparing idealized geometries and parameterizations, examining the effects of varying factors such as slab dip, plate convergence velocity, or subducting plate age, or modeling a small number of representative subduction zones (e.g., Davies and Stevenson, 1992; Peacock, 1996; Kincaid and Sacks, 1997; Peacock and Wang, 1999; Conder et al., 2002; van Keken et al., 2002; Gerya and Yuen, 2003; Kelemen et al., 2003; Abers et al., 2006; Cagnioncle et al., 2007). While these studies have been helpful in illuminating the effects that each of these individual parameters has on the thermal structure of a subduction zone they do not allow for a detailed comparison of the entire suite of parameters in combinations found over the global range of subduction zones. Recently, Wada and Wang (2009) discussed models for 15 arc segments with a specific focus on the nature of the cold fore-arc corner, referred to as the 'cold nose' (Kincaid and Sacks, 1997). The low temperature and low-attenuation nature of this corner is inferred to exist in a growing number of subduction zones from measurements of heat flow (e.g., Furukawa and Uyeda, 1989; Blackwell et al., 1990; Hyndman and Wang, 1995; Hyndman and Peacock, 2003; Yoshimoto et al., 2006) and seismic attenuation (Hashida, 1989; Takanami et al., 2000; Schurr et al., 2003; Stachnik et al., 2004; Rychert et al., 2008). The low-attenuation and low temperature nature of this region indicates that it is isolated from the large scale counterflow in the mantle wedge, which suggests that decoupling of the viscous interaction between the slab and overlying mantle wedge is necessary to a depth significantly below the downdip limit of the seismogenic zone. Based on heat flow constraints, Wada and Wang (2009) concluded that the depth to decoupling was uniform at ~80 km depth and that this indicates a universal mechanism governing the decoupling between slab and mantle, without specifying the details of this mechanism.

* Corresponding author. Tel.: +608 890 1019.
E-mail addresses: syracuse@geology.wisc.edu (E.M. Syracuse), keken@umich.edu (P.E. van Keken), abers@ldeo.columbia.edu (G.A. Abers).

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Table 1
Thermodynamic parameters used in thermal modeling.

Symbol	Name	Value	Units
A	Scaling factor[a]	3.5×10^{22}	s^{-1}
n	Stress exponent[a]	3.5	
m	Grain-size exponent[a]	0	
E^*	Activation energy[a]	540	kJ/mol
V^*	Activation volume	0	cm^3/mol
μ	Shear modulus[a]	80	GPa
ρ	Density	3300	kg/m^3
T_π	Potential temperature, mantle[b]	1421.5	°C
ΔT	Mantle adiabatic gradient	0.5	°C/km
c_p	Specific heat	1250	J/kg/K
κ_{crust}	Thermal conductivity, crust	2.5	W/m/K
κ_{crust}	Thermal conductivity, mantle	2.5	W/m/K
$q_{surface}$	Surface heat flow	65	mW/m^2
$q_{upper\ crust}$	Heat production, upper crust	1.3	W/m^3
$q_{lower\ crust}$	Heat production, lower crust	0.27	W/m^3

[a] Parameters used in Karato and Wu (1993) dislocation creep regime for dry olivine.
[b] Based on Stein and Stein (1992).

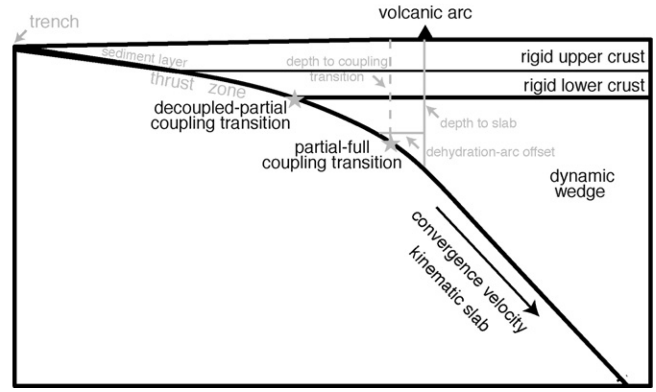

Fig. 2. An example parameterization of a subduction zone. The slab surface is characterized by its geometry, convergence velocity, sediment layer thickness and age. Its interface with the overlying plate and mantle are characterized by the depth at which the coupling between to the transitions from fully decoupled to partially coupled (50 km depth for all subduction zones) and the transition from partially coupled to fully coupled (see text). The overlying plate is characterized by its type and thickness or age.

In this study, we provide a significant extension to previous work and provide a global comparison of the thermal structure of subduction zones. We are particularly interested in how the cold corner can be maintained and wish to provide further diagnostics on the nature of the transition from decoupling to coupling between the slab and overriding mantle in subduction zones. To develop the global suite of models we parameterize the two-dimensional (2D) geometry of a large number of cross-sections that evenly space the global subduction system using a slightly improved and expanded version of the global geometry compilation of Syracuse and Abers (2006). We obtain a complete and uniform sampling of subduction zones and use high-resolution finite-element models to examine the range of thermal models.

2. Methods

2.1. Modeling approach

We develop 2D thermal models for 56 sections of volcanic arc encompassing virtually all subduction zone segments with well-constrained geometry, largely following the segments defined by Syracuse and Abers (2006) (Table 1 and Fig. 1). The modeling approach closely follows that of van Keken et al. (2002) in which the slab is defined kinematically by motion along a prescribed slab surface, and flow in the overlying mantle wedge is computed in response to this motion (Figs. 2 and 3). The mantle viscosity is defined by a non-Newtonian, temperature- and stress-dependent rheology based on the dislocation creep flow law for dry olivine of Karato and Wu (1993), and does not incorporate more complex flow laws such as those in Kneller et al. (2007). The governing equations are provided in the appendix. We assume the mantle to be incompressible and ignore compressible effects such as viscous dissipation and adiabatic heating and cooling. We also ignore the role of secondary convection in the wedge, which simplifies the models compared to those that taken into account strong thermal or compositional buoyancy in the wedge along with low mantle viscosities (e.g., Billen and Gurnis, 2001; Gerya and Yuen, 2003) The modeled temperature is effectively the potential temperature and we add an adiabatic gradient of 0.5 K/km a posteriori. Given the relatively shallow depths of the subduction zone models this provides an

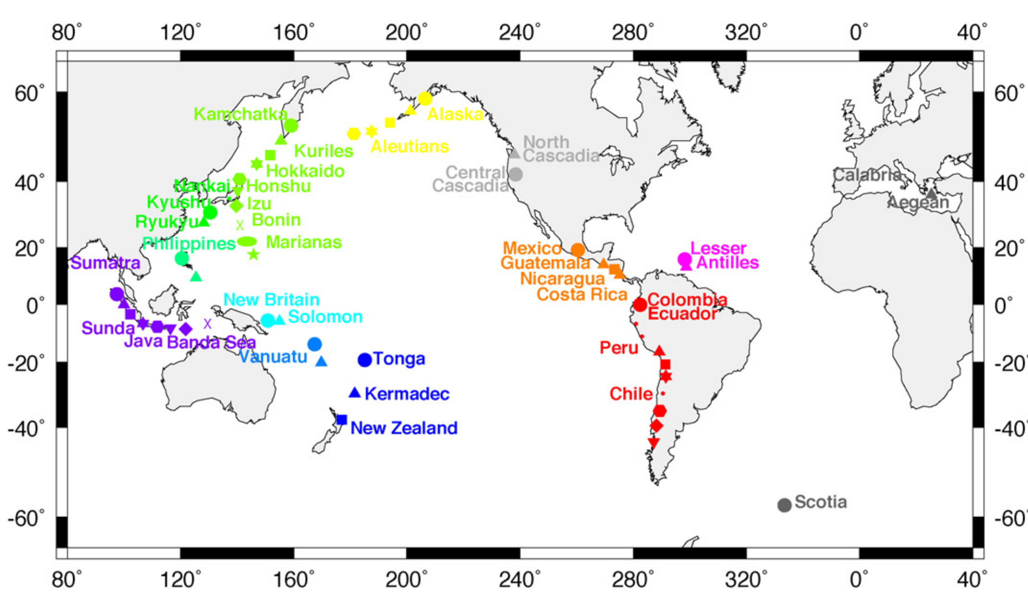

Fig. 1. A map of the subduction zones used in this study, following groupings of Syracuse and Abers (2006). The color and shape of symbols on the map are the same as those used in all following figures to indicate arc segment. Small circles indicate segments of subduction zones that are modeled but have no overlying arc.