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Preface

Thermal structure and dynamics of subduction zones: insights from observations and modeling

Introduction to the special volume on Thermal Structure and Dynamics of Subduction zones

Subduction zones form dominant tectonic features on the Earth and are the site of large underthrusting earthquakes and explosive arc volcanism. They are also the only locations with deep earthquakes in the Earth's interior. Major questions remain regarding the dynamics of subduction zones, including aspects such as the role of water in the formation of arc volcanism and deep earthquakes, the initiation and stress evolution of subduction zones, the temperature and volatile distribution in the deep slab and overlying mantle wedge, and the role of phase transitions in the upper mantle. The 11 papers in this special volume on the Thermal Structure and Dynamics of Subduction zones are based on presentations in a special session of the combined meeting of the European Union of Geosciences (EUG), the European Geophysical Society (EGS) and the American Geophysical Union (AGU), that was held in Nice, France in April 2003. The papers provide a snapshot of current research on these topics, with particular focus on improvements in observational and modeling techniques.

Both *S* and *P* waves that travel long distances along the top of the slab appear dispersed (e.g., Abers and Sarker, 1996). The dispersion is consistent with a constant velocity wave guide of constant thickness. By modifying the method of Gubbins and Snieder (1991), Abers (2005) solves for travel times for waves traveling through a low velocity channel with variable velocity with depth. Using both *S* and *P* waves from events deeper than 100 km recorded at GSN stations between 1992 and 2001, Abers compiles a dataset of 210 *P* waves and 156 *S* waves for study. Abers finds that the data from seven circum-Pacific arcs (Aleutian, Alaska, Hokkaido-S. Kurile, N. Honshu, Mariana, Nicaragua, and Kurile-Kamchatka) are consistent with a wave guide extending to greater than 150 km depth with a low velocity channel 2–8 km thick with anomalies as large as $d\ln V_p = -14\%$ compared with surrounding mantle, although there is substantial variability with depth. Below 150 km the wave guide velocity is close to the surrounding mantle velocity. The low velocities are consistent with either low temperature hydrated mafic rocks or metastable gabbros. The wave guide velocities also vary substantially from arc to arc, correlating with slab dip but not with other subduction related parameters (e.g., plate age, convergence velocity, thermal parameter). Abers favors fluids or hydrous minerals as opposed to variable metastability of anhydrous gabbro as an explanation pointing out that the variability with dip is consistent with fluids from shallow slabs being driven into the mantle wedge while for steeper slabs the fluid preferentially migrates up the sediment layer.

It is critical to understand the relationship between the slab–trench–wedge environment and global plate-mantle flow. Slab thermal models require simplifying assumptions at the boundaries. For example, most slab thermal models assume that the trench and the overriding plate are fixed. Heuret and Lallemand (2005)

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compile a series of observations related to the motion of the overriding plate, trench, and subducting plate for oceanic subduction zones. After excluding regions where continental lithosphere, volcanic arc crust, or oceanic plateaus are subducted, they divide the oceanic subduction zones into 159 segments with a uniform interval of two degrees of trench length. At each sampling location they compile the absolute motion of the overriding plate, the absolute motion of the trench, the subducting plate age, back-arc deformation rate and overriding plate strain regime. The absolute motions are given in the HS3-NUVEL1A reference frame (Gripp and Gordon, 2002). The back-arc deformation rate is calculated using focal mechanisms following the approach of Jarrard (1986). They find that there are as many locations where the trench is advancing as retreating with absolute trench motion limited to 50 mm/yr. There are two distinct populations in the trench motion data: one essentially with a stationary trench (in the absolute frame) and one with a retreat of nearly 50 mm/yr. In addition, there is at best a weak correlation between slab age and trench motion, with older subducting plates tending to be advancing, not retreating as predicted in some numerical models. Finally, they find back-arc extension when the overriding plate is retreating from the trench and back-arc compression when the overriding plate is advancing. The correlation between the absolute velocity of the overriding plate and the style of back-arc deformation is consistent with previous studies (e.g., Jarrard, 1986). They suggest that slabs are ‘partially anchored’ because of the slabs resistance to large-scale lateral flow (e.g., Scholz and Campos, 1995). The spread in the trench velocity data suggests that local flow effects, such as small-scale flow in the vicinity of retreating slab edges or tears or more regional scale flow associated with the shrinking of the Pacific plate area (e.g., Garfunkel et al., 1986) may significantly influence slab-trench dynamics.

Marton et al. (2005) use a thermo-kinetic model of subduction zone thermal structure with a thermal conductivity that depends on pressure, temperature, and mineralogy according to the recent study by Xu et al. (2004). Unlike the calculations in Peacock et al. (this issue), Conder (this issue), Arcay et al. (this issue), and Manea et al. (this issue), these calculations do not consider variable rheology. In fact, the entire slab is treated as an undeforming rigid body with advection of heat along the strike of the slab and diffusion perpendicular to it (cf., Minear and Toksoz, 1970). The thermal conductivity decreases exponentially with increasing temperature. The effect of pressure is much smaller, especially over the depth range of the upper mantle. In most cases the pressure dependence is neglected. They consider models with only lattice conductivity as well as models that include radiative transfer. With the effect of radiative transfer, they conclude that thermal conductivity of the slab could increase by more than 50%, leading to a 50–100 degree increase in the temperature of the interior of the slab compared to that in a standard model with uniform thermal conductivity. This result is independent of the slab geometry as represented by varying the thermal parameter (i.e., the vertical decent of the slab times the age of the lithosphere at the trench). Marton et al. use these models to address the question of olivine metastability and the ability of a metastable wedge to explain the pattern of deep seismicity. They conclude that the deepest earthquakes occur in regions that have already transformed to wadsleyite or ringwoodite, even when taking into account all of the uncertainties in their parameterization. In the case of Tonga the deepest earthquakes extend 140 km beyond the olivine metastability region.

The Mediterranean has had a complicated recent tectonic history with multiple subduction zones and stages of activity, including wide-spread back arc spreading, arc volcanism and continental collision. Carminati et al. (2005) investigate the differences between the Apennine subduction zone, where convergence has included slow subduction of continental material, and the more southerly and faster subduction of oceanic lithosphere in the Calabrian arc. The latter region is characterized by active arc volcanism and deep seismicity to nearly 500 km, while the former lacks volcanism and experiences seismicity only to shallow depths (less than 90 km). Carminati et al. investigate the hypothesis that the different depth extent of the Wadati-Benioff zone between the two arcs is due to the change in subduction from continental to oceanic material. This hypothesis is tested by using thermal models that predict the rheology in the slab, with particular focus on the depth of the brittle–ductile transition. The modeling includes the effects of crustal radiogenic heating and the olivine-to-spinel phase transition. The modeling shows that the maximum depth of the shallow and intermediate earthquakes to a depth of 350 km can be satisfactorily explained by the differences in composition and the subduction velocity, with the higher velocity in the Calabrian arc (3 cm/yr versus 1 cm/yr for the Apennine subduction) accounting for the persistence of a deeper cold portion in the slab. Modeling of the olivine–spinel phase transition in the Calabrian arc suggests the existence of metastable olivine to a depth of 430 km, which corresponds reasonably well with the maximum depth of seismicity in this arc.

The Vrancea zone in the south-east Carpathians of Romania is the site of occasionally destructive intermediate seismicity. The seismogenic nature of this zone is generally attributed to the dynamics of a relic and potentially delaminated slab (e.g., McKenzie, 1972; Sperner et al., 2001). Ismail-Zadeh et al. (2005) explore the stress state induced by the sinking of such a slab using a three-dimensional finite element model of instantaneous mantle flow and tectonic stress. The model incorporates results from the recent CALIXTO tomography experiment (Martin et al., 2001), seismic refraction studies, and constraints from gravity and heat flow. The high velocity body imaged in the tomography reaches a depth of 350 km, whereas the seismicity ends abruptly at 160 km depth. The preferred model for the instantaneous flow in this area uses realistic rheological values for the mantle and predicts areas of surface uplift and subsidence that correspond well to the observed surface motions. The model evaluates the stress in the mantle and finds maximum shear stress and horizontal compression in a zone that corresponds well with the Vrancea seismogenic zone with its limited depth extent. While uncertainties in the tomographic interpretation and model assumptions are acknowledged, it is encouraging to find good correspondence between the observed and model stress state. This model strengthens the hypothesis of the existence of a remnant slab below the Carpathians with a depth extent that exceeds that of the seismicity.

The two previous papers deal with particular examples of the closing stages of subduction, when the cold oceanic lithosphere which provides the main driving force for subduction has been largely consumed. Upon closure of an ocean basin subduction along the margin may continue but will start involving the dynamic effects of the buoyant continental crust which provides a major resistive force to subduction. Examples of this process on a large scale include the indentation of India with Asia and that of Arabia with Eurasia. Regard et al. (2005) use laboratory experiments to study the tectonic effects of indentation with applications to the latter example. The experimental set up includes a layering of sand and silly putty to mimic the brittle–ductile layering of the lithospheric rheology. The 3D experiments model subduction with variable size continents that allows the study of the effects of a lateral transition between subduction and collision. The two experiments presented by Regard et al. differ in the length of the subduction slab at the time continental collision starts. The results suggest that the upper plate deformation is quite dependent on the history of subduction. Compression in the case with a short slab, following the closure of a small ocean basin, suggests that significant continental subduction occurs before the indenter geometry appears. The tectonic evolution is predicted to be markedly different in the case where a larger ocean basin has been subducted. The strong slab pull at the time of continental collision causes the slab to break off, first below the continental part of the collision zone, followed by a lateral propagation of the tear below the oceanic part. This is quite similar to the scenario proposed by Wortel and Spakman (2000) for the Mediterranean–Carpathian region. It is suggested that the two different scenarios presented in this paper represent the asymmetry seen in the active subduction occurring on the western and eastern sides of the Arabian–Eurasian continental collision.

Pysklywec and Ishii (2005) examine the impact of the dynamics of subducted slabs in the transition zone on plate boundary dynamics. These models greatly simplify the complex thermo-mechanical properties in the subduction zone and wedge and focus on the interaction between the larger-scale mantle flow and subduction zones. 2D numerical models are employed with the slab flux through the transition zone is impeded by both phase transformation and an increase in viscosity. They considered models with a stagnant, deflected slab within the transition zone and models with stagnant cold material that is not directly connected to the overlying subduction zone. They find that continuity between the shallow slab and the deeper transition zone governs the extent to which the ‘avalanche’ influences the plate boundary. When the slab is continuous from the trench through the transition zone it acts as a barrier limiting lateral flow through the upper mantle. This is similar to the ‘slab anchoring’ effect described by Heuret and Lallemand (2005). In the models where the cold material in the transition zone is not connected to the shallow subduction zone, the avalanche-induced lateral flow in the upper mantle can have a significant effect on the plate boundary. For example, if the avalanche is below or forward of the arc, the avalanche-induced flow leads to increased trench migration. If the avalanche occurs over the back arc, it can lead to a reversal of subduction polarity. While simplifications have been made to keep the models tractable, their results clearly show that the deeper mantle can significantly influence the slab geometry and subduction zone dynamics.

Arcay et al. (2005) model subduction zone thermal structure with a viscous mantle including dehydration reactions and a rheology that depends on water content. They use a combination of fixed and free-slip boundary conditions to create a uniform plate and deformable subducting slab. The use of a 7 km thick layer of weak crustal material along the top of the domain that is ‘subducted’ to 47 km on a 30° oblique angle (initial condition) provides a weak ‘decoupling zone’ that enables the development of asymmetric subduction. The rheology is a function of pressure, temperature, strain rate (i.e., non-Newtonian) and water content. Consistent with other recent modeling of subduction zone thermal structure (e.g., Van Keken et al., 2002; Conder et al., 2002; Kelemen et al., 2004) they find that non-Newtonian rheology leads to a warmer slab surface temperature and greater erosion of the overlying plate than in isoviscous corner flow models. At high convergence rates, serpentine can be transformed into hydrated phase A, leading to recycling of water to significant depth (e.g., Staudigal and King, 1992). However, even in these cases, the mantle wedge is significantly hydrated within 250 km of the trench. This effectively broadens the low-viscosity zone near the tip of the slab wedge. Arcay et al. speculate that the effect of this hydrated weak wedge region may contribute to back-arc deformation.

Recently there has been a renewed focus on improved rheological descriptions in for subduction zones, made possible largely by the ability to use sufficient numerical resolution to accurately solve the governing equations. An important class of models involves a combined kinematic-dynamic description, where the slab velocity is prescribed but the flow in the hot mantle wedge is modeled dynamically. While the improvements in the description of the wedge rheology has led to new insights regarding the temperature conditions and evolution of subduction zones (see e.g., Arcay et al., this issue; Manea et al., this issue; Peacock et al., this issue), the description of the overriding plate and its decoupling with the subducting plate remains arbitrary. Conder (2005) provides a comparison of model techniques that have been used and suggests a approach that incorporates new rheological criteria. There are two traditional approaches to model the decoupling. The first assumes that both the overriding plate and wedge have viscous rheology and provide a decoupling using a weak zone, or a slipping fault. The second approach defines the overriding plate as a rigid zone below which the subducting slab couples with the viscously defined mantle wedge. Assumptions about the depth of decoupling, type of weak zone or slipping fault parameters are not well constrained by observations and this can lead to significant variations in for example the predicted temperatures in the wedge and subducting slab. Conder suggests a new formulation in which ambient temperature and strain rate define the brittle–ductile transition. This in turn defines the depth at which the boundary condition between slab and overriding plate changes from fully decoupled to fully coupled. A model comparison for a simple, but representative subduction geometry shows encouraging behavior, and compares well with observations of heat flow, seismic velocity, and seismic attenuation. An important consequence of this approach is that the slab surface temperature is generally higher than observed in other models, which may provide an explanation for the geochemical signatures for sediment melting in some subduction zone.

The final two papers in this volume provide improved numerical models for the influence of the subducting Cocos plate on the volcanism in Central Mexican Volcanic Belt (Manea et al., 2005) and in Nicaragua and Costa Rica (Peacock et al., 2005).

The Guerrero subduction zone in Mexico is characterized by a large segment of flat subduction with a distant volcanic arc. Previous models of this subduction zone (e.g., Currie et al., 2002) use an isoviscous mantle wedge which leads to quite low temperatures below the volcanic arc. Manea et al. systematically investigate the influence of temperature-dependent rheology on the temperature structure in the slab and wedge and find that the strong temperature-dependence causes significantly higher temperatures below the volcanic arc and predicts melting of wet peridotite in the mantle wedge. Temperatures at the slab–wedge interface are also sufficient to allow for a slab contribution to the arc volcanism from the melting of hydrated sediment and oceanic crust. This is in agreement with geochemical observations of magmas in the Central Mexican Volcanic belt that suggest the presence of both slab and mantle sources. The predicted flow structures are used to study the rise of low viscosity blobs that can mimic the buoyant rise of melt. Manea et al. use the location of the Popocatepetl volcano to estimate that magmatic blobs need to be larger than 10 km in diameter to be able to have reasonable trajectories in the mantle wedge with realistic estimates for viscosity. Smaller blobs can rise only if unrealistically low viscosities are assumed.

The Central American subduction zone in Nicaragua and Costa Rica is characterized by rapid convergence of young oceanic lithosphere. There are minor changes along strike of this subduction zone in the convergence speed and age of the lithosphere. Interestingly, dramatic variations in the depth of the seismicity and the geochemistry of arc volcanism are observed. Peacock et al. (2005) construct new high resolution finite element models along four profiles perpendicular to this subduction zone. The use of realistic stress- and temperature-dependent rheology in the mantle wedge is necessary to have sufficiently high temperature in the mantle wedge below the volcanic arc. The subtle along-strike variations in the convergence speed (increasing to the south west from 79 to 88 mm/yr) and age (decreasing from 24 to 15 Myr) counter act and the predicted slab-surface temperatures are remarkably similar throughout the subduction zone. The differences are larger at shallow depth in the oceanic crust and topmost mantle with maximum differences near 100°. This is primarily caused by the relatively large change in age of the subducting lithosphere which causes significant variations in the temperature-depth profile. A comparison with the phase diagrams for mafic (crust) and ultramafic (uppermost mantle) compositions (Hacker et al., 2003) suggests that the predicted temperature in the uppermost 500 m of the subducting oceanic crust is sufficiently high to cause a small contribution of partial melting if the oceanic crust and sediments are hydrated. More significant amounts of partial melting are predicted due to flux melting in the mantle wedge at a depth of 100 km below the volcanic front. Comparison of the predicted temperatures in the uppermost mantle suggest that dehydration is nearly complete beneath southern Costa Rica, but that significant amounts of water can be transported into the deep mantle below Nicaragua and NW Costa Rica. Yet, the predicted variations in the uppermost crust are not sufficient to explain the large along-strike variations in seismicity and arc geochemistry. It is increasingly likely that these variations are due to regional variations in sediment subduction, crustal structure and the distribution of hydrous minerals in the incoming lithosphere (e.g., Ruepke et al., 2002).

The papers in this collection demonstrate that a more complete model of subduction zone thermal structure will require a better understanding of rheology (Arcay et al., this issue; Manea et al., this issue; Peacock et al., this issue), thermal conductivity (Marton et al., 2005), and dehydration reactions (Arcay et al., 2005). The differences in calculated slab/wedge temperatures from these models have significant implications for melting, dehydration, heatflow, and gravity at subduction zones. These various assumptions and simplifications in thermal models could map into our interpretations. As thermal models become increasingly complex, there is a need for continued improvement of techniques (e.g., Conder, 2005) as well as a need to compare results from different techniques already in use. For example, the authors wonder about the effects of thermal conductivity within the non-Newtonian wedge framework and how more complex rheologies and thermodynamic formulations will impact the interactions of the slab with phase changes and deeper mantle flow. Fortunately, more detailed seismic observations are becoming available (e.g., Abers, 2005) and much more can be learned by detailed study of individual arcs (e.g., Peacock et al., 2005; Manea et al., 2005). There is even more to be gained by reviewing global compilations of observations (e.g., Heuret and Lallemand, 2005).

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