Thermal Structure and Metamorphic Evolution of Subducting Slabs

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Subducting lithospheric slabs represent the cool, downwelling limbs of mantle convection and the negative buoyancy of slabs (slab pull) drives plate tectonics [Forsyth and Uyeda, 1975]. Subduction zones are regions of intense earthquake activity, explosive volcanism, and complex mass transfer between the crust, mantle, hydrosphere, and atmosphere. In this contribution, I focus on the thermal, petrologic, and seismological processes that occur in subducting slabs. The dynamics of the mantle wedge, which is coupled thermally and mechanically to the subducting slab, is discussed in other workshop contributions.

General observations regarding subduction zones

Subduction zones are cool because oceanic lithosphere (the Earth’s cold boundary layer) descends into the mantle more rapidly than heat conduction can warm the slab. The chilling effect of subduction is reflected in surface heat flux measurements < 0.03 W/m² in subduction-zone forearcs (one-half of the average global surface heat flux). In well-studied subduction zones like Cascadia, forearc heat flux decreases systematically from the trench to close to the volcanic front [Hyndman and Wang, 1995]. Cold subducting slabs are well resolved as high-velocity regions in seismic tomography studies [Zhao et al., 1994]. Low-temperature, high-pressure metamorphic rocks (blueschists, eclogites) characterize paleosubduction zones and provide an important record of the unusually cool temperatures at depth in subduction zones.

Despite being cool, almost all subduction zones are distinguished by active arc volcanism which in turn requires that rocks melt in subduction zones. Early thermal models of subduction zones assumed a priori that arc magmas represented direct melts of the subducting slab and these models incorporated very high rates of shear heating [Oxbergh and Turcotte, 1970; Turcotte and Schubert, 1973]. Over time this view has evolved and most arc magmas are currently thought to represent partial melts of the mantle wedge induced by the infiltration of aqueous fluids derived from the subducting slab [e.g., Gill, 1981]. The origin of arc magmas, however, remains an area of active research and debate.
Thermal structure of subducting slabs

The thermal structure of subduction zones has been investigated by various analytical [e.g., Molnar and England, 1990] and numerical techniques [e.g., Toksoz et al., 1971; Davies and Stevenson, 1992; Peacock et al., 1994]. These studies have identified a number of important parameters which control the thermal structure including: (1) the convergence rate, (2) the thermal structure of the incoming lithosphere which is primarily a function of age, but is also affected by hydrothermal cooling and the thickness of insulating sediments, (3) the geometry of the subducting slab, (4) the rate of shear heating, and (5) the vigor and geometry of flow in the mantle wedge [see review by Peacock, 1996].

In general, there is good agreement among the different thermal models presented in the literature and much of the apparent variation in thermal structures results from different rates of shear heating (= shear stress x convergence rate). A number of recent studies suggest shear stresses in subduction zones are on the order of 10-30 MPa [e.g., Tichelaar and Ruff, 1993; Zhong and Gurnis, 1994; Peacock, 1996; Peacock and Wang, 1999] and that shear heating, while important, is not the primary control on subduction-zone temperatures.

The biggest uncertainties in determining the thermal structure of subduction zones results from uncertainties in the flow mantle wedge, a major topic of this workshop. Qualitatively, the subducting slab induces convection in the mantle wedge through viscous traction and thermal coupling. Induced mantle-wedge convection warms the subducting slab and a cool boundary layer forms in the mantle wedge adjacent to the slab [e.g., Kincaid and Sacks, 1997]. Another major source of uncertainty lies in the variation of thermal conductivity as a function of pressure ($P$) and temperature ($T$).

Recently, we have constructed a set of two-dimensional, finite-element, kinematic thermal models of specific subduction zones in order to test our models against seismological and magmatic observations. Thermal models constructed for NE Japan (a relatively cool subduction zone) and SW Japan (a relatively warm subduction zone) are depicted in Figure 1. Oceanic crust subducted beneath southwest Japan is 300 °C to 500 °C warmer than beneath northeast Japan [Peacock and Wang, 1999]. At 50 km depth, the calculated temperature along the slab-mantle interface is only 200 °C for NE Japan as compared to 500 °C for SW Japan. Beneath the volcanic front the slab-mantle interface temperature is 500 °C in NE Japan as compared to >800 °C in SW Japan. In both subduction zones, maximum mantle-wedge temperatures beneath the volcanic front are ~1200 °C.
Metamorphic evolution of subducting slabs

During subduction, sediments, oceanic crust, and oceanic mantle undergo metamorphic transformations which increase the density of the subducting slab. Many of these reactions involve the breakdown of hydrous minerals and release substantial amounts of H$_2$O. Some of the water released from the subducting slab hydrates the overlying mantle which dramatically alters the rheological properties of the wedge. In the Mariana forearc, active serpentine mud volcanoes provide dramatic evidence for hydration of the mantle wedge [Fryer et al., 1999]. Serpentine and other hydrous minerals in the forearc mantle may control the downdip limit of subduction thrust earthquakes [Hyndman et al., 1997; Peacock and Hyndman, 1999]. At depths >100 km, water released from the subducting slab can trigger partial melting in the overlying mantle wedge.

The volume and composition of pelagic and terrigenous sediments subducted in different subduction zones varies considerably [von Huene and Scholl, 1991]. At relatively shallow depths (<10 km), pore waters are expelled by sediment compaction and bound water is released at $T \sim 80$-150 °C during the transformation of opal to quartz and clay to mica. In warm subduction zones, mica will dehydrate and/or partially melt at $T \sim 800$ °C.

Most of the water liberated from subducting slabs at depths > 10 km is derived from the variably hydrated basalts and gabbros of the subducting oceanic crust [e.g., Peacock, 1990]. At temperatures of perhaps 300-500 °C substantial amounts of pore water may be expelled from the uppermost basaltic section by porosity collapse. Alternatively, this pore water may react to form low-temperature minerals such as zeolites which subsequently dehydrate. The progressive metamorphism of metabasalts involves complex, continuous reactions and calculated $P$-$T$ paths for subducting oceanic crust pass through a region of $P$-$T$ space where experiments are difficult to conduct. The most important reactions in subducting oceanic crust involve the transformation to eclogite, a relatively dense, anhydrous rock consisting primarily of garnet and omphacite (Na-Ca clinopyroxene). In a given subduction zone, the depth and nature of eclogite formation and slab dehydration reactions depends on the $P$-$T$ conditions encountered by the subducting oceanic crust. In the relatively warm SW Japan subduction zone the transformation to eclogite may occur at ~50 km depth. In contrast, calculated $P$-$T$ paths for relatively cool subduction zones like NE Japan pass through the blueschist facies and eclogite may not form until depths > 100 km (Figure 2). In warm subduction zones, such as SW Japan, subducted sediments and the uppermost oceanic crust may possibly melt. Calculated $P$-$T$ paths intersect partial melting reactions at ~100 km depth in agreement with the presence of adakites (dacitic lavas inferred to represent partial melts of mafic rocks) in warm subduction zones.
In the subducting mantle, olivine transforms to spinel at depths of 350 to 670 km and then to perovskite + magnesiowustite at 670 km depth \[e.g., Kirby \textit{et al.}, 1996a\]. These solid-solid reactions increase the density of the subducting slab. A number of studies \[\textit{e.g.}, Green and Burnley, 1989; Kirby \textit{et al.}, 1991; 1996a\] suggest that deep-focus earthquakes (>300 km depth) may be caused by transformational faulting associated with the metastable reaction of olivine to spinel.

**Testing the Thermal-Petrologic Models**

Lacking the ability to drill holes to 100 km depth, we must use indirect methods, such as seismological and geochemical observations, to test our thermal-petrologic models of subduction zones.

In global and regional seismic tomographic studies, subducting slabs are readily imaged as high velocity, low attenuation regions which reflect the overall cool nature of the slab \[\textit{e.g.}, Zhao \textit{et al.}, 1994\]. More detailed seismological investigations, using converted phases and waveform dispersion, have revealed a thin (<10 km thick), dipping low-velocity layer coinciding with the zone of thrust and intermediate-depth earthquakes \[\textit{e.g.}, Hasegawa \textit{et al.}, 1994; Helffrich, 1996; Abers, 2000\]. The seismic velocity of eclogite is comparable to mantle peridotite, thus the dipping low seismic-velocity layer is generally interpreted as subducted oceanic crust that has not transformed to eclogite. The low-velocity layer extends to 60 km depth beneath SW Japan and to 150 km depth beneath NE Japan, in good agreement with the predicted depth of eclogite transformation (Figure 2) \[Peacock and Wang, 1999\].

Subduction zones are regions of intense earthquake activity reflecting stresses generated by the interaction between the forces that drive and resist subduction, slab flexure, thermal expansion, and metamorphic densification reactions \[\textit{e.g.}, Spence, 1986\]. At depths > 40 km, high pressure and temperature should inhibit brittle behavior, but earthquakes in subduction zones occur as deep as 670 km. Kirby \textit{et al.} \[1996b\] proposed that intermediate-depth earthquakes (50-300 km depth) are triggered by dehydration embrittlement associated with the transformation of metabasalt/metagabbro to eclogite within subducting oceanic crust. The depth extent of intraslab earthquakes in NE and SW Japan agrees well with the predicted depth of dehydration reactions in the subducting oceanic crust \[Peacock and Wang, 1999\].

Paleosubduction zones containing blueschists and low-temperature eclogites provide insight into the thermal and petrologic structure of subducting slabs. These metamorphic rocks record subsolidus conditions and are consistent with thermal models with modest to no shear heating \[\textit{e.g.}, Peacock, 1996\]. Blueschist-facies metabasaltic clasts recovered from a serpentine mud volcano in the Mariana forearc record \(T = 150-250 \, ^{\circ}C\) at \(P = 0.5-0.6 \, \text{GPa}\) \[Maekawa \textit{et al.}, 1993\] and suggest shear stresses of \(\sim 20 \, \text{MPa}\) along the subduction thrust.
[Peacock, 1996]. Many hydrous minerals are stable in blueschists and low-temperature eclogites including sodic amphibole, lawsonite, phengite (mica), chlorite, and zoisite. These minerals are capable of transporting H$_2$O to depths > 200 km in subduction zones.

Arc lavas provide important information about the subduction factory and petrological and geochemical data may be inverted to gain insight into the thermal and petrologic structure at depth. Basalts are common in many arcs which argues for partial melting of the ultramafic mantle wedge as opposed to the mafic oceanic crust. Specific minor and trace elements of arc lavas (e.g., large-ion lithophile elements, B, Be) appear to be derived from the subducting slab [e.g., Gill, 1981; Hawkesworth et al., 1993; Davidson, 1996]. Most of these elements are readily transported in aqueous fluids, but recent experimental data suggest that the efficient transport of Be and Th from slab sediments into arc magmas may require sediment melting [Johnson and Plank, 1999]. Sediment melting requires temperatures > 800 °C at 3 GPa; such high temperatures are inconsistent with most thermal models and seismological observations. This inconsistency merits further study.

**Future avenues of research**

There are a number of important subduction-zone processes which are poorly understood at present and limit our understanding of the “subduction factory”. In my opinion, some of the most important questions to be investigated are (1) the vigor and geometry of mantle-wedge flow induced by the subducting slab and upper-plate extension; (2) variations in thermal parameters and rheology as a function of $P$, $T$, and composition; (3) metabasaltic phase equilibria and reaction kinetics at low temperatures and high pressure (e.g., 500 °C and 3 GPa); and (4) the amount and distribution of H$_2$O in the oceanic crust and mantle prior to subduction.
Figure 1. Calculated thermal structure of NE Japan and SW Japan (Nankai) subduction zones [after Peacock and Wang, 1999].
Figure 2. Calculated P-T paths and metamorphic conditions encountered by oceanic crust subducted beneath NE and SW Japan [after Peacock and Wang, 1999]. Hydrous minerals stable in the eclogite facies shown in italics [Poli and Schmidt, 1995]; partial melting reactions in red [see references in Peacock et al., 1994].
References Cited


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