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Editorial

Processes and consequences of deep subduction: introduction

1. Introduction

Subduction of slabs of oceanic lithosphere into the deep mantle involves a wide range of geophysical and geochemical processes and is of major importance for the physical and chemical evolution of the Earth. For example, subduction and subduction-related volcanism are major processes through which geochemical components are recycled between the Earth's crust, lithosphere and mantle. A large proportion of the world's earthquakes and volcanoes are related to subduction. Volcanism results from a range of processes including dehydration, melting and melt migration. The deepest known earthquakes occur in subducted lithosphere at depths of 660–700 km but their cause, which has long fascinated geophysicists, is still enigmatic. In addition, the motion and velocities of lithospheric plates at the Earth's surface are controlled largely by the buoyancy forces that drive subduction.

Because of the wide variety of processes involved, subduction zones can be regarded as natural laboratories through which dynamic behavior in the Earth's mantle can be studied. Many physical and chemical processes interact during subduction, and the complexity of the system necessitates an interdisciplinary approach involving seismology, mineral physics, geochemistry, petrology, structural geology, rock mechanics, and geodynamic modeling. For example, phase transformation kinetics determine buoyancy, rates of subduction and, therefore, thermal structure, with the latter feeding back to affect the kinetics. Rheology and therefore large scale slab dynamics may also be affected by mineral transformations and their kinetics. Seismology provides constraints on the elastic properties and the geometry of the down going plate as well as on the processes involved in deep earthquakes.

In September 1999, a 5-day interdisciplinary Alfred-Wegener Workshop, to discuss the major advances that have been made in recent years was conducted. A total of 56 contributions, consisting of keynote talks and posters, were presented (see Terra Nostra 99/7; Alfred-Wegener-Stiftung Berlin, 1999, for abstracts). Topics discussed included thermal structure and buoyancy forces, rheology of mantle minerals, stabilities of hydrous minerals, partial melting and the mechanisms and rates of melt migration, kinetics of phase transformations, mechanisms of deep earthquakes, geochemical recycling, and the processes of continental collision that result from subduction. The papers contained in this volume have resulted primarily from this workshop and have been contributed mostly by keynote speakers. Many of the papers contain a strong review element and it is our intention that this volume will serve as a comprehensive reference source for researchers in the coming years.

2. Complex interaction of slabs and upper mantle transition zone

One fundamental problem concerns the depth to which subducted lithosphere penetrates into the mantle because this is related to the scale of mantle convection and the Earth's evolution over time. Although Isacks and Molnar's (1971) pioneering work on slab seismicity allowed alternative views, the cessation of deep-focus earthquakes at a depth of ~700 km has often been used in arguments against the penetration

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of subducting slabs beyond the 660 km seismic discontinuity and, thus, in favor of the layering of mantle convection at that depth. In recent years, however, seismic imaging has revealed that some subducting slabs penetrate deep into the lower mantle.

Between the mid 1970s and late 1980s, Jordan and his co-workers used anomalous travel times, projected on to the so-called “residual sphere”, and wave forms of seismic body waves to argue for the presence of subducted slabs in the lower mantle beneath convergent margins in central America and the western Pacific (Jordan and Lynn, 1974; Jordan, 1975, 1977; Creager and Jordan, 1984, 1986; Fischer et al., 1991). These early claims for slab penetration across the 660 km discontinuity were confirmed by regional, high-resolution tomographic studies by van der Hilst and Spakman (1989), van der Hilst et al. (1991) and Fukao et al. (1992) (see van der Hilst et al. (1998) for a review). However, along with the detailed analysis of subduction zone seismicity (e.g. Okino et al., 1989; Ekström et al., 1990; Lundgren and Giardini, 1994) these studies also indicated that the morphology and fate of subducted slabs are more complex than expected from the end-member models of either whole mantle flow or convective layering at 660 km depth. Apparently, slabs can deflect horizontally in the upper mantle transition zone beneath some convergent margins whereas penetration to lower mantle depths can occur beneath other island arc segments. The different styles of subduction across the upper mantle transition zone, which are also borne out in recent global tomography studies (e.g. Bijwaard et al., 1998; Kárason and van der Hilst, 2000), are illustrated in Fig. 1 and have been interpreted in terms of the combined effects of relative plate motion and downward flow in a stratified mantle (Kincaid and Olson, 1987; Gurnis and Hager, 1988; van der Hilst and Seno, 1993; Griffiths et al., 1995; Guillou-Frottier et al., 1995; Davies, 1995; Zhong and Gurnis, 1995; Christensen, 1996, 2001), the weakening of the slab due to grain size reduction during phase transformations (Riedel and Karato, 1997; Karato et al., 2001), or the interaction of the subducting slab with localized upwellings (Gurnis et al., 2000). van der Hilst et al. (1997) and Grand et al. (1997) pointed out that many slabs have sunk into the lower mantle, in particular beneath America and southern Asia and Indochina, but Fig. 1 suggests that in the current snap-shot of convection not all of these deep slabs reach the core mantle boundary (van der Hilst and Kárason, 1999; Kárason and van der Hilst, 2000).

3. Slab dynamics and rheology

The first four papers in this volume are concerned with the dynamics of subduction, the interaction of the slab with upper mantle discontinuities, and the influence of slab mineralogy. King (2001) focuses on several classical subduction issues, including the variation in dip angle of subducted slabs in the upper mantle, the unbending of the downgoing plate, and the topography of deep sea trenches. Christensen reviews numerical and analog (laboratory) models of deep subduction and discusses the mechanisms that can produce the complex morphologies of lithospheric slabs as inferred from tomographic images. An increase of intrinsic density or viscosity with depth as well as phase transitions with a negative Clapeyron slope can all inhibit or delay deep subduction, and the tectonic conditions and the relative motion of the tectonic plates at Earth’s surface can also play an important role. Collier et al. (2001) present observational evidence from converted seismic waves for topography on the upper mantle discontinuities that mark the phase transitions of olivine to wadsleyite (at a global average depth of 410 km) and ringwoodite to perovskite and magnesiowustite (near 660 km depth). For the convergent margins studied, their data suggest that the olivine $\rightarrow$ wadsleyite transition occurs under (thermodynamic) equilibrium conditions. While the location of the discontinuity cannot be constrained everywhere in the slab, this result argues against the existence of a wedge of metastable olivine. Bina et al. (2001) discuss effects of slab mineralogy and phase chemistry on subduction dynamics (e.g. buoyancy, stress field), kinematics (e.g. rate of subduction and plate motion), elasticity (e.g. deformation and seismic wave speed), thermometry (effects of, e.g. latent heat, isobaric superheating), and seismicity (e.g. as due to adiabatic shear instabilities).

The next two papers deal with the rheology of mantle minerals, which is clearly of considerable importance in controlling the subduction process. Because of experimental limitations, rheology is exceedingly difficult to study experimentally at pressures of the transition zone and lower mantle (e.g. Karato and Rubie,

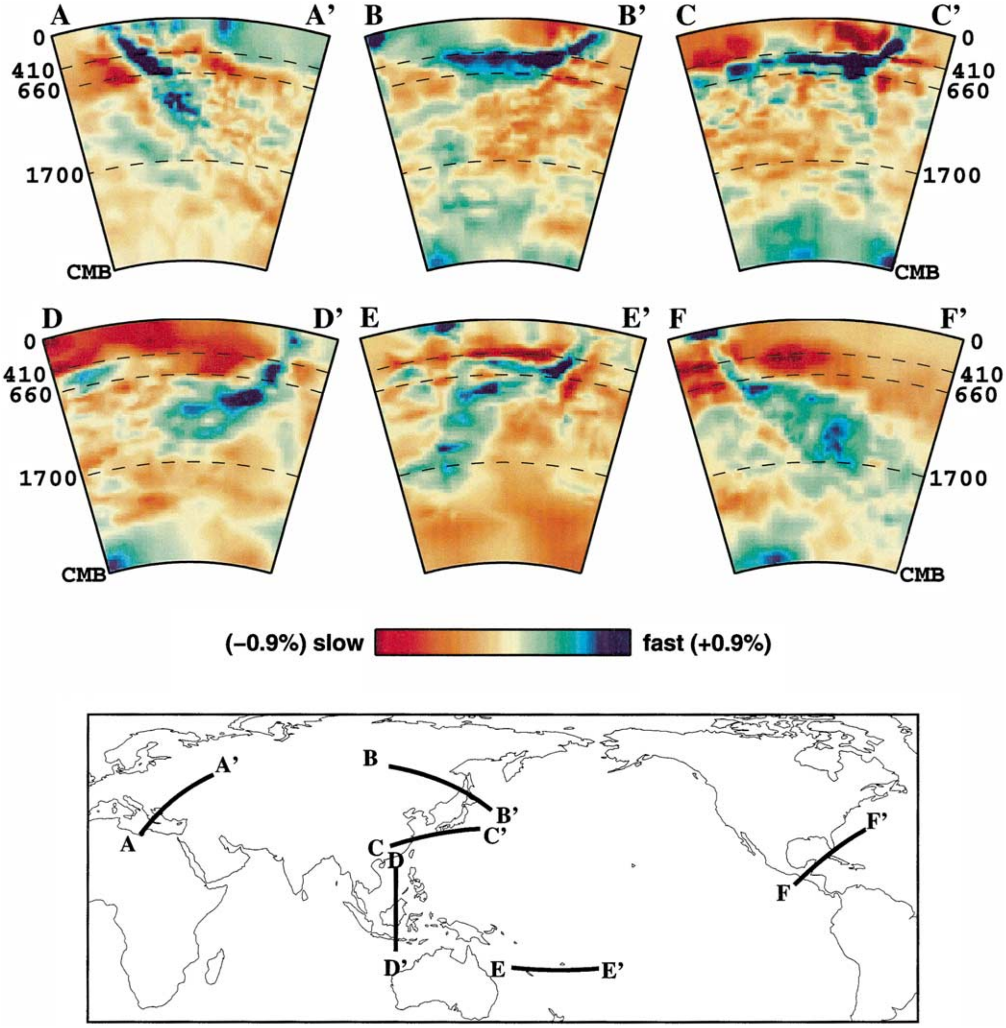

Fig. 1. Slab structure illustrated by vertical mantle sections across: (A) the Hellenic (or Aegean) arc; (B) the southern Kurile arc; (C) Izu Bonin; (D) the Sunda arc (Java); (E) the northern Tonga arc, and (F) central America (see Kárason and van der Hilst (2000) for more details).

1997). Weidner et al. (2001) have utilized an indirect method based on in situ stress measurements determined from the broadening of X-ray diffraction peaks. Sample strains can also be determined directly by in situ X-ray imaging techniques. Although the strains involved in these experiments are small, so that derivations of "steady-state" flow laws might be uncertain, the experimental approach has considerable potential. They review data for major mantle minerals and conclude that increases in strength are likely to occur as olivine transforms first to wadsleyite and ringwoodite and subsequently to perovskite + magnesiowüstite. Based on correlations between strength and temperature, they suggest that deep seismicity is likely to result from plastic instabilities, with the distribution of earthquakes being related to strength distribution and therefore slab mineralogy. Karato et al. (2001) propose a complex rheological structure for subducting slabs due to the effects of grain size reduction during phase transformations. Based on their model, rapidly-subducting and therefore relatively cold slabs should be weaker than slowly-subducting warm slabs.

They apply this model to explain the observed interactions of slabs with the 660 km discontinuity and, for example, how some slabs flatten out at the 660 km discontinuity — a feature previously explained by trench migration (e.g. van der Hilst and Seno, 1993).

4. Deep earthquakes

In their characterization of subduction zone seismicity, Isacks and Molnar (1971) noticed that not all seismic zones in subducted slabs are continuous and that some deep events seem to occur isolated from those at shallower depths. The continuity of the slab across gaps in the Wadati–Benioff seismic zone between deep earthquake clusters and shallow seismicity has been debated. Following an approach similar to the study of high-frequency wave propagation in slabs by, for instance, Barazangi et al. (1972), Snoke et al. (1974), Gubbins and Snieder (1991), van der Hilst and Snieder (1996) and Okal (2001) uses the observation and triggering mechanism of high-frequency oceanic "T" waves to argue for the mechanical continuity of (most) slabs across the deep seismicity gap. He argues that only the deep earthquakes beneath the north Fiji basin (the so-called Vityaz cluster) and the deep events beneath New Zealand may occur as detached events with no mechanical connection to the surface.

A problem that has concerned geophysicists for many years is how to explain the occurrence of deep earthquakes (e.g. Kirby, 1987). About 10 years ago, "transformation faulting" (or "anticrack" mechanism) was proposed as the mechanism for deep earthquakes largely on the basis of experimental observations (Kirby, 1987; Green and Burnley, 1989; Kirby et al., 1991; Burnley and Green, 1991). This mechanism involves a shear instability that develops during the incipient transformation of metastable olivine to wadsleyite or ringwoodite. The high-pressure phase is postulated to form in the shear zone with an ultra-small grain size that allows high-strain rate deformation to occur by grain size sensitive creep. Although this mechanism appeared to provide an appealing explanation for deep earthquakes (e.g. Kirby et al., 1996), most evidence for its operation is based on experiments performed on analogue materials at low pressures. There has been only one brief report, over 10 years ago, that transformational faulting might occur at transition zone pressures (Green et al., 1990) but this result has not been confirmed subsequently. Several papers in this volume address this issue from the perspectives of seismology and mineral physics.

Wiens (2001) reviews empirical parameters (e.g. fault dimension, focal mechanism, stress drop, temporal and spatial aspects of after shock sequences, magnitude–frequency relationships (*b*-values)) of deep earthquakes ($z > 300$ km) in comparison with shallow ($z < 70$ km) and intermediate depth events (70 km $< z <$ 300 km). He documents the lack of a seismically-detectable "wedge" of metastable olivine (see also Collier et al., 2001) and argues against both transformational faulting and dehydration-induced faulting based on the large fault dimensions of some deep earthquakes. Instead, he presents evidence for the sensitivity of deep earthquakes to the temperature of the slab and, thus, favors a temperature-activated phenomenon. Based on extrapolations of experimental kinetic data combined with two-dimensional thermal models of subduction zones, Mosenfelder et al. (2001) conclude that the maximum depths of olivine metastability are considerably less (perhaps by 200 km or more) than the depths of the deepest seismicity; the latter cannot therefore be explained by transformational faulting. This conclusion contrasts with results of previous studies in which thermokinetic models were based on olivine $\rightarrow$ spinel kinetic data from analog compositions such as Mg_2GeO_4 and Ni_2SiO_4 (e.g. Rubie and Ross, 1994; Kirby et al., 1996). Several papers in the volume thus reach a consensus, based on different approaches, that deep earthquakes result from thermal shear instabilities involving thermal run away and possibly localized melting, rather than from transformational faulting.

5. The effects of water and hydrous phases

Recently, the effect of water and hydrous phases on rheology, melting, phase chemistry, and earthquake triggering has received substantial attention. The stability of hydrous phases in subduction zones is reviewed by Angel et al. (2001). This topic is critical for evaluating a number of issues, including the causes of subduction-related volcanism through hydrous melting, dehydration embrittlement as a possible cause of intermediate and deep earthquakes, the reduced seismic wave speed in the mantle wedge above the slab beneath and beyond the volcanic arc (see also Zhao, 2001), and the possibility that water is transported into and stored in the lower mantle. Angel et al. (2001) conclude that slabs are likely to dehydrate as they enter the lower mantle. Based on elasticity data, they further conclude that the seismic detection of even significant amounts of hydrous phases in slabs may be difficult or impossible. The subsequent three papers consider some of these issues in the context of shallow processes in the slab and overlying mantle wedge.

Zhao (2001) reviews recent findings on the structure, magnetism, and dynamics of subduction zones. In particular, he presents evidence for the continuation of the low wave speed, high attenuation (low *Q*), and seismically anisotropic wedge to near 400 km depth beneath some back arcs. He argues that this may be explained by the persistence of hydrous phases to (and perhaps beyond) that depth and that magnetic systems are not limited to near-surface regions of the mantle. He also discusses links between dehydration of the slab, rupture nucleation and crustal earthquake triggering. The role of water in promoting partial melting of peridotite and how its presence affects the composition of partial melts are reviewed in detail by Ulmer (2001). In addition to significantly reducing the melting temperature, small amounts (0.1–0.5 wt.%) of H_2O in the source region can explain both the major element (magnesian-poor and silica-rich) and trace element characteristics of arc magmas and results in 1–7 wt.% H_2O in basaltic to picritic primary liquids. The necessity of high temperatures (1250–1300°C) in the melting regions is emphasized. Isotopic fractionation and transport during dehydration and fluid–rock interaction are discussed by Nakano and Nakamura (2001) using boron isotopes as an example. Boron contents and boron isotopic compositions of metasediments from the Sambagawa metamorphic belt, Japan, indicate a lack of bulk fluid–rock boron isotope fractionation during devolatilization. Boron that is contained in muscovite and chlorite at lower grades is found in tourmaline in the high-grade rocks.

6. Subduction and orogeny

The final two papers, by Ernst (2001) and O'Brien (2001), respectively, review the effects of subduction of crustal rocks during continental collision. Following subduction to depths greater than 90 km, slices of continental crust have been exhumed back to the surface very rapidly, thus ensuring the survival of the high-pressure minerals. The exhumation mechanism is not fully understood but is currently of considerable interest for geodynamicists and metamorphic petrologists. Ernst (2001) reviews several collision belts in which crustal fragments were exhumed from conditions of around 2.8 GPa and 600–900°C. He emphasizes the role of fluids in catalyzing eclogite-forming reactions and in-forming andesitic melts. He argues that when hydrous phases fail to dehydrate to produce such fluids, the consequences can be the metastable preservation of low-pressure mineral assemblages and a lack of volcanism. He notes that crustal slices in which ultrahigh-pressure assemblages are preserved are normally very thin (1–5 km thick) and were exhumed back to the surface at rates as high as 10 mm per year. Finally, O'Brien (2001) compares the Alpine and Himalayan chains. As well as discussing the mesozoic and tertiary evolution of these collision belts, he reviews evidence from seismic tomography for the present-day deep structure. In the Himalayan region, the subduction of several thousand kilometers of oceanic lithosphere may explain the presence of magmatic arcs, in contrast to the Alps where the volume of subducted lithosphere was relatively small. It is suggested that the rapid exhumation of crustal rocks from great depths (>90 km) is a consequence of slab break-off, a process that can be identified below both mountain belts.

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