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The structure and dynamics of the mantle wedge

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Abstract

A large amount of water is brought into the Earth's mantle at subduction zones. Upon subduction, water is released from the subducting slab in a series of metamorphic reactions. The resulting flux into the mantle wedge modifies its chemical and physical properties by mineral hydration with associated weakening, flux melting and changes in the dynamics and thermal structure of subduction zones. Water guides the formation of volcanoes, earthquakes, continent formation and the long-term chemical evolution of the Earth's mantle. Recent observational advances include the better documentation of the role of water in causing melting from minor and trace elements in arc lavas, improved structure of the mantle wedge derived from seismic tomography, and documentation of hydration of the mantle wedge from converted phases. High-pressure experiments allow for a quantification of the role of water on seismic velocities and attenuation and rheological changes, which provide essential input into models of subduction zones. Computational models provide additional evidence for the importance of the mantle wedge in subduction zone dynamics.

Keywords: subduction zones; mantle wedge; arc volcanism; seismic tomography; modeling; geodynamics; geodynamical modeling; seismic anisotropy; deformation mechanisms; Benioff zones

1. Preamble

The study of subduction zones requires input from multiple disciplines, each with specialized vocabularies, which makes it sometimes challenging for a non-specialist to make optimal use of the existing literature. Similarly, some terms will have different usage among or meaning for particular groups of specialists. In an attempt to optimize the usefulness of this review and minimize the use of unexplained jargon I will provide a short discussion of various terms that I will use, starting with the main causes and consequences of deformation in subduction zones.

Subduction zones occur at the boundaries where tectonic plates converge. The main driving force of this motion is *buoyancy*, which can cause material that is warmer than its surroundings to rise in the field of gravity. Subduction is caused by the sinking of dense oceanic lithosphere and is therefore driven by *negative buoyancy*. Buoyancy is directly proportional to density differences, which can be both thermal and compositional (i.e., chemical) in origin. The driving forces only have an effect when the material is sufficiently

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weak to deform under the applied force. The type of *deformation* that takes place is strongly dependent on temperature, pressure, applied stress and composition. At the low temperatures near the Earth's surface most silicate rock deforms in a brittle fashion leading to faulting and earthquakes. At higher temperatures *viscous deformation* takes over, which is non-recoverable deformation that takes place as soon as a force is applied. The rate of strain depends on stress and the viscosity of the material. If the strain rate and stress are linearly related the material is called a *Newtonian fluid*. In general, the effective viscosity of mantle silicates depends strongly on temperature and pressure. Often, the viscosity depends on stress as well, in which case mantle silicates behave like a *non-Newtonian fluid*, where an increase in applied stress leads to a non-linear increase in strain rate. A typical example of such viscous deformation is the flow of olivine at mantle temperatures. The deformation is accommodated at the microscopic level by the movement of crystal defects such as *dislocations* that can glide and climb through the crystal lattice. The continued application of stress in a particular direction can lead to a structural reorganization of the crystals (*lattice-preferred organization*, or *LPO*), in which microscopic features, such as the well-known optical anisotropy of olivine crystals, start influencing the way we view assemblages of minerals at a macroscopic level. This is of particular importance for seismology, because seismic waves will travel at different speeds depending on what direction they move through a seismically anisotropic medium.

A particular expression of seismic anisotropy is seen in the splitting of S waves, where waves that vibrate in one particular direction (the fast polarization direction) move more quickly than waves that vibrate in any other direction. If for example a P wave in the core triggers S waves at the core–mantle boundary, the presence of splitting between fast and slow S waves (called *SKS splitting*) indicates that the wave has traveled through anisotropic regions. Seismic waves are a form of *elastic deformation*. A perfectly elastic medium recovers completely from deformation once the applied force (in this case the seismic wave) is released. In general, mantle silicates also exhibit a small amount of viscous, or permanent, deformation due to the passing of the seismic waves, which causes *seismic attenuation*, with corresponding reduction of the amplitude of the seismic wave. The seismic attenuation is quantified by the *quality factor Q*, which is inversely proportional to the attenuation.

The term 'phase' is used in multiple contexts. One is that of the aforementioned *seismic phases*, such as the P, S or Rayleigh phases. A second is the phase of a material, which indicates whether it is a liquid, solid or gas. An extension of this is the mineralogical phase, which describes the solid state of minerals as a function of pressure and temperature. Minerals and mineral assemblages undergo solid–solid phase changes when ambient temperature and/or pressure are varied sufficiently; the phase boundaries that separate the distinct phases form lines or curves on a pressure–temperature diagram. A particularly important phase boundary is the *solidus*, which indicates the pressure and temperature range at which a material first undergoes partial melting. Melting can be induced by an increase in temperature, which is probably the most familiar form of melting, but also by a decrease in pressure (*pressure-release melting*) or by changing the position of the solidus in the phase diagram. An example of the latter mechanism is *flux-assisted melting* that occurs when the influx of a fluid causes the melting temperature of a rock to be reduced to below the ambient temperature.

Various tectonic phrases that are used are partly illustrated by the figures. The downwelling limb of the subduction zone is called the slab, which is dominated by the cold *oceanic lithosphere* (a mechanical term) and includes the *oceanic mantle*, *oceanic crust* and sediments (which are compositional terms). The slab changes on its descent due to warming and chemical changes, such as the scraping off of the sediments to form the *accretionary wedge* near the trench and potentially the melting of sediments. Subduction zones are far more dynamic than can be indicated by the cartoons. An important tectonic mechanism is *trench roll-back*, which occurs when the sinking velocity of the slab is greater than the convergence velocity. In those cases the overriding plate is in tension and extensional features such as basins or even oceanic spreading centers can occur. Due to their location with respect to the arc and the trench these are called *back-arc basins* and *back-arc spreading centers*. For a more detailed overview of subduction zones and related terminology see [1].

2. Introduction

Subduction zones are the dominant tectonic features of the Earth. They form the location of the major underthrusting earthquakes, explosive arc volcanism and are the only sites of deep earthquakes in the Earth's mantle. The role of subduction zones in the plate tectonic framework is reasonably well understood from the near-surface observations (Fig. 1). Pressure-release melting of the Earth's mantle at mid-oceanic ridges causes differentiation into a basaltic crust overlying depleted peridotite. Interaction with seawater by hydrothermal circulation, potentially aided by deep fractures, and deposition of sediments derived from biogenic activity in the oceans and from continental erosion add to the chemical diversity. While the mid-oceanic ridges are generally considered passive features caused by the pull-apart of the surrounding oceanic lithosphere, subduction zones form the main driving force for plate tectonics, through the sinking of old and dense lithosphere. The deformation is accommodated by bending of the oceanic lithosphere and by large underthrusting earthquakes in the seismogenic zone. From a long-term, geological point of view the earthquakes efficiently decouple the motion of the subduction slab from that of the overriding plate. The seismogenic zone is commonly assumed to end at the continental Moho, which forms the transition between the crust and the mantle of the overriding plate. Below this depth, where the top of the slab is in contact with the mantle, earthquakes generally occur within the slab, rather than at the interface. The *Wadati–Benioff zones* of earthquake seismicity are generally planar features that follow the descent of the slab. In some subduction zones a double Benioff zone

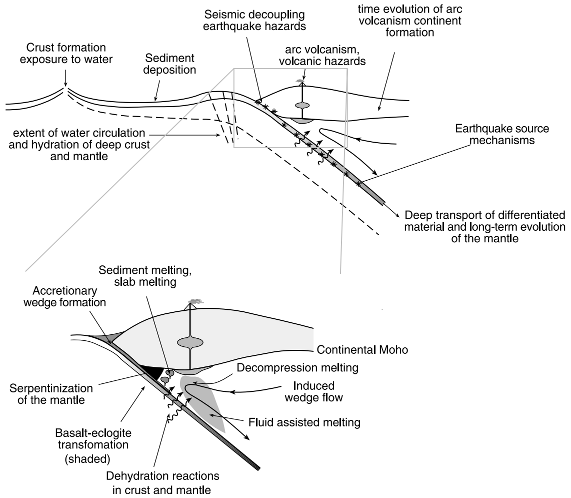

Fig. 1. Illustration of the importance of the mantle wedge environment in the structure and dynamics of subduction zones. Water released from the subducting slab by metamorphic reactions aids in the generation of arc volcanism and earthquakes. The release and transport of water and melt to the volcanic front is sensitive to the thermal structure of the slab and wedge environment.

is present, in which case a second plane of seismicity is observed at a depth of 20–50 km below the first plane. Down-dip from the seismogenic zone the slab is coupled to the overlying mantle and the viscous drag draws down the mantle along with the subduction slab. This flow in turn draws in mantle from below the overriding lithosphere (Fig. 1a). This zone of viscous deformation between the descending slab and the overriding plate defines the mantle wedge.

In addition to their dynamic and tectonic importance, subduction zones have a crucial role in the chemical evolution of the Earth. Upon subduction, the oceanic lithosphere encounters higher temperature and pressure, causing dehydration of sediments, oceanic crust, and hydrated portions of the oceanic mantle through a variety of metamorphic reactions. The flux of water into the overlying hot mantle wedge causes melting by lowering the melting temperature of peridotite. Partial melting of the subducted sediments and oceanic crust and pressure-release melting of the overlying mantle also contribute to the magmatism, which is responsible for arc volcanism and for the modification and formation of the continental crust. The deep subduction of the oceanic lithosphere is the major input of differentiated material into the Earth's mantle. The recycling of oceanic crust explains in part the observed chemical heterogeneity between basalts erupted at mid-oceanic ridges and those seen at hot spot islands.

In this review I will focus on the thermal structure and dynamics of the mantle wedge and its influence on subduction zone processes. A very important aspect that we need to consider first is the role of water in determining the physical and chemical structure of subduction zones.

3. The role of water in subduction zones

Large amounts of water are carried into the Earth upon subduction, both in the form of free water in sediments and oceanic crust and within hydrous minerals. The release of this water is thought to take place by dehydration reactions from the subducting oceanic crust and sediments in a near-continuous fashion to a depth of at least 200 km [2]. However, it is not clear how this water is transported to the volcanic front (e.g., [3]). The water that is liberated to the overlying mantle modifies the constitution and dynamics of the mantle wedge and has an important role in generating arc volcanism [4]. The dehydration reactions have also been considered an important candidate to explain intermediate-depth earthquakes in the slab [5,6]. The dehydration reactions and processes leading to melting and earthquake formation are strongly and non-linearly dependent on pressure (p) and temperature (T). The local (p,T) conditions are governed by the dynamics of the subducting slab and mantle wedge, which is determined largely by buoyancy and rheology. These in turn are strongly dependent on temperature and water content. These complicated and often convoluted processes take place at depth and are often hidden from direct observations. This makes study of subduction zones inherently difficult and a successful approach requires the integration of observational, experimental, and theoretical work. I will review recent developments in these fields in the sections below.

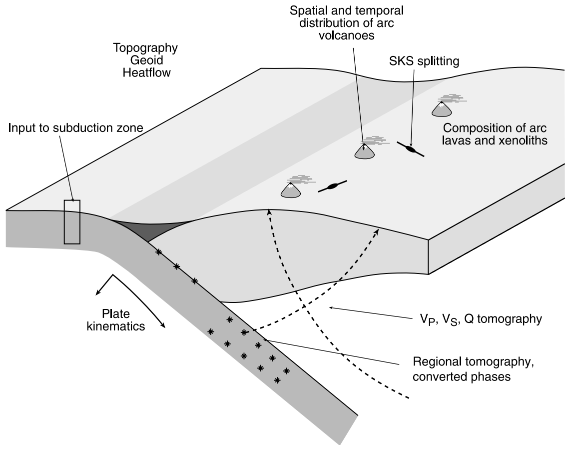

Fig. 2. Focus area of the main observational approaches that may be used to determine the physics and chemistry of the mantle wedge environment (see text).

4. The state of the slab and mantle wedge: observational constraints

Several observational approaches have been used to better understand the dynamics and the role of water in the mantle wedge (Fig. 2):

Input into the subduction zone

The hydration of the oceanic crust, mantle and overlying sediments determines the flux of water into the subduction zone [7]. It is therefore essential to understand the chemical composition of the incoming sediments [8], the potential for hydration of the oceanic crust and uppermost mantle through hydrothermal circulation and deep fractures [9,10] and shallow processes that modify the subduction zone input such as erosion along the margin and the formation of the accretionary prism (e.g., [11,12]).

Plate kinematics and paleogeography

The age and speed of the subducting slab provide major controls on its thermal structure. Model comparisons of young and slow vs. old and fast subducting zones show that the temperature at the slab–wedge interface can differ by several hundreds of degrees (e.g., [13]) with substantial consequences for the dehydration reactions in the slab [14]. The temporal evolution of slabs includes the effects of trench roll-back and continent–continent collision. Spatial complications can occur due to trench curvature and tears in the slab. These three-dimensional and time-dependent effects may have dramatic consequences on the near- and in-slab thermal structure.

Distribution of arc volcanism

The geometry of the volcanic arc in many areas can be described by the distribution of the distances between adjacent volcanoes, existence of volcanic gaps, and the possible existence of double arc chains (see [15], and references therein). In addition, the depth to the Benioff zone below volcanic arcs is typically around 100–125 km [4]. These geometrical relationships provide important constraints on the pathways of fluid and melt migration from the slab to the volcanic arc.

Composition of arc lavas

Chemical analyses of arc lavas provide fundamental constraints on the temperature and pressure conditions and the role of water in subduction zones. Glass inclusions in mafic arc lavas exhibit a wide range in water contents [16–19] which demonstrates the importance of water-assisted 'flux' melting in the wedge [4] but also indicates the presence of dry decompression melting in some arcs [20]. The enrichment of large ion lithophile elements (e.g., Rb, K, Cs) and light rare earth elements (La, Ce, Nd) compared to mid-oceanic ridge basalts also demonstrates the importance of slab-derived hydrous fluids in generating many arc lavas [21]. Equilibration temperatures of basaltic magmas provide constraints on pressure–temperature conditions in the mantle wedge demonstrating for example hot conditions (T = 1300–1450°C) at pressures corresponding to the quite shallow depth of 36–66 km in the Cascades [22]. Similar conditions are found in the Central Aleutian arc [23]. Arc lavas contain specific trace elements, such as B, Be, Th, and Pb, that are thought to derive from the slab. Elements such as B can be transported easily in aqueous solutions, but the efficient recycling of Be and Th from subducting sediments [24] appears to require sediment melting. The fluid-saturated solidus at 2 GPa has been measured, for different sediment compositions, between 650°C and 750°C [2,25,26]. High temperatures at the slab–wedge interface are also necessary for the melting of basalt or gabbro as inferred from high Mg andesites [27,28] although this is generally limited to arcs that are formed by the slow subduction of young oceanic lithosphere.

Seismic studies

The high seismicity of most subduction zones provides ample data for high-resolution seismic tomography which allows for determining the spatial structure of seismic P (v_p) and S wave velocities (v_s) and attenuation (Q^{-1}). Reflection and refraction studies make it possible to include the location of boundaries with high velocity contrasts, such as the Moho and Conrad discontinuities. Estimates of the position of the slab–wedge interface can be based on local tomography, hypocenter distribution and converted phases. A priori inclusion of these boundaries may greatly improve the quality of the tomographic inversion, particularly from the wedge perspective (Fig. 3) [29]. In most arcs, the seismic structure of the mantle wedge is characterized by an extensive zone of low seismic velocity that connects the plate–wedge interface between 150 and 200 km depth to the volcanic front or back-arc basins [30–35] although in some cases, such as in the Bolivian Andes, the velocity and Q anomalies in the wedge are much reduced [36]. Mapping attenuation is more complicated due to the influence of geometrical effects on the amplitude of seismic waves [37] but common observations of Q in subduction zones point to high attenuation below the volcanic front [38,39] which are generally in good agreement with regions of low seismic velocities [40,41].

P-to-S conversions occur when compressional seismic energy hits an interface between layers and triggers shear waves. The observations of P-to-S conversions in seismic records can be used to try to identify important interfaces in subduction zones such as the top of the slab [42]. In some instances complex conversions are observed that can be explained by a thin (10 km) anisotropic layer at the top of the slab, which could be evidence for the presence of a shear zone [43]. Converted phases also hint at the presence of hydrated oceanic crust to a depth of 250 km below subduction zones in the NE Pacific, suggesting that dehydration of the slab may not be complete upon fast subduction of old slabs [44,45]. The absence of a Moho in the tip of the mantle wedge

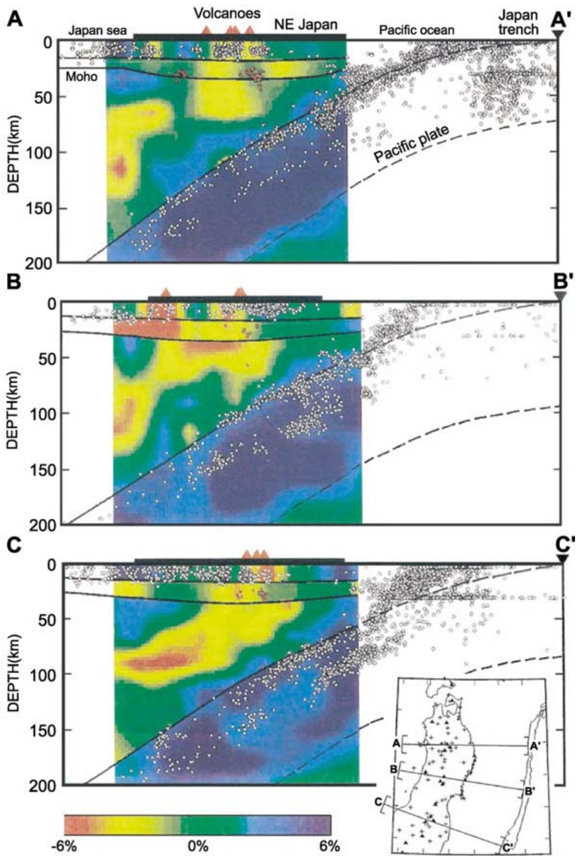

Fig. 3. Cross-sections through the P wave velocity structure under Japan as determined by Zhao (from [29]). Circles indicate earthquakes, triangles indicate active volcanoes. Thick curves indicate the location of the Moho, Conrad, and slab–wedge discontinuities that were used as a priori constraints in the tomographic inversion.

under Central Oregon, as seen in studies of teleseismic phases [46] and confirmed by reflection seismics [47], suggests widespread serpentinization of the fore-arc mantle. Serpentinite is an upper mantle rock that is of particular interest to subduction zone researchers because it can store significant amounts of water. Similar conclusions about widespread hydration of the mantle wedge are drawn for the Izu-Bonin subduction zone that is characterized by the occurrence of serpentine seamounts, which may be fed diapirically from the mantle wedge [48]. The weakening of the mantle associated with the serpentinization provides lubrication between the slab and overriding plate and can therefore help explain the down-dip limit of large underthrusting earthquakes in Cascadia and the near-absence of large earthquakes at shallow depths in Izu-Bonin. Serpentinite-aided decoupling between slab and wedge has also been suggested from the occurrence of exhumed eclogites in the Himalayas [49].

Observations of shear wave splitting have provided very interesting, though puzzling results for seismic anisotropy in the mantle wedge. Experimental and observational evidence suggests that olivine crystals align with mantle flow through the development of lattice-preferred orientation and that therefore the seismically fast directions in the uppermost mantle record the direction of the flow (e.g., [50]). For the simple configuration sketched in Fig. 1 we would predict that the olivine crystals align perpendicular to the trench. Although this prediction is borne out in a few locations [51–54], a more common observation is that the fast axis is (nearly) parallel to the trench [54–58]. This could be due to oblique convergence, remnant anisotropy or crustal processes, but an often-cited explanation is that this represents the actual flow direction in the wedge or the mantle underneath the slab. This may represent arc-parallel extension in compressive back-arcs [59], slab roll-back and escape of the underlying mantle as suggested from observations from the Andes [54,55], or mantle flow around tears in the subducting slab as suggested for Kamchatka [60,61] and Tonga [62,63]. Interestingly, zones of low velocity and high attenuation in Japan are also highly anisotropic [51,64] possibly due to alignment of magma-filled cracks.

Electromagnetic studies

Techniques using electromagnetic methods have been used to map high-conductivity areas in convergent margins [64–67] that can be interpreted as regions with high water and/or melt content. In general these studies are limited to depths of about 40 km [68]. In some cases deeper images can be obtained, such as those of the potentially fluid-rich zone in or above the Cocos slab to 150 km depth [69] and the conductor in the Andean mantle wedge between 80 and 180 km depth, which correlated well with models of seismic attenuation [70].

Heat flow, topography, gravity and geoid

The heat flow variations across subduction zones provide important constraints on the thermal structure. In general the heat flow in the fore-arc is low due to the subduction of cold lithosphere, moderately high in the back-arc and high in the volcanic arc (e.g., [71–73]). In the Cascades, the steep increase in the arc correlates strongly with the presence of volcanoes, hydrothermal fields, and the presence of a pronounced negative gravity anomaly, which can be explained by the presence of extensive melting at mid-crustal depths [72].

The geoid and topography over subduction zones provide additional, if indirect, constraints on thermal structure and dynamics since they are sensitive to the distribution of buoyancy and viscosity in the Earth's interior (see [74,75] for recent overviews). In summary, the topography is influenced by the age of the oceanic lithosphere, crustal variations and dynamics, such as the sinking of the slab and the corresponding mantle deformation. At short wavelengths, the geoid shows a minimum that corresponds with the deep trench topography, but in most subduction zones a positive anomaly is seen above the arc side. This can be attributed to resistance to slab subduction in the deep mantle, most likely due to an increase of viscosity at the base of the mantle transition zone.

5. Experimental approaches

The interpretation of the observations is greatly aided by experimental studies of Earth materials under high temperature and pressure. For example, melting experiments provide temperature and pressure constraints on the formation of melts that are observed with specific major or trace element compositions [17,21,24,25]. Predictions for the mineralogy and related seismic properties based on laboratory measurements and theoretical models allow an interpretation of seismically observed velocity variations. Deformation experiments allow for interpretation of the development of lattice-preferred orientation and provide the basis for the rheological description of dynamical models.

Of particular interest is the role of water in modifying the physical properties of mantle minerals. Many hydrous minerals significantly reduce friction coefficients [76] and subduction of clay minerals can provide decoupling between the slab and wedge, at least in the depth and temperature ranges in which these minerals are stable. High temperatures in the majority of the subduction zone and mantle wedge prevent stability of hydrous minerals, but significant amounts of water can be dissolved in the form of hydrogen (H^+) and hydroxyl (OH^-) ions in minerals such as olivine [77,78]. The associated hydrogen-related defects and enhanced grain boundary processes in minerals cause important changes in electrical, seismic, and slow creep properties [79–82], which allows for the prospecting of water in the Earth's mantle using various observational techniques. A recent overview of this approach is provided by Karato [83] who observes that: (1) major element chemistry strongly influences seismic velocities (v_p, v_s, and v_p/v_s) through the elastic properties; (2) attenuation and plastic deformation are coupled and both are strongly influenced by the concentration of water as has been described quantitatively by high-pressure experiments [84]; (3) high water content of olivine can change the dominant slip system and substantially change the formation of lattice-preferred orientation compared to dry olivine [82]; (4) the effects of water and partial melt on seismic velocities is similar, but the effect of water on attenuation is much stronger than that of partial melt [85–87]; (5) it is unlikely that a sufficiently high melt fraction can be sustained in the minerals [88] and that seismic properties are unlikely to be affected by partial melting. Application of these findings to the seismic observations confirms the low melt fraction in the mantle wedge and suggests high water concentrations, in excess of 1000 ppm H/Si [83]. In addition it is predicted that the change in dominant slip system in wet olivine causes trench-parallel SKS splitting, which is similar to that observed in many subduction zones [82].

The influence of water on the seismic properties of mantle minerals can also be investigated using phase diagrams of the major rock compositions computed from theoretical and experimental thermodynamics (e.g., [14,89]). Application of these techniques suggests that the lower oceanic crust worldwide is partially hydrated and that the high v_p/v_s ratio obtained from seismic tomography can be explained by up to 20% alteration of the wedge to stable hydrous minerals such as serpentine [14]. In addition, the existence of a thin low-velocity layer in the subducting slab at a depth of 100–250 km may be explained by the seismic properties of lawsonite eclogite indicating the presence of hydrated minerals at those depths [89]. In general, the high v_p/v_s ratio has been used to confirm the presence of water or fluid-filled cracks [48,90,91].

At the high pressures and temperatures below 50 km depth most minerals are predicted to deform plastically and it is difficult to explain earthquakes below that depth by brittle failure. In recent years it has become clear that dehydration of hydrated minerals can cause temporary brittle behavior in the minerals. Dehydration embrittlement has therefore been suggested as a possible mechanism for the generation of intermediate-depth earthquakes [5]. The observation of acoustic emissions during the experimental dehydration of serpentine [92] strengthens this suggestion. Similarly, the correlation of large earthquakes with low-velocity zones in Japan [93] and the presence of earthquake clusters in low-Q areas [39] are indicative of the role of water in earthquake generation. Dehydration embrittlement has also been suggested as an explanation for the occurrence of the second plane of seismicity in double Benioff zones. For example, Peacock [6] suggests that the upper plane of seismicity can be explained by dehydration of basalt during the transformation to eclogite while the lower plane of seismicity is caused by serpentinite dehydration. The pressure and temperature conditions that are predicted at the locations of the lower-plane earthquakes are consistent with the proposal [6,94].

6. Subduction zone modeling

Computational modeling of subduction zone thermal structure and dynamics provides quantitative tests that employ the fundamental laws governing the conservation of mass, momentum and heat. Attempts have also been made to simulate the dynamics of subduction zones using analogue models of viscous flow in laboratory tanks. In combination with the observational and experimental approaches, these modeling studies provide important quantitative constraints to conceptual ideas (as expressed for example by the cartoons sketched in Fig. 1). Models for subduction zones are based on a description of the interaction between the main driving force (the negative buoyancy of the subducting slab) and the rheological response of the slab, overriding plate and underlying mantle.

The incorporation of these physical processes in computational models is part of the development towards a full understanding of the dynamics of subduction zones, which is currently incomplete. Major obstacles exist in the road to full self-consistent models of subduction, particularly because of our lack of understanding of the role of rheology and the interaction of physical processes at short spatial and temporal scales with those of interest at geological scales. Nevertheless, substantial progress has been made in recent years. See [95] for a recent review of the approaches that may lead toward the integration of plate tectonic processes in mantle convection models.

7. The cornerflow model for wedge dynamics

As a consequence of the incomplete dynamical description of subduction many researchers have focused on models that describe the slab kinematically and focus on the dynamics of the wedge and geometry of the overriding plate. In some cases analytical solutions describing the temperature distribution in subduction zones can be found after a number of simplifying assumptions (e.g., [96–98]). Due to the growth of computational resources, it has become common to use numerical methods, such as finite-element or finite-difference methods, which allow for accurate and consistent solution of the heat equation and solution of the dynamical equations in the mantle wedge.

It is common to associate mantle wedge dynamics with the cornerflow model as sketched in

Fig. 1. The main features of this model are the viscous coupling of the subducting plate below the seismogenic zone, the associated advection of mantle wedge material to greater depth, and the resulting flow of mantle from under the overriding plate into the corner formed by the base of the lithosphere of the overriding plate and the top of the slab. If the boundaries of the flow are straight planes and the wedge flow is isoviscous an analytical solution exists [99], which has been conveniently exploited in various models of the subduction zone thermal structure (e.g., [11,96]; see [100] for a review).

The isoviscous cornerflow model is conceptually instructive, but oversimplified because of its assumptions of the geometry, driving forces and rheology. The sketch in Fig. 4 indicates a number of physical processes that should be taken into account in order to develop a better understanding of wedge dynamics. These include: (a) slab parameters such as geometry, age and speed; (b) slab evolution, with particular emphasis on temporal variations in slab age and speed, trench migration and 3D effects such as slab tearing and inflow of mantle material around slab edges; (c) the nature of the overriding plate, in particular the rheology and buoyancy of the crust and uppermost mantle; (d) the rheology of the wedge which is influenced by temperature, pressure, strain rate, and composition (including the distribution of hydrated minerals, water, and melt); (e) buoyancy forces in the wedge, which become important upon sufficient reduction of mantle wedge viscosity. This potentially adds a secondary type of convection in addition to the main circulation driven by the sinking of the slab.

In recent years, several studies have addressed one or more of these issues using kinematically driven or fully dynamical models of subduction zones. For example, it has been shown that the rheology of the wedge exerts important controls on the thermal structure of the slab and wedge environment [101–105]. The strong temperature dependence of mantle silicates causes a distinct change in the mantle flow pattern compared to isoviscous calculations. Fig. 5 shows the thermal structure of the Izu-Bonin subduction zone as recalculated from [106] using the high-resolution finite-element approach described in [102]. The results for an isoviscous wedge (Fig. 5a) show the inflow of hot material from the back-arc into the toe of the mantle wedge. The effects of temperature-dependent viscosity (Fig. 5b) much enhance this flow into the wedge tip as a non-linear consequence of the reduced viscosity in the hot regions. The strong increase of the temperature at the slab–wedge interface leads to strong temperature gradients in the sediment and oceanic crust of the slab. This may explain the apparent conflict between high slab temperatures derived from the melting of sediments [25] and the lower temperature estimates from the release of B [107] if we assume that the boron is released from dehydration reactions in the oceanic crust that is still relatively cool [102].

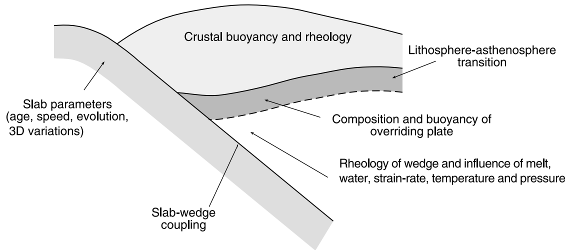

Fig. 4. Illustration of the main dynamical controls on the mantle wedge environment.

The steady-state results show the balance between heat advected into the wedge towards the slab and the cooling of the top and slab sides of the wedge. In this model the effects of thermal buoyancy in the wedge are ignored. Substantial low-viscosity regions may develop because of high temperature, high strain rate, and high volatile content, in which case thermal buoyancy and related time-dependent convection may become important in the mantle wedge [105]. The distinct upward component of flow towards the trench side of the wedge could provide a moderate contribution of pressure-release melting to the arc lavas [103].

The geometry of the wedge in Fig. 5 is controlled in part by fixing the depth of the overriding plate (50 km) and decoupling the interface between the slab and wedge to a depth of 70 km. Both assumptions keep the wedge flow from rising to shallower depths towards the trench. If

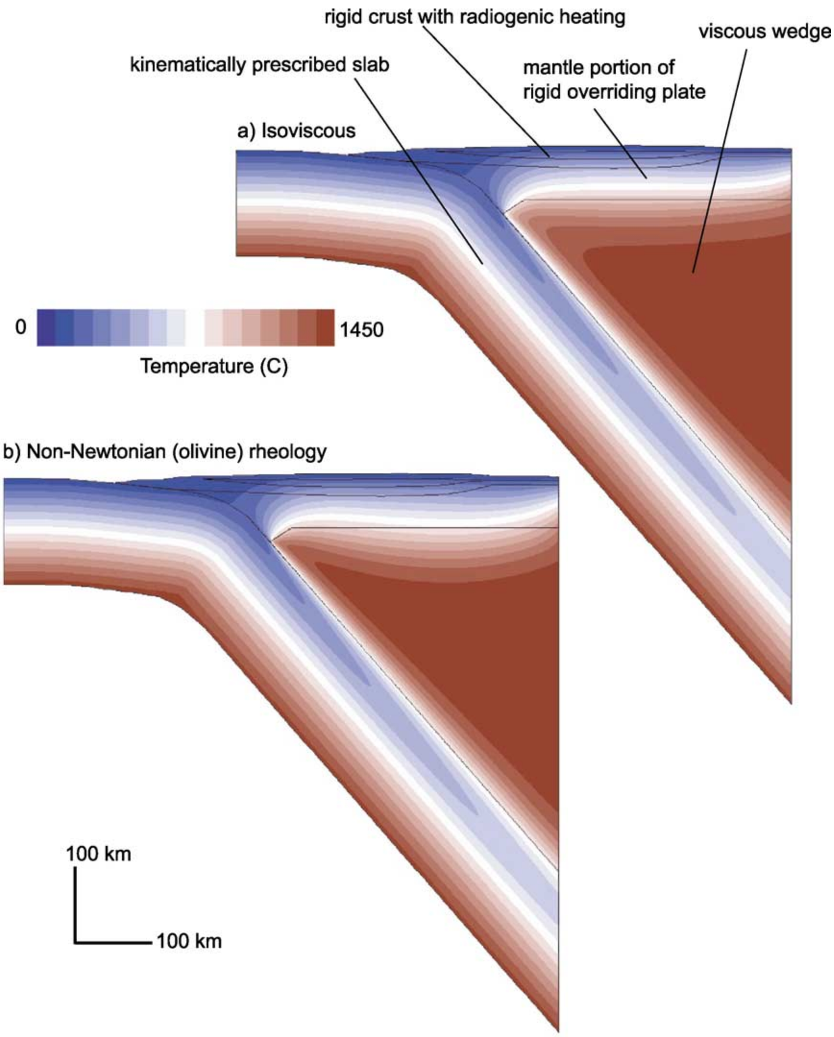

Fig. 5. Steady-state thermal model of the Izu-Bonin subduction zone demonstrating the strong difference in wedge dynamics between a wedge with isoviscous (a) and non-Newtonian (b) rheology. The non-Newtonian rheology is based on a dislocation creep law for olivine [124]. The modeling follows that of [102] closely. For this model the age of the incoming oceanic lithosphere is 130 Myr and the convergence speed is 56 mm/yr. The temperature at the arc side boundary is that of a 20 Myr oceanic lithosphere. The crustal model is based on seismic studies [125]. Crustal radiogenic heating is 1.3 $\mu W/m^2$ in the upper crust, 1.0 $\mu W/m^2$ in the middle crust and 0.27 $\mu W/m^2$ in the lower crust. There is no shear heating imposed. The temperature dependence of olivine causes focusing of the flow toward the tip of the wedge with a significant increase of the slab surface temperature.

the overriding plate is described in a more consistent manner, by the formation of the cold lithosphere of the overriding plate, the depth of decoupling between the slab and wedge becomes dominant. A logical upper limit to this depth is the down-dip extent of the seismogenic zone. This is typically at the Moho around 40 km depth [108] but note that on occasion this can be significantly deeper such as in the Andes [109]. A shallow limit to the decoupling zone causes the influx of hot mantle close to the Earth's surface [103,105]. This has been used to explain the presence of pressure-release melting [103] or components of slab melting in arcs overlying old oceanic lithosphere [105]. It should be noted that this type of model requires an offset in the maximum of heat flow away from the location of the volcanic arc toward the trench and the assumption that the observed high heat flow over the volcanic arc is dominated by conductive, rather than advective processes dominated by the emplacement and slow cooling of plutons [72]. The strong thermal erosion that is predicted in these models has been used to suggest that the compositional buoyancy of the overriding plate, rather than its rheology, controls the geometry of the overriding plate [110]. The hydration of the overlying wedge provides another important mechanism to reduce the thermal erosion of the overriding plate by decoupling the slab and wedge to greater depths [101]. Dynamically it can be shown that the decoupling is required in order to have any thermal erosion of the overriding plate, since otherwise the overriding plate is entrained and the subduction becomes two-sided (e.g., [104]).

8. Dynamic subduction models

In recent years we have also seen a better development of subduction zone models in which the slab is not kinematically prescribed but sinks dynamically under its own weight. It is necessary to provide some form of decoupling between subducting and overriding plates in order to allow for one-sided subduction to take place. Most recent work includes the use of weak zones [74,111] or special finite-element formulations that allow for this decoupling in viscous models [112,113].

Dynamical models allow for the investigation of the trade-off between driving and resistive forces and the time-dependent evolution of subduction zones. For example, models of subduction zone initiation [111] suggested that the slab surface temperature reaches a steady state after some 500–600 km of subduction and that variable viscosity causes the stagnation of the slab wedge corner due to the cooling from the initial state, although it can be expected that the effect of volatilization of the wedge will counteract this rheological effect. The subduction of oceanic plateaus provides additional chemical buoyancy. This may cause flat subduction, unless counteracted by the increase in density of the oceanic crust upon transformation to eclogite [113]. The observed flat subduction in for example the Andes or Shikoku (Nankai trough) suggests that the basalt must remain metastable in the eclogite stability field, which appears consistent with the seismic observations in Japan [114]. A study on the relative contribution of slab driving forces in the presence of trench roll-back for starting slab shows the formation of an eddy in the back-arc region which causes shallow slabs to be sucked up to the overriding plate [115]. These last few studies strongly suggest that the mantle wedge has to be weak.

In contrast to the kinematically driven cornerflow models these dynamic models allow for the calculation of dynamic topography, which allows for use of the observed topography and geoid in validating the models [74,75,111,116]. Instantaneous 3D flow models for the Tonga subduction zone show that the mantle wedge has important consequences for the force balance. A substantial viscosity reduction is necessary to explain the observed gravity and geoid [116] as well as the presence of back-arc extension and shallow slab compression, and absence of deep back-arc basins [75].

Computational models have also been used to investigate the development of seismic anisotropy [117–119]. The use of strain markers allows for the prediction of regions where anisotropy may occur with associated directions and magnitude. These studies so far have concluded that strong flow parallel to the strike of the subduction zone is necessary to explain the observed SKS splitting signals.

9. Perspective

In recent years, the combined use of observational, experimental and theoretical work has yielded significant advances in our understanding of the mantle wedge environment. We can identify a number of key areas of future research in which the role of water is particularly important:

1. Input to the mantle wedge through the dehydration of the slab. Associated with this are the role of metamorphic reactions in generating

seismicity and volcanism, as well as quantification of volume of flux melting compared to slab or decompression melting and the ability of water transport to the deep mantle [120].
2. Transport of water and melt from the slab to the volcanic front [3]. It is still largely unknown whether melt is transported through cracks, in diapirs or by porous flow [15,121, 122] although recent laboratory models in conjunction with seismic observations of the correlation between volcanoes and the velocity structure in the shallow mantle may suggest a revival of the diapiric transport model [121].
3. Role of water in changing rheological and seismological properties. This is essential for understanding how geophysical tools can be used in prospecting for water [83] and for improving dynamical models of subduction (e.g., [123]).

Successful answers to the questions above will require input from multiple disciplines. The complicated nature of subduction zone research makes it essential to strengthen existing and foster new interdisciplinary research. A potentially important contribution to such integration may arise from the further development of computational models. A primary contribution of modeling is the potential for checking the validity of hypotheses using conservation laws as fundamental constraints. In addition, it provides the mechanism to visualize the structure and dynamics, allows for the integration of experimental results and provides a direct comparison with observations. The virtual explosion of affordable computing power also adds the potential for Monte Carlo-style parameter searches, which should eventually lead to the development of formal inversions of surface observations to yield the subsurface structure.

There are several avenues towards improvements and extension of existing models. We may expect that in the next few years we will see major developments, for example, in the understanding of the thermal and petrological conditions in subduction zones by tracing chemical input into thermal models and comparing the predicted volcanic outputs with the observations; in the ability to explain subduction zone anisotropy using dynamical models that incorporate experimentally derived creep laws for the mantle which in turn will shed light on the 3D dynamical structure of subduction zones; and in the further development of physical mechanisms for intermediate seismicity that combine thermal modeling with laboratory work and seismology.

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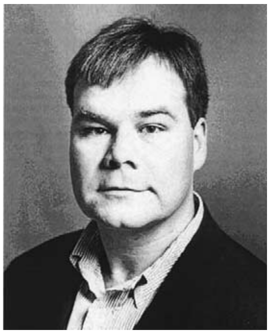

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