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Book Review

Inside the Subduction Factory

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Subduction zones, where Earth's lithospheric plates return to the deep mantle, are responsible for spectacular explosive volcanic eruptions, the planet's greatest earthquakes, and some of our most valuable concentrations of economic ores. Subduction's delivery of surficial materials to the mantle means that it plays a primary role in terrestrial element cycling. On a larger scale, subduction helps drive plate tectonics, as plate movement is chiefly driven by the downward pull of oceanic slabs sinking into the mantle. Moreover, the magmatism generated at convergent margins most likely accumulated over time to generate the continental crust.

The raw materials of subduction zones include the downgoing lithospheric slab, which is composed of altered oceanic crust and mantle lithosphere with a veneer of sediment. Lithosphere and asthenosphere are trapped above this slab, forming a wedge of mantle material. Subduction generates strong thermal and chemical disequilibrium, which causes mineral transformations, slab devolatilization, melting and perturbations of mantle flow. Thus, subduction zones process inputs (subducted material and incoming asthenosphere) to generate outputs (volcanic products, residues expelled to the deep mantle) by performing mechanical and chemical work. From this description, subduction geosystems call to mind the metaphor of an industrial plant. But if the analogy holds, this is a factory which conducts much of its business in a remote and guarded location, deeply buried and out of view of geoscientists who wish to understand its inner workings. We gain insight only through a few grimy windows. The AGU Monograph *Inside the Subduction Factory* is a guided tour through this tectonic sweatshop that serves to summarize our understanding of the machinery and inner operations of subduction zones. The volume does not claim completeness; rather, it highlights some of the key standing or emerging issues in the study of this setting. The volume is of interest to *Geofluids* readers because much of the chemical and physical work involves H_2O, and the papers highlight the fact that the contributions of H_2O remain one of the least understood – hence most exciting – aspects of the subduction factory.

The papers in the volume are organized into four thematic sections: the subducted slab, the mantle wedge, natural subduction systems, and syntheses. This organization provides a simple progression through the topic. However, the ordering of the papers, to an extent, shifts focus away from the fundamental problems at the forefront of subduction-zone studies. The contributions address, to varying degrees, four cutting-edge questions about subduction zones: (1) How do temperature, composition and rheology of the mantle wedge differ from upper mantle elsewhere in Earth? (2) Where do melts form in subduction zones and what processes control their characteristic compositions? (3) What governs the thermal structure of subduction zones and how does it influence their evolution and internal processes? (4) To what extent can knowledge of geophysical structure and geochemical inputs and outputs be combined to construct a predictive model of particular subduction zones? These questions provide the framework for an alternative path through *Inside the Subduction Factory.*

PROPERTIES OF THE MANTLE WEDGE

Visualization of mantle structure has improved because of the steady advance of tomographic studies. The images of subduction zones from these investigations are so informative that they are now found in virtually every modern introductory Earth Science textbook. Although typically constructed using gradational red–blue color schemes (which evoke temperature variations in the image area), the causes of the anomalies and their variations are not certain. After a useful review of seismological and electromagnetic techniques by Helffrich, Wiens and Smith provide an excellent summary of the anomalies in seismic velocity and attenuation which yield such striking views of subduction zones. Variations in temperature, partial melt, and volatiles are probably the predominant controls on perturbations in the mantle wedge. By comparing the magnitudes of observed anomalies in well-studied subduction zones, Wiens and Smith infer that low-velocity regions typically imaged immediately above slabs represent hydrated mantle, primarily related to minor H_2O in olivine. In a separate chapter, Karato reaches the same conclusion by applying a model of the effect of H_2O on olivine properties. The low-velocity regions could be the source region of many arc magmas.

A topic of growing interest is seismic anisotropy, which holds promise for imaging the mantle flow pattern in the wedge. Karato and Wiens and Smith show that both trench-normal and trench-parallel flow are observed. This may result from complex balance between viscous coupling and trench rollback, along with local subduction geometry.

If the flowing mantle wedge contains minor, variable H_2O in nominally anhydrous mantle minerals, chiefly olivine, then it is essential to understand the links between H_2O and olivine rheology. The paper by Hirth and Kohlstedt reviews the voluminous experimental work on this problem. H_2O in olivine (as H-related point defects) may reach 0.1 wt %, and it exerts a fundamental control on mantle rheology by lowering viscosity, all else being equal. Hirth and Kohlstedt summarize a variety of constraints that point to low mantle-wedge viscosities, consistent with high water content and temperature.

MAGMA GENERATION IN SUBDUCTION ZONES

The seismological, mineral-physics, and rheologic constraints on the mantle wedge provide excellent background for papers on magma production in subduction zones. The most salient fact is that arc magmas contain more H_2O than any other terrestrial magma type. Gaetani and Grove draw chiefly on experimental studies to show that H_2O plays a major role in the production of melt in subduction zones. H_2O is quite soluble in partial melts from peridotite, leading to reduced melting temperature and changes in melting reactions and major oxide concentrations. H_2O also modifies physical properties, causing an increase in melt connectivity and decreases in density and viscosity, which lead to highly efficient separation of H_2O-rich melts from their sources. The chapter by Tatsumi builds on the experimental framework reviewed by Gaetani and Grove. He notes that there are systematic variations in the locations and distributions of volcanoes and magma chemistry in arcs that offer clues about melting mechanisms in the mantle wedge. Tatsumi suggests that variations in extent of hydration and melting of mantle-wedge peridotite exert the main controls on melt production in volcanic arcs.

Gaetani and Grove and Tatsumi show that melting in subduction zones is complicated and may occur by several processes simultaneously in the same system. Flux of H_2O from the slab may trigger melting deep in the mantle wedge. In addition, adiabatic decompression melting occurs in the shallow mantle where hot mantle flows trenchward from the back arc into the wedge corner. A third possible process is melting of hydrous mantle diapirs during buoyant ascent. Although Tatsumi has previously supported this mode of magma genesis, recent constraints on magma ascent velocities from U-series disequilibria make it unlikely, a point made both by Tatsumi and by Gaetani and Grove.

The source of the all-important H_2O enrichment that gives arc magmas their distinctive properties must ultimately be the subducted slab. But arc magmas also carry other chemical signals from the slab. How are these slab tracers delivered to arc magmas? One way to answer this question is to study those trace elements and isotopes in magmas which give insight into the melt source. Elliott provides a useful review of this subject. End-member models for the origin of the slab signal include direct melting of the sediments and/or altered mafic rocks of the slab, and transport of key elements to the site of melting by an H_2O-rich fluid liberated by metamorphic dehydration reactions in the slab. Elliott concludes that trace element systematics of arc magmas require that both occur. While this is perhaps unsurprising, the real advance is that relative contributions of these two processes can now be quantified and compared from arc to arc. Moreover, such results can be combined with U-series isotopic studies with great success. For example, Elliot highlights the exciting observation that magma ascent velocities must be quite rapid in systems in which lava geochemistry points to transport of the slab signal by H_2O, but slow where sediment melt is the likely carrier of slab tracers.

THERMAL STRUCTURE OF SUBDUCTION ZONES

Elliott's conclusion that part of the slab signal in arc magmas may be delivered by sediment melts brings into focus another key issue in the study of subduction zones. Many early models of melt production in this setting assumed that the slab itself partially melted to produce arc magmas. However, this model was largely abandoned as it became clear that most thermal models suggested that, beneath the arc front, temperatures were too low to melt metamorphosed sediments or basalts of the slab. Moreover, experimental studies reveal that it is extremely difficult to generate primitive basaltic arc magmas by such a simple mechanism. This led to models in which most arc magmas were produced by flux melting of mantle wedge peridotite, with the slab signal carried as dissolved solutes in H_2O. Slab melting has been viewed as exceptional, occurring only in the hottest subduction zones. But in view of the robust indications that slab sediments are a component in some arc magmas, it is necessary to revisit the thermal models of subduction zones.

Inside the Subduction Factory contains two chapters on the thermal structure of subduction zones. These contributions – fittingly, the first and last chapters of the volume – suggest that thermal structure remains at once a poorly understood yet important aspect of subduction zones. Peacock shows that subduction-zone thermal structure depends on the convergence rate, the age of incoming lithosphere, slab geometry, shear stress and the mantle-wedge flow field. The first three parameters are generally well known for any specific subduction zone, but the last two are not. When a simple isoviscous model of the mantle wedge is used, shear stresses can be adjusted within reasonable limits to reproduce key independent observables such as surface heat flow, metamorphic conditions, trench topography and the upper plate stress field. Further argument that the models are returning realistic pictures of the heat budget at depth is the conclusion that the arc fronts in modeled subduction systems directly overlie the locations of key dehydration or dehydration–melting reactions in the slab. These results are generally consistent with, and to a large extent inform, the 'standard model' of hydrous mantle–wedge melting several tens of kilometers above the slab.

A key problem with these models is that the simplifying assumption that the mantle-wedge viscosity is constant results in relatively cool P–T paths. Kelemen *et al.* present models which show that, when more realistic temperature-dependent parameterizations of mantle wedge viscosity are employed, hotter slab temperatures are predicted. The predicted high temperatures at the slab–mantle interface are consistent with some heat flow data and geothermal gradients inferred from studies of exposed sections of arc lower crust. These models support melting of subducted sediment and even metabasalt over a much wider range of subduction parameters and may help explain the conclusion that some form of slab melting appears to be quite common in subduction zones.

MODEL NATURAL SYSTEMS

In light of the questions addressed or raised by the chapters discussed above, how close are we to being able to link geological, geophysical and geochemical observations to explain individual subduction zones? Three chapters provide overviews of well-studied systems which were, at the time of writing, focus areas for the Margins program of the U.S. National Science Foundation. These include the Izu–Bonin–Mariana system (Stern *et al.*), the Central American system (Carr *et al.*), and the Aleutian island arc (Kelemen *et al.*). The three systems differ in terms of fundamental controlling parameters – for example, age of incoming crust, thermal structure, and amount of subducted sediment. Stern *et al.* give a comprehensive review of the Izu–Bonin–Mariana subduction system. Any reader seeking a thorough synthesis of the geology, geophysics and geochemistry of a single subduction zone should begin here. By contrast, Carr *et al.* and Kelemen *et al.* focus almost exclusively on geochemistry. The Central American subduction system displays regional trends in a suite of key geochemical tracers. These trends help constrain the variations in slab component and controls on melting. Similar results are obtained for the Aleutians, but implications are explored at a more fundamental level. In particular, Kelemen *et al.* conclude that primitive andesites in the western Aleutians do not derive from basalt fractionation, but rather from eclogite melting followed by reaction with the mantle wedge during ascent. It is inferred that this process is essentially common to most subduction zones, but is obscured where the mantle wedge produces larger volumes of basalt than in the western Aleutians. Kelemen *et al.* propose that this model leads to calculated melt compositions which agree well with the average continental crust – an important test of any model, since it is generally accepted that the continental crust represents the time-integrated products of arc magmatism.

CONCLUDING REMARKS

Inside the Subduction Factory provides an excellent overview of what is known and unknown about subduction zones. It is by no means a complete survey – for example, there are no contributions on magnetotellurics, seismicity, accretionary wedge processes, or slab rheology – but the monograph is nevertheless an extremely useful exploration of many of the key processes at work in the subduction factory. Because fluids participate in virtually all these processes, *Inside the Subduction Factory* is an essential addition to the libraries of researchers interested in geofluids in the solid Earth.

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